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Enhanced Coal Exploitation through Underground Coal Gasification in European Lignite Mines

(COAL2GAS)

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Enhanced Coal Exploitation through Underground Coal Gasification in European Lignite Mines (COAL2GAS)

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Enhanced Coal Exploitation through Underground Coal Gasification in European Lignite Mines

(COAL2GAS)

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1. FINAL SUMMARY

WP1: Coordination and Reporting

WP Leader: ISPE Partners: GIG, DMT, CERTH, MCE, TNO, CEO, VELEN

WP1's scope was to provide reports and communications regarding the research results throughout the COAL2GAS project. The Annual, Mid-term and Final reports were submitted to the European Commission and TGC1. As means of dissemination used during the project, a project website (www.coal2gas.eu) was organised and five technical papers were published based on research conducted within the project (this year two more papers have been accepted for publication). Additionally, presentations were given on international scientific conferences. On 27th of June 2017, ISPE organised the COAL2GAS dissemination workshop. The event was attended by about 40 representatives of governmental authorities, coal and power industry, private companies and RDI institutes, students and academia. All coordination activities took place as scheduled in the Technical Annex.

WP2: Data Analysis and Site Selection

WP Leader: DMT Partners: ISPE, CEO, MCE, GIG, CERTH, VELEN

Work Package Objectives

The main objective of this WP is to determine the conditions and parameters of the Oltenia deposit and other European deposits and to learn from phenomena like coal fires, with the aim of site selection and transfer potential.

The specific objectives are:

- Determination of the geological, tectonical, hydrogeological and mining conditions and the coal quality parameters of the Oltenia deposit, and to evaluate the suitability of the geological conditions in other European deposits.
- Investigate analogues between UCG and phenomena of other coal combustion
- Setup of site selection criteria
- Selection of suitable location for UCG test in Oltenia deposit
- Transfer of findings to other European coal sites.

Task 2.1 – Analysis of geological, hydrogeological, coal and mining parameters in the Oltenia deposit, including set-up of models

An analysis of information available on the Oltenia Coal Basin was carried out by thorough literature review. The study area of the COAL2GAS project is located on the southern flank of the Carpathian Mountains within the Oltenia Coal Basin in Romania. Geological, tectonical, hydrogeological and mining conditions as well as coal quality data on the Oltenia basin were collected. Geologically, it is situated within the Getic Depression, which is regarded as the Tertiary foredeep that developed in front of the Southern Carpathians. The ground is built up by 2-7 km thick Tertiary sediments. Coal occurs in the upper Miocene and Pliocene. The most recent tectonic activity is related to small-scale local folding and thrusting, and major structural activities were present in the late Miocene Samartian and earlier. Neither of them is affecting the Pliocene deposits of the foredeep and the lignite deposits of the Oltenia region, which are younger.

In the Oltenia Basin, 22 main lignite beds exist, which possess varying thickness according to their geographic location. The lignite succession is best expressed and most regular in the depocenter of the basin, i.e. in the area delimited by the Carpathians, the Danube and the Olt Rivers.

Based on the collected information in this task and following the site selection in Task 2.4 a location close to the Urdari underground mine was chosen for the study. Based on data provided and on the drill results achieved in WP3, a detailed 3D structural geologic model of the site has been built.

Task 2.2 – Analysis of geological, coal and mining parameters of other comparable deposits in home countries of partners and elsewhere in Europe

The main aim of this task was to review available data and information on the lignite deposits in project partner countries and elsewhere in Europe in terms of underground gasification technology. Deposits were analyzed in Poland, Greece, Slovenia, Romania and Germany by using a list of site selection criteria previously established within the task. The assessment of essential site selection criteria was based on the knowledge gained by the review of currently available best practices in UCG, as well as on the international COAL2GAS project partners experience with their own data, and an extensive literature review. Taking into account the feasibility and competitiveness of operations of prospective UCG-CCS sites, geological, hydrogeological, geotechnical, technological, geographical and economic site selection criteria were identified and listed.

Task 2.3 – Establishing site selection criteria and assessment of potentially suitable deposits and areas based on lessons learned from previous UCG projects, relevant natural and man-made phenomena

Based on a thorough literature research of previous UCG projects and the experiences with local governmental rules related to confidentiality, a total of 24 site selection criteria have been set up for the Oltenia region in order to determine and evaluate the most suitable site of the deposit. These site selection criteria have been assessed for four sites and the most suitable site has been identified (see Task 2.4). Technical site selection criteria may be coupled to other site selection criteria as is evident for e.g. coal seam thickness and economic viability.

In all cases, and specifically for the site selection process in Oltenia, one important site selection criteria is the legal/license situation.

Task 2.4 - Site selection

The overriding objective of this task was to apply the previously set up site selection criteria (see Task 2.3) to select a potential test site. Once the site has been chosen, drilling locations of exploration boreholes have been defined. Access and drilling permission have been obtained. Upon completion of the exploration phase the UCG well design was determined.

WP3: Testing and Drilling

WP Leader: GIG Partners: DMT, CEO, CERTH, VELEN

Work Package Objectives

This WP has four main objectives:

- To use laboratory, large scale experiments using bulk samples from respective mining areas (Romania, Slovenia, Poland) to improve the understanding of the underground coal gasification process at different reagent, coal type, pressure and temperature conditions for upscaling to field scale UCG operations
- To perform test drilling at a selected sites in the Oltenia basin to improve the site specific data base e.g. by geophysical logging of test drills and to acquire site specific samples for further testing:
- To carry out additional lab testing of drill samples
- To evaluate options for different end uses of the produced gas through testing different reagents under different pressure conditions

Task 3.1 – Preparation and characterisation of coal bulk samples from active mining areas

This task involved extraction and preparation of large coal block samples from respective mining areas to be used in the large-scale experiments under Task 3.2. The coal samples have been extracted from Premogovnik Velenje (Slovenia) and CE Oltenia (Romania) and sent to GIG in Poland. The coal characterisation of samples from both Velenje and Oltenia has been undertaken and included proximate and ultimate analysis, sulphur form analysis, Fischer assay analysis, and determination of ash fusion temperature in oxidative and reducing environments. These coal properties would have a predominant influence on the coal gasification process. Results of the task also served as an input data for numerical simulation studies in WP4 and for the preparation of pilot project under WP6.

Task 3.2 – Large scale gasification tests on selected coal bulk samples

Four large scale, multi-day trials were conducted using large scale gasification facilities of the GIG's Clean Coal Technology Centre. Two different kinds of lignite were tested, i.e. Velenje lignite (Slovenia) and Oltenia lignite (Romania) provided by the project industrial partners. The surface experimental simulations of UCG were conducted in artificial coal seams under two distinct pressure regimes - atmospheric and high pressure (35 bar). The following were investigated: the role of gasification mixture and coal properties on coal gasification rates, composition of products and process efficiency; the influence of natural coal moisture, and the role of selected parameters on the formation, release and migration of UCG-related contaminants. The main aim was to assess feasibility of the high caloric value gas production from low grade and high moisture lignite seams through in situ gasification (UCG). The experiments demonstrated that the physicochemical properties of lignite considerably affect the UCG process. For the similar process conditions (coal seam dimensions, oxygen supply rates) gasification of Velenje lignite resulted in much better gas quality and process performance both in atmospheric and high-pressure gasification regime. Although the maximum energy efficiency obtained was approximately 45% (Velenje lignite, atmospheric UCG), it was still much less than the values usually achieved during UCG of hard coals, i.e. 60-70%. However, the experiments results indicate that UCG may be a feasible option for exploitation of lignite deposits, especially in the case of the Velenje lignite. The over-stoichiometric water content in the lignite seam eliminates the need for supplying of additional reagent water, at least at the early stages of the gasification process. The excessive water, however, may result in a decrease in the gasification efficiency due to considerable heat loss for the evaporation of coal moisture.

Task 3.3 – Test drilling at selected sites

A drilling program was set up aiming at obtaining high density information of the target area. Five vertical drillholes with lengths between 50 m and 141 m were drilled. All five boreholes have been equipped with perforated and unperforated PVC tubes and backfilled with gravel and sand for groundwater monitoring.

Coal and rock formations were sampled during the drilling campaign obtaining core from the underlying seams and the interburden rocks – maximum down to Seam IV.

Task 3.4 – Logging of test drills

A thorough borehole and drill core investigation program was completed in order to gain a detailed understanding of the test site. The program included geophysical well logging, hydrogeological testing, geologic and geotechnical core logging and field testing, core scanning with DMT CoreScan®, topographic surveying of collar positions and sampling of coal and surrounding rocks for subsequent geomechanical and coal quality analyses.

The geophysical borehole logging program covered measurement of natural and spectral gamma ray and dual induction logging in order to determine lithological and stratigraphic boundaries, geotechnical properties and radiometric analysis of different lithological layers, optical scanning and full wave sonic logging to inspect the well construction and to measure deviation of the monitoring wells, salinity/temperature and flowmeter logging in order to detect and to inspect outflow or inflow zones of the groundwater, and milieu logging in order to inspect chemical properties of the different ground water levels in situ.

Lithological correlations of natural gamma ray logs, spectral gamma ray logs and dual induction logs correspond well to the performed core logging, and especially the grain size distributions are showing good correlation. Geotechnical properties are well described and can be assigned to appropriate lithological layers. Furthermore, all core losses could be identified and described. Coal seams, silt, clay, and sand layers have been correlated on the basis of performed analyses and interpretations.

After a correlation of all results of chemical measurements a zonation of the water column could be recognized, dividing it into three zones: reacting zone, saturation zone and equilibrium zone.

The data and results obtained from the drill campaign served for refinement of geologic and numerical underground models and the assessment of suitability for UCG.

Task 3.5 – Lab testing of drill samples

The objective of this task was to characterise fresh coal samples. For this reason, a field drilling campaign was organised. The performed analysis included identification of the coal rank, determination of the chemical and petrophysical properties of the coals in order to allow comparison of bulk and core sample parameters. The coal samples were also characterised based on the results from proximate and ultimate analysis, sulphur form analysis, free swelling index, Fischer assay, ash fusion temperature and composition, auto ignition temperatures in oxidative and reducing environments. The data were used for the correlations of the experimental data and for the preparation of the demonstration project that was developed in WP6. Laboratory tests carried out in this project also included: assessment of UCS, Brazilian tests of coal and rock, specific gravity, RQD, fracture toughness, fracture propagation in coal, orientation and distribution of separation planes for detection of pathways of gases and heat. The lab testing of the drill samples were carried out by CERTH and DMT, in their respective laboratories.

WP4: Panel and Well Design and Engineering for Integrity and Safety / Surface Plant Assessment

WP Leader: MCE Partners: DMT, CERTH, TNO, GIG, ISPE

Work Package Objectives

UCG requires a comprehensive understanding of the well configuration, the geological and hydrogeological parameters of potential sites and their influences on the various processes that will take place in this complex system. A careful geological and hydrogeological assessment and selection of sites suitable for UCG is a pre-requisite for a successful operation.

The specific objectives are:

- Site specific technology selection criteria;
- Identification of appropriate panel and well design;
- Selection of suitable technical and monitoring plans for safe, reliable, sustainable, efficient and lowest environmental impact UCG operations and configurations;
- Solutions for safe well operation and abandonment;
- Assessment of thermal-hydro-mechanical-chemical impact of UCG operations by applying respective software for process modelling.

Task 4.1 – UCG technology update and UCG-module performance comparison

In this task, the current state-of-the-art UCG technologies were discussed with reference to the results of previous and current UCG studies and trials. Specific attention was given to the most promising UCG technologies that could be deployed in different geological conditions.

For the scale-up to commercial operations from a "pilot" project, a complete and detailed description of previous and current UCG demonstration trials worldwide was compiled, together with a list of the key process parameters for the trials. A glossary of the main terms used in UCG was first set up and the lessons learnt were then presented as a guide to the designing, planning and construction of future commercial well/module/panel configurations, UCG-plant operations and module/panel decommissioning.

Task 4.2 – Selection of suitable process operation and monitoring techniques

To prepare the report of the task, a workshop on "Definition of the optimum UCG configuration, selection of process operations and monitoring techniques for the pre-selected site(s) in Oltenia coalfield" was hosted by MCE, at its Liège office, in Belgium, on 11th of May 2015.

This task was focussing on existing experiences and technologies for monitoring UCG reactors, and other relevant underground activities, such as oil and gas, conventional coal mining, geothermal and natural coal seam fires.

From the study, a wide range of instrumentation capable of measuring all of the important UCG process parameters were identified as available to UCG projects. The instrumentation can be deployed in the process wells themselves, in monitoring wells drilled around the UCG well field or in surface equipment.

The task was also focussing to model the Linear Controlled Retracting Point (L-CRIP) reactor/module performance of three (3) study cases representative of the coal seam conditions at the Oltenia coalfield in Romania.

Concerning the study cases, the principal variable investigated was the depth to the coal seam. As can be seen in Table 2.2.18 in this report; increasing the depth from 50 m to 300 m has a significant effect on average gasification rate (38-230 tonne/day), average syngas production rate (55,000-260,000 Nm^3), average dry syngas heating value (9.2-12.1 MJ/Nm^3) and total energy converted per module (0.09-0.23 PJ). Improvements in gasification and syngas production rates result mainly from being able to inject oxygen at greater rates and higher pressures into deeper coal seams, whereas improvements in syngas heating values are in large part caused by the formation of greater proportions of methane in syngas at higher pressures. The increase in the amount of energy recovered per module with increasing depth results mainly from the effects of increasing the in-seam completed length (see details in Task 4.2 in section 4.3 of this report).

Task 4.3 - Well design & engineering for integrity and safety

This task was concerned with criteria on the operational integrity of the sub-surface and the post-operational abandonment of wells to ensure environmental risks from a UCG project are minimal in both the short and long terms. Available technical and engineering options were analysed and evaluated to protect the different types of well required to operate UCG module(s)/panel(s).

Based on data/results on previous on-going tasks, a joint expert panel workshop was organised between MCE and TNO at their Utrecht premises on February 2-3, 2016. During the joint expert panel workshop, the guideline list of the required well drilling and completion, as well as the in-well instrumentation to maintain integrity and safety of all UCG wells and project phases were established.

The guideline list established was: i) definition of stratigraphic units (and sub-units, if necessary) and hydrogeological conditions of each units/sub-units, (ii) definition of project phases (and sub-phases, if necessary), (iii) definition of well configuration and well positioning (three (3) types: injection, production, and transverse monitoring wells), (iv) aspects of underground module/reactor(s) to be considered, (v) others aspects of the design to be considered (per type of well); and (vi) well control and monitoring techniques (per type of well).

Based on the guidelines here-above, MCE and its partners involved in WP4 (GIG, CERTH, DMT, ISPE and TNO) have developed, the pilot-scale well pre-design and engineering with the focus on operational integrity, post-operational abandonment, and others technical issues and monitoring techniques.

The design was adapted / finalised in May 2017 following the specific conditions and data obtained from the drilling campaign realised at Urdari selected site from December 2016 to January 2017.

Task 4.4 - Thermal-hydro-mechanical-chemical impact of UCG operations on surrounding rocks

In this task, the mechanical impact on the surrounding rocks of an L-CRIP UCG operation, which is simulated based upon site-specific data for a UCG pilot site, the Oltenia coalfield in Romania, is discussed. Numerical geomechanical models were used to assess the impact of an underground cavity formed by the UCG operations on the mechanical integrity, stability and sealing capacity of the rock and soil layers surrounding the underground UCG cavity. The focus of modelling was on the stability of the UCG cavern in the relatively weak unconsolidated deposits at the pilot site. In case the cavities are unstable, coupled thermal, flow and chemical effects would play a minor role, because an instable cavity, causing e.g. ground movements and creating flow pathways through the sealing formations would present a potential showstopper for operations in the simulated target seams.

The numerical geomechanical models for the Oltenia site are based on the available geological, hydrological, geomechanical and operational information. In the targeted pilot area of the Urdari – Valea cu Apa site four coal seams are potentially suitable for UCG, i.e. coal seams X, VIII, VI and V. Here two UCG scenarios were defined and modelled:

Scenario 1: Gasification in lignite seam VIII, located at approximately 34-37 meter depth;
Scenario 2: Gasification in lignite seam V, located at approximately 103-108 meter depth.

Model results show that considering the mechanical stability of the two lignite seams VIII and V, stability of an UCG cavity in seam VIII is higher than for seam V. This is mainly due to the higher stiffness and strength (Young's modulus, cohesion and tensile strength) of seam VIII compared to seam V and the higher in-situ stresses encountered at the depth of seam V. The model results of the 2D and 3D geomechanical models indicate that for the chosen geometry, soil parameters and stress conditions, cavities of limited dimensions in seam VIII could remain stable. However, modelling results also indicate that the maximum dimension of the cavity that is still stable depends on the actual geometry (i.e. for circular plane strain cavity diameter Dmax is 4 m, for 3D cylindrical Dmax= 2 m) and the vertical position of the cavity, which may in practice be hard to assess upfront and to control. In all cases, large spans of unconsolidated clay soils in the roof and bottom should be avoided, as the bearing capacity of the clays is relatively low. As the sealing clay layer above the lignite seam VIII has a limited and varying thickness, loss of clay seal integrity and stability issues due to uncontrolled water and sand inflow at this stage cannot be completely excluded, and should be accounted for when assessing the risk of shallow UCG operations at the Urdari – Valea cu Apa pilot site.

WP5: Risk Analysis, Environmental Issues and Legislative Background

WP Leader: TNO Partners: ISPE, MCE, DMT, GIG, CERTH, CEO

Work Package Objectives

The overall aim of this WP is to perform a risk analysis of environmental impacts of UCG activities, exemplified by the selected pilot UCG site(s) in Romania. Identified environmental issues and legal requirements for UCG in the EU and Romania will drive this risk analysis.

Specific objectives are:

- Define a risk assessment framework which is appropriate for the analysis of UCG, exemplified by the selected shallow UCG demo site in Romania;
- To compile site-specific information and parameters which are important for the risk analysis, to define the UCG concept including measures to ensure containment of toxic substances resulting from the UCG process;
- To specify the performance indicators of the risk analysis;
- Build a database of risk factors for UCG;
- Identify and screen environmental risk factors for the selected demo UCG site in Romania, and develop and semi-quantitatively characterize scenarios;
- Evaluate UCG-related contaminants
- Assessment of the results from the semi-quantitative analysis on the basis of existing legal requirements

Task 5.1 - Define a risk assessment framework for UCG

This task is concerned with more specific information related to project set up and site specific geological information. The project set up depends on specific geological input parameters, such as coal quality information and a variety of other parameters which are also included in the risk assessment (RA). Transferring site specific information into the RA as outlined in Task 5.1 requires the existence of a database where data on all relevant parameters are included. The available data was presented and discussed in this report.

Task 5.2 - Qualitative and quantitative assessment of the UCG-related environmental contaminants

The main objective of this task was to investigate the phenomena of formation of organic and inorganic UCG-related contaminants and their potential to be release into the underground environment during and after the UCG process. Laboratory studies on the formation and release of UCG-related contaminants were performed during the four ex-situ gasification tests conducted by GIG under Task 3.2. Effects of gasification pressure and lignite properties on the quantitative and qualitative characteristics of the UCG-derived contaminants were investigated. A broad scope of potential environmental contaminants was characterized both qualitatively and quantitatively by

analysing the main streams of gasification by-products, i.e. post-processing waters and solid residues remaining in the post-gasification cavity (ash, char).
The group of target contaminants included: phenols, aromatic hydrocarbons, selected inorganic ionic species (including metals and metalloids) and some non-specific water parameters. Environmental risk in the post-gasification phase was assessed based on physicochemical characterisation of solid UCG by-products and elution tests conducted in laboratory quasi-static–dynamic conditions.
The study showed that composition of UCG wastewaters significantly varied over the time of the particular experiments, which reflected changes in the gasification thermodynamic conditions and development of oxidation and pyrolysis zones. The effect on lignite properties and gasification pressure was also confirmed in the study. The elution tests carried out for char residues from both gasification trials showed that the elements with the highest mobility into the aqueous phase were As, B, Zn, Al, Mn, Fe and, to a lower extent Mo and Se. Therefore these elements may be regarded to be of greatest concern for the groundwater environment in the post gasification phase. Another observation was that the metal elution potential to a larger extent related to the physicochemical properties of UCG residues than to the content of specimens in the eluted material. The possible negative environmental effects due to release of organics from UCG char was found negligible for lignites under study.

Task 5.3 - Compile site-specific information (assessment basis)

The general objective of this task was to define and prepare base data and the context for the subsequent risk assessment (RA). The so-called assessment basis, the objective of this task, determines the type of risks that have to be scrutinized. For the Oltenia demo project this basis comprises risks of an environmental nature, risks concerning the technological and operational feasibility, and risks concerning the legal situation. During this preparatory work for the RA, legal requirements, the UCG concept and containment of fluids were defined, objectives of the RA and performance indicators defined, and relevant site-specific information compiled.

Following the identification of a potential test site regional and local geological information were used to characterize the test site. The L-CRIP configuration has been identified to be the most suitable for the proposed test site in Romania.

Task 5.4 - Develop a database with UCG risk factors

In this task we described the UCG database to be used as part of the risk assessment for UCG activities in the Oltenia region.

Furthermore, we explained how the database is to be used by individual experts, and as a means to enhance collective awareness of the risks involved, but also to obtain a general picture of the potential risks for Health, Safety and Environment.

The FEP database will accompany all activities in the four phases of a UCG operation (pre-operational, operational, post-operational and decommissioning). This is in line with the demand that risk assessment must be based on the best / latest information one has obtained.

In this report we described also how the experts will act, individually and collectively, to bring up the most complete and up-to-date risk assessment, counteracting tunnel vision.

Task 5.5 - Screen risk factors, and develop and characterize scenarios

This task comprises the screening and evaluation of risk factors starting from the database developed in Task 5.4. Risk parameters were selected and ranked with respect to the current knowledge on the potential UCG site at Oltenia. Where applicable they were combined to risk scenarios. The general agreement on the largest risks emerging was as follows.

1) Legislative issues are important for the Oltenia UCG project to get started. Oversights in this realm are easy to make. Such oversights may hamper progress, perhaps even killing the project before it has even started. Legal documents tend to be extensive and they require scrutiny of legal professionals.

2) The documentation provided on the Oltenia site and its surroundings was (at the time of the workshop) predominantly on the stratigraphy and the coal / lignite properties. Questions were raised as to how up-to-date the information was.

   The large-scale continuity of the coal / lignite was seen as important. Is that warranted?

   Are all aquifers mapped out to a sufficient degree of completion? They should be, as they form a gateway of pollution to the ”outer world”.

   The obvious remedy for lacking specific data is to acquire more of them. However, new data does not necessarily help to support a UCG operation (see item 4)

3) Not surprisingly the integrity and the possibility of subsidence was felt as a serious risk. The UCG activities are deemed to take place at shallow depths. In order to acquire confidence on the sustained roof / cavity integrity and expected subsidence geo-mechanical

modeling is indispensable. Hard data on the geological layering, the porosities and stresses are important for the credibility of this research activity.

4) Information from the drilled cores (for details please refer to WP3 results) led to the following results, and principally supported the earlier findings
    a. The depths of the envisaged target seams no. VIII and V was shallower than previously reported what shifts risk related to shallow location (e.g. subsidence or containment) even more into the focus
    b. The thickness and continuation of the seams and the sealing layers vary strongly, which confirms the high risks of uncertainties related to the structural set-up of the site
    c. Coal seam VIII sample analysis revealed that the seam is stiffer as expected, which has a positive effect on the integrity, but still the (updated) geomechanically modelling shows risks for the containment of pollutants
    d. Overall, the updated simulations (still) indicate risks of cavity collapse and loss of integrity for both target seams. This confirms the outcomes of the earlier risk assessment workshop.

Task 5.6 - Assess the calculated risks on the basis of legal requirements

In this task an overview regarding the applicable existing legislation at EU and national levels, the UCG selected process for the test site in Oltenia region – Romania and the proposed risks management methodology and monitoring plan has been performed.

The legislative frameworks from EU and project partner countries were screened. For Romania a review of the responsible authorities and the current legal and regulatory frame was presented, with a focus on the documentation needed for issuing the legal permits by the National Mineral Resources Regulatory Authority (ANRM), in order to approve the launch of a future UCG pilot project. A correlation between the recommendations made within previous COAL2GAS deliverables on the site selection criteria, the design & engineering, the associated RA and monitoring-control strategies, and the requirements of the existing national / EU legislative framework and BAT- BREFs (Best Available Techniques) has been made.

The synthetic result was a Risk - Legal Requirements matrix that was structured according to the project stages of development (construction / operation / post-operation / decommissioning) and filled with information related to risk themes, RA (general FEP and impact/probability range) and legal requirements. Also recommendations on the treatment of residual risks, in terms of site characterisation and selection, monitoring and risk reduction measures, for the design of the pilot project in the selected mining test site in Romania have been made.

WP6: Preparation of Demonstration Project

WP Leader: ISPE Partners: CEO, DMT, GIG, CERTH, MCE, TNO, VELEN

Work Package Objectives

This WP has five main objectives:

- Development and assessment of site specific technologies for the selected project site;
- To establish action plans and monitoring techniques;
- Draft site-specific proposal for future use of the syngas;
- Development of (site-specific) strategies as guidelines for similar future UCG projects;
- Preparation of necessary permit applications for a subsequent demonstration project depending on results of previous WPs

Task 6.1 - Final assessment of the most suitable site and design of site specific technologies

In this task the results obtained from the investigations in the previous work packages were interpreted and evaluated in order to assess the most suitable site and technologies for UCG in Oltenia. Based on the conducted work like geologic and numerical modelling, laboratory testing and field investigations, UCG is principally possible in the shallow lignite seams at the selected Urdari site. Although numerical models indicate partly difficulties with stability of larger cavities, this is not regarded as a major constraint for the underground gasification. In contrast, benefit of the soft and only little consolidated cap rocks is their ductile behaviour and good sealing capacity compared to hard rocks, which are brittle and form open fractures when the roof of the UCG cavity breaks. The defined UCG technologies and process monitoring concept should allow a successful UCG trial. However, due to the close distance to the surface and the groundwater situation, thorough care has to be taken for the environmental protection by proper monitoring.

Task 6.2 - Selection of monitoring techniques and design of monitoring plans

Site-specific monitoring plans and procedures have been set up for the potential tests site in Oltenia. Generally, two monitoring aspects have to be considered, which are process monitoring during and after (decommissioning) the actual test phase, and monitoring of environmental parameters, before, during and after the underground gasification. Suggested process monitoring concentrates on pressure and temperature control, injection point position, monitoring of gas, liquid and solid composition (syngas and injected gasification agents), calculations of gas loss, energy balance, and equilibrium conditions, and the underground syngas residence time distribution by tracer tests.

Plans and the techniques for monitoring environmental parameters like subsidence, groundwater and surface water composition and dynamics, soil and soil gas were set up. At least 4 multi-level groundwater monitoring wells, as well as surface water observation points have been suggested specifically for the planned UCG panel layout and module configuration. A minimum of 4 soil and soil gas sampling locations are proposed. All environmentally related modelling techniques rely on the acquisition of sufficient baseline data to decipher anomalous data or impacts caused by the UCG from normal data and naturally occurring irregularities.

Task 6.3 - Draft site-specific proposal for syngas utilization

The main objective of this task was to establish the most appropriate type of utilisation of the produced syngas by an UCG facility. Syngas is a versatile product that may be used in a wide range of applications (chemicals, synthetic materials, nitrogen fertilizers, synthetic fuels, power generation). Different technical applications of syngas were documented and presented, like the use of syngas for the chemical industry, for obtaining synthetic hydrocarbon fuels and for power generation. In order to define and compare the most suitable options of using the UCG produced syngas, the syngas generation costs and quantities were assessed. The levelised cost of syngas was considered as reference figure to compare the influence of syngas over the profitability of different possibilities of using it in different technical applications.

The following options of using the potentially produced syngas by local applications were analysed: (i) using it for industrial applications in the chemistry sector, (ii) using it for fuelling residential consumers in the surrounding area, (iii) using syngas for power generation. Using syngas for chemical industry instead of natural gas would result in increasing the cost of final product of this industry, having in view that the levelised cost of syngas is about three times greater than the price of natural gas. Using obtained syngas for fuelling residential consumers in the surrounding area could be an option if the cities around were connected to a gas network. Having in view that there is no gas network around, using syngas for fuelling the residential consumers in the surrounding area implies high investment costs in gas networks and connections.

Taking into consideration the location of the syngas production unit, the most appropriate use of syngas was for electricity generation. Based on the simplified cost-benefit analyses performed for the identified options of using syngas, it appears that at this point of UCG estimated development costs, the most suitable option could be, in certain conditions, the use of syngas on site in a new facility for electricity generation. The conditions in which this option can be sustainable are related to: (i) financing of syngas production and treatment facilities from grants, (ii) decreasing of OPEX of syngas production and treatment facilities which can occur along with the maturity of the technology and (iii) supporting scheme for this kind of projects. The supporting scheme should include feed-in tariff for electricity, grants for OPEX of UCG facility.

Task 6.4 - Preparation of necessary permit applications for a subsequent demonstration project

The main objective of this report was to identify and prepare the documentation needed for obtaining the required permits for a potential UCG pilot project.

According to the Romanian legislation, a package of seven documents is necessary for the required permits: (i) technical documentation for the delimitation and background of the exploitation perimeter; (ii) the operation framework method for UCG; (iii) documentation regarding the evaluation of mineral resources and useful mineral reserves; (iv) feasibility study on mineral resources utilization and deposit protection; (v) mineral resources / reserves exploitation plan; (vi) environmental restauration plan; and (vii) social impact study.

In this task, the framework method for coal exploitation through underground gasification in Romania (shortly named OMRom-UCG) has been developed. This is the statement paper that must be submitted to and approved by the responsible authority, the National Agency for Mineral Resources (ANRM), prior to any documentation needed for issuing the legal permits for exploration, construction & commissioning, operation and decommissioning.

OMRom is covering all stages of a UCG project - from concept - planning / design to construction, operation, post-operation and decommissioning. OMRom has been prepared by following a structure imposed by the regulatory authority (ANRM) for mining activities, which considers the following important aspects of the UCG technology implementation: general data related to the mining method; site selection approach; operating method – design and engineering principles; works schedules;

necessary underground and surface tools and equipment; monitoring plan; risk assessment and prevention measures.

Task 6.5 – Development of site-specific framework method, as a guideline for similar future UCG projects

As an introduction to the guideline, MCE has first summarised/integrated, to the general lessons learned from the global UCG technology review (see Task 4.1 in section 4.3 of this report), the particular lessons learned from the first UCG trial in a framework of community collaboration (SF/369/91; 1991-1997). The so-called El Tremedal UCG trial was jointly sponsored by Spanish, Belgium and UK organisations, with support of the CEC as part of the "THERMIE" framework programme.

The in-situ coal conversion experiment at El Tremedal (Alcorisa, Teruel, Spain) demonstrated the feasibility of carrying out in-situ coal conversion process at an intermediate depth (500 to 600m) from Sub-bituminous C (ASTM) soft coal very similar to the Oltenia coal (ASTM-Lignite B coal) and the Velenje coal (ASTM-Lignite A coal) analysed in the framework of the COAL2GAS project.

The project established also the potential viability of using the linear CRIP technique recommended to be used in future UCG projects. The geological/hydrogeological conditions of the overburden at El Tremedal site are also similar (at the exception of the depth) to the conditions encountered at the Oltenia site.

Based on both UCG and Mining terms' glossaries, the practical site-specific guidelines were then developed, integrating to the previous, the risk management and assessment of the UCG project lifecycle, and legal requirements applicable for mostly Romania and the EU. The content of the guidelines are (i) the lessons learned from the El Tremedal project and the global UCG technology review, (ii) the integrated risk assessment methodology, (iii) the recommended mining plans and commercial deployment, (iv) the guidelines for the legal and environmental requirements and (v) the optimisation of the EU coal supply chain, and the potential processing and recycling routes.

2. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

2.1. *Objectives of the project*

The main objective of the project was to assess the feasibility of coal extraction by means of UCG in shallow lignite seams, having in view the geological, technical and environmental aspects, and to illustrate this for a selected deposit in Romania. To achieve the main objective a site-specific framework method has been developed as a guideline for similar future UCG projects in shallow lignite seams. The site-specific framework method was prepared based on the results obtained from large-scale gasification tests on selected coal bulk samples from Oltenia and Velenje mines conducted in artificial coal seams under two distinct pressure regimes - atmospheric and high pressure (35 bar), analysis of UCG-related contaminants and laboratory tests of drill samples (compression tests, Brazilian tests of coal and surrounding rocks, porosity and density, moisture and water content, grain size distribution assessment, consistency limits, water permeability, ignition loss, penetrometer tests), data collection from logging of test drills, numerical modelling of UCG operations on surrounding soil layers and rocks, selection of suitable process operation and monitoring techniques and development of well design and engineering, development of risk assessment framework and database with risk factors for coal seam extraction by means of UCG in shallow lignite seams and assessment of the calculated risks on the basis of legal requirements.

2.2. *Description of Activities and Discussion*

2.2.1. *WP1: Coordination and Reporting*

Task 1.1 – Project coordination and communication

The specific objective for this task was to organize regular communication between the consortium partners in order to speed up the process of decision taking, review progress against objectives and milestones and ensure the smooth progress of the project.

Seven consortium meetings have been organized during the entire project period: the kick-off meeting took place in September 2014 in Bucharest - Romania, the second meeting in February 2015 in Mikołów – Poland, the third in October 2015 in Tg. Jiu – Romania, the fourth meeting in June 2016 in Essen – Germany, the fifth in October 2016 in Athens – Greece, the sixth in March 2017 in Velenje – Slovenia and the last meeting in June 2017 in Craiova – Romania.

Task 1.2 – Progress monitoring and reporting

This task was concerned with the preparation of technical and financial progress reports showing how the project deadlines and objectives have been met.

Two annual technical reports, a mid-term implementation report and a draft final technical report together with the accompanying financial statements, have been submitted to TGC1 and the EC and accepted. The Publishable Report is delivered along with the present document.

Task 1.3 – Dissemination

For disseminating the project outcomes a project website (www.coal2gas.eu) was created and five scientific papers have been published during 2016 and 2017 (this year two more papers were accepted for publication). Additionally, presentations were given on international scientific conferences. On 27th of June 2017, ISPE organised the COAL2GAS dissemination workshop. 40 participants representing the coal and power industry, private companies and RDI institutes, students and academia, and governmental authorities have formed the audience for the lectures kept by the COAL2GAS researchers.

2.2.2. *WP2: Data Analysis and Site Selection*

Task 2.1 – Analysis of geological, hydrogeological, coal and mining parameters in the Oltenia deposit, including set-up of models

In this task information and data on the Romanian Oltenia deposit were collected from scientific literature and the local project partners CEO and ISPE. Regional information on the coal mining area of Oltenia – including general geology of the coal basin, the hydrogeology and rock mechanical properties – was acquired and relevant information evaluated and summarized The geologic data were incorporated into a 3D geologic model of the target site.

Location and stratigraphy

The project area is located within the Getic Depression, which is regarded as the Tertiary foredeep that developed in front of the Southern Carpathians. Beneath the approximately 2-7 km thick

Tertiary lithologies lay about 3 km thick Jurassic – Triassic detritic sandstones, shales and limestones, 5 km Permian – Triassic clastic shales and sandstones, and 6.5 km Cambrian – Westphalian detritic shales and limestone.

Figure 2.2.1 shows a stratigraphic column of the uppermost Cretaceous and Tertiary sediments. It shows the occurrence of coal in the upper Miocene and Pliocene. The most recent tectonic activity is related to small-scale local folding and thrusting within the Moesian Platform, thus not affecting the Pliocene deposits of the foredeep. Major structural activities are shown to be present in the late Miocene Samartian and earlier, again not affecting the lignite deposits of the Oltenia region, which are younger.

22 main lignite beds (called A to D and I to XVIII) with varying thickness according to their geographic location exist. The lignite succession is best expressed and most regular in the depocenter of the basin, i.e. in the area delimited by the Carpathians, the Danube and the Olt Rivers (Popescu et al. 2006). Figure 2.2.2 outlines the distribution of coal seams of the project area and a cross section, showing the stratigraphic arrangement of coal seams. Clauzon et al. (2005) describes the lignite seams as part of a Gilbert type delta and that the seams have been deposited in an alluvial environment.

Data interpretation and modelling

Based on the approach towards site selection that is summarized in the description of Task 2.3 of this report, a location close to the Urdari underground mine was been chosen for detailed investigation. Initial 3D modelling – based on data contained in a geological report provided by CEO and ISPE – was performed using PETREL. Drillhole data of 11 drill holes in the vicinity of the potential test site including also descriptions of clay (= seals) and sand layers (= aquifers), as well as two lithostratigraphic cross-sections, were incorporated into the model.

The coal seam correlation presented in Figure 2.2.3 is based on graphical interpretation and the descriptions of coal layers provided in the geological report of Iamandei & Ticleanu (2015). Using the data from Figure 2.2.3 a standard lithological log has been constructed (see Figure 2.2.4), that was updated after new drill results became available. Drillhole locations (Easting / Northing / Elevation) have been derived by georeferencing the exploration map provided in the geological report. Since the provided exploration maps did not contain a labelled coordinate grid, georeferencing was performed using specific landmarks. Therefore the obtained coordinates of historic drillholes are subject to uncertainties, which can be assumed to be in the range of several decametres, but geologic structure in the demo site could be confirmed by the new exploration wells. Due to the graphical depth derivation of lithological units these depths have also to be regarded with some caution.

Topographic data was compiled both from NASA's SRTM data with roughly 90 m horizontal resolution and the EU-DEM provided by the European Environment Agency (≈25 m horizontal resolution). Figure 2.2.5 shows the surface and the modeled horizons of the target seams VIII and V in PETREL.

In addition to the drillhole information, also the fault line, horizon outcrop line of Seam XI and cross section lines were digitized from the provided exploration map. The digitized data were transferred to PETREL for subsequent modelling workflows. In addition the sandstone and clay intersections were correlated to assess the continuity of the aquifers and aquitards.

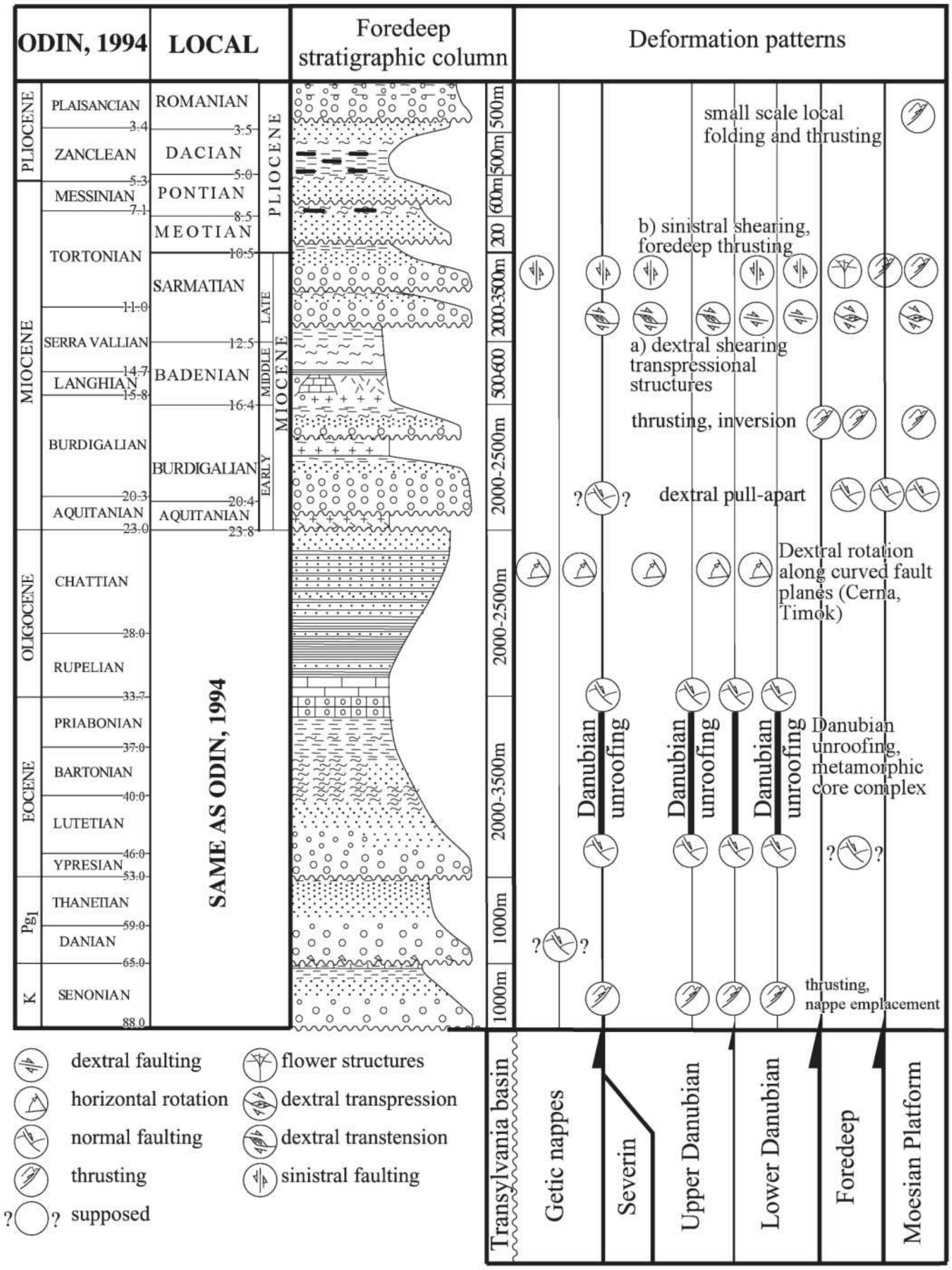


Figure 2.2.1: Stratigraphic column of the foredeep with phases of tectonic deformation (from Matenco et al. (2003)). The lower part of the lignite beds that have been investigated in the Urdari test site (seams IV to VII) corresponds to the regional Dacian stage, the upper layers (VIII to XI) belong to the regional Romanian stage.

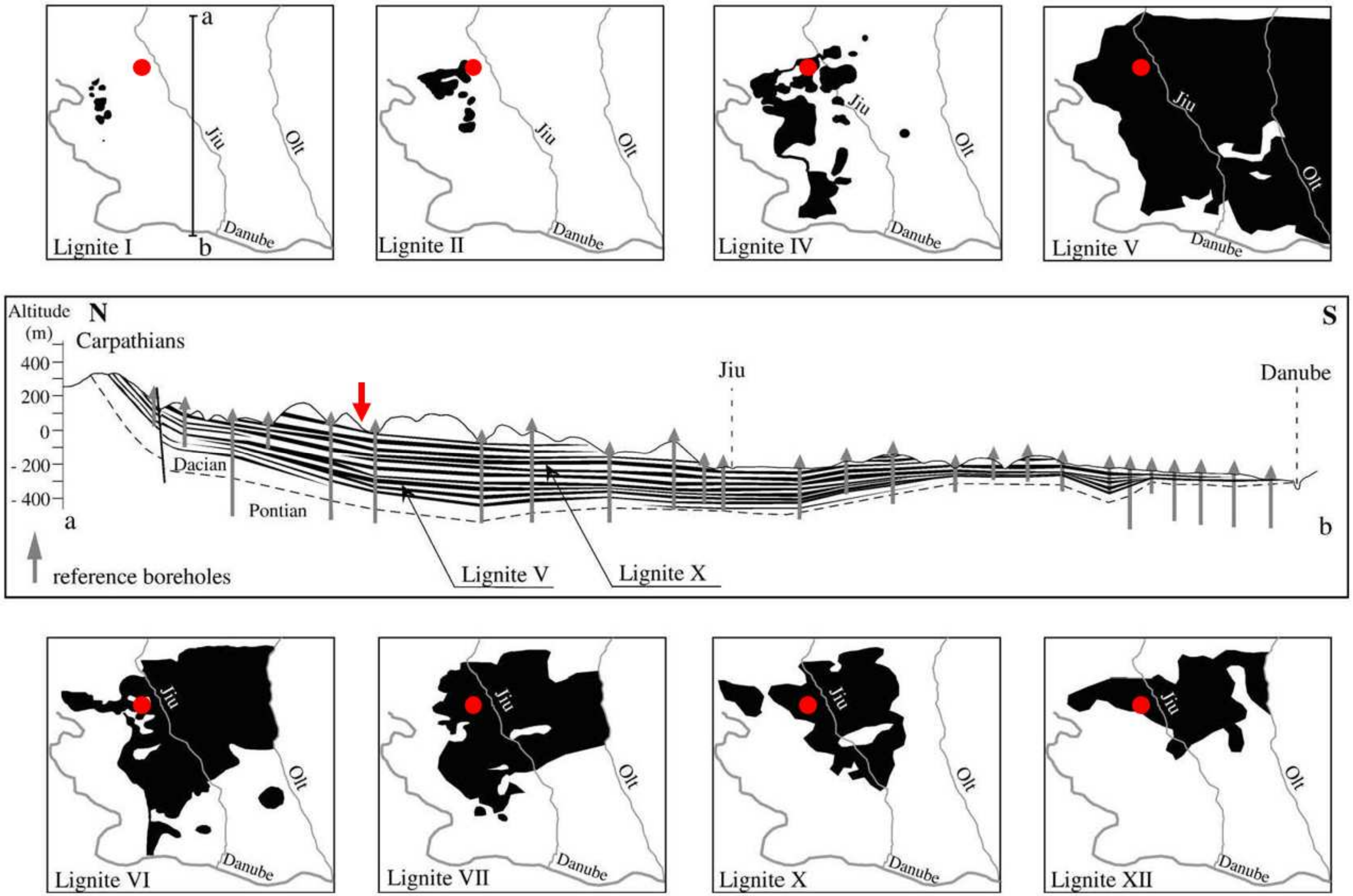


Figure 2.2.2: Maps showing the distribution of coal seams within the Oltenia Basin and a cross-section displaying the stratigraphic arrangement of coal seams (from Popescu et al. (2006). The red points mark the location of the Urdari test site. The red arrow projects the site location to the vertical profile.

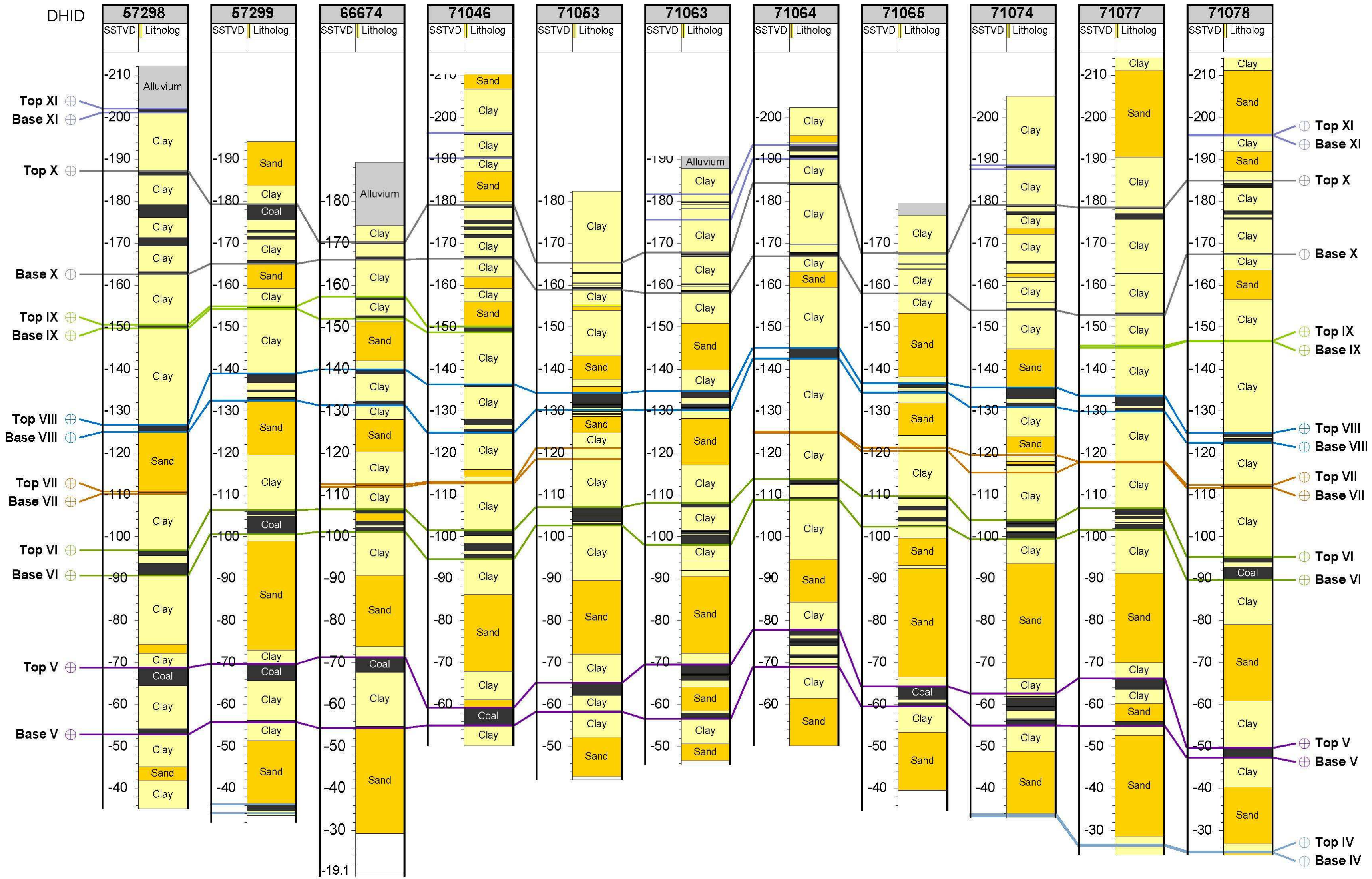


Figure 2.2.3: Lithological logs and modified seam markers of exploration drillholes at Urdari and close surrounding of the test site (DHID = Drill Hole ID; SSTVD = Sub Sea Total Vertical Depth)

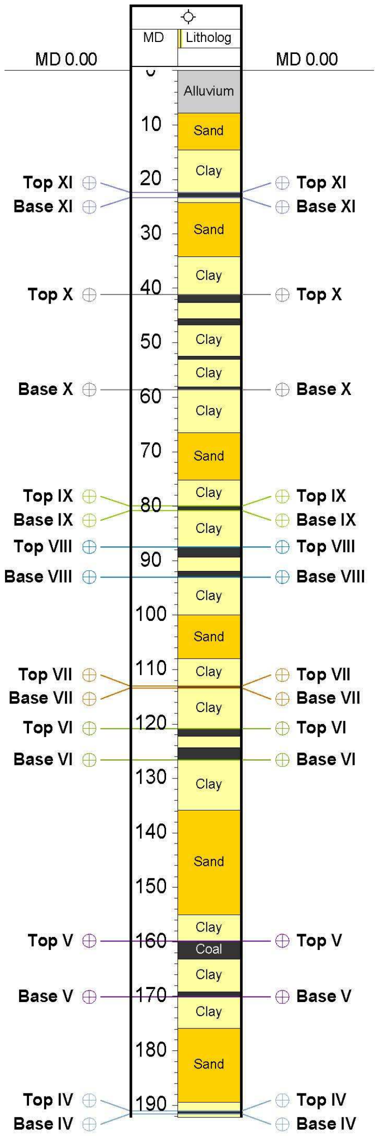


Figure 2.2.4: Standard section of Urdari site generated using available drillhole logs

Figure 2.2.6 and Figure 2.2.7 show the inclusion of the fault line into the 3D model. The fault cross-cuts all units. The proposed drillhole locations (WP3) were included into the modelling platform for visualization purposes in conjunction with the model.

Subsequent to the completion of the drill campaign and the acquisition of new and detailed results from drill core and geophysical logging (WP3) the 3D model was updated. Based on the 3D structural model, initial hydrogeological simulation could be performed and geotechnical and other quality parameters could be modelled as well. Due to the ambiguities in the drillhole lithological log data of the historic wells, some uncertainty remains for parts of the 3D model outside the central Urdari location where detailed data from the drilling conducted under WP3 is now available. The borehole logs could be generalized to construct a standard profile, which can be used as basis for a pilot test. If an operational test is sought, a detailed drilling program will have to be set up in order to clarify the geological conditions for a larger field, also with respect to the location of structural elements, e.g. faults.

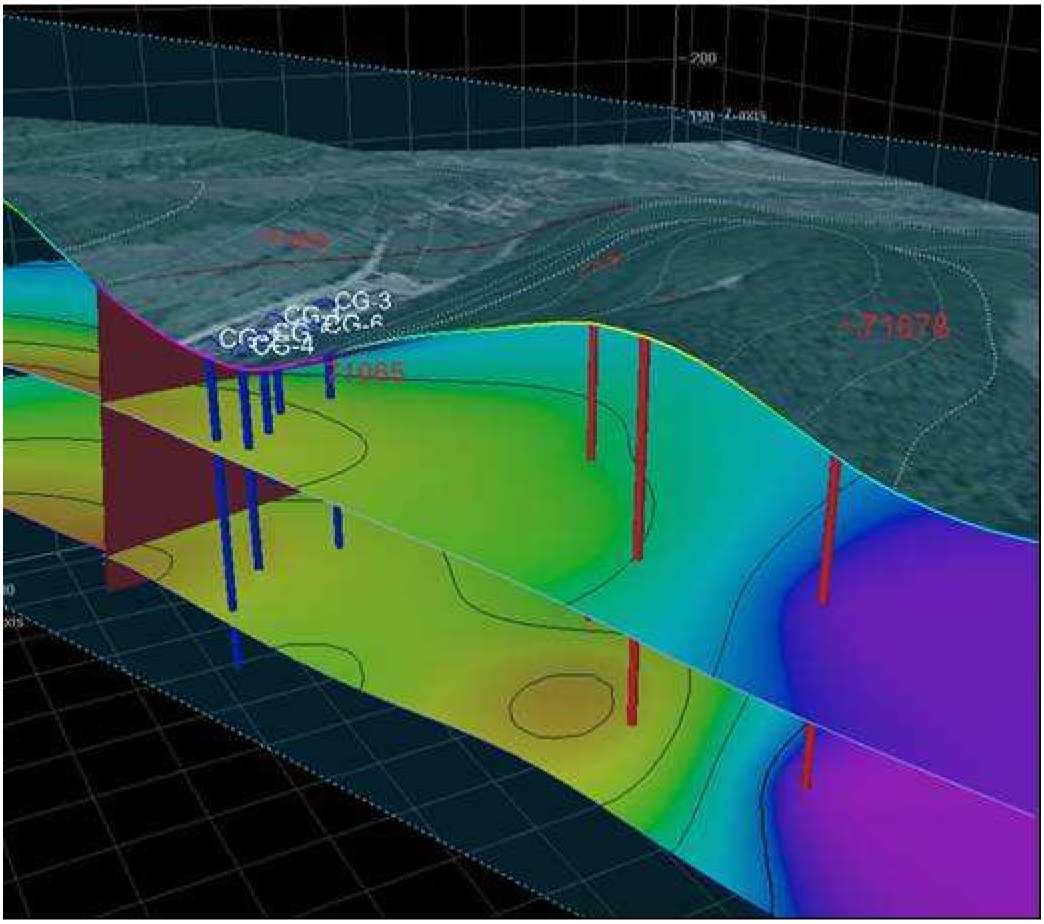


Figure 2.2.5: EU-DEM topography layer with superimposed satellite imagery and proposed drill holes as well as modelled horizons for seam bases VIII (upper plane) and V (lower plane), view from SW, Z-scale 2:1. Colour shading of coal seams indicates elevation. Yellow colours indicate relatively high elevation, whereas purple colours indicate comparatively low elevation.

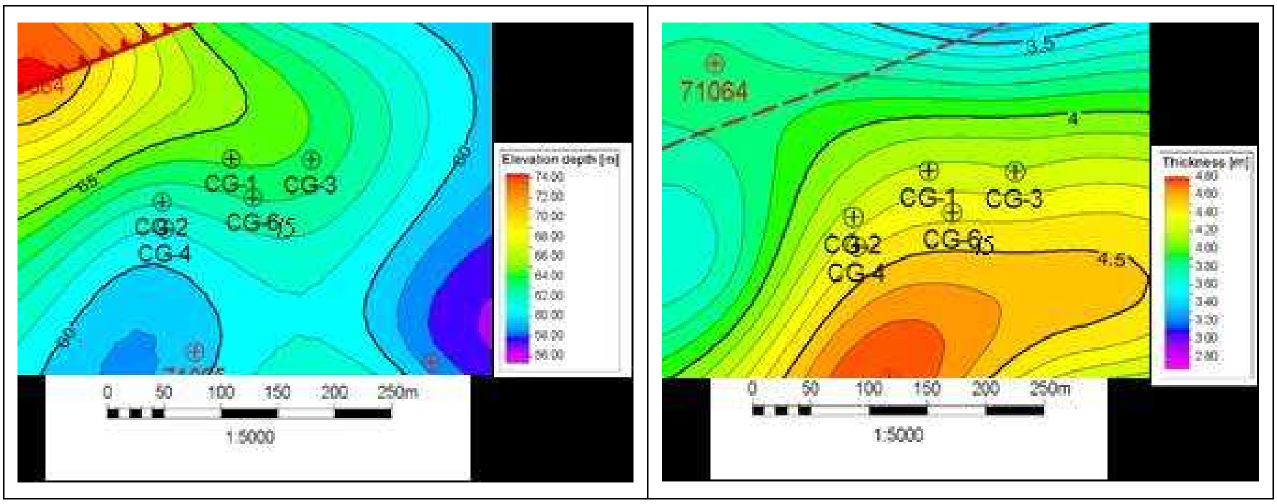


Figure 2.2.6: Seam VIII depth of floor (left) and total thickness (right).

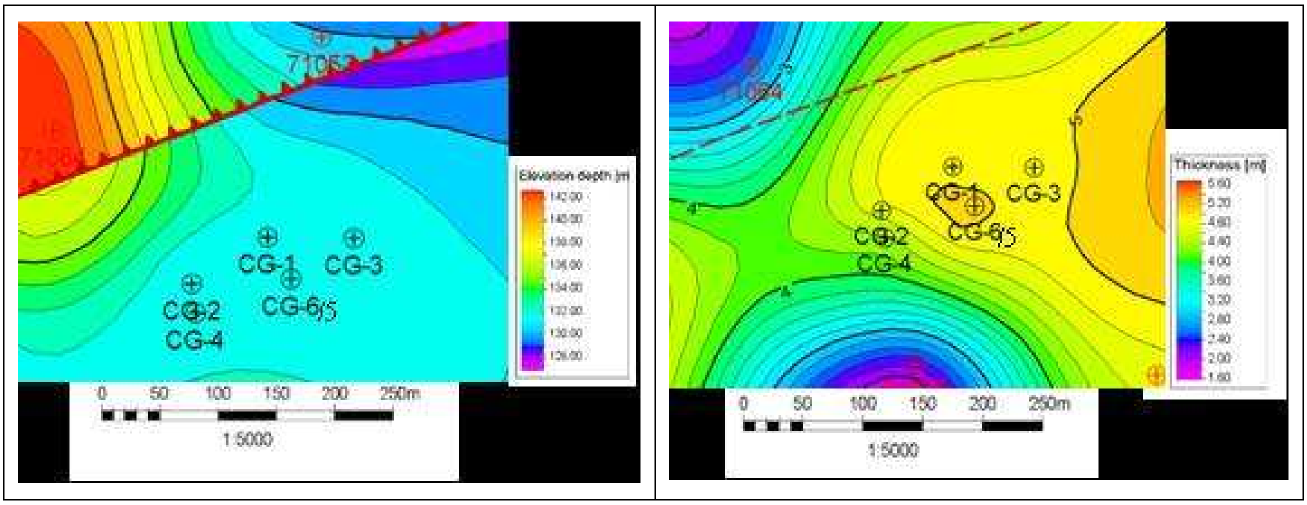


Figure 2.2.7: Seam V_{upper} depth of floor (left) and total thickness (right).

Hydrogeological Conditions of the Oltenia Deposit

Groundwater aquifer horizons in Oltenia basin develop mainly in alluvial deposits of river flood plains and their terraces in depths from 0.3 m to 6 m. Their filtration coefficient ranges from 2.5 up to 96 m/d (Fodor et al., 2006). Deeper horizons are formed in layers due to the regional development with thicknesses from 5 m to over 100 m. Their dominant direction of flow is from NW to SE with a filtration coefficient of 1 m/d and less for fine grained sands. Due to the mining activities there are several locations where water is discharged from the ground (altogether about 95 Mm^3/a), leading to significant local drawdown and changes to the natural water tables.

With respect to the hydrogeological conditions at the selected site in the Urdari - Valea cu Apa perimeter a total of 5 aquifers have been identified (see Table 2.2.1 and Figure 2.2.3) with general flow direction from NW to SE (Iamandei & Ticleanu, 2015).

Due to the clay layers and coal seams that act as seals it can be assumed that the connectivity between the individual groundwater horizons is fairly low. However, in particular with respect to monitoring purposes all aquifers have to be monitored individually to ensure that potential contaminants do not migrate from one aquifer to another. A potential pathway for groundwater might be the fault north of the test site. Figure 2.2.8 schematically illustrates the hydrogeological situation at Urdari, also showing wells used for drinking water.

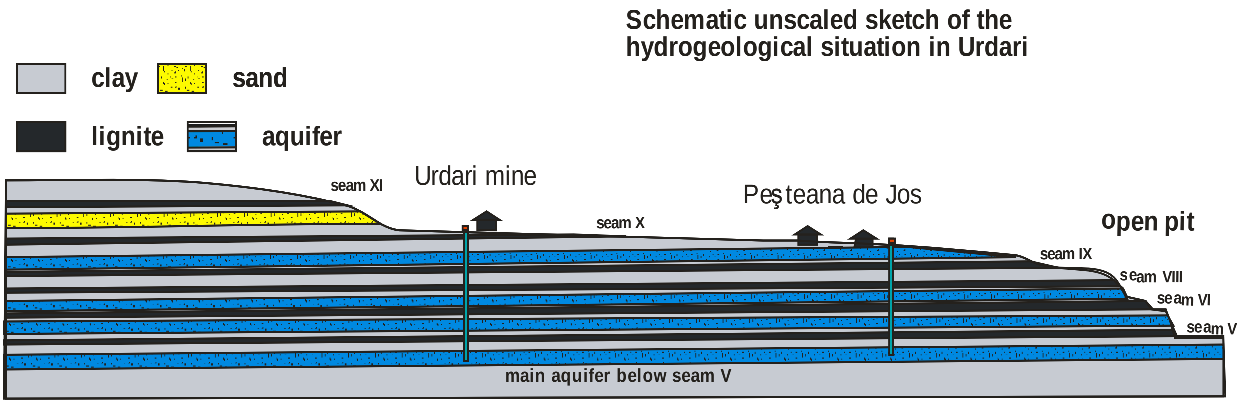


Figure 2.2.8: Schematic unscaled sketch of the hydrogeological situation in Urdari.

Table 2.2.1: Aquifer properties

	Aquifer				
	Layer V bed	Layer V-VI	Layer VII-VIII	Layer VIII-Xc	Surface Aquifer
Flow (cm/day) min	65.68	2.60	0.50	-	no data
Flow (cm/day) max	495.13	255.16	329.78	-	
Hydrostatic Pressure (mWC) min	90.0	28.53	18.65	2.85	
Hydrostatic Pressure (mWC) max	150.0	110.96	91.6	19.15	
Permeability (m/s) min	4.50E-07	1.16E-08	3.24E-07	5.79E-08	

Permeability (m/s) max	1.18E-04	4.91E-05	2.38E-05	7.06E-06	
Transmissivity (m^2/s) min	4.94E-06	2.37E-07	3.40E-07	3.47E-07	
Transmissivity (m^2/s) max	1.46E-03	1.33E-03	4.33E-04	1.65E-04	

Geotechnical parameters

Geotechnical parameters, like compressive strength, consistency limits, specific gravity, were analysed from the drilled core and are described under WP3. They were used to construct geotechnical models in Flac3D in order to gain a first insight into geomechanical aspects of the proposed test site (see Task 4.4).

Task 2.2 – Analysis of geological, coal and mining parameters of other comparable deposits in home countries of partners and elsewhere in Europe

A set of parameters has been generated specifically for this task, which have been taken as guideline for the descriptions of lignite deposits in the home countries. These criteria have been the subject of several previous works. The most important characteristics that affect the possibility of UCG include:

- geologic structures both above and below the coal seam, especially the geomechanical properties of the coal seam, overburden, and the hydrogeological properties,
- depth, thickness and dip of the coal seam,
- coal seam integrity,
- coal characteristics - particularly coal rank and reactivity, including ash content, moisture, sulphur and methane content - defining geochemical and mineralogical characteristics of the coal seam and surrounding rocks including the possibility of potential contaminants such as sulphides, heavy metals, phenols, etc.
- permeability of the roof, depending on the pore structure and the presence of natural fractures. Furthermore, fault planes or shear zones near the seam are of great importance, as they can provide leakage paths for syngas.
- expected subsidence. The range and nature of the subsidence of the surface depend on the type of overburden rocks. At the same time, it should be noted that the majority of coal ash remains underground and acts as a buffer to reduce the surface subsidence.

The parameters are presented in Table 2.2.2.

Table 2.2.2: Parameters serving as guideline for lignite deposit descriptions.

CRITERION	PREFERRED CONDITIONS
Caloric value	Minimum amount 8 MJ
Volatile matter	below 50 %
Ash content	Below 20 % (25 %)
Natural moisture	Below 55 % (theoretical value from laboratory experts. UCG gasification laboratory experiments have been carried out until a moisture content of 53 wt% at GIG Poland.
Sulphur content	Below 4 %
Deposit thickness	2 m up to 4 m
Minimal depth	over 150 m (in case of the deposit not associated with glacial activity it can be lower)
Deposit type	single-seam deposit preferred. If multi-seam, then the distance between seams should be > 20 m
Inclination angle of the deposit	Horizontal or slightly inclined
Surrounding rocks	Roof rocks are clays and silts of very low permeability
Position relative to aquifers	Aquifers in the vicinity of coal are always present. Clay seal at the respective thicknesses needed – see below.
Tectonics	no cracks and faults, no significant tectonic disturbances within the mining fields
Porosity of the surrounding rocks	roof and the floor should have lower gas permeability than the lignite seam, while the thickness of poorly permeable rocks surrounding the seam should be 1-2 m (for a 2 m thick seam) or 2-4 m (for a 3-10 m thick seam)
Area required for UCG plant	min. 50 ha for pilot plant; 100 ha for commercial

Deposits were analyzed in the following countries: Poland, Greece, Slovenia, Romania and Germany. The list of characterized deposits is presented in Table 2.2.3.

Table 2.2.3: List of deposits which have been characterized

Country	No.	Deposit
POLAND	**1**	Gostyń
	2	Kamieńsk
	3	Krzywiń
	4	Ścinawa-Głogów
	5	Torzym
	6	Węglewice
GREECE	**1**	Kozani
	2	Florina
	3	Prosilio
	4	Almyros- Western Deposit
	5	Almyros- Eastern deposit
SLOVENIA	**1**	Velenje
	2	Šoštanj
	3	Lendava
	4	Globoko
	5	Ilirska Bistrica
	6	Krmelj
	7	Kanižarica
ROMANIA	**1**	Lupoaia
	2	Ploştina Nord
	3	Tehomir
	4	Urdari – Valea cu apă
GERMANY	**1**	Rhineland area
	2	Lusatian area
	3	Central German area
	4	Helmstedt area

Task 2.3 – Establishing site selection criteria and assessment of potentially suitable deposits and areas based on lessons learned from previous UCG projects, relevant natural and man-made phenomena

The objective of this task was to develop site selection criteria (SSC) for UCG that can be applied to shallow lignite deposits and specifically to the conditions of Oltenia. For this purpose established approaches from previous and ongoing trials were reviewed. As coal occurs in a large variety of geological settings and specific parameters like rank, coal quality, seam structure etc., as well as boundary conditions like for example infrastructural, legal and administrative situation, every investigated or currently used UCG site is unique. Therefore the existing SSC can only be regarded as a starting point for further discussion. In addition, not many well documented examples from UCG in shallow lignite exist. As a new approach, natural coal fires and methods of fire detection and extinction were compared as analogues to UCG. Experiences gained with such natural fires were used with respect to monitoring and preventing any uncontrolled development of UCG.

Site selection is essential for:

- Reducing environmental risk: some previous trials, particularly the infamous "Hoe Creek" series of trials in the USA, resulted in environmental impacts such as surface subsidence and groundwater contamination;
- Selecting the correct coal quality: selecting the wrong kind of coal (e.g. swelling coal) can prematurely end an UCG project for specific configuration e.g. the Princetown UCG trial in West Virginia was shut-down prematurely partly because the process wells became plugged by swelling coal. The L-CRIP configuration is much less sensitive to this risk; and
- Selecting the correct geomechanical-hydrogeological regime: the geomechanical response of the rocks overlying (and underlying) a coal seam to changes in stress caused by UCG can have a profound effect on the flow of groundwater into and away from an UCG reactor. Trials such as those at El Tremedal, Spain and Hoe Creek III, USA both encountered increased groundwater influx from overburden during UCG. In both cases, the groundwater influx was poorly managed and indirectly led to temporary or premature stoppage of the trials.

Other points that should be taken into consideration, when assessing site selection, are:

- Selecting a site within a fit-for-purpose regulatory regime: in some areas of the world (e.g. Queensland, Australia), UCG licence tenements have overlapped with other licences such as mining or coal bed methane. The location of pre-existing licenses, and the potential for future licences, that may conflict with UCG should be investigated during UCG site selection;
- Selecting a site that can support a commercial UCG project e.g.: (i) there must be enough coal to support the commercial project over its lifetime, (ii) the syngas or end-product must have a market; and (iii) the syngas or end-product must be produced at commercially competitive cost.

Some of the considerations above can be examined qualitatively, whereas others require quantitative analysis via the use of modelling (Task 4.4) and additional exploratory works (Tasks 3.3 to 3.5). A number of quantitative and semi-quantitative criteria have been published in order to aid site selection. Many of the criteria are also coupled; for example, coal seam thickness has a profound impact on the economics of an UCG project because it affects the volume of coal that can be gasified per module. It is not just the volume of coal that can be gasified per module that it is important, however. The "energy in place" per module is the critical factor, and this depends on the energy density (GJ per m^3 in-place) of the coal as well as the volume of coal converted. The site selection process for commercial UCG deployment must account for this fact.

The site selection criteria of technical nature have been complemented with criteria reflecting the local infrastructure and regulatory framework. A total of 24 site selection criteria have been set up and compared, comprising both technical, as well as legal and infrastructure related aspects. The site selection criteria are: infrastructure, distance from populated areas, distance from major highway and rail, distance from rivers and lakes, distance from active mines, distance from abandoned mines, land-ownership, availability of previous exploration data, caloric value, volatile matter, ash content, natural moisture, sulphur content, deposit thickness, minimal depth, deposit type, inclination angle of the deposit, surrounding rocks, position relative to aquifers, tectonics, porosity of the surrounding rocks, presence of coal bed methane, area required for UCG plant.

The important aspects here for Oltenia are the possibility to acquire the necessary licences to obtain additional exploration results as well as distance to settlements and mining operations. The acquisition of new geoscientific information from drilling and borehole geophysical logging for site assessment was conducted in Tasks 3.3 to Task 3.5.

For the evaluation of a potential site it is suggested that an assessment of type, quality and quantity of (geological) data may be (and from an economic viewpoint has to be) performed in an analogous way to the reporting of coal resources and reserves as outlined e.g. in the JORC code. If several sites are discussed an assessment can be made based on the confidence levels of the available geological data. It is common practice to confirm historical exploration data with new techniques or confirmation drilling. This has been performed at the test site in Oltenia, where historical data is present.

From the study of naturally occurring coal fires (e.g. Gielisch 2008, Gielisch et. al. 2010, Gielisch & Kayser 2010) it can be concluded that micro seismic monitoring, as well as magnetic surveys, may yield valuable information to monitor the propagation and development of fractures and the propagation of the combustion front, provided that the heat source is at relatively shallow depths (above 200 m) and presence of magnetite and hematite. Both types of information may become important in the unlikely case of uncontrolled leakage of contaminants into groundwater reservoirs or influx of oxygen through fractures. In addition, the knowledge of the burning front propagation speed may influence operating decisions such as the moment for retracting the injection point or oxidant composition. With respect to gas monitoring purposes it can be derived from natural occurring coal fires that gas leakage is not limited to the area immediately above the coal fire. Therefore, gas monitoring should be extended to the surrounding areas taking the regional fault and fracture pattern into account.

Task 2.4 - Site selection

At the beginning of the COAL2GAS project, CEO suggested four (4) site locations for further analysis, namely: Tehomir, Urdari, Lupoaia-Prigoroiu and Plostina. Figure 2.2.9 shows the proposed site locations. Site selection at Oltenia was strongly influenced by the license situation (Criteria 4, see Task 2.3). On the basis of the license and permit situation, one site has been chosen, close to the Urdari Mine (at approx.1 to 2 km). To further evaluate this particular site (Criteria 1 to 3), it was imperative to obtain as much information as possible on the coal quality (ref. Tasks 3.1 & 3.2) and the geological and hydro-geological situation (ref. Task 2.1). A geological report has been made for the proposed test site, which formed the basis for the 3D geological model. Evaluation and refinement of the 3D model with respect to the site specific properties were done when the results of tests performed after the drilling campaign have become available.

The necessary geological information for the evaluation of the proposed sites was difficult to access due to the classification of data as confidential. ISPE has done great efforts for the de-classification of this data, which was time consuming but, eventually, successful. The available information that could be found was acquired by ISPE from the Romanian Geological Institute (IGR). The result of this activity and additional information provided by CEO consisted in a "Geological Report containing data and information on "Western Oltenia-Motru" lignite mining perimeters, with special focus on "Urdari - Valea cu Apă" perimeter" that was prepared by ISPE and CEO.

Using this report site selection has been performed on the basis of choosing a location with the presence of coal seams V to X with thicknesses above 2 m and at a suitable depth below surface. Due to the fact that access to available detailed information is difficult, the selection of the Urdari test site has also been driven by the consideration to obtain relevant detailed information on coal seams and the surrounding strata and potential cap rocks. For this purpose the Urdari test site is ideal, since the license situation allows CEO to perform such tests.

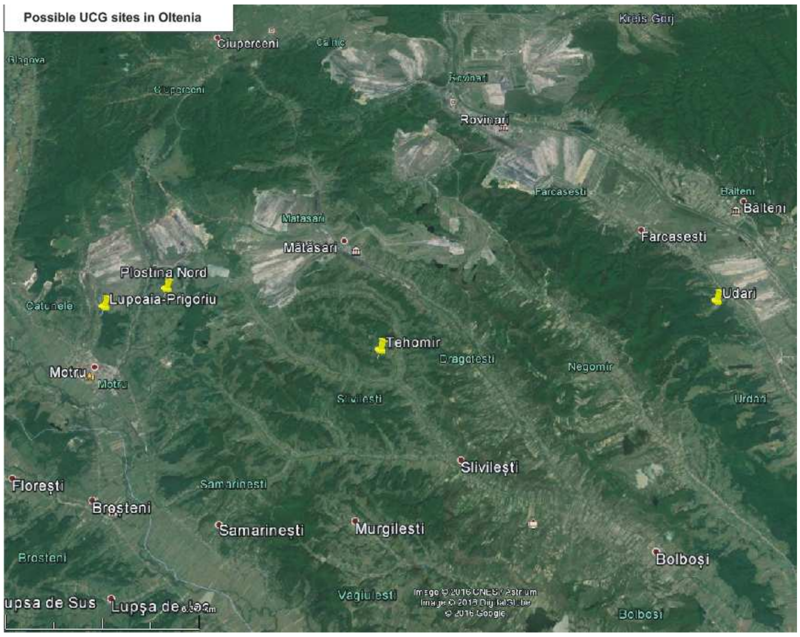


Figure 2.2.9: Locations of proposed sites

A total of 6 exploration borehole locations have been proposed during a site visit by the members of the research project, which, subsequently, have been reduced to 5 boreholes due to budget reasons. The drillholes were primarily designed as exploration drillholes.

2.2.3. *WP3: Testing and Drilling*

Task 3.1 – Preparation and characterisation of coal bulk samples from active mining areas

The coal samples used for UCG tests were extracted from two lignite deposits: Premogovnik Velenje and CE Oltenia. At Velenje Coal Mine coal blocks were collected in January 2015 from the active underground longwall face (Figure 2.2.10.a). The coal samples from CE Oltenia were collected in September 2015 from the active open pit mine Peşteana (Figure 2.2.10.b).

a)

b)

Figure 2.2.10: Coal sampling place: a) at the Velenje Coal Mine (longwall face), b) at Pesteana CE Oltenia (open pit)

A physicochemical characterisation of coal samples was performed by Department of Solid Fuels Quality Assessment of Central Mining Institute (ISO/IEC 17025 accreditation certificate). The analyses included:

- proximate and ultimate analysis,
- sulphur forms (speciation),
- ash fusion temperature,
- Fischer assay.

Results of proximate and ultimate analyses revealed that both samples were characterized by relatively high moisture content (Table 2.2.4), however for the Oltenia lignite, this parameter was significantly greater, i.e. 45.64%wt compared to 31.62%wt obtained for Velenje lignite (as received basis). The coal moisture content is one of the crucial parameters determining the gasification conditions, the quality (calorific value) and yields of UCG gas, as well as the suitability of lignite for UCG. Romanian lignite was also characterized by higher ash and sulphur contents and lower volatiles. It resulted in considerably lower calorific value of the Oltenia coal, which classifies it to the category of Lignite B coal according to the classification of coals by the American Society for Testing and Materials (ASTM).

Table 2.2.4: Proximate and ultimate characteristics of coals used for ex-situ gasification tests

No.	Parameter	Coal sample	
		Velenje	**Oltenia**
	As received		
1	Total moisture W_t^r, %	31.62	45.64
2	Ash A_t^r , %	4.29	8.86
3	Volatiles V^r, %	43.67	25.78
4	Total sulphur S_t^r, %	0.51	1.49
5	Calorific value Q_i^r, kJ/kg	13 615	10 642
	Analytical		
6	Moisture W^a, %	11.13	11.49
7	Ash A^a, %	5.57	14.42
8	Volatiles V^a, %	56.76	41.98
9	Heat of combustion Q_s^a, kJ/kg	19 719	20 001
10	Calorific value Q_i^a, kJ/kg	18 427	18 860
11	Total sulfur S^a, %	0.66	2.43
12	Carbon C_t^a, %	49.86	49.49
13	Hydrogen H_t^a, %	4.67	3.94
14	Nitrogen N^a, %	0.64	1.34
15	Oxygen O_d^a, %	27.83	17.12

Sulphur analysis in coals included determination of the total sulphur content and speciation of its four forms: pyritic, sulphate, ash sulphur and combustible sulphur. The Oltenia lignite was characterized by considerably higher content to total sulphur compared to the Velenje sample, i.e. 2.75% and 0.74%, respectively (Figure 2.2.11). The studies carried out showed that in both coals, pyritic sulphur is the main chemical form of sulphur. For the Oltenia lignite more than 90% of total sulphur occurs in combustible form. About 55% of total sulphur of Velenje coal remains in the ash/slag. With respect to the UCG process, the ratio of ash sulphur to combustible sulphur is a crucial parameter governing partitioning of the total sulphur between the post gasification ash/slag left underground and product gas recovered on the surface.

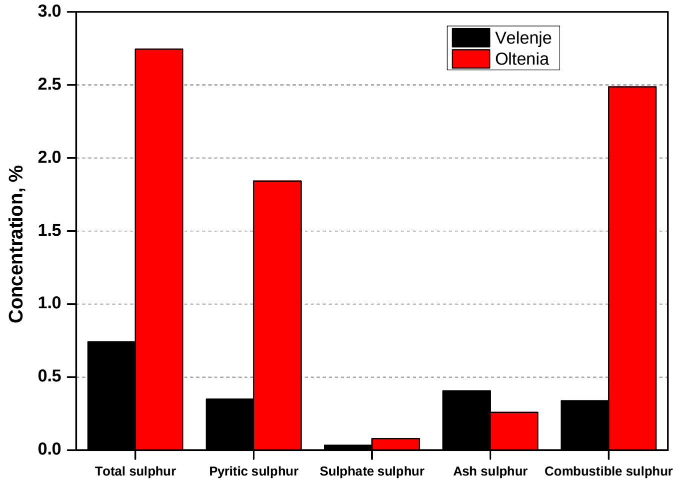


Figure 2.2.11: Sulphur forms in lignites used for ex-situ gasification tests

Task 3.2 – Large-scale gasification tests on selected coal bulk samples

Four large-scale gasification experiments were conducted using UCG test facilities of GIG's Clean Coal Technology Centre according to the experimental plan presented in Table 2.2.5. For each of the two studied lignites, gasification tests under atmospheric and elevated pressure conditions (corresponding to the hydrostatic pressure of the coal seam) were done. The main objectives of the experimental campaign were to investigate:

- the role of gasification mixture and coal properties on coal gasification rates, composition of products and process efficiency,
- the influence of natural coal moisture,
- the influence of gasification pressure (natural hydrostatic regime) on the product gas composition and process efficiency.

Table 2.2.5: Experimental plan for the ex-situ UCG tests within COAL2GAS project

Parameter	**Experiment no.**			
	1	**2**	**3**	**4**
Coal type	Lignite	Lignite	Lignite	Lignite
Origin	Premogovnik Velenje (SLO)	CEO S.A. (RO)	CEO S.A. (RO)	Premogovnik Velenje (SLO)
Gasification reagent	O_2	O_2 /steam	O_2	O_2
Gasification pressure	atmospheric	ambient	10 bar	35 bar
Coal seam dimensions	0.8 x 0.8 x 6.0 m	0.8 x 0.8 x 6.0 m	0.4 x 0.4 x 3.5 m	0.4 x 0.4 x 3.5 m
Experiment duration, h	120	96	72	72

Athmospheric pressure UCG experiments (No 1-2)

The installation makes it possible to simulate atmospheric UCG process in the laboratory conditions. The main part of the test facility is a gasification chamber (Figure 2.2.12), where underground geological conditions simulated both in respect to coal seam and surrounding strata. The maximum length of the artificial coal seam is about 7 m. Oxygen, air and steam can be used as gasification reagents, supplied individually or in mixtures. N_2 is used as a safety and inertizing agent. The raw UCG-derived gas is subject to scrubbing with water to reduce its temperature, remove particulate matter and condense high boiling tar components. The subsequent gas treatment steps involve separation of aerosols. Produced gas is finally neutralized in a natural gas fuelled thermal combustor. Concentrations of the main gaseous components are analyzed using gas chromatography (GC) technique. The distributions of temperature fields during the experiments are recorded by thermocouples (Pt10Rh-Pt) installed directly in various zones of the coal seam and surrounding strata. The inlet and outlet gas temperatures and pressures are also monitored as crucial operational parameters.

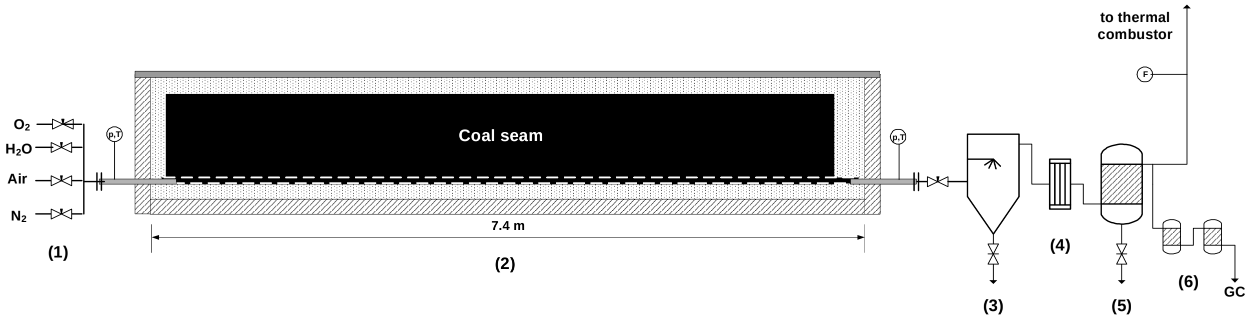


Figure 2.2.12: Schematic view of the UCG installation: (1) reagents supply system, (2) gasification chamber, (3) water scrubber, (4) gas cooler, (5) separator, (6) filters

The gasification channel was drilled along the bottom part of the seam and its dimensions were 0.1 x 0.1 m. Sand was used to fill the voids between reactor's walls and the coal seam and for the preparation of the roof stratum. 20 thermocouples were installed inside the reactor to record the temperature profiles during gasification (Figure 2.2.13).

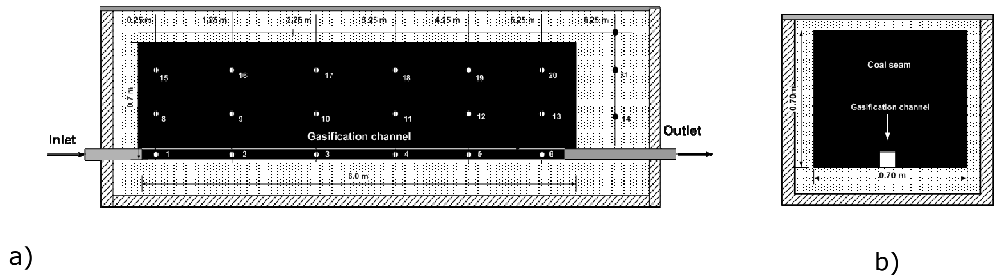


Figure 2.2.13: Sections of the artificial coal seam (proportions are not respected): a) longitudinal b) cross-section

The coal seams were ignited using a pyrotechnic charge. The gasification process was started by putting oxygen (99.5 % purity) into the ignited coal seam. An initial oxygen supply rate was 2-3 m^3/h and it was gradually increased over the course of the experiment, up to maximum value of 5 m^3/h in the final phase of the gasification processes. Due to over-stoichiometric water content in the raw coal, no water addition was applied during the first test with Velenje lignite. In the second UCG test with Oltenia lignite, the influence of steam addition was tested. Both gasification tests were conducted under near-ambient pressure conditions. Concentrations of the syngas components (H_2, CO, CO_2, CH_4, N_2, O_2, C_2H_6, H_2S) were analysed in one hour time intervals.

Large scale high-pressure UCG experiments (No 3-4)

The high-pressure laboratory installation used for the tests enables simulations of UCG in an artificial coal seam with dimensions of 3.5 x 0.4 x 0.4 m. Flow chart of the high pressure UCG test facility is presented in Figure 2.2.14. Gasification parameters are as follows:

- max gasification temperature: up to 1600 ºC
- gasification pressure: up to 5 MPa
- oxidizing media supply rate: 1 - 10 Nm^3/h
- gas production rates: 2 - 20 Nm^3/h

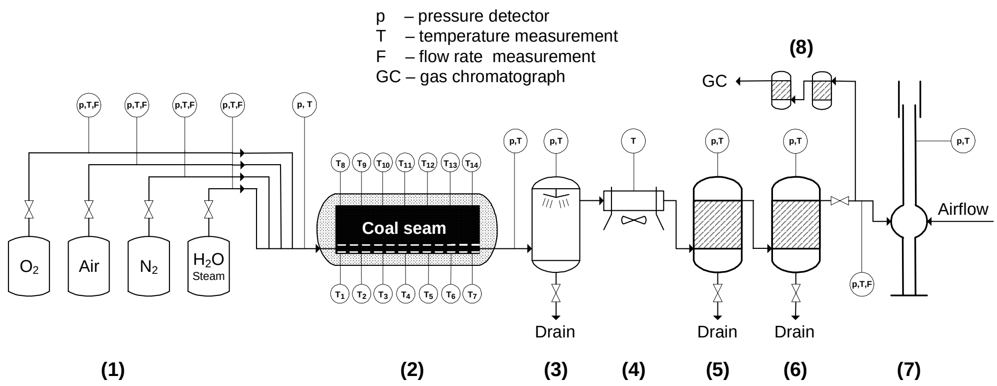
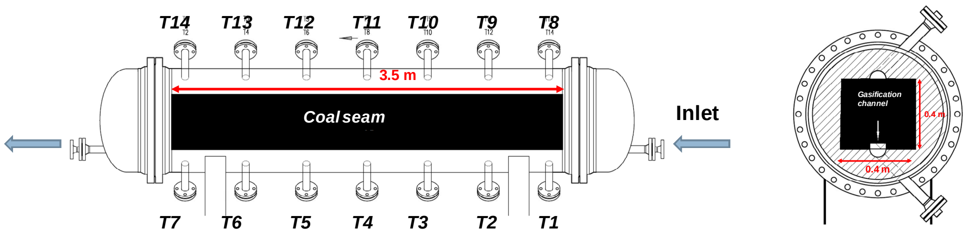


Figure 2.2.14: Scheme of the ex-situ high pressure UCG installation: (1)- compressed reagents, (2)- pressure reactor, (3)- wet scrubber for gas cleaning, (4)- air cooler, (5,6)- gas separators, (7)- thermal combustor, (8)- gas treatment module prior to GC analysis.

The cross sections of the UCG reactor for the high pressure tests are presented in Figure 2.2.15.



a) b)

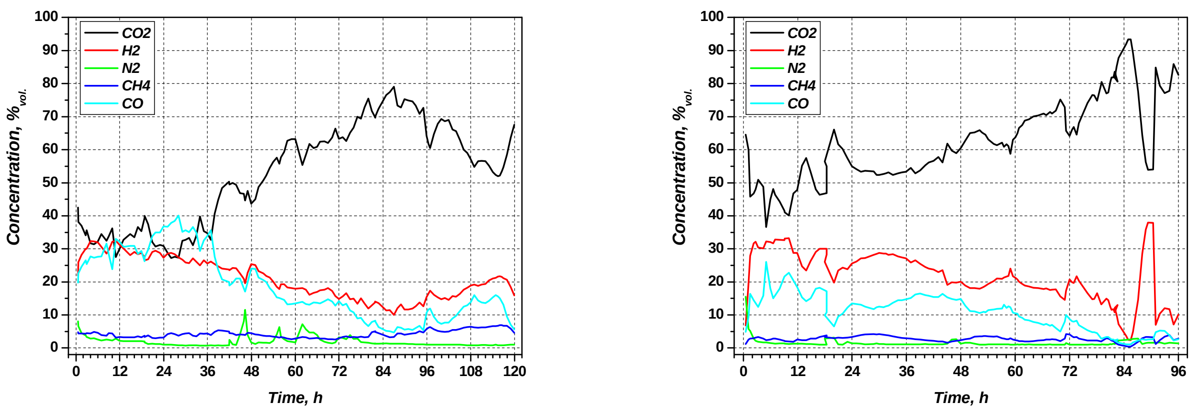
Figure 2.2.15: Cross sections of the high pressure UCG reactor: a) side cross-section, b) vertical cross-section

Distributions of temperatures during the gasification process were controlled by 14 high-temperature thermocouples (Pt10Rh–Pt). Thermocouples T1-T7 were located in the gasification channel and thermocouples T8-T14 in the roof strata.

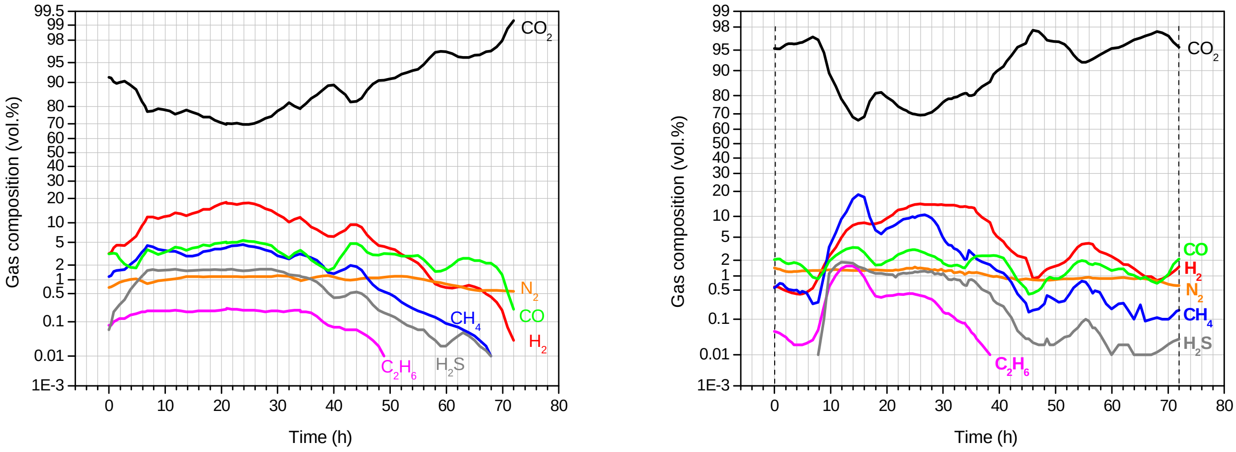
Results

UCG gas composition and calorific value

Changes in the product gas composition and gas calorific value for the experiments carried out are presented in Figure 2.2.16 and Figure 2.2.17, respectively.



a) b)



c) d)

Figure 2.2.16: Changes in gas composition over the course of the gasification experiments: a) No. 1 Velenje lignite atmospheric , b) No. 2 Oltenia lignite atmospheric , c) No. 3 Oltenia 10 bar d) No. 4 Velenje 35 bar

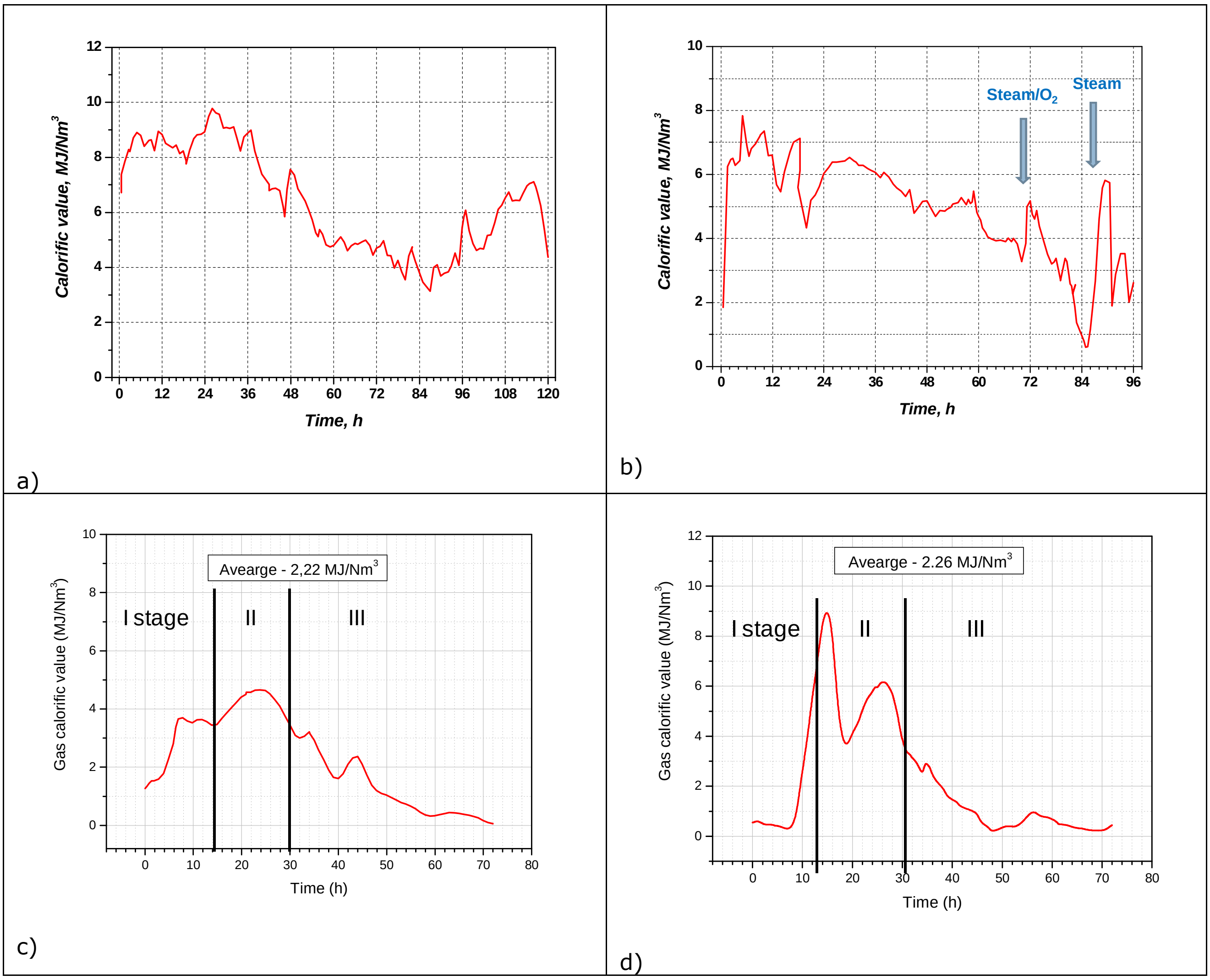


Figure 2.2.17: Changes in gas calorific value over the course of the gasification experiments: a) No. 1 Velenje lignite atmospheric , b) No. 2 Oltenia lignite atmospheric , c) No. 3 Oltenia 10 bar d) No. 4 Velenje 35 bar

As can be seen from the graphs, the initial gasification periods for both **atmospheric pressure experiments** were characterized by a good quality product gas with an average calorific value of ~9 MJ/Nm^3 and ~7 MJ/Nm^3 for Velenje and Oltenia process, respectively. A gradual decrease in the gas production rate accompanied by a significant deterioration of gas quality, expressed by the content of combustible components (H_2, CH_4, CO) and its calorific value, were observed from about the 48th hour for both experiments. In the Oltenia trial, in 70th hour of the experiment steam was additionally supplied to the reactor with a constant rate of 2kg H_2O/h, which resulted in a short increase in the gas quality. The gas quality again improved after increasing the oxygen supply rate in the 84th hour of the experiment. The final gaseous products of both atmospheric pressure experiments are characterized by relatively high hydrogen and methane contents.

During both **high pressure experiments**, three distinct gasification phases were distinguished as presented in Figure 2.2.16 and Figure 2.2.17. As can be seen from the graphs, the initial gasification periods (stage I) for both experiments were characterized by a relatively low gas calorific value. The gasification conditions favourable for the production of gas with a relatively high calorific value were attained in the stage II of both experiments. In the stage II gas calorific values were ~4.2 MJ/Nm^3 and ~5.8 MJ/Nm^3 (on average) for Oltenia and Velenje trials, respectively. A gradual decrease in the gas production rate accompanied by a significant deterioration of gas quality, expressed by the content of combustible components (H_2, CH_4, CO) and its calorific value, were observed from about the 40th hour for both experiments. In the final stage II of the experiments, combustion reactions started to dominate, leading to the gradual increase in concentrations of CO_2.

Average gas compositions for the UCG experiments conducted are presented in Table 2.2.6 to Table 2.2.8.

Table 2.2.6: Average gas compositions obtained in the atmospheric pressure experiments No.1 and No. 2

Experiment	**Lignite**	**Composition, %vol.**								**CV, MJ/Nm³**
		CO_2	**C_2H_6**	**H_2**	**O_2**	**N_2**	**CH_4**	**CO**	**H_2S**	
No. 1	Velenje	52.5	0.2	21.0	1.0	2.0	4.3	18.6	0.5	6.4
No. 2	Oltenia	63.3	0.2	21.3	0.2	1.5	2.7	10.2	0.6	4.8

Table 2.2.7: Average gas compositions obtained in the particular stages of the experiment No. 3: 10 bar Oltenia

Stage	**Composition, %vol.**								**CV, MJ/Nm³**
	CO_2	**C_2H_6**	**H_2**	**O_2**	**N_2**	**CH_4**	**CO**	**H_2S**	
I	83.8	0.2	8.3	0.0	0.9	2.8	3.1	1.0	2.6
II	72.7	0.2	15.9	0.0	1.2	3.8	4.7	1.6	4.2
III	90.5	0.0	4.5	0.0	0.9	1.0	2.6	0.4	1.3
Average	82.3	0.1	9.6	0.0	1.0	2.5	3.5	1.0	2.7

Table 2.2.8: Average gas compositions obtained in the particular stages of the experiment No. 4: 35 bar Velenje

Stage	**Composition, %vol.**								**CV, MJ/Nm³**
	CO_2	**C_2H_6**	**H_2**	**O_2**	**N_2**	**CH_4**	**CO**	**H_2S**	
I	93.9	0.2	1.1	0.8	1.3	1.5	1.8	0.3	1.1
II	72.8	0.5	11.5	0.0	1.3	10.0	2.6	1.2	5.8
III	90.8	0.0	5.4	1.3	0.9	1.2	1.4	0.3	1.3
Average	85.8	0.2	6.0	0.7	1.2	4.2	1.9	0.6	2.7

The process balance calculations both in respect to materials and energy for the particular experiments are presented in Table 2.2.9 to Table 2.2.11. According to the energy balance estimations, the Velenje atmospheric process was characterized by highest gross energy efficiency, i.e. 44.6 % (calculated as a ratio of the energy input in coal to the energy output in gas), compared to Oltenia atmospheric trial (33.4%) and to both high pressure experiments. For the high pressure tests the maximum gross efficiency value, obtained in stage II for the Velenje trial was 35.2 % compared to 27.2 % obtained for Oltenia trial. The lower energy efficiencies obtained for both Oltenia experiments resulted from the higher moisture content in the raw lignite, which led to higher heat losses due to water evaporation. The significantly lower energy efficiencies for the high pressure trials (No. 3 and No. 4) indicate that gasification conditions were not appropriate for the formation of combustible gas components. It may have resulted from inappropriate coal seam geometry (e.g. too short the length of gasification channel) for the UCG under high pressure regime, which could have led to a self-combustion of UCG gas (gas cannibalism phenomenon).

Table 2.2.9: Balance calculations for the Velenje and Oltenia atmospheric pressure experiments

Parameter	Velenje	Oltenia
Estimated total coal consumption (kg)	730	790
Average coal consumption rate (kg/h)	6.1	8.2
Average gas production rate (Nm^3/h)	5.7	6.1
Average reactor power (kW)	10.3	8.1
Gross energy efficiency (%)	44.6	33.4

Table 2.2.10: Balance calculations for the Oltenia 10 bar experiment

Parameter	Gasification stage			Total/ Average
	I	II	III	
Estimated total coal consumption (kg)	140.8	131.1	313.1	585
Average coal consumption rate (kg/h)	10.8	8.1	7.5	8.8
Average gas production rate (Nm^3/h)	0.63	0.70	0.60	0.6
Average reactor power (kW)	4.9	6.5	1.6	4.3
Gross energy efficiency (%)	15.5	27.2	7.3	16.7

Table 2.2.11: Balance calculations for the Velenje 35 bar experiment

Parameter	Gasification stage			Total/ Average
	I	II	III	
Estimated total coal consumption (kg)	121.3	146.9	322.8	591
Average coal consumption rate (kg/h)	9.3	8.6	7.7	8.5
Average gas production rate (Nm^3/h)	0.74	0.83	0.78	0.8
Average reactor power (kW)	2.0	11.5	2.1	5.2
Gross energy efficiency (%)	5.7	35.2	7.1	16.0

Task 3.3 – Test drilling at selected sites

A drilling program with closely spaced drill holes was set up to enable a high data density in the target area. Five vertical HQ-diameter drillholes with lengths between 50 m and 141 m were drilled (Figure 2.2.18), obtaining core from the underlying seams and the interburden rocks – maximum down to Seam IV. All five boreholes have been equipped with perforated and unperforated PVC tubes and backfilled with gravel and sand for groundwater monitoring. Specifications of boreholes and depth of each filter section are shown in Table 2.2.12.

The closely spaced drilling gave detailed insight into the geological and hydrogeological conditions within the potential UCG test site. The available regional information could be verified as well as small-scale variability assessed (e.g. in coal seam thickness). Results were used for verification and refinement of the initial geologic model (see Task 2.1), as well as for rock mechanical and coal quality testing to provide exact data for the geomechanical calculations and the assessment of suitability of the seams for UCG.

Table 2.2.12: Design parameters of the drilled holes and groundwater monitoring wells (coordinates in UTM WGS84)

Drillhole Name	Number assigned by Drilling Company	Length [m]	X	Y	Z [m a.s.l.]	Inner Pipe Diameter [mm]	Pipe Wall Thickness [mm]	Filter Sections [m]
CG-01	F1	50	678856	4966104	172.00	67	4	15-31 / 47-49
CG-02	F4	141	678778	4966072	173.20	76	7	125.4-140
CG-03	F5	140	678936	4966111	170.40	76	7	16.2-36.2 / 46.2-51.2 / 81.1-101.1 / 121.2-138.5
CG-04	F3	80	678810	4966037	172.71	76	7	66-80
CG-06/ 05	F2	50	678882	4966074	170.63	76	7	24-29 / 44.1-49.1

Coal and rock formations were sampled during the drilling campaign. A total of 104 samples were collected. The sampling concentrated on the following coal seams: V, VI-VII and VIII, which was complemented as well by their roof and bottom rock/soil horizons. Further sampling of typical rock/soil was carried out, for additional soil mechanical characterization of the strata. Drill hole CG-03 was predominantly used, in order to obtain a representative layer sequence.

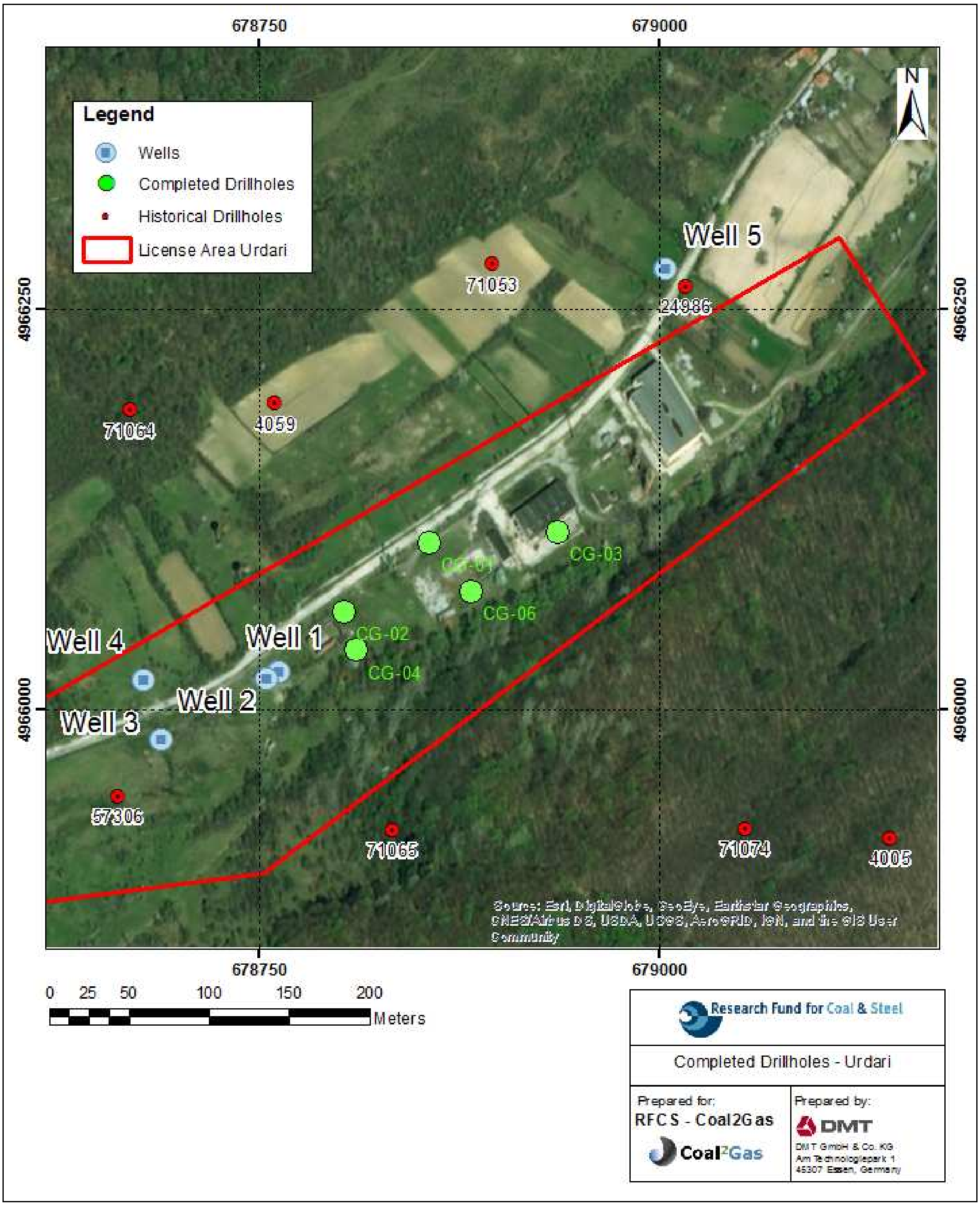


Figure 2.2.18: Overview map of completed drillholes CG-01 to CG-05/06, existing wells and historical drillholes

Task 3.4 – Logging of test drills

To assess the site specific conditions and select most suitable technologies for UCG testing, the five boreholes drilled under Task 3.3 and the obtained drill core were investigated in detail. The drill core was lithologically and geotechnically logged, sampled for laboratory analyses (performed under Task 3.5), and scanned with the DMT CoreScan3®. A variety of geophysical wireline logging was conducted in the boreholes:

- Natural Gamma Ray Log (QL40 GR) – to determine location of lithological boundaries, grainsize distribution;
- Spectral Gamma Ray (S.GR) – to determine location of lithological boundaries and radiometric analysis (Figure 2.2.20);

- Dual Induction Log (DIL) – to investigate the distribution of water bearing zones and geotechnical properties (Figure 2.2.20);
- Optical Borehole Scanner (OPTV) – for optical scanning of the PVC casing of the monitoring wells and measuring borehole deviation (Figure 2.2.21);
- Full Wave Sonic log (FWS 50 RX1) – for cement bond logging of the monitoring wells and inspection of the back filling quality (Figure 2.2.21);
- Salinity and Temperature (SAL/Temp) (Figure 2.2.22) and Tracer Fluid Logging (TFL) – for determination of water levels, inflow and outflow zones of groundwater, detection of infiltration water, determination of filtration rate and determination of total mineralization in water;
- Flowmeter Log (Flow) – to detect inflow and outflow zones of groundwater, and
- Milieu Logging (OCEAN) – to measure the chemical properties, density and groundwater quality, pH value, redox potential, salinity, temperature, and O2 content (Figure 2.2.22).

Figure 2.2.19: Geophysical well logging at CG-02

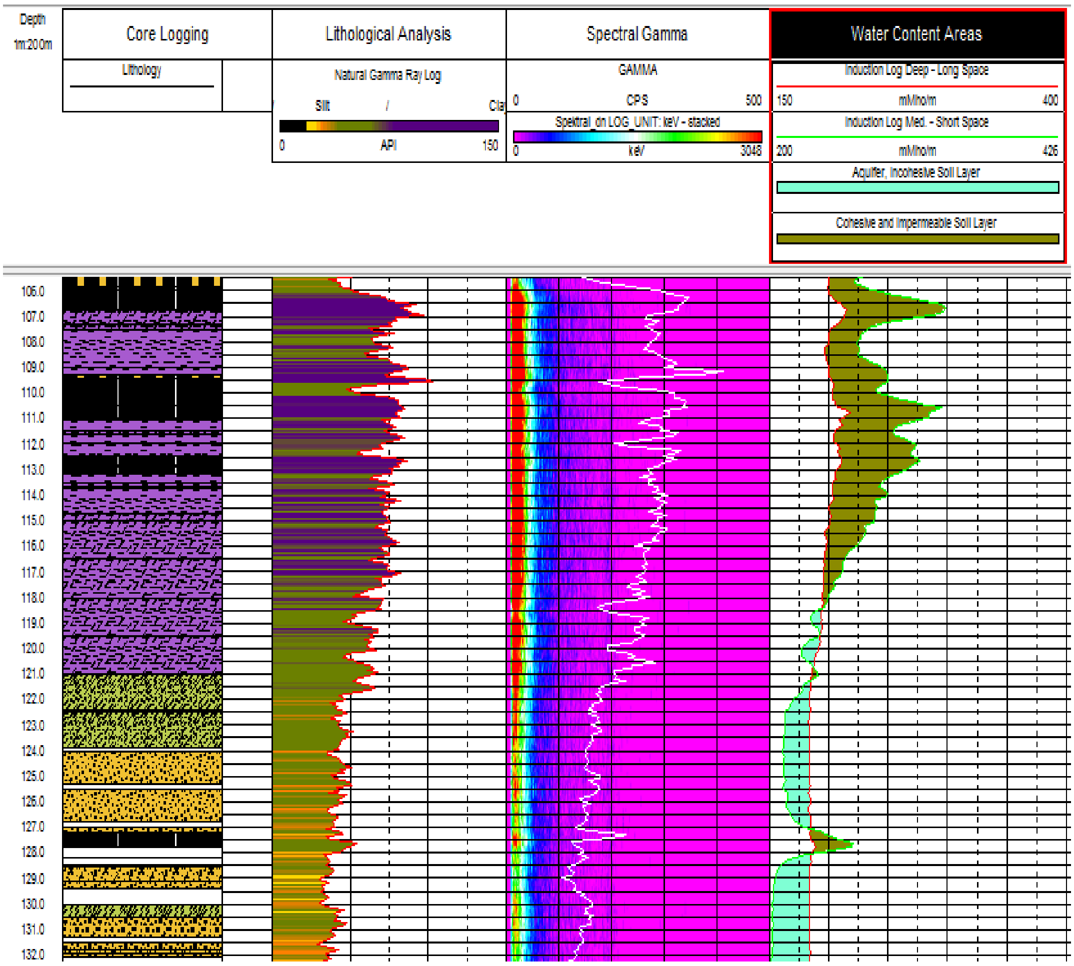


Figure 2.2.20: Lithological interpretation, example from CG-03

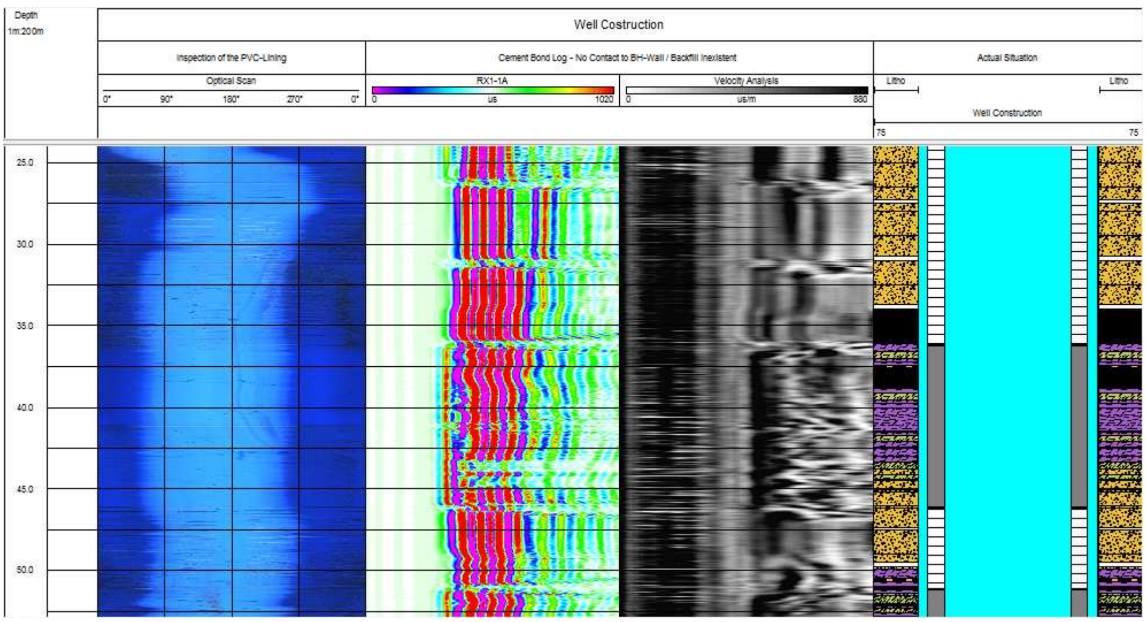


Figure 2.2.21: Example of well construction inspection, CG-03

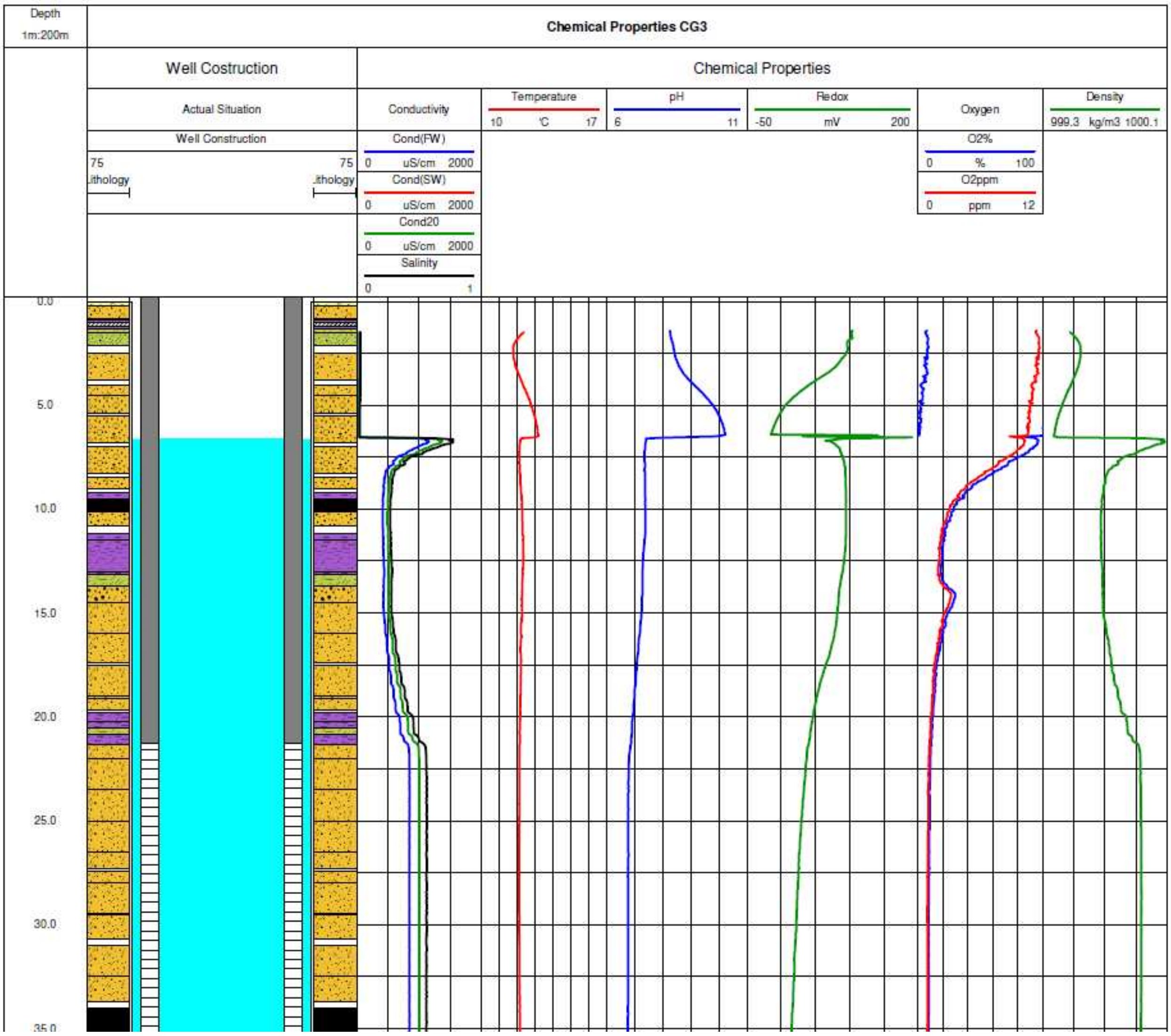


Figure 2.2.22: Example for logging of hydraulic properties, CG-03

The casing inspection with OPTV corresponds very well to the well design stated by DMT. Detected differences in construction depth are caused by the length of the casing and are smaller than 10 – 20 cm. Construction analysis of cement bond logs are showing bad bound between casing and formation, which indicates a non-existing back filling.

A cross-sectional lithologic interpretation from the well logs was compiled. The measured natural gamma ray (GR) values are typical fingerprints of the coal seams and allow a correlation between the boreholes. But coal seams are not the only strata which have left significant and typical fingerprints within of the measured data. Regarding to GR, DIL and UCS log and taking the core log as a basis for lithological interpretation, a distinction could be made between the different sediment layers or at least between cohesive/impermeable and incohesive/permeable layers. Coal seams, silt and clay layers and sand layers have been correlated on the basis of analyses and interpretations performed for each borehole (Figure 2.2.23). Lithological correlations of natural gamma ray logs, spectral gamma ray logs and dual induction logs correspond well to the performed core logging and helped to fill gaps where core losses occured.

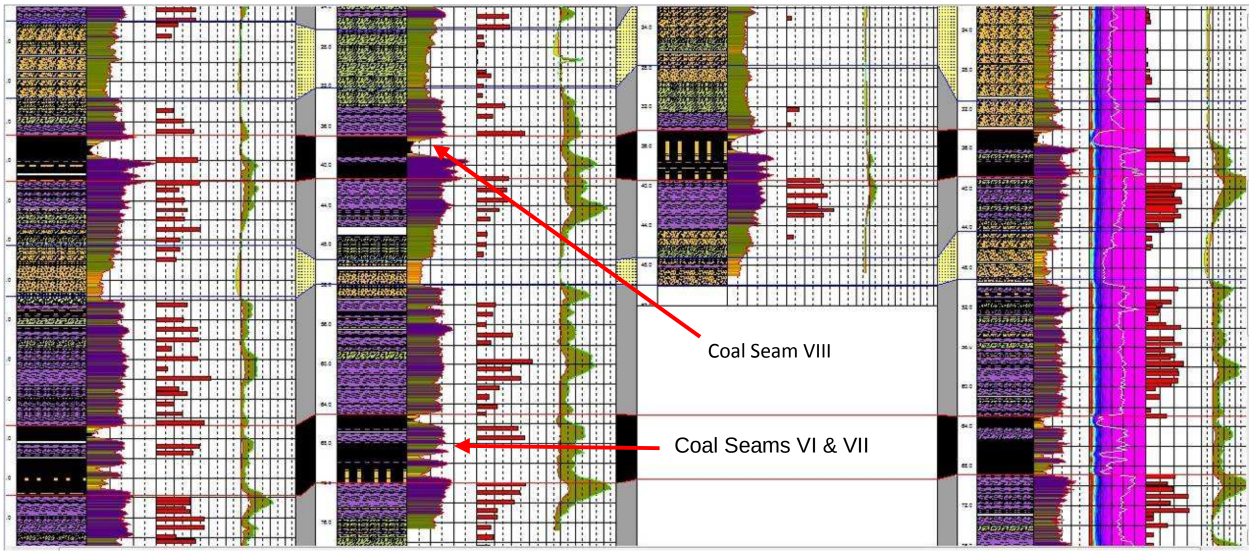


Figure 2.2.23: Example of lithological correlations between the observation boreholes on the basis of core logging and performed geophysical downhole surveyes

Lithological and geotechnical drill core logging was performed on all drillholes according to best industry practice. The lithologies in the investigated area of interest consist of mostly soft to moderately stiff clay, silt, sand of varying grain size, and intermediate varieties like silty clay, which are intersected by several meters thick lignite seams. Lithologic strip logs were generated using Coredat and PETREL software (Figure 2.2.24).

The upper main target seam VIII was intersected by all boreholes. It has a total thickness of 4.29 – 4.96 m. The seam is usually developed with a thicker (about 2.1 – 3.6 m) upper coal layer, and a thinner lower bed that sometimes contains several clayey coal layers. The two coal beds are separated by a waste rock parting with a thickness of 0.50 – 1.31 m. The lower main target seam V was reached by two boreholes. Having a total thickness of up to 10.4 m, the seam is split up in three coal plies. The upper, most attractive coal seam layer has a thickness of about 4.2 m. It is situated on a 1.55 / 2.52 m thick clay and partly silty parting. The middle coal layer shows a thickness of 0.48 / 1.66 m. It is separated by a 0.42 / 1.48 m thick clay layer from the lower, 1.50 / 0.58 m thick coal ply. In addition, seam VI, which was intersected by three of the boreholes, was revealed to possess significant thicknesses of 3.50 – 4.08 m.

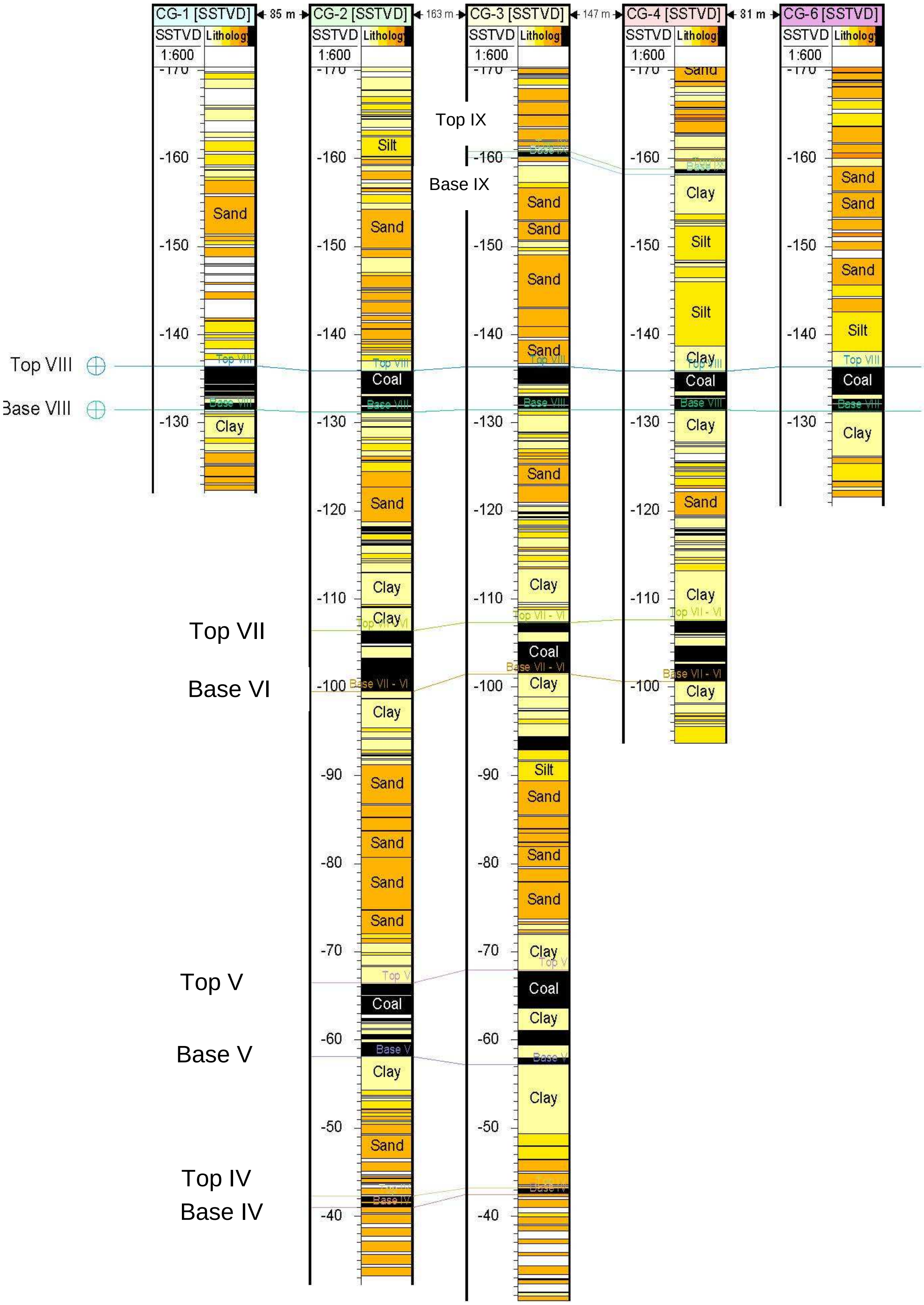


Figure 2.2.24: Lithological strip logs of the new boreholes showing coal seam stratigraphy and interburden lithologies

Figure 2.2.25: Coal seam VIII in drillhole CG-02 bounded by soft clay

Figure 2.2.26: Geological core logging and lignite core scanned with the DMT CoreScan3® (unrolled 360° image)

In addition to the tests on the boreholes and the drilled core, a topographic survey to determine the collar positions of the boreholes was conducted by DMT. X and Y coordinates were obtained using a conventional hand held GPS with an accuracy of <2 m. The Z-coordinates were determined using a Leica Sprinter 150M with an accuracy of 2.5 mm. In addition to the completed drillholes 5 existing wells and one historical drillhole have been measured in the same way. Hydrogeological tests and observations were made, i.e. measurements and monitoring of water levels in the boreholes and adjacent wells, pump tests, and infiltration tests. An AQUATOS web GPRS data logger was installed into different boreholes for monitoring water level and temperature. The system consists of a pressure and temperature measuring with a data logger combined with GPRS data transmitter. In addition to the installed online monitoring system, manual measurements were conducted in all boreholes and also in nearby wells and the river frequently during the field campaign. Calculated hydraulic properties both from tracer fluid testing in CG-03 and from a pump test in CG-06/5 show similar results: hydraulic conductivity $k_f = 3.4*10^{-6} – 5.5*10^{-6}$ m/s and transmissivity of the rock mass $T_{RM} = 1.2*10^{-4} – 3.2*10^{-4}$ m²/s. These values can be assigned to confined sandy clay or clayey sand aquifers.

From the hydro-geophysical investigation in observation wells CG-04, CG-06/5 and CG-03 three horizons of water column can be distinguished. The first horizon presents the surface water. It reaches from the water table to the first decrease point of redox potential and is characterized by high redox potential and O_2-content and low density and conductivity values. Most of the solids are being solved in this horizon. The next zone is characterized by decreasing redox potential and O_2 content and increase of density and conductivity. This saturation zone indicates the continuous process of solution of solids, where saturated surface water gets more and more dense and starts to sink towards the ground of the well. The lower zone is where the water gets oversaturated by dissolved soils and the process of solution of soils stops. This equilibrium zone is characterized by almost constant values of all chemical properties. This zonation of water column could not be inspected in observation well CG-02. Figure 2.2.27 shows a cross-sectional correlation of the chemical water properties in the boreholes.

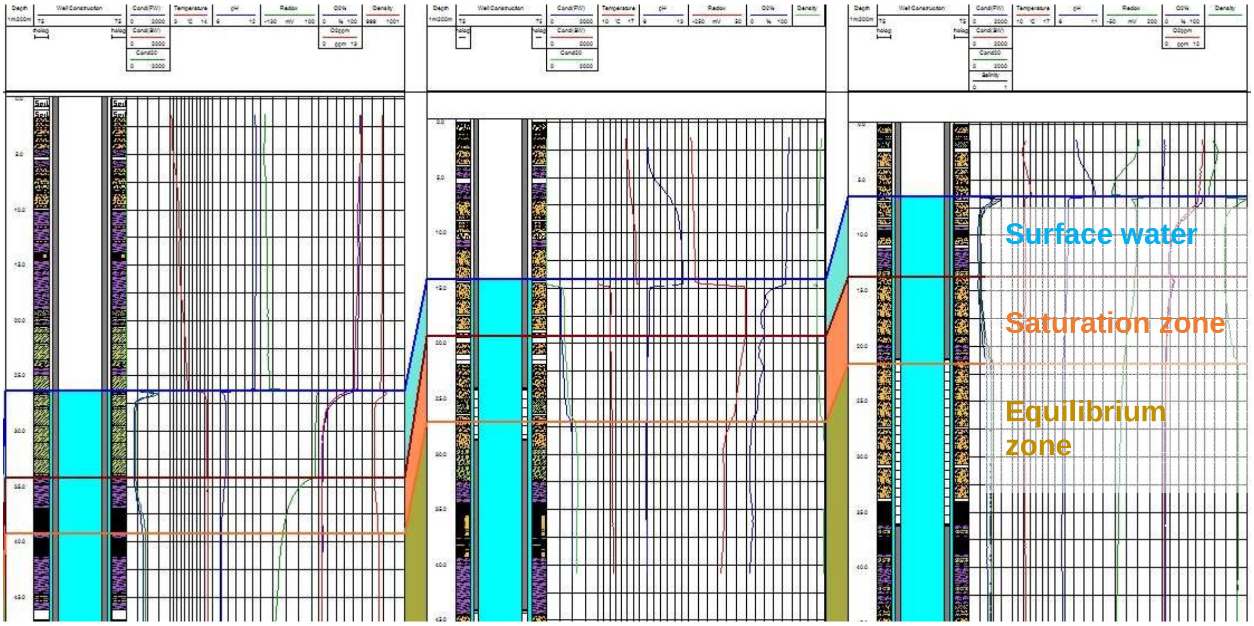


Figure 2.2.27: Zonation of the water column within of the observation wells CG-04, CG-06/5 and CG-03 (from left to right). Blue = surface water; orange = saturation zone; brown = equilibrium zone

Task 3.5 – Lab testing of drill samples

Following sampling, a recording of the drillhole, the depth interval and the geology of the samples was made. That was also verified by CERTH upon the receipt of the samples. The samples were analysed for their mechanical and physical properties. DMT also analyzed several coal samples with respect to coal petrography (maceral analysis, ROM, VEL, PL). The samples that were delivered belong to the drillholes CG-02 CG-03, CG-04, CG-06.

The proximate and ultimate coal analysis indicates that we are dealing with lignite horizons whose carbon content is significant, reaching 60%wt (on dry basis). In addition, the lignite's hydrogen content is fairly close to 5-6%wt. It is noteworthy that the coal has moisture content of over 40% for the majority of the samples. The lowest percentage of moisture appears in coal seam VII of borehole CG-04. The ash content ranges from 9% to 19%, except in CG-04 borehole where it can reach as high as 53%. Overall, we noticed a consistency in the results of the coal analyses. However, an exceptional case was observed related to the borehole CG-04. The extreme values observed for CG-04, compared to the other neighboring drillholes, could be a result of clay minerals that are present in this specific drillhole.

Regarding Sulphur content, this ranges from 1% to 3.7%, which corresponds to typical and expected values for coal. The coal samples tested are classified as "lignite B" in the coal grade classification. The higher heating value of the tested lignite samples ranges between 7,193 and 14,445 KJ/Kg, which falls inside the lignite B coal grade (with upper limit 14,700 KJ/Kg).

The specific surface area of the coal samples calculated using the BET method ranges from 0.74 m^2/g to 1.26 m^2/g. In consistency with the aforementioned results, the coal samples from drill hole CG-04 show exceptional values reaching up to 8.41 m^2/g. The specific pore volume of the coal sample in CG-04/S1 and CG-04/S2, for example, reaches 0.019 cm^3/g and 0.048 cm^3/g respectively, which are much higher than the values in the surrounding drillholes which have a range of 0.005-0.009 cm^3/g. The pore size ranges between 29 and 37 nm. According to the IUPAC classification, the material is classified as macroporous (Sing et al. 1985). As an example, the pore volume diagrams originated by the accomplishment of BJH method in seam V are included in this report (Figure 2.2.28).

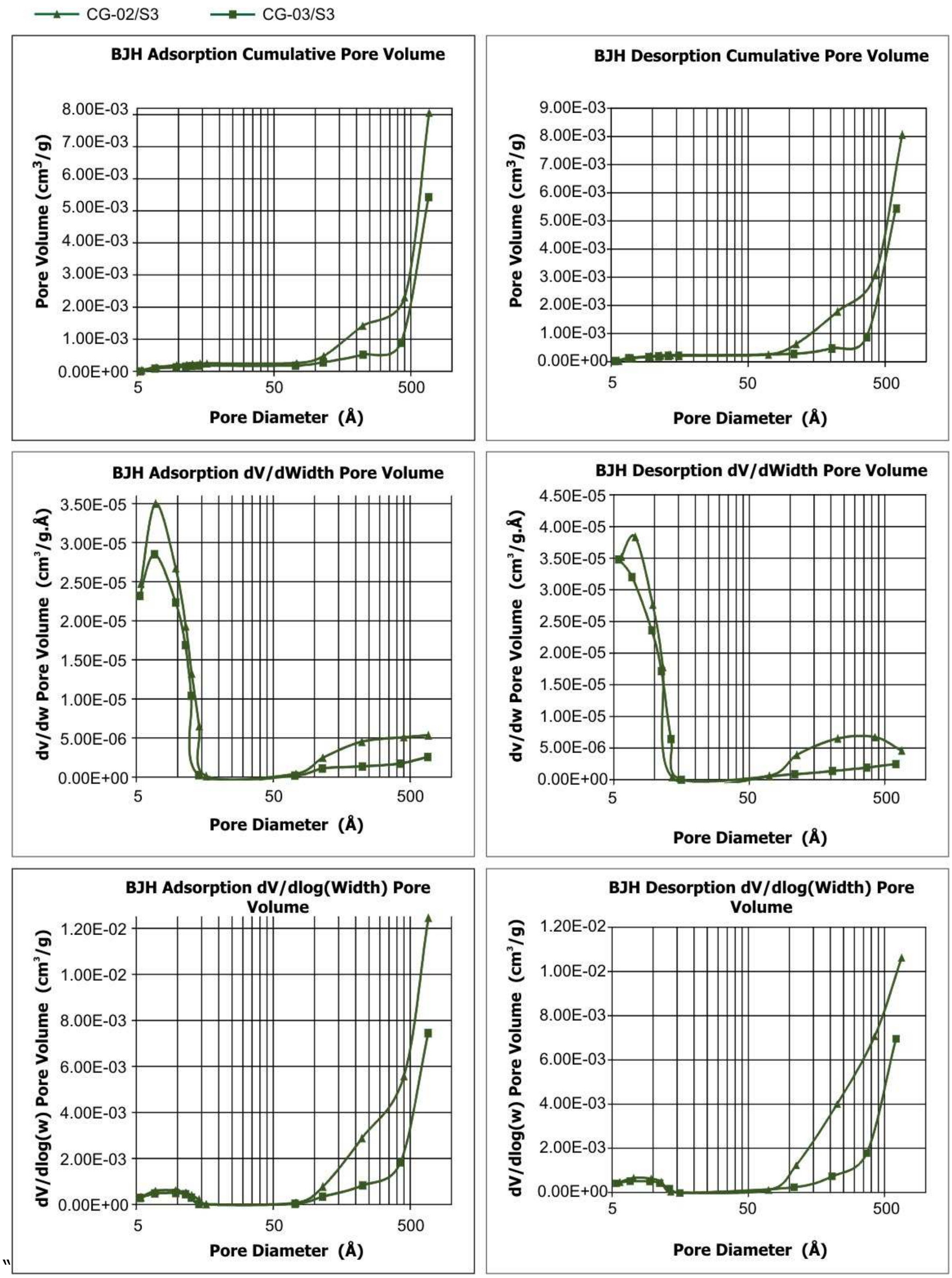


Figure 2.2.28: Pore volume diagrams originated by the accomplishment of BJH method in seam V

Coal petrography

Three coal samples from Romania (provided by CEO), were used for petrographical investigation. This was undertaken in parallel with the coal received from Slovenia (provided by Premogovnik Velenje) and Poland (provided by GIG as a reference), for comparison reasons.

For this comparative analysis, the polish coal was used as a reference, as it showed a very different performance in the previous UCG lab tests compared especially to the Romanian coal. The results are given in the following table:

Table 2.2.13: Maceral analysis of coal samples from Oltenia, Velenje and Poland.

Maceral				Oltenia	Velenje	Poland
Group	Sub-group	Maceral	Sub-maceral			
			Textinite A	0.0	0.0	0.1
			Textinite B	4.1	4.4	0.0
		Textinite		*4.1*	*4.4*	*0.1*
			Texto-Ulminite	8.0	25.6	13.8
			Eu-Ulminite	45.7	20.5	3.3
		Ulminite		*53.7*	*46.1*	*17.1*
	Humotelinite			***57.8***	***50.4***	***17.2***
		Attrinite		0.1	2.6	23.8
		Densinite		22.6	28.9	9.8
	Humodetrinite			***22.7***	***31.6***	***33.6***
		Corpohuminite	Levigelinite	5.8	1.1	0.7
			Porigelinite	2.6	4.6	0.1
				0.1	0.2	0.0
	Humocollinite			***8.5***	***5.9***	***0.8***
Huminite				**89.0**	**87.9**	**51.5**
		Sporinite		0.0	0.0	3.1
		Alginite		0.0	0.0	0.0
		Resinite		1.0	0.3	1.4
		Cutinite		0.6	6.4	2.0
		Chlorophyllinite		0.3	0.0	0.0
		Fluorinite		0.0	0.0	0.0
		Suberinite		0.8	0.5	0.0
		hum. lipt. matrix		0.0	0.0	0.4
		Liptodetrinite		3.6	3.6	35.6
Liptinite				**6.2**	**10.7**	**42.5**
		Sclerotinite		0.3	0.7	1.2
		Fusinite		0.0	0.0	1.9
		Macrinite		0.0	0.0	0.1
		Inertodetrinite		0.0	0.0	0.2
Inertinite				**0,3**	**0.7**	**3.4**
		Iron compounds		1.7	0.6	0.3
		Clay		2.6	0.0	2.4
		Quartz		0.2	0.1	0.0
		Biogene		0.0	0.0	0.0
Minerals				**4.4**	**0.7**	**2.7**

For all three coals, huminites are the major constituent, with the highest one being in the coal of Oltenia (89%). The Polish coal consists mainly of humodetrinite, whereas the Slovenian and Romanian coal of humotelinite (Table 2.2.13). The smallest constituent is humocollinite, which has the highest proportion in the Oltenian coal sample.

Liptinite is the second-largest constituent (42.5% in the Polish coal and 6.2% in the Oltenian coal). On the other hand, inertinite is the smallest constituent where, its highest proportion is found in the Polish coal, where it consists predominantly of fusinite (fossil charcoal) and sclerotinite (residues of fungus).

The Oltenia coal has the highest amount of mineral matter, which is made up mainly of clay and iron compounds (mainly pyrite in framboidal form or single crystals).

Geomechanics of coals

The geomechanical analysis on the various coal samples tested by CERTH provided the results of the following Table 2.2.14. The samples are from each drillhole and from each of the penetrated seams, namely seam V, VI-VII and VIII. The test results are presented in terms of different drillholes containing different kinds of lignite horizons.

Table 2.2.14: Results of laboratory tests-rock mechanics

									UNCONFINED COMPRESSION TEST				SHEAR TEST			
BOREHOLE	SAMPLE	SPECIMEN	DEPTH	DESCRIPTION	POROSITY	DENSITY	BULK DENSITY	MOISTURE CONTENT	STRESS	STRAIN	MODULUS OF ELASTICITY	POISSON RATIO	ANGLE OF DISCONT. FRICT φ	APPARENT COHESION c	RESIDUAL SHEAR STRENGHT φ	BRAZILIAN TEST
			M		%	gr/cm^3	KN/m^3	%	Mpa	%			0	Mpa	0	Mpa
CG-1	S1	1	36.00-36.50	COAL	46.52	0.75	12.1	61.4					41	0.28	34	
CG-2	S1	1	38.78-39.1	COAL	54.41	0.68	12.3	78.3	7.62	5.74	604.00	0.37				1.57
CG-2	S2	1	67.27-67.67	COAL	54.69	0.68	12.2	79.6	7.36	4.85	858.00	0.36				1.31
CG-2	S3	1	109.15-109.55	COAL	55.41	0.72	12.8		6.57	4.97	691.00	0.38	18	0.22	16	
CG-3	S1	1	34.90-35.32	COAL	52.50	0.70	12.3	74.2	11.97	6.31	963.00	0.36	43	0.22	32	1.70
CG-3	S2	1	67.11-67.56	COAL	50.14	0.75	12.5	66.6	6.45	5.26	667.00	0.34	42	0.21	26	1.49
CG-3	S3	1	106.40-106.80	COAL	53.77	0.70	12.4	75.1	11.91	7.32	808.00	0.34				0.78
CG-4	S1	1	38.35-39.01	COAL	59.43	0.62	12.2	93.7	7.01	4.96	981.00	0.35	37	0.37	21	1.05
CG-4	S2	1	69.37-69.70	COAL	55.32	0.69	12.4		7.26	6.77	1219.00	0.37	44	0.19	20	
CG-6	S1	1	35.10-35.50	COAL	45.01	0.78	12.3	56.6	7.37	3.34	1092.00	0.36				1.95

Legend:
SEAM VIII
SEAM VII
SEAM V

Geomechanics of the surrounding rock strata

Except the analyses carried out for the lignite horizons, geomechanical analysis were also conducted for the surrounding clays and are presented in Table 2.2.15 below. These correspond to the tests on the clays overlying and underlying each of the lignite seams V, VII and VIII. The test results are presented in terms of clay samples that originate from different drill holes at various depths.

Table 2.2.15: Results of laboratory tests-rock mechanics on the clay samples

a)

BOREHOLE	SAMPLE	SPECIMEN	DEPTH	DESCRIPTION As DESCRIPTION the name of the Group according to ASTM from the grain size classification of the sample using the ASTMUSCS system is used and not the description (according to the borehole logs) of the layer where the specimen was taken from:	BULK DENSITY		MOISTURE CONTENT
					WET γwet	DRY γdry	
			m		kNm^3	kNm^3	%
CG-1	S2	1	34.70-35.00	CLAY	21.0	18.1	17.8
CG-2	S4	1	37.00-37.30	CLAY	18.0	13.4	31.6
CG-2	S5	1	42.13-42.43	CLAY	18.7	16.5	15.4
CG-2	S6	1	106.25-106.59	CLAY	21.3	18.2	21.5
CG-2	S7	1	115.15-115.50	CLAY	19.9	16.1	22.4
CG-3	S4	1	62.50-62.96	CLAY	20.4	18.7	21.5
CG-3	S5	1	69.56-70.00	CLAY	20.4	16.7	25.8
CG-3	S6	1	101.95-102.40	CLAY	21.0	18.0	15.9
CG-3	S7	1	108.70-109.00	CLAY	21.0	17.7	17.5
CG-4	S3	1	41.57-41.90	CLAY	20.8	17.8	18.7
CG-4	S4	1	67.40-67.84	CLAY	19.8	15.9	25.1
CG-4	S5	1	72.60-72.79	CLAY	21.0	17.6	20.5
CG-6	S2	1	34.11-34.55	CLAY	20.5	17.2	27.8
CG-6	S3	1	39.65-39.95	CLAY	21.3	18.4	18.0

Legend:
- SEAM VIII
- SEAM VII
- SEAM V

b)

BOREHOLE	SAMPLE	SPECIMEN	DEPTH	FIELD DESCRIPTION/ ASTMUSCS DESCRIPTION	ANGLE OF INT FRICTION φ	COHESION	RECIDUAL ANGLE OF INT FRICTION φ	RESIDUAL COHESION c
			m		0	kNm^3	0	kNm^3
CG-1	S2	1	34.70-35.00	CLAY	27	16.8	24	15.0
CG-2	S6	1		CLAY	15	85.6	15	61.0
CG-2	S7	1		CLAY	23	46.3	20	32.0
CG-3	S4	1		CLAY	22	13.1	21	12
CG-3	S5	1		CLAY	16	8	16	7

CG-4	S3	1		CLAY	25	13.9	23	12
CG-6	S3	1		CLAY	17	11.6	15	10.0
CG-6	S3	1		CLAY	39	16.5	19	15.0

Legend: SEAM VIII, SEAM VII, SEAM V

Table 2.2.16 presents the results from the tests conducted in the DMT's laboratories.

Table 2.2.16: Analytical results of laboratory tests on rock strata by DMT

Drill hole	**Depth**		**Laboratory test results (DMT)**												
	from	to	W	Density		Grain-size distribution				Consistency limits				Ignition loss	Water Conductivity
	[m]	[m]	w [%]	ρ [g/cm³]	ρd[g/cm³]	Cl [%]	Si [%]	Sa [%]	Gr [%]	w_L [%]	w_P [%]	I_P [%]	I_c [-]	V_{gl} [%]	kf_{10} [m/s]
CG-02	77.7	77.8	22.5	1.99	1.63	0	59.0	41.0	0.0					2.0	2.0E-08
	103.1	103.3	19.7	2.09	1.75	25.8	69.5	4.7	0.0	45.5	26.5	19.0	1.36	4.4	2.2E-10
CG-03	11.5	11.7	22.0	2.06	1.69	23.1	64.2	10.1	2.6						
	13.1	13.4	19.2	2.10	1.76	18.9	70.8	9.2	1.1						
	16.0	16.4	24.8	1.88	1.50	0	7.7	92.3	0.0						
	20.2	20.5	18.9	2.14	1.80	24.8	51.1	22.5	1.6	55.7	28.9	26.8	1.37		
	20.7	20.9	18.4	2.11	1.78	13.0	34.3	51.6	1.1	40.1	22.4	17.7	1.23		
	22.9	23.1	28.2	1.90	1.48	0	9.8	90.1	0.1						
	32.5	32.9	25.2	1.95	1.56	0	17.6	82.4	0.0					1.1	9.0E-06
	36.2	36.6	19.5	2.07	1.73	26.8	61.7	11.3	0.2	30.7	25.2	5.5	2.02	4.0	
	39.4	39.7	17.5	2.13	1.81	24.2	57.0	18.7	0.1	37.6	21.4	16.2	1.24	2.9	4.6E-10
	40.7	41.0	18.3	2.04	1.73	23.2	49.2	27.4	0.1	49.5	25.2	24.3	1.28		
	43.4	43.7	22.9	2.03	1.65	12.9	44.1	42.0	1.1						
	45.5	45.7	28.3	1.88	1.47	0	15.3	84.6	0.2						
	46.9	47.1	14.2			0	4.4	84.4	11.2						
	53.2	53.5	20.3	2.07	1.72	23.2	65.6	11.2	0.1	35.7	23.3	12.4	1.24		
	57.1	57.3	22.7	1.98	1.61	46.5	52.1	1.5	0.0	81.1	38.5	42.6	1.37		
	61.7	62.0	21.8	2.05	1.68	30.0	64.9	5.1	0.0	51.7	26.8	24.9	1.20	4.4	2.2E-10
	72.0	72.3	16.9	2.21	1.89	23.2	65.9	9.5	1.4	45.4	23.1	22.3	1.27	5.1	1.9E-11
	75.0	75.1	21.8	1.94	1.59	12.0	54.4	33.2	0.4						
	77.5	77.7	22.1			2.0	43.6	54.4	0.0						
	78.7	78.9	26.1			2.6	43.6	53.9	0.0						
	90.6	90.8	23.9			0	8.3	91.7	0.0						
	100.0	100.2	17.7	2.11	1.79	19.9	67.7	12.4	0.0						
	101.5	101.7	21.7	2.09	1.72	16.2	61.5	22.3	0.0	48.7	26.6	22.1	1.22	4.9	2.0E-11
	108.4	108.7	19.7	2.15	1.79	26.6	61.3	12.1	0.0	47.1	26.2	20.9	1.31	5.4	
	111.5	111.9	20.5	2.09	1.74	10.1	67.5	22.5	0.0	35.5	22.7	12.8	1.17	2.1	
	113.5	113.8	18.1			25.9	54.3	19.3	0.5	48.4	25.7	22.7	1.33		
	115.6	115.9	17.9	2.13	1.81	14.9	53.4	30.8	0.9						
	118.9	119.0	22.1	2.10	1.72	12.2	54.2	29.4	4.3						
	129.0		31.2	1.88	1.43	0	8.1	91.8	0.1					1.4	

	130.3		28.1	1.91	1.49	0	7.1	92.5	0.4					1.5	
CG-04	30.5	30.6	25.2	1.96	1.57	0	17.6	82.4	0.0						
CG-06/5	49.0		17.6	2.05	1.75	0	6.0	86.5	7.5						

2.2.4. *WP4: Panel and Well Design & Engineering for Integrity and Safety/Surface Plant Assessment*

Task 4.1 – UCG technology update and UCG-module performance comparison (study cases)

In conducting this task a UCG technology background has been performed. A number of UCG technologies exist, which are similar to the extent that they require a minimum of two process points linked within the coal seam: (i) an injection point to inject the gasifying agents and start ignition; and (ii) a production point to recover the syngas produced (Figure 2.2.29).

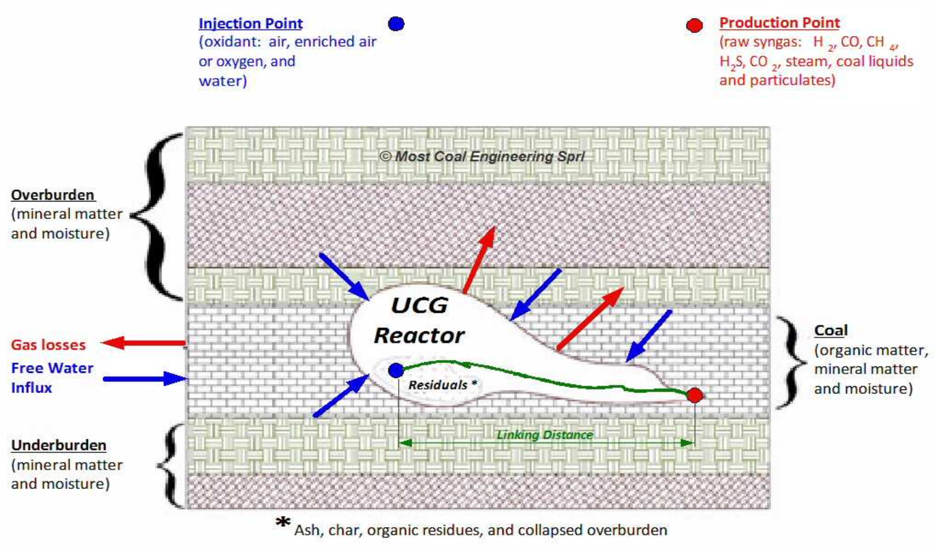


Figure 2.2.29: UCG module schematic

There are three generic categories of module configuration concepts currently used worldwide in UCG: (i) the Controlled Retracting Injection Point (CRIP) concept; (ii) the Linked Vertical Well (LVW) concept; and (iii) the Steeply Dipping Bed (SDB) concept. Two of the main generic module concepts are themselves further divided: (i) the CRIP concept is divided into the Linear-CRIP (L-CRIP) and the Parallel-CRIP (P-CRIP) configurations; and (ii) the LVW concept is divided into the standard LVW (LVW) and the Enhanced- or Extended-LVW (E-LVW) configurations.

The linear controlled retracting injection point (L-CRIP) configuration

A L-CRIP module comprises a deviated injection well drilled along the base of a coal seam and linked to a vertical production well. The process wells are linked together by directional drilling: either the injection well to intersect the production well or vice versa, depending on which well was drilled first (Figure 2.2.30).

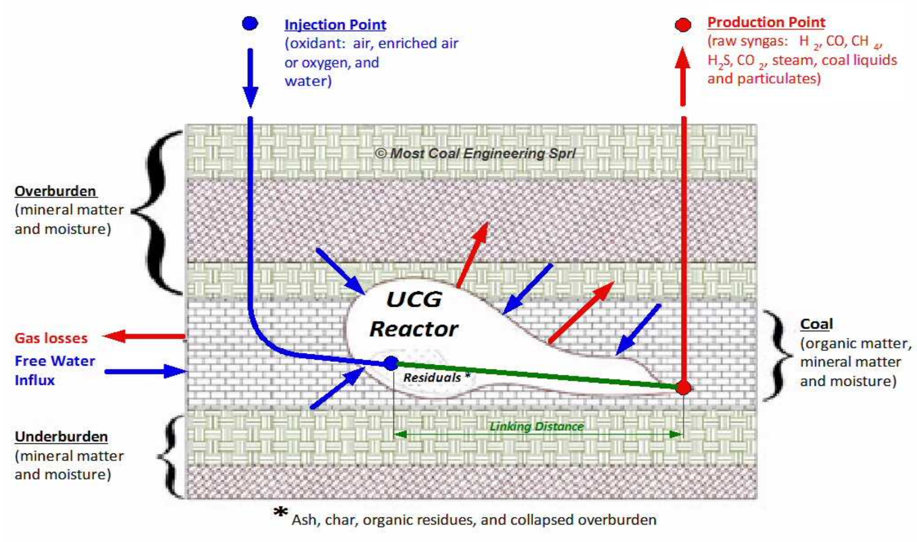


Figure 2.2.30: Schematic of the L-CRIP configuration with the injection point, production point and linkage concepts

The parallel controlled retracting injection point (P-CRIP) configuration

In the parallel (or edge) CRIP configuration (hereinafter P-CRIP), both process wells are deviated and drilled in-seam parallel to each other. Once the in-seam section has reached a pre-determined length (typically >500m), the two process wells are deviated again and drilled towards each other to converge into a third borehole. The third borehole, known as the ignition well, is drilled conventionally (i.e. vertically) and used to ignite the coal at the start of operations and provide a target for the directionally drilled process wells (Figure 2.2.31).

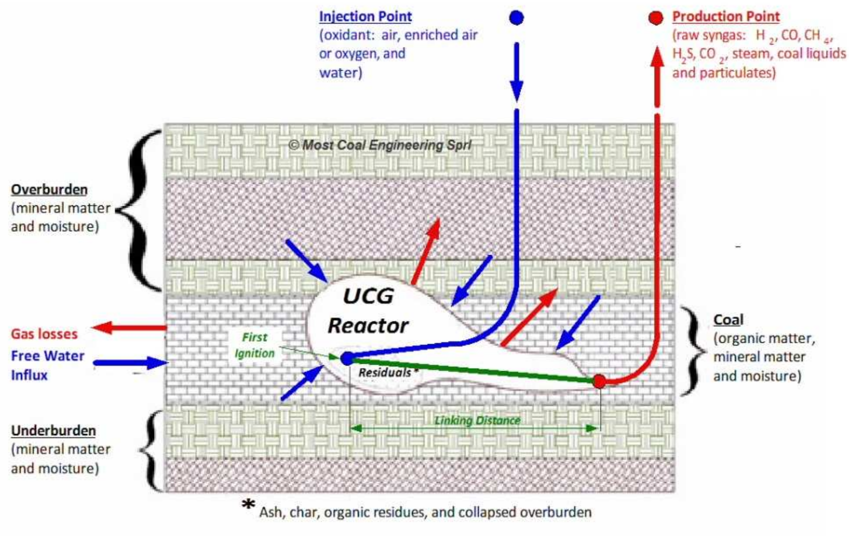


Figure 2.2.31: Schematic of the P-CRIP configuration showing the location of the process points, and first ignition point (well)

The linked vertical well (LVW) configuration

In this concept, the process wells comprise at least two vertical wells drilled into the coal seam. The injection point is located at the completion base of the vertical injection well and the production point at the completion base of the vertical production well (Figure 2.2.32). Linkage between the wells is typically achieved by enhancing natural permeability using a number of possible techniques, such as reverse-combustion followed by forward-combustion, electro-linking and hydro-fracking.

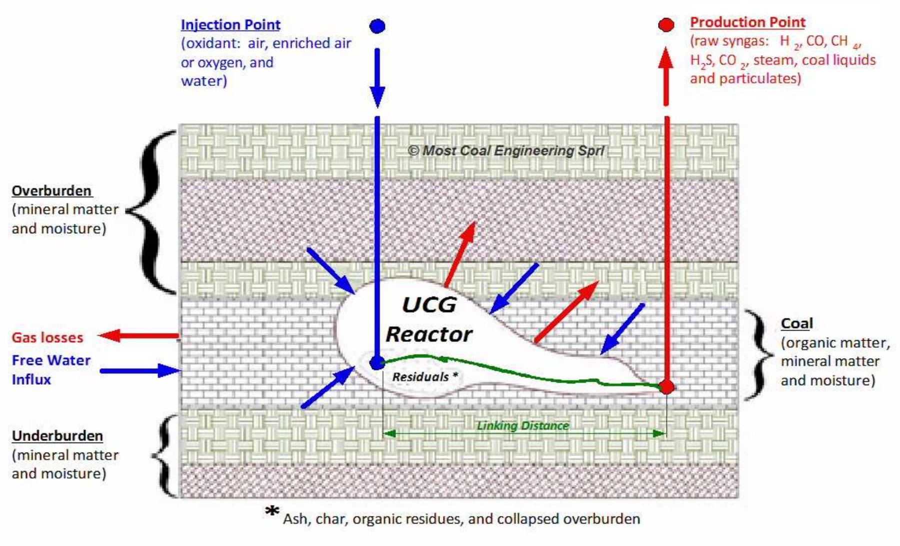


Figure 2.2.32: The LVW configuration

The enhanced linked vertical well (E-LVW or ELW) configuration

The enhanced, or extended, vertical well configuration (E-LVW or ELW) is very similar to the LVW but uses a deviated in-seam borehole to link the vertical wells (Figure 2.2.33). Use of the deviated in-seam borehole allows for greater distances between the vertical wells, enabling a greater volume of coal to be converted per process well pair compared with standard LVW.

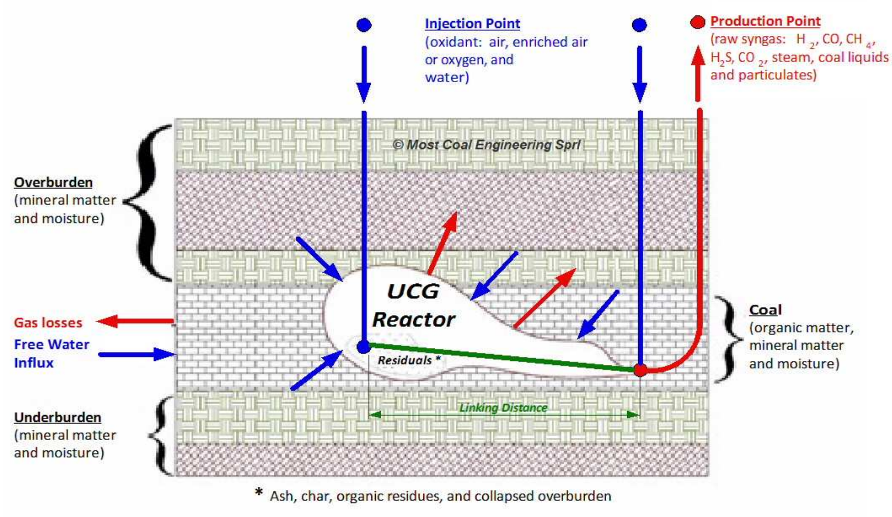


Figure 2.2.33: The E-LVW or ELW configuration

The steeply dipping bed (SDB) configuration

The Steeply Dipping Bed (SDB) configuration has been used in coal seams with high dip angle (>60°). The SDB configuration comprises two slanted boreholes (Figure 2.2.34): the production well is drilled in-seam to a predetermined distance above the base of the injection well, which is drilled initially beneath the coal seam until it intersects the coal seam.

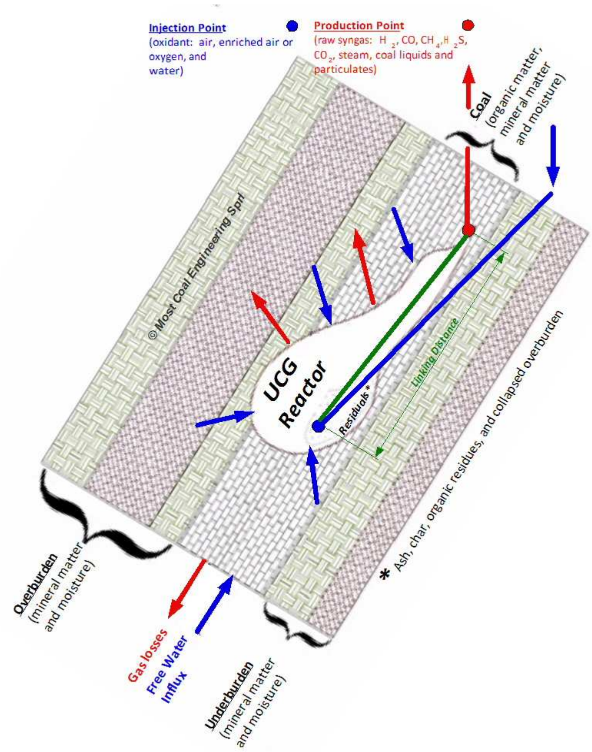


Figure 2.2.34: The SDB configuration

Comparison of UCG methods

The UCG configurations summarised above have been tested in various geological settings around the world in coal ranging from lignite to anthracite in rank.

In this task a detailed comparison of the UCG methods was done considering the following key performance indicators: (i) the gasification efficiency i.e. the proportion of chemical energy in the coal that is converted into useful energy in the syngas, (ii) the oxygen required to produce a unit of energy from gasification (e.g. tonnes O_2 per GJ), (iii) the coal mining efficiency i.e. the proportion of coal "in-place" per module that is successfully gasified (i.e. the geometrical or mining sweep efficiency), and (iv) the "Energy Return On Energy Investment (EROEI)" of the complete resource recovery process (i.e. the energy spent by drilling, and producing and injecting the oxidants compared to the energy produced at the production wellhead).

Scale-up to commercial UCG operations

Scaling-up projects from the initial single module to full commercial operations involves increasing the number of modules to match the total syngas production required by the project. Experts recommend that the commercial scale-up is done incrementally, as expanding from 2 (or 3) modules in parallel to, perhaps 10 or more, has not yet been attempted and consequently a number of factors need to be better understood before moving straight to full-scale commercial operations. These include: (i) the response of the geology and hydrogeology to multiple modules running simultaneously; (ii) the optimum spacing between modules to ensure minimum interaction between the active UCG reactors, the exhausted reactors (outlet goaf area) and the decommissioned reactors; (iii) the optimum spacing to ensure maximum resource utilisation while ensuring the overburden remains supported by pillars between modules (room-pillar configuration); (iv) the design and operation of surface facilities able to process and utilise multiple syngas streams that may differ in composition and heating value over time; and (v) yhe finance strategy required for funding the expansion from early- to full-commercial scale operations.

There are two aspects to commercialising an UCG project: (i) scaling-up of the UCG well field and (ii) scaling-up of surface facilities. The design of the single module in the trial phase of a project is essentially identical to that of modules used during the commercial phase. Scaling-up of the well field simply requires replication of modules until the number required producing a predetermined output is reached. The configuration of multiple modules operating simultaneously is called an "UCG panel".

A key aspect to well field scale-up, however, is the requirement for a drilling rig and crew to install the new modules. The frequency of commercial drilling and completion operations depends on two main factors: (i) the number of modules in parallel; and (ii) the module lifetime. For example, if a module's lifetime is equal to one year and 10 modules were required in parallel, and then 10 modules would have to be drilled per year to maintain operations. This also requires that the geology of the new area to be used is understood such that the commercial panel configurations can be properly planned.

The actual amount of drilling and basic completion will be site and project specific, but significant drilling and completion operations for a large UCG project can be expected.

A typical mining plan for a targeted coal resource divides the well field into the following panels (the series of required panels are represented schematically in Figure 2.2.35):

- Future expansion panel;
- Drilling panel;
- Gasification panel;
- Venting and cooling panel; and
- Depleted and decommissioned panel.

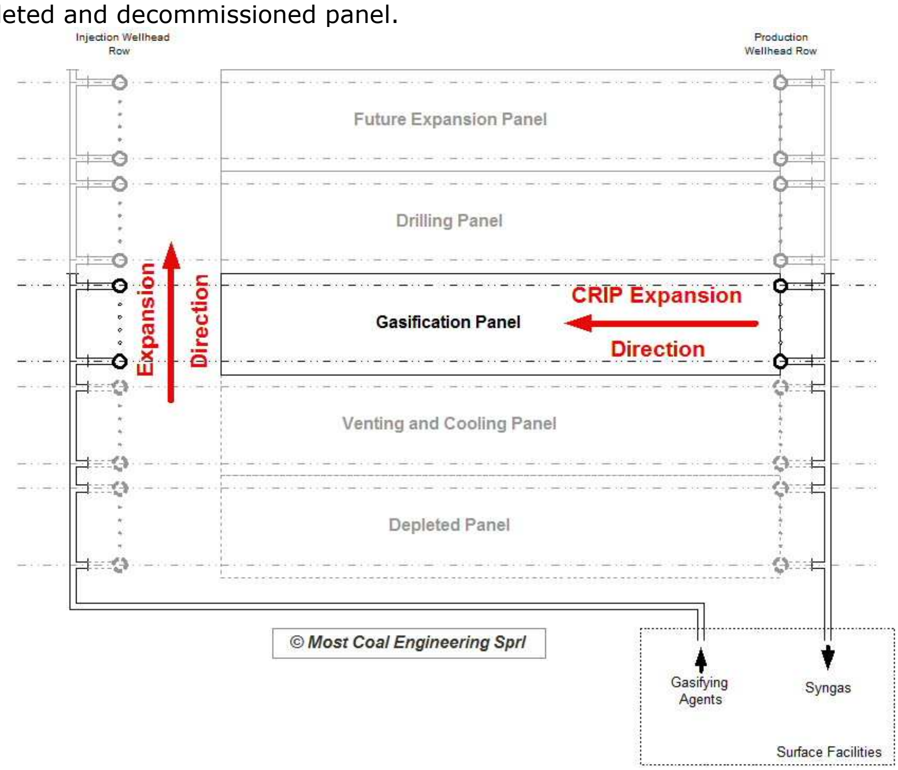


Figure 2.2.35: General layout of well field panels (plan view) based on the L-CRIP configuration (on-shore)

Site decommissioning

The principal aim of decommissioning a module is to continue to minimise environmental risks from UCG after gasification operations have ceased. Significant volumes of potentially contaminative compounds, such as benzene, toluene, ethyl-xylene, and xylene (BTEX) and polycyclic aromatic hydrocarbons (PAH) can remain in the UCG module post-gasification. These, and other compounds, can be found in the reactor walls and in the goaf/rubble pile area of spent UCG reactors. Sufficient heat to continue to pyrolyse coal and vaporise water also remains in UCG reactors post-gasification. If a module were to be simply sealed post-gasification, two processes would raise environmental risks: (i) continued pyrolysis would produce ever greater volumes of potentially contaminative compounds; and (ii) steam production would raise the reactor pressure, potentially beyond the hydrostatic pressure, thereby causing the release of potentially contaminative compounds.

The experts (Moody, 1990, Mallett, 2014) recommend the application of the "clean cavern" technique for decommissioning UCG reactors and managing environmental risks post-gasification.

The cavity gasification (L-CRIP, LVW or SDB) was identified as having the smallest environmental impact (e.g. smallest amount of in-situ coal pyrolysis) of the UCG module configuration options. Consequently, L-CRIP (or LVW and SDB) is the UCG configurations that will require the lowest volumes (and consequently costs) of post-burn cavity flushing and residual contaminant treatment.

The clean cavern technique includes three simple operational constraints to minimise groundwater contamination: (i) gas losses must be eliminated, (ii) the flow of pyrolysis products into the module goaf area must be eliminated post-gasification, and (iii) heat remaining after gasification must be reduced significantly and quickly. These constraints must be an integral part of any successful decommissioning method to mitigate UCG groundwater contamination.

Lessons learnt and first guidelines

From our detailed reviews of the available UCG configurations (some of which is given in this document), it is concluded that L-CRIP (and SDB) is the most sustainable, reliable and efficient UCG configuration with the lowest environmental impact. This configuration is applicable to all coal seam dip angles, from horizontal to dip angles exceeding 60°, and is also applicable to all coal seam depths and types of coal.

The main findings and lessons learnt in UCG are then:

(i) During active gasification, the counter-pressure of the underground reactor(s) should always be maintained at pressures significantly less than the minimum hydrostatic pressure of the underground UCG system. This ensures that syngas (and contaminants) cannot escape into the natural environment and further ensures a constant supply of water to the UCG reactor;

(ii) The design and build of each gasification reactor/module/panel should ensure that in each module the injection point is positioned low in the coal seam as possible. This ensures that the maximum volume of coal is converted into syngas and avoids the over-riding effect (where oxygen bypasses the coal);

(iii) Commercialise the project by progressively expanding from 2 (or 3) initial reactors/modules to, perhaps 10 or more modules operating simultaneously during the commercial phase;

(iv) Apply, from inception to commercial deployment of the project, a risk assessment strategy (technical, operational, environmental and financial) based on successive layers of protection, starting from site/configuration selection and mining plans, sub-surface design and control, critical alarms and safety systems, and emergency plans; and

(v) Consider from the outset of the project that future activities will necessarily include geological and hydrogeological exploration, installation of process wells, operating process wells and module decommissioning.

Task 4.2 – Selection of suitable process operation and monitoring techniques

Based largely on the results of previous trials, particularly the RM-1 trial, and recent developments in drilling, borehole completion and survey technologies, it was concluded that L-CRIP was the optimum UCG module configuration for the Oltenia coalfield and that: (i) during gasification, the counter-pressure of the underground reactor(s) should always be maintained significantly less than the minimum hydrostatic pressure of the underground UCG system, (ii) the design and construction of a UCG module should ensure that the injection point is positioned as low in the coal seam as possible, and (iii) commercialisation of a UCG project should be undertaken by gradually increasing the number of modules operating simultaneously i.e. from two initial reactors to, perhaps, 10 or more.

It was also concluded that, as for advanced surface gasifiers, the use of pure oxygen, instead of air or oxygen-enriched air, is now preferred in modern UCG. The main reasons for this are: (i) an improved calorific value of the dry syngas produced (from lower than 5 MJ/Nm^3 with air to more than 12 MJ/Nm^3 with pure O_2), (ii) an improved gasification efficiency (up to 20% increase); and (iii) reduced volumes of injection and production gases (thus requiring smaller diameter injection and production well drilling and completion equipment).

UCG operational parameters and module performance

The L-CRIP module (shown in Figure 2.2.30) comprises a deviated in-seam injection well linked to a vertical production well. The module is completed by either: 1) drilling the injection well along the coal seam (no more than 1 m from the base) to link with the previously-drilled production well; or 2) the production well is drilled to intersect an injection well already in place.

The initial open (or cavity) volume of an L-CRIP UCG module is the volume of the in-seam section of the deviated injection well. During UCG, the cavity volume of the module will relate to the volume of coal gasified minus the volume of ash, rubble and char left in the cavity (reactor). During L-CRIP, the first reactor is generated above an ignition point located towards the end of the injection well and at the base of the coal seam. The reactor volume is initially low and surrounded by un-reacted coal. As gasification proceeds and coal is gasified, the reactor grows within the coal seam and extends in three-dimensions around the injection point until it intersects the roof rock.

With continued gasification, the area of exposed roof rock increases and it begins to collapse, which is important because it increases lateral growth of the reactor into the coal seam (increasing the amount of coal gasified per module). This causes the syngas quality to steadily decrease, because the heat lost to the roof rock is no longer available to drive the (endothermic) reactions that produce the main combustible gases in syngas (CH_4, H_2 and CO). Loss of heat also increases the proportion of coal pyrolysed to that gasified in a reactor, which results in the production of larger volumes of condensable contaminative compounds. It becomes necessary to stop gasification when the gasification efficiency deteriorates below a pre-determined value (which, in commercial projects, will be defined by economics) and/or the volume of roof collapse presents unacceptable subsidence risks.

The reactor volume is controlled by stopping gasification (i.e. remove the supply of oxygen) and retracting the igniter and burner to create another injection point, where a new reactor is initiated. L-CRIP is unique amongst the possible UCG configurations because it enables the operator to control the size of the cavity and, hence, to optimise the geometrical (sweep) and energy conversion (gasification) efficiencies, manage subsidence risks and reduce the volume of condensable compounds.

Control volume concept and process control

As direct observation of the reactor volume is not feasible during UCG, a combination of computational modelling, in-situ instrumentation and mass balance calculations are required to calculate UCG reactor volumes. The first phase of reactor volume management, however, involves definition of "control volume," which is the volume (which increases over time) of the reactor within a corresponding block of coal (Figure 2.2.36).

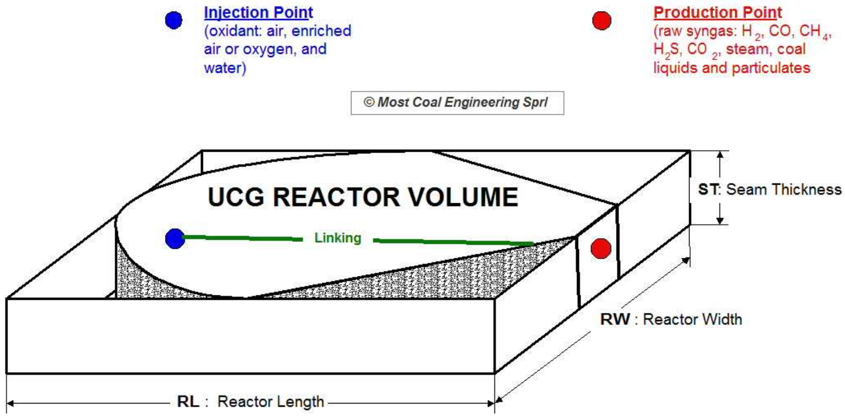
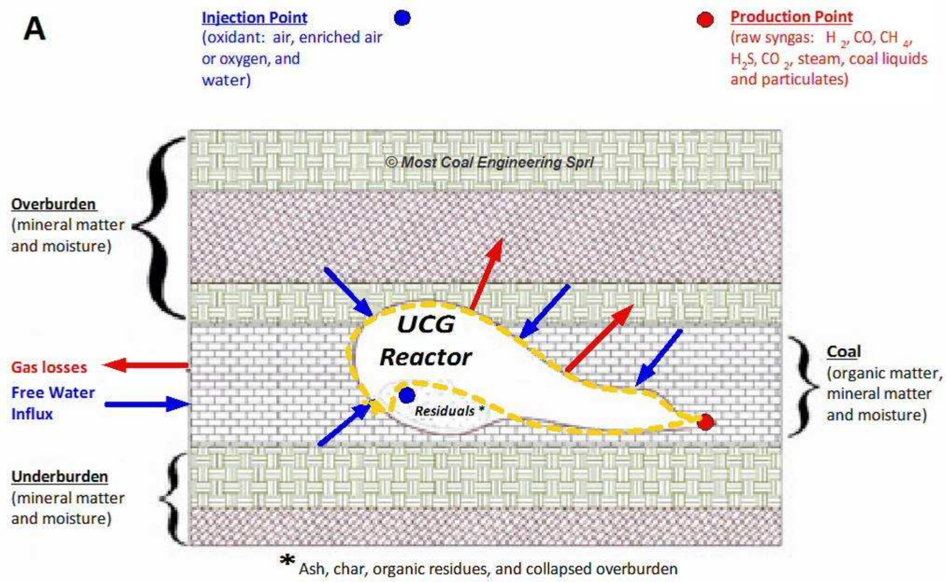


Figure 2.2.36: Schematic of UCG reactor volume compared to the block of coal in-place

The evolution of the control volume is calculated by estimating and/or measuring masses entering it (e.g. oxidant injection and natural water influx), those leaving it (e.g. syngas) and the volume of char, rubble and ash remaining within it (see Figure 2.2.37 A and B).



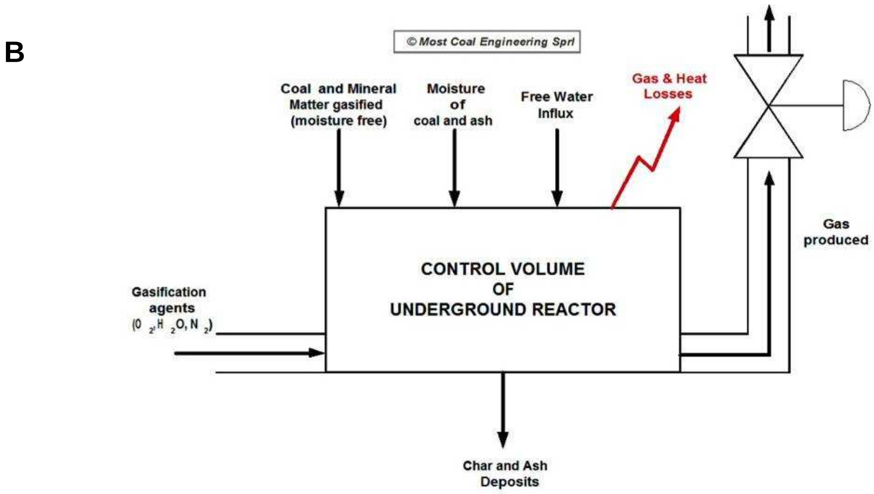


Figure 2.2.37: Schematic of UCG control volume balances

Each reactor is controlled from the surface by: (i) the rate of oxygen injected, (ii) the water/oxygen ratio, (iii) the reactor counter-pressure, and (iv) the position of the injection point in the coal seam, as follows:

(i) The rate of oxygen injection determines the rate of gasification (or mining) and the amount of thermal power (i.e. the product of syngas heating value and syngas flow rate) crossing the production wellhead;

(ii) The water/oxygen ratio controls gasification efficiency because, although an important reactant, excessive water will reduce gasification efficiency as it consumes heat during vaporisation. Experience from previous trials indicates that the optimum water/oxygen ratio in the UCG reactor is around 2:1–2.5:1, higher ratios can be used to reduce the risk of excessive slagging (from melting ash) around the injection point;

(iii) The pressure of the underground reactor will control: (i) free water influx coming from the surrounding underground system, and (ii) gas and heat losses to the surrounding underground system. To minimise losses and contamination in the underground system, the counter-pressure of the underground reactor should be maintained at significantly less (15–20% less) than the minimum water pressure of the surrounding underground system, thereby creating a positive pressure gradient towards each reactor. The counter-pressure of each UCG reactor is controlled from the production wellhead; and

(iv) The position of the injection point is controlled by retracting the igniter and burner. The point at which it becomes necessary to undertake a CRIP manoeuvre is either when the gasification efficiency drops below a pre-determined level (Figure 2.2.38) or when the risk of problematic subsidence becomes too great.

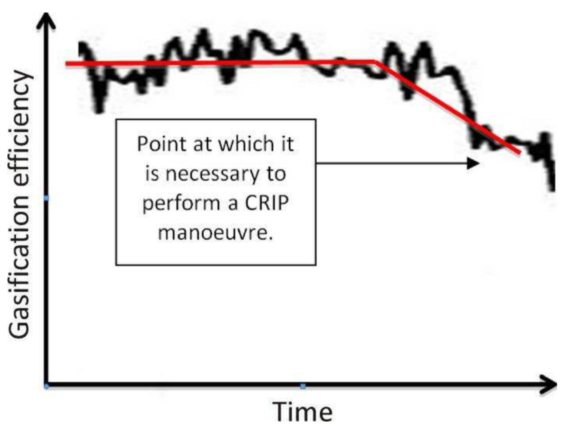


Figure 2.2.38: Gasification efficiency as a function of time during cavity gasification. The injection point is relocated when performance declines below a pre-determined value

Management of UCG reactors post-gasification

Post-gasification, a large volume of hot rock and coal/char rubble remains inside the reactor. The rubble has been heated to temperatures in excess of 800°C, and, unmanaged, this sensible heat is sufficient to continue to pyrolyse coal and vaporise water for a long period of time (in the order of years). This combination of continued coal pyrolysis and steam generation is of concern because it could cause the reactor pressure to exceed the hydrostatic pressure, forcing the pyrolysis products into the surrounding coal and strata, and increasing environmental contamination risks.

It is therefore necessary to maintain the reactor pressure significantly below the hydrostatic pressure; this is achieved by carefully venting syngas and/or steam from the production well, which has the added benefit of encouraging water influx into the cavity, thereby cooling the reactor sidewalls and rubble zone, and limiting coal pyrolysis.

L-CRIP module performance estimation

The focus of this section was to model the L-CRIP reactor and module performance of three case studies representative of the coal seam conditions expected at the Oltenia coalfield. Table 2.2.17 summarises some of the assumptions in each of the case studies and Table 2.2.18 summarises some of the key performance indicators.

Table 2.2.17: Summary of case study assumptions

Case #	Coal name and quality (*)	Depth (m)	Avg. seam thickness (m)	In-seam length (m)
1	Oltenia lignite	50	5	150
2	As above	150	5	250
3	As above	300	5	400

(*) Proximate analysis data used in the models are estimates for the coal occurring in the Oltenia coalfields and were taken from the Site Visit and first Data Summary Report by DMT; more precise/accurate data (following CERTH coal sample analysis) were used by MCE for further UCG-process modelling.

Table 2.2.18: Summary of key performance indicators

Depth (metres below ground level)	**50 m**	**150 m**	**300 m**
Mean coal gasification rate (tonne/day)	38	114	230
Mean raw syngas production rate (Nm^3/day)	55,274	143,127	258,459
Mean dry syngas heating value (HHV) (MJ/Nm^3)	9.2	10.8	12.1
Total energy converted underground per module (PJ)	0.09	0.14	0.23

The principal variable investigated by the three case studies is depth to the coal seam. As can be seen from Table 2.2.18, increasing the depth from 50 m to 300 m has a significant effect on average gasification rate (38–230 tonne/day), average syngas production rate (~55,000–260,000 Nm^3), average dry syngas heating value (9.2–12.1 MJ/Nm^3) and total energy converted per module (0.09–0.23 PJ). Improvements in gasification and syngas production rates result mainly from being able to inject oxygen at greater rates and higher pressures into deeper coal seams, whereas improvements in syngas heating values are in large part caused by the formation of greater proportions of methane in syngas at higher pressures. The increase in the amount of energy recovered per module with increasing depth results mainly from the effects of increasing the in-seam length (which is limited by the amount of weight acting on the drill bit).

Module instrumentation and process optimisation

A wide range of instrumentation capable of measuring all of the important UCG process parameters is now available to UCG projects. The instrumentation can be deployed in the process wells themselves, in monitoring wells drilled around the UCG well field or in surface equipment (e.g. in syngas flow-lines). Figure 2.2.39 shows how instrumentation for process optimisation could be deployed around an L-CRIP module.

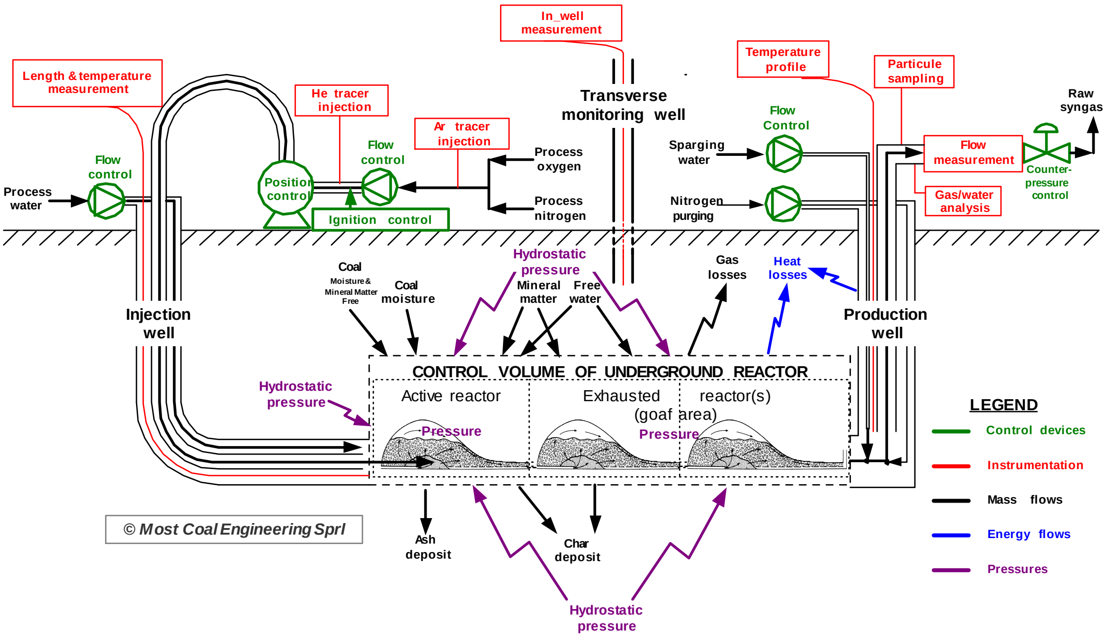


Figure 2.2.39: Instrumentation deployment strategy around a L-CRIP module

UCG process optimisation has the following objectives: (i) to produce a sustainable high quality syngas with minimal compositional variation, (ii) to maximise the energy conversion (gasification) efficiency, (iii) to maximise the geometrical (mining sweep) efficiency, (iii) to minimise coal pyrolysis (char/coal ratio indicator), and (iv) to minimise gas and heat losses.

To manage UCG process efficiency, it is necessary to measure in-situ pressures, temperatures and the injection point position. Instrumentation available for this includes Time Domain Reflectometry (TDR) and the Distributed Temperature Measurement (DTM) technologies, both of which can be deployed along the injection and production wells.

The measurement of in-situ mass flow rates is more problematic, but it can be achieved indirectly by measurements made at the production wellhead, where other instrumentation such as gas flow rate meters, water analysers and process gas analysers should be deployed. More sophisticated instrumentation, such as chromatographs and/or mass spectrometers can also be installed.

To estimate the residence time distribution of the syngas in the UCG module, and the amount of gas/mass lost from the underground system (and thereby correct estimations of in-situ mass-flow rates), "tracer tests" are also required. Tracer tests involve continuously and intermittently injecting known volumes of rare gas, such as argon and helium (which are not present or are at very low concentrations in the underground system) into the oxidant stream.

The combined use of the instrumentation outlined above will enable the following parameters to be measured during UCG operations:

- Gas losses (continuously via rare gas mass balance);
- Mass and energy balance, and calculation of the underground reactor control volume (via continuous measurement of syngas flow rate and syngas composition together with reactor temperature and pressure), which will in turn allow estimation of: (i) gasification rate and efficiency; (ii) water influx rate; and (ii) char/coal ratio (pyrolysis indicator);
- Gasification equilibrium conditions (e.g. water-gas shift and methanation reactions). Measurement of the natural isotope (deuterium, carbon13) balance could also be used to predict the reacting water origin and confirm the equilibrium conditions;
- The injection point position (via TDR measurement along the in-seam section of the injection well);
- Temperature and hydrostatic pressure in the transverse water monitoring well(s);
- Measurement of composition and (if any) flow rate of the gas phase in the transverse water monitoring wells; and
- Underground syngas residence time distribution via intermittent tracer tests.

Control of water ingress and gas leakage

The management of water ingress and gas leakage begins at the site selection stage; essentially, a coal seam suitable for UCG should be a confined aquifer i.e. a coal seam surrounded by thick, water saturated, low permeability rocks (aquitards) that restrict both the migration of water into the coal seam and syngas out of the coal seam. In water-saturated rocks, water exists in the pore spaces between the mineral grains that comprise the rock. If these spaces were left open (as in unsaturated rocks), syngas would be free to migrate through them and escape to the surroundings. However, if the pore spaces are occupied by water, the flow of syngas is restricted (or blocked if the pore water pressure is greater than the syngas pressure), by the presence of the water and only diffusive transport occurs (very slow).

The management of water ingress and gas leakage is also linked to UCG operational conditions (pre-gasification, gasification and post-gasification). When undertaken below the groundwater level, the UCG reactor can be described as a "groundwater bubble" as it is essentially a gas-filled void existing in water-saturated rocks. The pressure inside the bubble (the "reactor pressure") is the syngas pressure, which is mainly controlled by a valve on the production wellhead assembly. The pressure acting on the reactor is the hydrostatic pressure. The hydrostatic pressure acts in 3-dimensions on the reactor. If the reactor pressure is less than the surrounding hydrostatic pressure, water will flow into the reactor. The amount of water infiltrating into the cavity, can to some extent, be controlled by the difference between the reactor pressure and the hydrostatic pressure at the corresponding depth; the smaller the reactor pressure relative to the hydrostatic pressure the greater the water influx.

Based on the relationship between hydrostatic and reactor pressure, it should be clear that the reactor pressure should never exceed the hydrostatic pressure during all operating phases, including decommissioning, because this will cause syngas and pyrolysis products to be forced out of the reactor. In addition to affecting the syngas yield at the production well, loss of syngas can lead to groundwater contamination in poorly selected sites.

Another important aspect of UCG process management is to gasify the coal as efficiently as possible, which requires that the most efficient UCG module configuration is adopted in addition to managing the process conditions within the reactor (e.g. oxidant injection rates). In essence, inefficient coal conversion during UCG can cause large volumes of coal to be pyrolysed, which can result in large volumes of condensates to form within the reactor; if not properly managed, the condensates can present a risk to the natural environment. It is therefore necessary to minimise the amount of heat lost to the coal seam by gasifying the coal as efficiently as possible.

The correct operation of the UCG reactor is also essential during reactor shutdown. It will be necessary to use the "clean cavern" techniques that were tested during UCG trials in the USA and Australia (see also previous Section).

Monitoring techniques

In all UCG projects, several environmental and process parameters must be monitored to ensure a safe and efficient operation of the UCG module, before, during and after gasification.

Monitoring can be direct or indirect, i.e. direct measurements to control the underground conditions or indirect measurements to verify by simulations and predictions the underground conditions. Baseline measurements before UCG are essential for proper interpretation of data obtained during UCG. Additional contingency/alarm monitoring will be required and should be combined with early warning signals (e.g. following HAZOP analysis).

Principally, monitoring environmental effects of UCG, and monitoring of the underground process parameters can be distinguished. Geophysical methods are widely applied, which can be carried out from surface or from inside wells. New developments that are promising for monitoring wells are smart borehole casings, which are provided with a densely spaced network of sensors before they are placed into the borehole (e.g. seismic probes, ERT electrodes, tiltmetres, EMIT coils, thermocouples, fibre optics etc).

Whilst exists long-lasting experience with monitoring for "conventional" mining, and oil and gas, monitoring for UCG is a less investigated situation. Also official regulations and monitoring concepts specifically for UCG only exist to a very limited extent and even an EU directive (like for CCS) specifying the monitoring requirements have not been prepared until now.

Task 4.3 - Well design & engineering for integrity and safety

Based on its practical engineering experience of previous UCG trials and the conclusions/guidelines of Task 4.1, MCE has first developed the guideline for the well design and engineering applicable to the four pre-selected site locations. The guidelines are:

- Definition of stratigraphic units (and sub-units, if necessary) and hydrogeological conditions
- Definition of phases (and sub-phases, if necessary)
- Definition of well configuration and well positioning (3 types of wells)
- Aspects of reactor(s) to be considered
- Aspects of the design to be considered (per type of well)
- Well control and monitoring techniques (per type of well)

Once Urdari – Valea cu Apa was selected as the test site and the necessary information was declassified and made available through the geological report "Western Oltenia-Motru" lignite mining perimeters, with special focus on "Urdari – Valea cu Apa", MCE has developed the detailed well engineering and design for the Urdari – Valea cu Apa site. The draft report was updated with the new data reported in Task 3.4 and 3.5 that contain the results of the tests conducted on the samples collected during the drilling campaign at the Urdari site.

Stratigraphic units and hydrogeological conditions in the targeted area

Stratigraphic units in the targeted area

In the targeted area of the "Urdari – Valea cu Apă" site, four coal seams were first identified suitable for UCG: (i) the coal seam X (ii) the coal seam VIII, (iii) the coal seam VI, and (iv) the coal seam V. The shallow coal seam VIII was considered as the *basic study case* and the deeper coal seam V was considered as the *optional study case*.

First results of the geological interpretation (performed in Task 2.1) indicated the coal seam VIII at an approximate depth of 50 to 65 m, at the proposed location of test drilling, with an average net thickness of ~2.9 metres and the coal seam V at an approximate depth of 115 to 135 m with an average net thickness of ~4.3 metres (see also the standard section representing the stratigraphic units and sub-units in Figure 2.2.4.

First estimates of the average proximate analysis for the targeted coal seams (Task 3.1) were 45.6% wt. moisture, 8.9% wt. ash, 25.8% wt. volatile matter, 19.7% wt. fixed carbon, and approximately 11 GJ per tonne of coal in place. Refined estimates established by combining the data received from GIG and CERTH were at that time: 44.2% wt. moisture, 9.5% wt. ash, 29.3% wt. volatile matter, 17.1% fixed carbon, and approximately 12 GJ per tonne of coal in place; these estimates were used for both coal seams.

The new geological information obtained from the drilling campaign at the Urdari pilot site were used to define final depths and thicknesses of both coal seams targeted (coal seam V and coal seam VIII). Figure 2.2.24 (from Task 3.4 in this report) presents the geological profile, which has been used. This geological profile for the Urdari site is based on interpretations by DMT of borehole data at the defined pilot site and forms the basis of the geometrical conditions for the preparation of the demonstration pilot project.

From Figure 2.2.24, coal seam VIII (complete with inter-band) is indicated at an average depth (bottom of coal seam) of 40 m, with an average gross (inter-band included) thickness of 4.7 metres and the coal seam V (upper layer only) at an average depth of 109 m with an average net (pure coal of upper layer) thickness of 4.1 metres.

From the tests performed in Task 3.5 the average proximate analysis for (i) the coal seam VIII (including inter-band) are finally estimated 41.8% wt. moisture, 17.1% wt. ash, 25.1% wt. volatile matter, 16.0% wt. fixed carbon, and approximately 11 GJ per tonne of coal in place and (ii) the coal seam V (upper layer only) are finally estimated 43.8% wt. moisture, 7.5% wt. ash, 29.6% wt. volatile matter, 19.1% wt. fixed carbon, and approximately 13 GJ per tonne of coal in place.

The hydrogeological conditions of the targeted area

With respect to the hydrogeological conditions at the selected site in the Urdari - Valea cu Apa perimeter a total of 5 aquifers have been identified (see Table 2.2.1 and Figure 2.2.3) with general flow direction from NW to SE (Iamandei & Ticleanu, 2015).

Due to the clay layers and coal seams that act as seals it can be assumed that the connectivity between the individual groundwater horizons is fairly low. However, in particular with respect to monitoring purposes all aquifers have to be monitored individually to ensure that potential contaminants do not migrate from one aquifer to another. A potential pathway for groundwater might be the fault north of the test site. Figure 2.2.8 schematically illustrates the hydrogeological situation at Urdari, also showing wells used for drinking water.

Operational stages of a module

The essential operational stages/phases of a module are:

- Module commissioning phase (water communication sub-phase, water to nitrogen exchange sub-phase, and nitrogen communication sub-phase);
- Module operating phase (including ignition/start sub-phase, temporary shutdown sub-phase(s) and subsequent re-start sub-phase(s));
- Module venting with nitrogen phase and cooling with water phase; and
- Module decommissioning phase (including well cementing and abandonment sub-phases).

The anticipated operational parameters of the essential stages are:

- Water communication: (i) Pressure: max. water column (approx. 4 bar for the basic study case; approx. 10.9 bar for the optional study case); (ii) Temperature: ambient; (iii) Duration: days;

- Water to nitrogen exchange: (i) Pressure: max. water column (approx. 4 bar for the basic study case; approx. 10.9 bar for the optional study case); (ii) Temperature: ambient; (iii) Duration: minutes;
- Nitrogen communication: (i) Pressure: approx. 1.9 bar for the basic study case; approx. 8 bar for the optional study case; (ii) Temperature: ambient; (iii) Duration: days;
- Gasification operations: (i) Pressure: approx. 1.9 bar for the basic study case; approx. 8 bar for the optional study case; (ii) Temperature: from more than 1,300°C in the central area of the active reactor to 300°C controlled at the bottom of the production well (average 500 – 600°C); (iii) Flow rates and syngas composition; (iv) Duration: 172 days for the basic study case; 79 days for the optional study case;
- Venting with nitrogen (and temporary shutdown): (i) Pressure: from 1.9 bar to atmospheric for the basic study case; from 8 bar to atmospheric for the optional study case; (ii) Temperature: progressive decrease from gasification temperatures; (iii) Duration: weeks (or days for temporary shutdown);
- Water cooling: (i) Pressure: from atmospheric to max. water column (approx. 4 bar for the basic case study; approx. 10.9 bar for the optional case study); (ii) Temperature: continued progressive decrease to ambient; (iii) Duration: weeks;

Pre-design of the well configuration and positioning

The wells will be designed and constructed following existing standards like American Petroleum Institute, British and New-Zealand Thermal Well standards to meet the operating conditions (pressure, temperature, flow rates and compositions). The three types of wells will be designed and constructed as follows:

Injection well:

The deviated in-seam injection well is designed from bottom-up, with the liner and in-seam diameter requirements defining the drilling and casing diameters at higher intervals in the borehole (as well as requirements for screening out any aquifers) => telescopic configuration. Typically, the in-seam liner will have a diameter of 4.1/2″ (114 mm). Assuming this starting point, the basic elements of the well will be as follows:

- ✓ A 4.1/2″ (114 mm) liner with in-well instrumentation clamped outside is run from surface in a 6.1/2″ (165 mm) hole to Total Depth (TD);
- ✓ A 7″ (178 mm) process casing is run and cemented in a 8.1/2″ (216 mm) hole from surface to the end of the vertical or deviated section of the well; and
- ✓ A 9.5/8″ (244 mm) surface casing (optional) is run and cemented in a 12.1/4″ (311 mm) hole drilled from surface to a pre-determined depth (typically 20 to 50 m) to isolate any surface aquifers.

Production well:

The production well (vertical, S-shape or slant) is designed around the size of the production tubing required to transport the volume of syngas produced by UCG under the pre-defined hydraulic limit (typically less than 30 m per second in the site-specific conditions of the project). From the selection of a 5″ or 4.1/2″ (127-114 mm) production tubing, the basic elements of the production well will be as follows (from bottom to top):

- ✓ A 7″ (178 mm) slotted liner in front of the coal seam. The liner will be in special high-temperature (350-900°C) resistance alloy;
- ✓ A 9.5/8″ (244 mm) process casing is run and cemented in a 12.1/4″ (311 mm) from surface to the top of the coal seam; and
- ✓ A 13.3/8″ (340 mm) surface casing (optional) is run and cemented in a 17.1/2″ (445 mm) hole drilled surface to a pre-determined depth (typically 20 to 50 m) to isolate any surface aquifers.

Transverse water monitoring well (crossing the targeted coal seam):

The transverse water-monitoring well (vertical) is designed around the size of the in-well monitoring guiding tubing required to support and run-in the permanent and/or intermittent in-well instrumentation. From the selection of 4.1/2″ (114 mm) guiding tubing, the basic elements of the well will be as follows (from bottom to top):

- ✓ A 7″ (178 mm) process casing is run and cemented in a 8.1/2″ (216 mm) hole from surface to the top of the immediate roof of coal seam (see the definition of stratigraphic units here-above); and
- ✓ A 9.5/8″ (244 mm) surface casing (optional) is run and cemented in a 12.1/4″ (311 mm) hole drilled from surface to a pre-determined depth (typically 20 to 50 m) to isolate any surface aquifers.

Final linking:

In addition to the in-seam section of the deviated injection well, effective final linking between both module process wells is imperative for commissioning, starting and continuing UCG operations. In order to minimise risk, directional drilling and contingency well completion should be designed to obtain a final linking distance of maximum one metre between both well completions. If final linking is not obtained directly via drilling, contingency techniques such as well re-drilling, open-hole reaming and/or high-pressure water injection will be used to finalise the necessary linking (competent process gas circuit).

The module basic well completions of both study cases are presented schematically in Figure 2.2.40 and Figure 2.2.41.

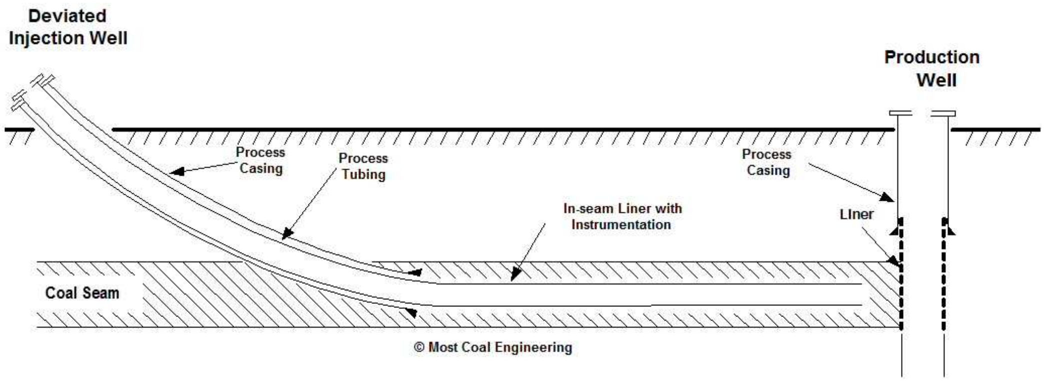


Figure 2.2.40: Schematic diagram of the basic study case
(coal seam VIII with inter-band, depth 40 m, gross thickness 4.7 m)

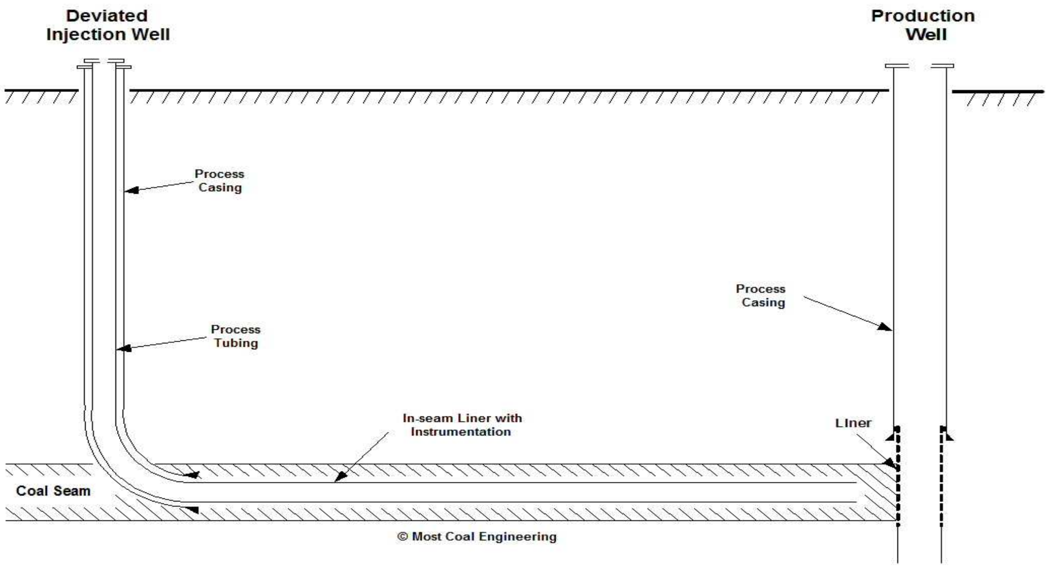


Figure 2.2.41: Schematic diagram of the optional study case
(coal seam V: upper layer only, depth 109 m, net thickness 4.1 m)

Aspects of the reactor to be considered

Reactor control volume

Details are given in previous Task 4.2 of this report.

Reactor sections

A mature, active reactor is composed of four (4) main areas: (i) the central rubble, (ii) the coalface, (iii) the cavity roof, and (iv) the outflow channel.

The four main areas are the:

- Central rubble: the predominant reactions in this area are the homogeneous combustion reactions, where syngas is combusted in the presence of injected oxygen;
- Coalface: the predominant reactions in this area are the two main heterogeneous reactions that take place at the surface of the pyrolysed coal face and/or char rubble: (i) the Boudouard reaction, and (ii) the water-gas reaction;

- Cavity roof: heat transfers by (i) radiation, (ii) conduction and (iii) convection take place in this area once the roof rock has been exposed (because the coal has been gasified);
- Outflow: the predominant reactions in this area are the homogeneous methanation and shift reactions. Due to the very high gas residence time (up to 1-2 hours) in the active reactor, both reactions are assumed to reach nearly equilibrium in the range of temperatures 650-750°C. Additional heat exchange occurs along the outflow channel with the coal surrounding the linking in this area (additional char and pyrolysis gas production).

The active reactor cavity growth is limited by the combined heat and mass transfer from the central rubble (around the injection point) to the coalface (at the periphery of the central rubble). The cavity development is based on a consistent cavity shape (the cavity shape is limited by the surface of roof exposed compared to the coalface surface).

Other aspects of the design to be considered (per type of well)

Other aspects of the design to be considered are:

- ✓ Wellheads and spacers – Christmas tree design (pressure, temperature integrity and passing through instrumentation);
- ✓ Controlled Retracting Injection Point (CRIP) system integrity and reliability;
- ✓ Equipment cleanliness;
- ✓ Casing/tubing coupling and daub selection for oxygen and corrosion control;
- ✓ Permanent in-well instrumentation integrity and reliability; and
- ✓ Integrity logging tools (drilling/completion pre-gasification module(s) and post-gasification depleted module(s))

Control and monitoring strategy

Figure 2.2.39 (see more details in Tasks 4.2 & 6.2 in section 4.3 of this report) shows how instrumentation for process optimisation and integrity could be deployed around an L-CRIP module. Redundant in-well instrumentation will be added to the process instrumentation to control the well integrity during the gasification operations.

Task 4.4 - Thermal-hydro-mechanical-chemical impact of UCG operations on surrounding rocks

In this task the mechanical impact on the surrounding rocks of an L-CRIP UCG operation is simulated based upon site-specific data for a UCG pilot site, the Oltenia coalfield in Romania. We use numerical geomechanical models to assess the impact of an underground cavity formed by the UCG operations on the mechanical integrity, stability and sealing capacity of the rock and soil layers surrounding the underground UCG cavity.

The focus of modelling was on the stability of the UCG cavern in the relatively weak unconsolidated deposits at the pilot site. In case the cavities are unstable coupled thermal, flow and chemical effects would play a minor role, because an instable cavity, causing e.g. ground movements and creating flow pathways through the sealing formations would present a potential showstopper for operations in the simulated target seams.

Based on preliminary site-specific calculations for the Oltenia pilot site, operational parameters and dimensions for a single UCG cavity and commercial UCG module were calculated. Table 2.2.19 summarizes these main operational parameters and dimensions. Based on this information, and additional information obtained from the drilling campaign at the pilot site early 2017, we constructed 2D and 3D geomechanical models to analyse the stability of the UCG cavity and the sealing capacity of the clay layers in the roof and bottom of the cavity.

Table 2.2.19: UCG specific parameters, used as input for modelling

Model parameter	Base scenario (coal seam VIII)	Optional (coal seam V)
Cavity depth	34m-42m	103m-111m
Coal thickness	2m-4m	4m
Max. cavity width (average)	9m (6m)	12m (8m)
Cavity length	13-14m	17-18m
Number of cavities (per module)	11	15
Module length	140-160m	250-270m
Total volume UCG (per module)	1900-2000m^3	5700-5800 m^3
Coal volume production rate	28 m^3/day	67 m^3/day
Average cavity temperature	500-600°C	500-600°C
Gasification pressure	1.8 bar	8 – 9.5 bar

We used geological information obtained from the drilling campaign at the Urdari pilot site, to define geomechanical units in the models. Figure 2.2.24 (from Task 3.4 in this report) presents the geological profile that has been used for modelling as basis for 2D and 3D geomechanical models by CERTH and TNO. Lithological units in the geomechanical models are based on the sequence of lithologies encountered in borehole nr. CG-4. This geological profile for the Urdari site is based on interpretations by DMT of borehole data at the defined pilot site.

UCG cavities are simulated in both lignite layer VIII and V. The presence of sealing layers above and below the coal seams is crucial for cavity stability. During UCG operations, pressures within the cavity will be maintained at levels below hydrostatic pore pressures, to prevent the outward flow of contaminants from the burning coal seam into the sandy aquifers. In case of absent or insufficient clay seals, sands and silts will flow into the cavity and jeopardize cavity stability during UCG operations. At locations CG-04 and CG-06 the lignite seam VIII is separated from the upper and lower unconsolidated sandy aquifers by unconsolidated clay layers (aquitards) at the top, and respectively at the base of the lignite layers. The sealing clay layers on top of the lignite seam VIII at locations CG-01 to CG-03 are either, very thin or absent.

Geomechanical models for the UCG cavity in layer VIII are based on the sequence of layers as encountered in borehole number CG-04. At the location of CG-04, a 4.3m thick coal seam is encountered at a depth between 37.0 m and 41.3 m, with a 3m thick clay layer on top and a clay layer of at least 5.7 m thickness directly below the coal seam.

Geomechanical models for the UCG cavity in layer V are based on the sequence of layers as encountered in borehole number CG-03. At the location of CG-03, a 4.1m thick coal seam is encountered at a depth between 102.6 m and 106.8 m, with a 4m thick clay layer on top and a clay layer of at least 14 m thickness directly below the coal seam.

Pore pressure gradients in all layers are assumed to be hydrostatic. During gasification of the lignite layers, the counter-pressure of the underground reactor(s) (effective cavity pressure) has to be maintained significantly lower than the minimum hydrostatic pressure of the underground UCG system, to prevent contaminants spreading from the underground reactor to the surrounding layers. For modelling, an effective counter pressure of 1.8 bars (shallow lignite seam VIII) and resp. 8-9.5 bars (lignite seam V) was maintained within the cavity.

Table 2.2.20 shows the input geotechnical parameters used for modelling. The geomechanical properties assigned to the lignite and clay units are mostly obtained from experiments performed by CERTH on both clay and lignite samples from the recent drilling campaign at the Oltenia pilot site. In addition, data supplied by ISPE and CEO for the Oltenia region were used for geotechnical characterization. As no experimental data for the sand and silt layers were available, parameters for sands and silts are based on literature values. Ranges are assigned to capture the parameter uncertainty.

Table 2.2.20: Geomechanical parameters ranges, based on experimental results for clay and lignite samples from the Oltenia pilot site. Stiffness parameters for the clays were estimated based on index geotechnical parameters (pocket penetrometer, Atterberg limits) and/or literature values (*in blue*). Tensile strengths for the clays were derived from literature. No specific data were available for the sands and silts; these data were based on values reported in literature.

Soil layer	Depth (m bsl)	Density (kg/m^3)	Young's modulus (kPa)	Poisson's ratio (-)	Friction angle (°)	Cohesion (kPa)	Tensile strength (kPa)
Sand	0-10	2000	50e3-150e3	0.2-0.3	30-35	-	-
Clay	10-19	1950	5e3-50e3	0.3-0.4	15-27	8-86	10-100
Silt	19-34	2000	100e3-150e3	0.2-0.3	25-35	-	-
Clay	34-37	2000	50e3-150e3	0.3-0.4	15-27	8-86	10-100
Lignite VIII	**37-41**	**1220**	**604e3-1092e3**	**0.35-0.37**	**37-43**	**220-370**	**1050-1950**
Clay	41-46	2000	50e3-150e3	0.3-0.4	15-27	8-86	10-100
Silt	46-50	2100	50e3-150e3	0.2-0.3	25-35	-	-
Sand	50-53	2100	150e3-250e3	0.2-0.3	30-35	-	-

Soil layer	Depth (m bsl)	Density (kg/m³)	Young's modulus (kPa)	Poisson's ratio (-)	Friction angle (°)	Cohesion (kPa)	Tensile strength (kPa)
Clay	53-77	2050	50e3-150e3	0.3-0.4	15-27	8-86	10-100
Sand	77-98	2100	150e3-300e3	0.2-0.3	30-35	-	-
Clay	98-102	2080	50e3-200e3	0.3-0.4	15-27	8-86	10-100
Lignite V	**102-106**	**1260**	**691e3-808e3**	**0.34-0.38**	**18**	**220**	**780**
Clay	106-124	2080	50e3-200e3	0.3-0.4	15-27	8-86	10-100
Sand	124-140	2100	150e3-300e3	0.2-0.3	30-35	-	-
Underburden (undifferentiated)	140-170	2100	100e3-350e3	0.2-0.4	15-35	10-100	10-100

Both 2D (Plaxis) and 3D (FLAC3D) models were used for geomechanical modelling of the UCG cavity stability. For the 2D models so-called plane strain conditions were assumed, in which cavity length, i.e. the dimension of the cavity in the out-of-plane direction of the 2D-model, is assumed to be infinite. In these 2D plane-strain models the effect of the stresses and deformation in the out-of-plane direction, is not taken into account. The 2D-models generally have the advantage that model construction is straight-forward and calculation times are shorter than for 3D-models. Generally, for very elongated cavities, the plane-strain approach is a valid assumption, but subsidence can be overestimated for cavities with smaller length/width ratios. As can be seen in Table 2.2.19, final UCG cavity dimensions are expected to be elongated, with final length/width ratios varying between 1.4 and 2.3. In all cases in the 2D models, the cavity vertical cross section itself was assumed to be circular. The cavity in the 2D models is fully embedded within the lignite layer.

To test the impact of stresses and deformations in the third dimension on cavity stability and the validity of the plane strain assumption, 3D models were also constructed. Cavity dimensions in the 3D models were chosen to be laterally equidimensional (i.e. with a circular horizontal cross-section, in which cavity width equals length). As opposed to the 2D models, vertical cross sections in the 3D models were assumed to be rectangular (in fact, the cavity is modelled as a cylinder with vertical axis).

Combining results of both 2D models and 3D models, we can obtain insight in the impact of varying cavity dimensions (varying length-width ratio and cavity cross sections) on cavity stability, as actual cavity growth and final dimensions of the UCG cavity during UCG operations are uncertain. In theory, 3D models could be further extended to include the effect of multiple UCG cavity interaction, which is however beyond scope of the present project. In Table 2.2.21 below the main 2D and 3D model assumptions and model results are presented.

Table 2.2.21: Summary of 2D and 3D model assumptions and model results

	2D	3D
Model assumption	Plane-strain	Radial-symmetrical
Cavity length/width ratio	Infinitely elongated	Equidimensional
Cavity vertical cross section	Cylindrical	Rectangular
Cavity height (m)	3-4	0.5-4
Cavity width (m)	3-4	0.5-6
Cavity length (m)	Infinite	0.5-6
Lithology cavity roof / bottom	Lignite	lignite or clay seal
Cavity stability seam V (deep lignite seam)	Slight/minor stability problems	Minor stability problems up to D=2m
Cavity stability seam VIII (shallow lignite seam)	Severe stability problems	Severe stability problems

2D Plaxis models of seam VIII and seam V were performed by CERTH, for a cavity with circular cross section with a radius of R = 1.5 m and R = 2 m. Average values were used for the geotechnical parameters, based on parameter ranges derived from geotechnical laboratory test results on clay and lignite samples from the pilot site. In case of lack of site-specific information, parameters were based on values from literature. 2D numerical modeling results in Plaxis indicate that, assuming a circular cross section of the UCG-cavity, slight to minor stability problems are expected in the shallow lignite seam VIII (Figure 2.2.42). Figure 2.2.42 shows the analysis results for the cavity in the shallow lignite seam VIII in terms of vertical deformations u_y.

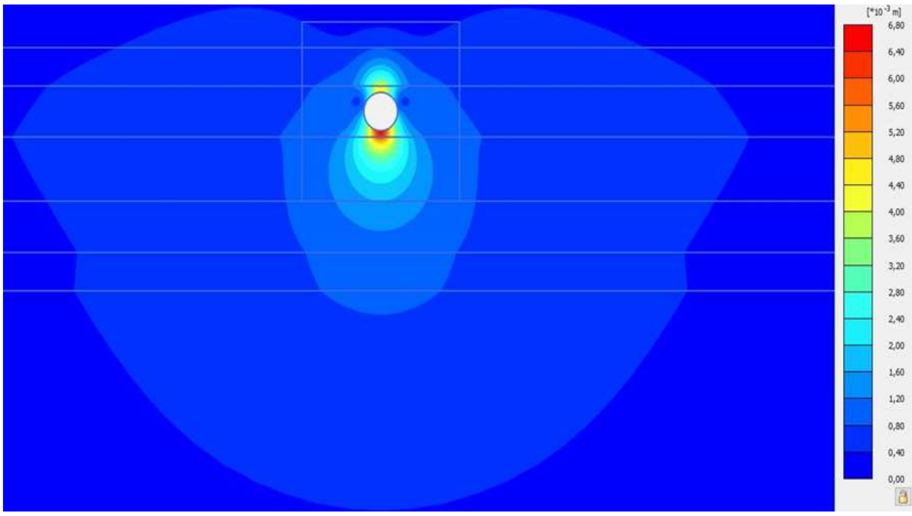


Figure 2.2.42. Cavity's vertical displacements for a D=3.0 m diameter opening in lignite seam VIII; u_y=0.007 m; modelled in FLAC 2D

Maximum computed vertical displacements at the top of the UCG cavity are approximately 6 cm. On the other hand, from the 2D Plaxis results for the deeper lignite seam it was observed that stability conditions for the UCG cavities in the deeper seam V are less favorable. For seam V very severe to extreme squeezing problems are expected for the R =1.5 m (Figure 2.2.43), and respectively for the R = 2.0 m caverns.

3D FLAC3D models of seam VIII and seam V were performed by TNO, for a cavity with a cylindrical geometry, and cavity radius varying between 0.25 m and 3.0 m and cavity height varying between 0.5 m and 4.0 m. Similar to the 2D modelling, average parameter values were used for modelling. 3D modelling results in FLAC3D indicate that, for a cavity with dimensions of up to D = 2.0 m, which is entirely embedded within the relatively strong and stiff lignite seam, no severe stability problems are expected within the shallow lignite seam layer VIII (Figure 2.2.44).

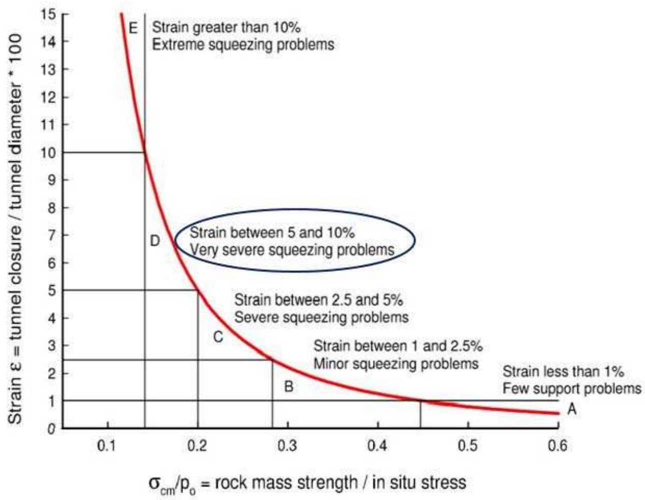


Figure 2.2.43. Modelled strain levels indicate that very severe squeezing problems are expected for the D=3.0 m cavity in lignite seam V

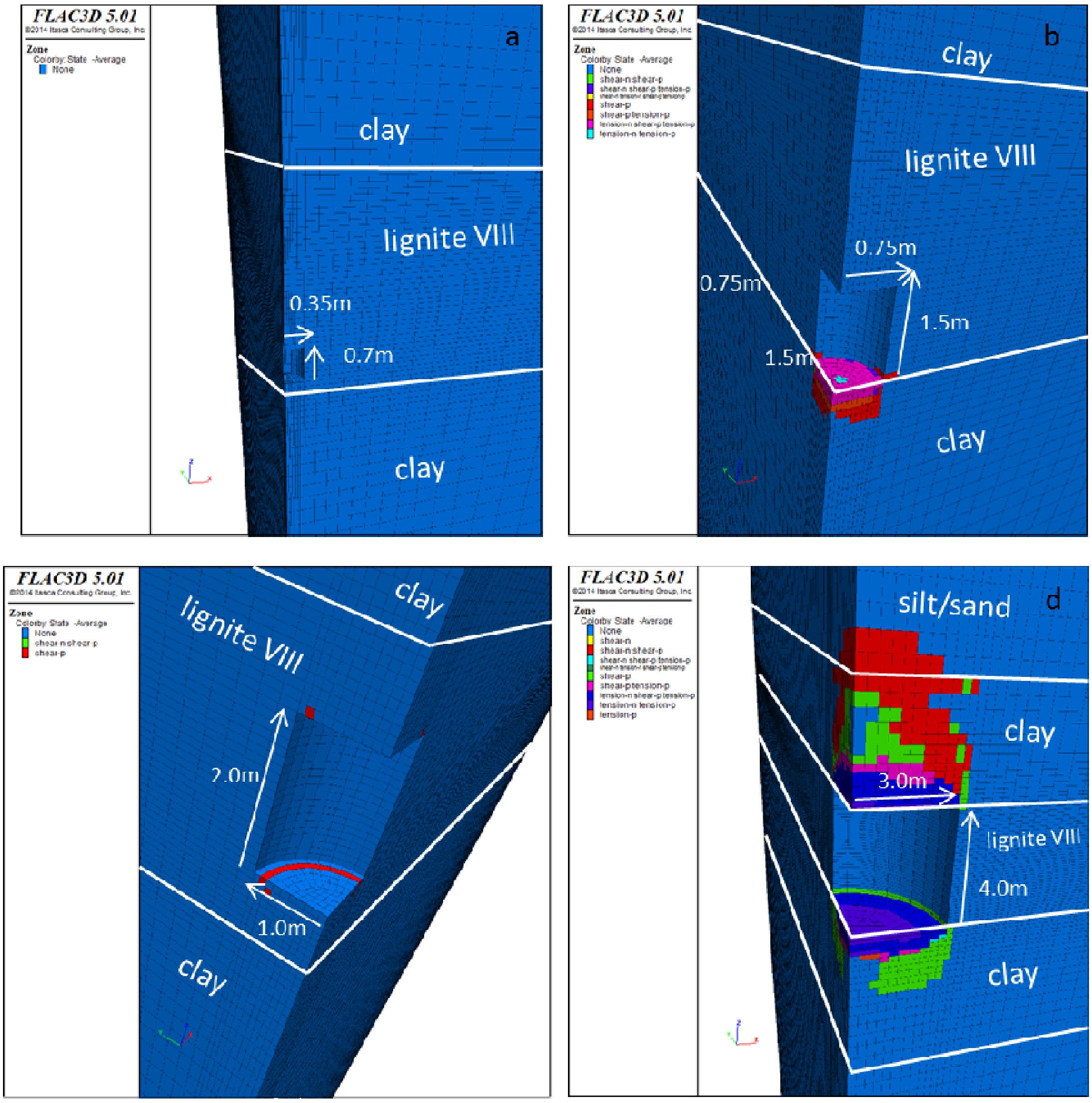


Figure 2.2.44. Modelling UCG cavity in lignite layer VIII – with increasing cavity dimensions. a) cavity dimensions: radius x height: 0.35 m x 0.7 m, located at bottom of seam VIII b) radius x height 0.75 m x 1.5 m, located at bottom of seam VIII c) radius x height 1.0 m x 2.0 m, located at the centre of seam VIII d) radius x height 3.0 m x 4.0 m, seam VIII gasified over entire height. First plastic failure occurs at the bottom rocks below the UCG cavity (a and b). Cavity embedded within the lignite seam is stable (c). As the cavity grows upwards and diameter increases also plastic failure of the roof rocks is observed (d). The plastic deformation zone extends into the sandy aquifer above lignite layer VIII. Model convergence problems are encountered for configuration b and d: only 70-80% of the total loading can be imposed, the extent of the plastic deformation zones shown in this figure should be considered a minimum.

However, if cavity dimensions increase as the lignites above and below the cavity are gasified and the clay layers with less bearing capacity are exposed in either the bottom or the roof rocks, extensive deformation and plasticity occur in the bottom and roof rocks, and numerical convergence problems are observed in the FLAC3D models. It is noted here that if gasification is started close to the bottom of the seam, significant sections of the bottom clay layers may become exposed at an early stage of gasification.

Regarding UCG operations in the deeper lignite seam V, FLAC3D model results show that cavity stability is problematic (Figure 2.2.45), as also shown by the 2D modelling results.

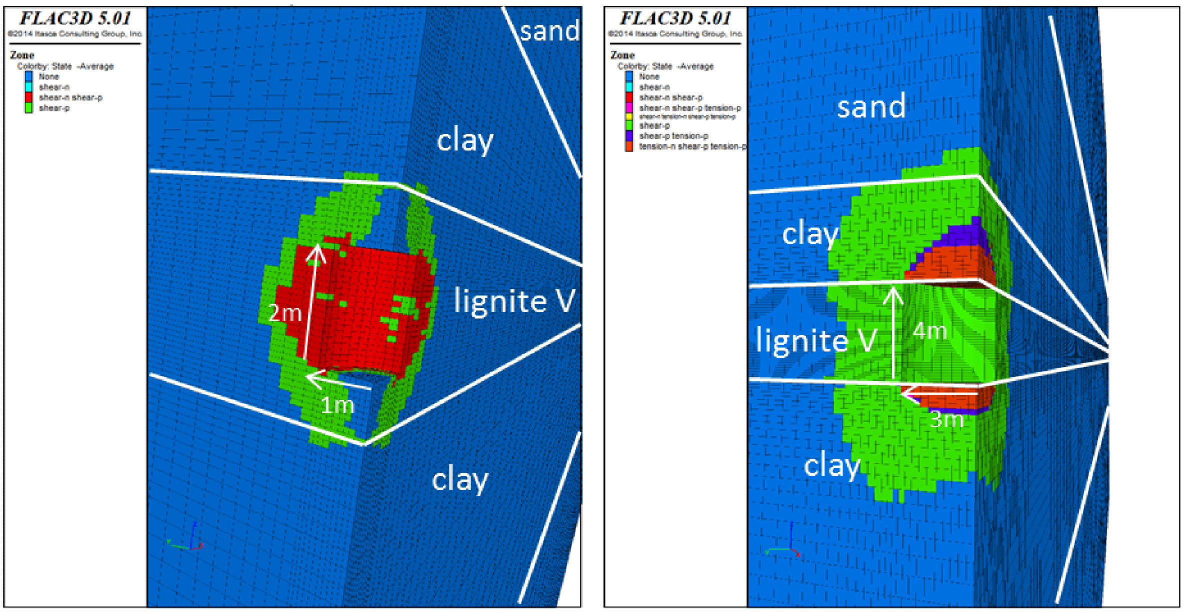


Figure 2.2.45. Plastic failure in the roof, bottom layers and sidewalls of the UCG cavity in lignite V. Left: Cavity R = 1 m and H = 2 m right) cavity R= 3 m and H = 4 m. Numerical convergence problems are encountered in case of the larger cavity: As model calculations diverge at 80% of the total loading imposed, the extent of the plastic zones shown in this figure should be considered a minimum extent.

From the above results it is concluded that considering the mechanical stability of the two lignite seams VIII and V, stability of an UCG cavity in seam VIII is higher than for seam V. This is mainly due to the higher stiffness and strength (Young's modulus, cohesion and tensile strength) of seam VIII compared to seam V and the higher in-situ stresses encountered at the depth of seam V. It is noted here that the number of test results, specifically for seam V is still limited. First indicative model results of the 2D and 3D geomechanical models indicate that for the chosen geometry, soil parameters and stress conditions, cavities of limited dimensions in seam VIII could remain stable. However, modelling results also indicate that the maximum dimension of the cavity that is still stable depends on the actual geometry (i.e. for circular plane strain cavity diameter D_{max} is 4 m, for 3D cylindrical D= 2 m), and the vertical position of the cavity, which may in practice be hard to assess upfront and to control.

In all cases large spans of unconsolidated clay soils in the roof and bottom should be avoided, as the bearing capacity of the clays is relatively low. As the sealing clay layer above the lignite seam VIII has a limited and varying thickness, loss of clay seal integrity and stability issues due to water and sand inflow at this stage cannot be completely excluded, and should be accounted for when assessing the risk of shallow UCG operations at the Urdari – Valea cu Apa pilot site.

2.2.5. *WP5: Risk Analysis, Environmental Issues and Legislative Background*

Task 5.1 - Define a risk assessment framework for UCG

This task is concerned with a Risk Assessment (henceforth RA) Framework for UCG.

After consulting with the partners, it was decided that the risk assessment should be based on the so-called FEP method (Features, Events and Processes). We present an outline of the various issues from a procedural point of view.

The work in this task aims at providing a risk analysis methodology, a framework of risk analysis and management based on the so-called FEP method (Yavuz et al. 2009). This method is well established worldwide and has been used by TNO in consultancy, and has been applied and investigated in large projects together with partners from universities, research institutes, and major players in the hydrocarbon business (Sijacic, Schelland and Wildenborg 2014).

Underground Coal Gasification (UCG) is being considered as a cost competitive and effective option to utilize coal reserves not exploitable by conventional mining technologies. (e.g. Friedmann et al. 2009 and Klimenko 2009). However, there are risks associated with UCG under HSE aspects, but also from an economic point of view. Therefore, a proper risk evaluation methodology will be the fundament for safe, sustainable and economic UCG operations, from a global and specifically from a site-specific perspective.

To analyze the risks of UCG in the project site the following steps need to be concluded: Initially, all potential risks associated with the project target have to be identified comprehensively. As a second step the detected risks will then be classified and evaluated, and in the third step solutions like corrective measurements or precautions need to be found to minimize or totally eliminate the risk. Generally, a risk assessment is based on an evaluation of the level of probability that an incident occurs, and the consequences of its occurrence. Figure 2.2.46 shows a common approach for risk assessment, the risk matrix combining the severity and likelihood of an event.

In order to perform this task properly it is necessary to define a risk framework. Such a framework defines the concept according to which risk analysis is performed. There are three basic demands for any risk framework one wants to devise. The method should:

- be transparent,
- allow updating,
- aim at completeness.

		Impact / Consequences		
		Minor	Moderate	Major
Likelihood / Probability	Likely	Medium	High	High
	Possible	Low	Medium	High
	Rare	Low	Low	Medium

Figure 2.2.46: Risk Assessment approach (green = low risk, acceptable; yellow = medium risk, possibly acceptable, red = high risk, not acceptable)

Transparency allows scrutiny by stakeholders like the responsible authorities, NGO's, municipalities etc. It also provides a necessary basis for updating the results when needed at any time. Striving at completeness counteracts tunnel vision, and makes the outcome of risk analysis and subsequent risk management trustworthy for the general public.

Although experiences from realized UCG projects exist, there is still a high uncertainty for many aspects with respect to both the probability and the severity of the risk they pose. Therefore, the following conservative assessment was recommended. Based on the identified risks the target should be to define safeguards and measures, which at least reduce, but better eliminate, the detected risk, Moreover, is vital to be able to react in the best possible way to unforeseen events.

MCE proposed a Layers of Protection Analysis (Mostade 2014). Indeed, this is a cogent way of high-level structuring the analysis, which can subsequently be performed with the FEP method. This means that a detailed work plan for the risk assessment of the Oltenia mine has basically been contained in the report of Task 5.1 where the crucial targets for the RA are defined.

The issues mentioned by MCE deal with the following broad topics:

- UCG site selection
- UCG operability and reliability
- Module control and performance
- Upscaling to commercial operations
- Site decommissioning.

The report then usefully breaks these issues down to a far greater detail. This makes it feasible to nominate a relevant group of experts which deals with the various sub-issues.

It has to be noted that the targets for an RA are also set by the authorities, i.e. the relevant legislation. Clear information on this point has been presented by ISPE in Task 5.1 by highlighting the relevant authorities and the laws that have a bearing upon UCG. Here we mention amongst others:

1) RA has to observe European laws, and Romanian laws. This entails that the stricter obligations will always prevail- a logical consequence also from the fact that EU-legislation is to be incorporated into the national legislations of the EU Member States.

The relevant laws include issues of Health, Safety and Environment (HSE), waste, land management, water management, fire-fighting, and formal administrative issues regarding licensing.

2) In Romania no less than seven authorities play a role, each with well-defined authority. This may have consequences for communication issues.
3) It appears that a geological research methodology is in effect, which is approved and imposed by the National Agency for Mineral Resources (ANRM), one of the seven instances. This methodology has a direct influence on what has to be done in RA. Interestingly, in the description offered there seems to be no direct mention of any obligatory modelling activity.

Task 5.2 - Qualitative and quantitative assessment of the UCG-related environmental contaminants

Studies of UCG post-processing water

Qualitative and quantitative characterisation of the UCG wastewaters produced during the four COAL2GAS UCG experiments was the main aim of the study. The raw UCG product gas contains water vapour, originating mainly from the evaporation of coal moisture, the coal-pyrolysis process (pyrogenic water) or undesired hydrogen combustion. This gas moisture tends to condense onto the cooler parts of the installations, such as the internal surfaces of gas pipelines or in particular devices of the gas-treatment module. To prevent environmental pollution during the UCG operations, the resulting post-gasification water condensates are systematically collected and transported for off-site treatment. Post-processing waters produced in water scrubbers Figure 2.2.12 and Figure 2.2.14 were periodically sampled within the whole course of the all gasification experiments in order to measure the rate of the wastewater and contaminants production at any phase of the experiment and to correlate the type and concentrations of produced contaminants with the coal characteristics and process parameters (e.g. effect of pressure).

Apart from the two standard water parameters as the conductivity and pH, the following inorganic parameters were determined in the condensates: total ammonia nitrogen, nitrites, chlorides, cyanides, sulphates, and 17 metal and metalloid trace elements (Sb, As, B, Cr, Zn, Al, Cd, Co, Mn, Cu, Mo, Ni, Pb, Hg, Se, Ti, and Fe). The organic analysis of the effluents included polycyclic aromatic hydrocarbons (PAHs), phenolics, benzene with its three alkyl homologs toluene, ethylbenzene and xylene (BTEX). The conductivity, pH, biological oxygen demand (BOD_5), chemical oxygen demand (COD_{Cr}) and total organic carbon (TOC) were additionally determined in the representative post-gasification effluents as typical nonspecific industrial wastewater parameters. The chemical analyses were performed applying standard analytical methods.

Average values of the parameters determined in the post-processing waters originating from ex-situ gasification experiments are presented in Figure 2.2.16. As can be concluded from the presented results, the effect of lignite used and gasification conditions on the values of physicochemical parameters of the wastewaters is evident. When analysing the atmospheric pressure results, for most of the organic compounds (or non specific parameters correlated with the organic species, i.e. TOC, BOD-5, COD), higher values were observed in the wastewaters from Velenje lignite experiment. The higher values of conductivity in the wastewaters from Oltenia trial derived from the higher concentrations of selected ionic inorganic species. This could be due to a greater ash content of the Oltenia coal, i.e. 8.9% compared to 4.3% of ash in the Velenje coal (on as-received basis). An opposite effect of the coal feed is observed for pressurized experiments. The values of the measured parameters were significantly higher for the Oltenia wastewaters. As the increase in gasification pressure usually leads to the intensification of tar cracking phenomena, the difference in the gasification pressure between the two experiments may be one of the main reasons of the observed differences, especially regarding concentrations of tar components (aromatic hydrocarbons, phenols, TOC) and some non-specific parameters related to the contents of organics, i.e. BOD, COD.

Table 2.2.22: Average values of parameters determined in the post-processing UCG waters

Parameter	Unit	Atmospheric pressure experiments		High pressure experiments	
		Velenje	Oltenia	Velenje 35 bar	Oltenia 10 bar
conductivity	µS/cm	2,478	3,155	1,770	5,253
pH	pH	7.3	7.7	6	5.1
BOD-5	mg/l O2	4,373	1,048	300	2,105
COD (Cr)	mg/l O2	5,060	2,010	691	4,177
ammonia nitrogen	mg/l N	280	463	189	778
nitrite ammonia	mg/l N	910	<0.3	<0.3	<0.3
total nitrogen	mg/l N	314	473	207	785
nitrites	mg/l	18	<1	<0.3	<1
total cyanides	mg/l	1.31	1.01	0.70	3.0
free cyanides	mg/l	0.54	0.84	0.69	3.0
bound cyanides	mg/l	0.77	0.24	0.01	0.2
Phenol Index	mg/l	488.3	187.5	28.4	240.5
TOC	mg/l	2,400	882.5	167.0	1,250
sulphates	mg/l	45.7	44.3	105.0	204
sulfides	mg/l	0.35	0.25	0.20	26
ammonia ion	mg/l	483.3	597.5	243.8	1,000
Sb	mg/l	0.03	0.03	0.03	0.070
As	mg/l	0.04	0.21	<0.005	0.159
B	mg/l	0.21	0.04	0.58	0.480
Cr	mg/l	0.00	<0.005	0.17	1.746
Zn	mg/l	0.06	0.08	0.18	0.300
Al	mg/l	0.06	<0.01	0.22	1.413
Cd	mg/l	<0.001	<0.001	0.001	0.002
Co	mg/l	<0.005	<0.005	0.01	0.043
Mn	mg/l	0.01	0.05	0.13	0.340
Cu	mg/l	0.01	0.01	<0.005	<0.005
Mo	mg/l	<0.01	<0.01	0.02	0.011
Ni	mg/l	0.05	0.01	1.16	2.830
Pb	mg/l	0.01	<0.01	0.04	0.277
Hg	mg/l	<0.0005	<0.0005	<0.0005	0.003
Se	mg/l	0.04	0.03	<0.01	0.066
Ti	mg/l	<0.003	<0.003	0.004	0.055
Fe	mg/l	0.05	0.02	2.49	21.980
benzene	µg/l	1,189.2	1,190.3	512.3	1,072.0
toluene	µg/l	356.3	277.0	175.2	236.3
ethylbenzene	µg/l	238.7	263.5	24.4	209.8
m,p-xylene	µg/l	81.3	<1	32.8	0.0
o-xylene	µg/l	128.5	53.3	59.6	44.0
Total BTEX	**µg/l**	**1,994**	**1,784**	**804**	**1,562.0**
phenol	mg/l	476.4	142.6	8.6	140.2
o-cresol	mg/l	115.9	50.7	4.4	41.4
m,p-cresol	mg/l	140.4	52.5	4.1	25.9
Total phenol	**mg/l**	**733**	**246**	**17**	**201.0**

It was found that values of the measured physicochemical parameters significantly varied over the time of gasification for the particular experiments. These variations reflected changes in the gasification conditions (temperature) and development of oxidation and pyrolysis zone over the experiments.

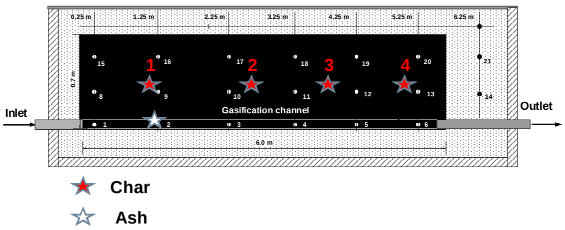
Studies of the post-gasification solids

The solid residues left underground may be a source of secondary groundwater contamination during the post gasification phase of UCG process. The post-gasification studies included sampling and analysis of solid process residues remaining in the UCG cavity in order to assess the potential environmental risk in the post-gasification stage. Char and ash samples were taken from the post-burn cavities after completion of the gasification experiments Figure 2.2.47

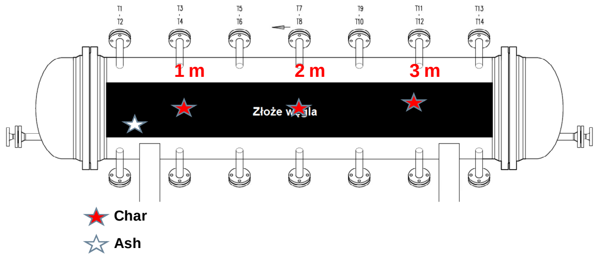
a) b)

Figure 2.2.47: Post gasification residues after completion of Velenje 35 bar experiment:
a) inlet view (ash), b) outlet view (char)

The post-gasification chars were sampled at three different distances from the reactor inlet as presented in Figure 2.2.48.



a)



b)

Figure 2.2.48: Sampling points of post-gasification residues:
a) atmospheric reactor, b) high-pressure reactor

The collected char and ash samples and feed lignites were tested for 18 elements, including selected metals and metalloids being considered of main concern for the water environment. Analysis of results revealed that for both lignites effect of gasification pressure on the concentrations of metals in the solid residues was noticeable. For the atmospheric pressure experiments, the highest enrichment coefficients for tested chars (raw lignite as a reference) were found for Cr, Mn, Sb, Fe. On the other hand, the char residues originating from the pressurized UCG tests were characterized by highest enrichment coefficients for B, Co, Mn, Sb, Al and Fe. Boron and cobalt were identified as these elements, for which effect of gasification pressure on their concentrations in solid residues was most pronounced. It should be noted, however, that the varying values obtained for the particular char samples may result from inhomogeneities of the coal seam (different shares of particular petrographic species and contents mineral matter). The post-gasification ash collected from the bottom of the UCG cavity was mainly enriched in such elements as: Mn, Pb, Sb, Al, Fe and K with some variations in enrichment coefficients depending on lignite used and gasification pressure applied. To estimate the possible mobility of the elements into groundwater environment, in a subsequent step laboratory leaching test were conducted for the selected solid residues.

The elution tests shown that the elements with the highest mobility into the aqueous phase are As, B, Zn, Al, Mn, Fe and, to a lower extent Mo and Se (Table 2.2.23 and Table 2.2.24). Therefore these elements may be regarded to be of greatest concern for the groundwater environment in the post gasification phase. The majority of the metals examined showed a tendency to elute to a higher extent from post-gasification char than from raw lignite. The only exception is As and Zn for Velenje char, for which higher concentrations were obtained for the raw lignite leachates. Lower concentrations of As resulted from its high volatility during the thermo-chemical coal conversion. Differences between the samples originating from the two experiments may result from the way the elements are incorporated into the coal molecular structure (speciation). The quantitative composition of examined water extracts originating for chars sampled from different parts of the post-gasification cavities varies significantly, which reflects the extent of thermal transformation. No positive correlations between the content of elements in the aqueous leachates and their concentrations in char residues were found. For the both lignites under investigation, the highest concentrations of eluted specimens in aqueous solutions were obtained for the char samples obtained in a distance of approximately 1 m from the reactor inlet. This was a zone of highest temperatures (UCG oxidation zone), which resulted in highest rates of coal thermo-chemical conversion. This observation supports a theory that the metal elution potential to a larger extent relates to the physicochemical properties of the carbonaceous residues themselves than to the content of given specimen in the material being eluted.

Elution potential of organic compounds expressed as Dissolved Organic Compounds (DOC) varies significantly between the lignites under study. For Velenje char, concentrations of eluted organics decrease with a distance from the reactor inlet, and they are reversibly proportional to the degree of coal thermal conversion. This may be explained by a possible decrease in sorption capacity of the chars with the decrease in carbon content. Because for almost each of the tested chars DOC concentrations were smaller or had similar values to those obtained from leaching of adequate raw lignites, the possible negative environmental effects due to release of organics after UCG may be regarded as a negligible for the coals under study.

Table 2.2.23: A physicochemical composition of water extracts obtained from elution tests for Velenje samples

Parameter	**Unit**	**Char 1m**	**Char 2m**	**Char 3m**	**Char 4m**	**Raw lignite**
DOC	mg/l	**350**	**210**	**200**	**160**	**310**
Sb	mg/l	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
As	mg/l	**< 0.01**	**< 0.01**	**0.016**	**0.012**	**0.028**
B	mg/l	**0.35**	**0.24**	**0.17**	**0.13**	**0.17**
Cr	mg/l	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003
Zn	mg/l	**0.034**	**0.048**	**0.043**	**0.037**	**0.098**
Al	mg/l	**0.12**	**0.36**	**0.13**	**0.21**	**0.094**
Cd	mg/l	< 0.0005	< 0.001	< 0.001	< 0.001	< 0.0005
Co	mg/l	< 0.003	< 0.003	< 0.003	< 0.003	0.0052
Mn	mg/l	**0.34**	**0.18**	**0.09**	**0.14**	**0.25**
Cu	mg/l	< 0.005	< 0.005	< 0.005	< 0.005	0.0058
Mo	mg/l	**0.039**	**0.019**	< 0.003	**0.0036**	< 0.003
Ni	mg/l	< 0.005	< 0.005	< 0.005	< 0.005	**0.0074**
Pb	mg/l	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Hg	mg/l	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Se	mg/l	**0.01**	**0.0071**	< 0.005	< 0.005	< 0.005
Ti	mg/l	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003
Fe	mg/l	**0.01**	**0.24**	**0.025**	**0.023**	**0.025**

Table 2.2.24: A physicochemical composition of water extracts obtained from elution tests for Oltenia samples

Parameter	**Unit**	**Char 1m**	**Char 2m**	**Char 3m**	**Char 4m**	**Raw lignite**
DOC	mg/l	**110**	**110**	**120**	**100**	**100**
Sb	mg/l	< 0.005	**0.014**	< 0.005	< 0.005	< 0.005
As	mg/l	**0.12**	**0.028**	**0.026**	**0.024**	**0.012**
B	mg/l	**0.24**	**0.85**	**0.5**	**0.48**	**0.039**
Cr	mg/l	< 0.003	< 0.003	< 0.003	< 0.003	< 0.003
Zn	mg/l	**0.092**	**0.029**	**0.13**	**0.041**	**0.054**
Al	mg/l	**0.19**	**0.034**	**0.19**	< 0.03	**0.051**
Cd	mg/l	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Co	mg/l	**0.01**	< 0.003	< 0.003	< 0.003	< 0.003
Mn	mg/l	**0.24**	**0.099**	**0.1**	**0.15**	**0.092**
Cu	mg/l	**0.0075**	< 0.005	< 0.005	< 0.005	< 0.005
Mo	mg/l	**0.012**	**0.055**	**0.014**	< 0.003	< 0.003
Ni	mg/l	**0.0054**	< 0.005	< 0.005	< 0.005	< 0.005
Pb	mg/l	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Hg	mg/l	< 0.0005	< 0.0005	< 0.0005	< 0.0005	< 0.0005
Se	mg/l	< 0.005	< 0.005	**0.011**	**0.0066**	**0.0081**
Ti	mg/l	<0.003	<0.003	**0.0074**	<0.003	<0.003
Fe	mg/l	**0.12**	**0.005**	**0.1**	**0.022**	**0.029**

Task 5.3 - Compile site-specific information (assessment basis)

The general objective of this task was to define and prepare base data and the context for the subsequent risk assessment (RA). The method used for the RA, as defined under Task 5.1, is the so-called features, events and processes (FEP) method. This general method forces the risk analysts to name, investigate and evaluate features, events and processes that may have influence on the safety of the proposed activities. This task is dedicated to name a few of them, which will require attention based on the data available. The so-called assessment basis, the objective of this task, determines the type of risks that have to be scrutinized. For the Oltenia demo project this basis comprises risks of an environmental nature, risks concerning the technological and operational feasibility, and risks concerning the legal situation. The objectives of this task comprise preparatory work for the planned RA, i.e.:

- the definition of the existing legal requirements
- the objective of the risk assessment
- determination of the performance indicators
- compilation of relevant site specific information
- definition of the UCG concept and containment of fluids

Definition of existing legal requirements

Both national/Romanian and EU legal requirements which may influence the UCG test trial in Romania have been screened and listed in this task. A total of 22 UCG relevant laws and regulations have been identified at national level. At EU level a total 29 directives have been identified which may have an impact on the potential UCG test trial. A total of 7 national authorities are responsible for the compliance of the national laws with respect to potential UCG operations. These institutions are:

- National Agency for Mineral Resources (ANRM)
- Ministry of Economy (ME)
- Ministry of Environment and Climate Changes (MMSC)
- National Environmental Protection Agency (ANPM)
- National Environmental Guard
- Romanian Waters National Agency (ANAR)
- General Inspectorate for Emergency Situations (IGSU)

Considering the directives and national laws an environmental impact assessment plan is mandatory for the proposed UCG test in Romania.

Objective of the risk assessment

The ultimate goal of risk assessment is to prevent unwanted effects to the environment by identifying and addressing potential influencing factors, using national and EU regulations as guidelines. For underground operations numerous methods exist to identify the influencing factors. The FEP (Features, Events and Processes) method has been used to achieve the above mentioned goal. Commercial aspects of risk assessment have been neglected, since the Oltenia trial is a scientific research project.

Using the COVRA FEP-database a total of 8 FEPs have been identified, which can relate to geo-scientific items and another eight FEPs related to the interaction between UCG-related activities and the host rock.

Determination of the performance indicators

Following an extensive literature review of previous UCG operations the following key-performance indicators have been identified:

- Geometrical efficiency (or mining sweep efficiency);
- Energy conversion efficiency (or gasification efficiency including heat and gas losses).
- Syngas mass and energy flow rates;
- Syngas composition and quality;
- Underground gasification and deposition rates (coal consumption, ash and char deposition);
- Oxygen and water consumption rates;
- The energy availability and lifetime of each module;
- The well surface occupation footprint; and
- The Energy Return on Energy Investment (EROEI) of the whole process.

Compilation of relevant site specific information

Site specific information has been provided by ISPE and CEO SA and through an extensive literature research. In addition two site visits have been performed with representatives from DMT, ISPE and CEO, where open pit mines as well as the potential test site near Pesteana open pit mine have been inspected. Information on the following geoscientific topics have been collected, which also reflect the identified FEPs:

1) Stratigraphy
2) Lithological variability
3) Hydrogeology / groundwater flow patterns / nearby aquifers
4) Stress state
5) Geochemical state
6) Geomechanical state

7) Faults and fracture / pathways to the surface
8) Seismic activity

The compilation of all relevant information has led to the construction of a generalized lithological profile at the test site. This lithological profile has been matched to geotechnical data from nearby Pesteana mine, thus providing basic information on the geotechnical properties of the lithologies in the test area. Geochemical information has also been provided by CEO SA. Unfortunately the analysis methods have not been reported. However, the analyses provide a rough indication of what can be expected for coal seam chemical composition at the test site.

Definition of the UCG concept and containment of fluids

Based on previous projects the theoretical outline of the UCG concept, including panel layout and containment of fluids has been described. The L-CRIP configuration has been assessed to be the most suitable. The panel layout descriptions includes the subsurface module design as well as all elements of the subsurface panel design namely the future expansion panel, drilling panel, gasification panel, venting and cooling panel, depleted and decommissioned panel.

Liquids produced during UCG are derived from 5 main sources:

- Injected water
- Naturally occurring groundwater
- Non-aqueous-phase fluids
- Release of inherent water held within the coal
- Water produced by chemical reactions

The containment of the fluids, i.e. the prevention of leakage of contaminants into surrounding aquifers is a task of utmost importance. During UCG operation the reactor pressure should be lower than the surroundings, to insure influx into the reactor. Prior to UCG operation the hydrogeological conditions have to be investigated in detail and boundary conditions defined.

Task 5.4 - Develop a database with UCG risk factors

This task was dedicated to the development of a database with risk factors which will be used in the qualitative assessment of risks and the development of scenarios for the release of toxic fluids to the biosphere.

The FEP-method was chosen to assist the RA of potential UCG operations at Oltenia (See Task 5.1). A specific site may have particular features that may be conducive to certain hazards. Processes may develop that may lead to risky situations. By having them identified and noted one does not lose sight of them, and perhaps these small risks turn out to be larger than envisaged in the early process.

For the above reasons the FEPs should be brought together in a database. Developing a database with UCG risk factors is a task that is multifaceted. Consequently, all partners have to partake in this exercise. The first two questions to be answered are the following:

Which FEPs will have to be part of the database? In which way will the database be organized?

In order to construct an inventory the FEPs (preliminary) have been organized in three groups:

1) FEPs related to site-specific basic geo-scientific knowledge regarding the host rock.
2) FEPs related to interaction between UCG or UCG-related activities and host rock.
3) FEPs related to Economic issues.

The first group contains: Stratigraphy, lithology, hydraulic state / flow patterns / nearby aquifers (Hydrology), stress state, geochemical state, faults and fractures / pathways to the surface, geological history, seismicity. These items are needed to give a description of the system, quite apart from its intended use.

The second group contains: Integrity of the overburden of UCG reactor, impact of UCG on cavity, movement of gaseous / liquid components through host rock, contamination drinking water (aquifers), host rock damage as a result of construction activities, thermal evolution, geo-mechanical processes / hazards, processes w.r.t. man-made structures (wells) / well failure, monitoring issues. For each of these items a sub-list was drawn up of FEPs that would find a place in these contexts.

The third group lists the FEPs coal thickness, coal quality, syngas quality, syngas production steadiness, remediation risks/costs, post-closure risks/costs.

It appears natural, then, to organize the database according to the phases in a UCG project. In the very first phase one will construct a picture of the risks. All potential risks that could occur throughout the entire project must be included in a preceding RA performed in this phase. In the operational phase one has to bring in the new data (as a result of the operations) to scrutinize whether the risks come to play a role. In the last two phases one has to perform risk assessment beforehand. Thus, RA in the operational phase goes alongside with the operations.

Thus we have:

- Construction (or preparatory) phase
- Operational phase
- Post-operational phase (until decommissioning)
- Post-Decommissioning phase (some monitoring might continue after decommissioning)

In each phase the FEPs are organized according to certain themes.

In the construction phase these are:

- Geological build-up, divided in geometry-related issues and physicochemical issues.
- Societal issues around the target zone
- Integrity issues
- Monitoring issues
- UCG process issues

These are the things one has to scrutinize before the project is allowed to enter the operational phase at all. Some or all of them are needed to obtain licenses required by law.

In the operational phase the themes are:

- Integrity issues
- Monitoring issues
- UCG process issues

While the operations are ongoing these issues are relevant in the light of new incoming data. As mentioned in Task 5.1 RA will go on over the entire lifetime of the project.

In the post-operational and the post-decommissioning phases the themes of integrity, monitoring and UCG process play a role again, emphasis being on slightly different FEPs. In the last phase, for instance, the risks for the operator (at Oltenia) may be foremost of a financial nature, depending on the liability in case of hazards, as detailed in European and Romanian law.

Having introduced the FEPs the next task is to enable the experts to give their opinion on both the impact and the likelihood of the FEPs. The experts must know how to use the database. Therefore, in this task's deliverable ("Description and manual of database with risk factors") a chapter was included to introduce them to a full-fledged use of the database – Chapter 4: Use of the database within Risk Assessment. In preparation of the Workshop (after 31/12/2015), where the database comes to full use this Chapter is indispensable as background for the experts. An important part of the activities has been to disseminate the deliverable amongst the partners, who will have to work with the database.

The experts who evaluate the risks by the means of the risk factor database play a special role. They need to, based on their experience and general knowledge of the site, rank and evaluate the likelihood and impact of each risk factor with respect to the UCG operations planned in Oltenia.

An important tool for an expert / reviewer is the so-called risk matrix (Figure 2.2.46, see Task 5.1 above). The matrix is a simple conceptual tool, enabling the reviewer to visualize his "verdicts". The two axes of the matrix are the probability or likelihood axis and the impact axis.

The qualification in classes of likelihood (rare, possible & likely) and classes of impact (minor, moderate & major) is basically imposing a logarithmic division on the magnitudes of either. If one gave each class a number it would be appropriate to define the risk (i,j) as the sum of the numbers associated with the likelihood (i) and impact (j) of the event / process. The risks so defined should, again, be interpreted in a logarithmic vein. One should notice that this procedure accommodates the basic rule "Risk = likelihood x impact". Risk ratings defined are low, medium and high. Figure 2.2.49 explains the risk categories and gives examples for the different impact classes.

	Risk category		
Impact class	Low	Medium	High
Humans (casualties)	Up to 10^{-5} per year	up to 10^{-2} per year	Larger than10^{-2} per year
Environment (grade of pollution)	Not harmful to environment and/or small expansion (inside the operational	Slightly harmful to environment and/or medium expansion (slightly	Seriously harmful to environment and/or expansion far outside the permit

	permit	outside the operational permit)	
Costs	< 100,000€	< 500,000€	> 1,000,000€

Figure 2.2.49: Risk categories and impact classes for UCG risk assessment

Obviously, qualitative descriptions like "possible" or "major" are fuzzy. It is recommended that the committee that oversees the RA process mitigates this fuzziness as much as possible. This is done by giving a more concrete meaning to the various likelihood and impact classes. This must necessarily depend on the context. This interpretation of the various classes should be made known to reviewers before the completed questionnaires are being evaluated.

For example, a hazard may be called "rare" in a certain context if its likelihood is less than 0.01 / year, but less than 10^{-5} / year in a different context, depending on the severity / acceptability of the consequences. The last figure would typically apply when the risk of human lives is concerned.

In defining the impact classes one may face the need to bring together impacts of quite differing nature. For instance, one may define the class "Major" as containing such diverse impacts as the loss of human life, an expected economic loss of 10^6 USD, and significant pollution of a drinking water reservoir. Although the list, drawn up by the committee overseeing the RA process, may not be exhaustive a reviewer will understand the "scale" set by the committee.

The database was deployed, tested and improved during the Risk Assessment Workshop to develop risk scenarios in Task 5.5.

Task 5.5 - Screen risk factors, and develop and characterize scenarios

In Task 5.4 "Description and manual of database with risk factors" the UCG database and its use were described. The database contains risk factors grouped into risk themes with respect to an UCG process that is intended to take place at the Oltenia site in Romania. After the database was made available to the parties in the investigations, experts were presented with documentation on the site. They were then asked to comment on the risk level or impact (minor, moderate, major) as well as on the likelihood (low, medium, high) of the individual FEPs to play a role at the UCG process at the site. This was done on an individual basis at first, with help of standardized forms. Subsequently, a workshop was organized at TNO, Utrecht to discuss the results. This was done so as to pinpoint differences in opinion, and for reaching a "communis opinio" if possible.

The risks were determined for four phases in the project, the Construction (or preparatory) phase, the Operational phase, the Post-operational phase, and the Decommissioning phase.

In the Construction phase all risks were to be considered as far as possible, and also which extra data might be needed. Moreover, in this phase it should also be discussed which modelling efforts would have to take place before a go/no go decision. The Operational phase contains almost all risks already considered, but the incoming data as a result of the operations might require updating of the judgment on these risks, or even introduce new ones... The Post-operational phase begins when the UCG has been terminated, when monitoring actions - already present in the Operational phase – play a prominent role. The Decommissioning phase starts when the site is left on its own and long-term effects are scrutinized.

The expert group agreed on certain preconditions and created a study case in order to provide a realistic risk assessment based upon operational and site-specific information gathered in WP2 and WP4, such as coal seam thinckness and depth, gasification rate, panel design, etc.

The risk assessment workshop focussed on seam VIII and some general aspects were transferred afterwards to the properties of seam V and it was estimated if seam V could present a better target.

The important data sources have been the details of the operational parameter for both case studies obtained by modelling performed by MCE and the Geological-Report on the Oltenia-Basin.

Evaluation criteria

To rank the risks (impact x likelihood) estimated by the experts and for a proper illustration a risk matrix (Figure 2.2.46 in Task 5.1) and risk categories/impact classes (Figure 2.2.49 in Task 5.4) explained above have been used, which uses the following categories:

1. Impact/consequences:
    a. Minor (green, factor 1)
    b. Moderate (yellow, factor 2)
    c. Major (red, factor 3)
2. Likelihood/probability
    a. Rare (green, factor 1)

b. Possible (yellow, factor 2)
c. Likely (red, factor 3)

The **sum** of both factors reveals the risk of a certain scenario.

- Low Risk: 2 and 3 (green)
- Medium:4 (yellow)
- (too) High: 5 and 6 (red)

When several experts have filled out their excel sheets the results must be combined. TNO designed in Task 5.4 a so-called "Master" sheet to automatically evaluate the answers of the experts. This evaluation set the agenda for the workshop for the various experts to attend.

In total 10 questionnaires completed by various experts from the project team were received and evaluated by TNO's risk database tool. All risk parameters for the four phases (construction, operation, post-operation and after decommissioning) provided in the risk database were considered. In order to ensure an effective workshop and focussed discussions, TNO identified the key-risk (scenarios) that should be discussed during the workshop. A risk factor was subject of discussions, i.e. considered as severe if the following thresholds were passed:

- The average of expert rankings for the **impact** of a certain risk parameter/scenario was above the factor 2,5 (moderate to high, see above) or
- The average of expert rankings for the **likelihood** of a certain risk parameter/scenario was **above 2** (possible)
- Special attention was paid to risk factors that fulfilled both criteria above: Average impact above 2,5 and probability above 2
- The expert opinions were varying, i.e. the experts had different opinions about a risk. special need for discussions and clarification was assumed
    - If the standard deviation of given opinions on either impact or likelihood of a certain risk parameter was higher than 0.8 or
    - if at least two experts ranked the probability of a certain risk parameter as rare and at least two others ranked it as likely at the same time or
    - if at least two experts ranked the impact of a certain risk parameter as minor and at least two others ranked it as major at the same time

The results for all risk parameters were illustrated in risk matrices. An example is given for the "risk theme" Target Zone Integrity during the operational phase with four associated risk factors (Figure 2.2.50). The risks factors, except drilling activity, have been ranked as high and were discussed controversially during the workshop (as all other severe risk as defined above).

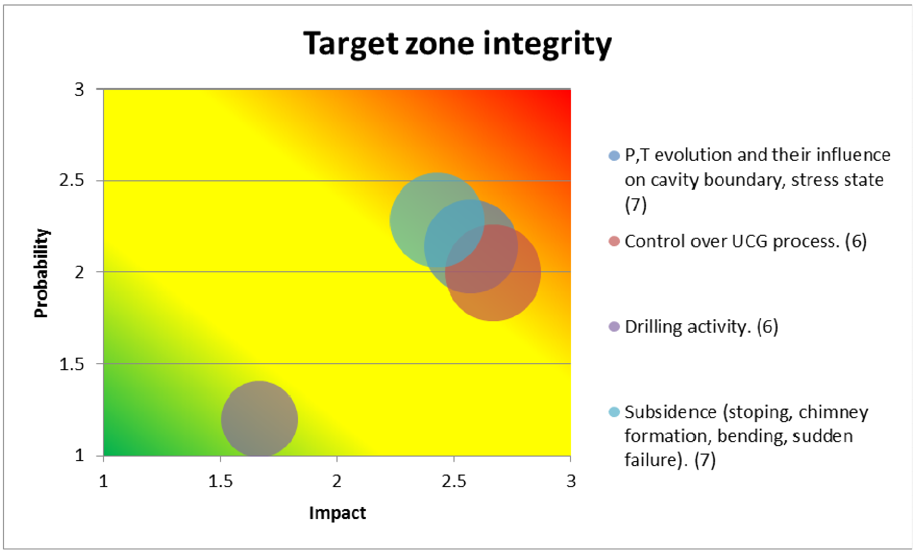


Figure 2.2.50 Example of the evaluation of risks in the risk matrix (based upon Figure 3.4.5 above). Here for the target zone integrity during the operational phase. The number in brackets behind the risk factor indicates the number of expert rankings received for this particular parameter.

Main outcomes of the risk assessment workshop

The workshop on the risks was held on 2nd and 3rd February 2016 at the TNO premises, Utrecht. The preparations included the communication of the personal views of the participants, and the summary thereof in a so-called Master sheet. This master sheet contains and structures all relevant detailed information the experts provided, including its evaluation. The main risks and/or themes identified were illustrated in figures (see Figure 2.2.50 above) based upon the risk matrix as described above. This helped to understand and analyse the results of the questionnaire.

The discussions were fruitful, and resulted in a desired "communis opinio" on the main risks. The main risks as perceived by the participants of the workshop are now described per phase.

The Construction Phase

Based on the evaluation of the experts opinions and the discussion during the workshop, the following risks have been considered highest for the study case assumption:

1) **Legislative Issues**. Before anything can be done full clarity is required on the legislative issues. Existing legal obligations, ownership issues and general safety issues should be clear. Shortcomings in dealing with these issues might result in delays or even downright refusal of the necessary permits.

2) **The reliability and completeness of the existing documents and reports**. Are there any nearby, conflicting mining activities? Is the data on geological parameters up to date? Are the nearby aquifers mapped out in full? The obvious remedy for inadequacies with respect to these issues is drilling new wells in (around?) the selected site.

3) **Integrity and subsidence of the target area and its surroundings**. The intended UCG operations will take place at shallow depths in material that may not be very consolidated. This makes integrity and subsidence issues of truly major importance. In the Construction phase geo-mechanical modeling based on real data is therefore indispensable.

4) **Protection of (groundwater) aquifers.** It is known that aquifers are in contact with lignite seems. Hence, they form a gateway for pollution to areas outside the target area. This would constitute a major problem if such aquifers are in contact with reservoirs for potable water.

5) **Geological uncertainties.** Uncertainties in the following geo-scientific subjects constitute the main risks.

    a. **Stratigraphy**. This concerns the target area as well as the overburden / underburden and a sizeable area around the actual site. Knowledge of the stratigraphy is related to the all-important issues of subsidence and integrity. Knowledge of the stratigraphy is a necessary input for geo-mechanical modeling work that is indispensable in view of the fact that the target depths (~50 -115 m) are very shallow. Indeed, the integrity of the site at these depths might be compromised during the operations and after.
    b. **Hydraulic State**. Issues are here: the exact location of aquifers with respect to the target area and the surroundings. Is there any chance they are used for / connected with aquifers that provide drinking water? Groundwater aquifers must be protected from UCG waste products entering.
    c. **Faults and Cracks**. There should be a proper picture of the network system of faults and main cracks in and around the target area. They form a possible gateway between the cavity used for UCG and air / aquifers.
    d. **Large-scale continuity of coal / lignite seams.** This is an issue for the execution of the UCG process and for the economic feasibility of the activity.

6) **Economic feasibility**. The following issues have an impact on this: uncertainties w.r.t. the geological model such as *the large-scale (dis)continuity of the coal seems*, control over the UCG process (which ultimately has a bearing on the quality and quantity of the syngas). The only remedy against uncertainties in the geological model is to acquire more geology-related data by drilling new wells, which is envisaged after the workshop was scheduled.

The Operational Phase

The risks in this phase are basically the ones already scrutinized in the Construction phase. New data as provided by the operational activities may exacerbate the risks, compromising economic feasibility. Special attention is now paid to the risk related to actual operation, in particular the risk factors in the theme "UCG process issues" have very high impact values.

Extra emphasis in this phase will be on:

1) **Integrity and subsidence of the target area.** The target zone integrity and protection of the ground water is seen as a major risk based on the available information. Special attention needs to be paid to operational hazards caused by leaking wells. Risks related to target zone and caprock integrity are ranked with relatively high probabilities compared to other categories in this phase (average value of ~2 = medium).
2) **UCG process monitoring and economic aspects** such as injection control (water, O_2) and syngas quality and steadiness (process control). Being able to "play" properly with water influx was mentioned by the expert as an important capability. Proper linking of the

injection and production wells and proper well design are ranked highest. The “theme process control” received highest impact and probability factors.

3) **Proper monitoring of soil, air, water** with respect to the presence of waste products. Monitoring must be performed with a resolution in space and time that is deemed proper. There might be some risk that the procedure followed does not yield an adequate picture (This could be due to too low a resolution in time or space, high variability in the results, malfunctioning of down-hole monitoring devices). Again, the far field effects are among the highest ranked risk scenarios with both, high impact and probability.

The Post-operational and Decommissioning phase

The Post-operational phase starts when no syngas is produced any more. The de-commissioning phase starts when the site has actually been abandoned and needs to be transferred back to the competent authorities. The identified risks are basically the same in these phases, but with slightly varying impact or probabilities. Overall the experts believe - given a proper (post) operation and abandoning phase is ensured - that the risks are lower in the decommissioning phase.

1) The main risks are the **integrity of the target area** and **the far-field effects,** the ‘after’-effects of the UCG process: pollution of the air with toxic gases, contaminants in water and soil. Hence:
2) **Proper monitoring** is all-important. The risks involved have already been mentioned. The partners in the workshop did mention the proper monitoring of subsidence/seismicity and target zone integrity. It might be necessary that some monitoring activities at the surface such as air and ground water monitoring will not cease with decommissioning in order to observe any potential migration of pollutants towards the surface or ground water aquifers on long term.

The decommission phase describes the time after this point in time. Although the site is “abandoned”, key risk factors such as groundwater quality might be monitored further by methods that can still be deployed after P&A, like soil or groundwater monitoring in water wells. This is supported by the fact that the far-field effects still have a high impact factors. However, the probabilities related to risks in this phase are lower than in previous phases.

Implications from the risk assessment and recommendations

Considering the above results, the following general picture emerges.

Legislative issues are important for the Oltenia UCG project to get started. It was felt that oversights in this realm are easy to make. Such oversights may hamper progress, perhaps even killing the project before it has even started. Legal documents tend to be extensive and they require scrutiny of legal professionals.

The documentation provided regarding the Oltenia site and its surroundings was predominantly on some aspects of the local geology. Remarks made by individual participants include:

- Nearby mining activities may affect hydrological conditions
- Older data on pore pressures etc. may be unreliable

The obvious remedy is to acquire more data by drilling new wells. It is important to map out the aquifers that are in contact with the target area.

Not surprisingly the integrity and the possibility of subsidence was felt as uncertain and with that as a risk. The intended UCG activities are deemed to take place at shallow depths. In order to acquire confidence on the sustained roof / cavity integrity and expected subsidence geo-mechanical modeling is indispensable. This activity has been performed as part of Work package 4 and is considered in the section below.

Based on the available information at the time of the workshop the uncertainties with respect to the geological set-up and target zone integrity, but also UCG process issues, are currently substantial. Ensuring a safe and economic UCG operation would require further in-depth data and better understanding of the site.

An important part of any risk assessment is establishing these uncertainties and their importance, and deciding on how to eliminate them to a sufficient measure. In this project, unsurprisingly, it is the geological uncertainties that dominate. Once eliminated, the geo-mechanical modeling, which seems to be at the core of the necessary preliminary investigations, can be done more accurately as soon as new site-specific data becomes available with sufficient confidence in the results.

Removing uncertainties with respect to any connections between the target area and the surroundings (aquifers, faults) will enable proper risk management, i.e. the design of suitable monitoring and mitigating plans.

It should be noted that at the time of the risk assessment certain site-specific parameters were missing because results from the envisaged drillings were not (yet) available. As new data was provided by lab testing the drill samples collected from the drilling campaign, the geomechanical model and general aspects of the risk assessment that might have changed as result of the interpretation of the new data were updated and included in the conclusions.

Risk factors and scenarios

Risk analysis as performed in the Oltenia UCG project is based on FEPs and risk factors. However, the risk factors are merely "stepping stones" to potentially adverse scenarios that may ensue. The scenarios of interest lead to states that are undesirable. Ultimately, it is these scenarios and these states that are of particular interest from a risk management point of view.

1) They are the subject of closer scrutiny in order to evaluate how harmful they are in the particular circumstances at the site. Such an evaluation sometimes requires detailed modeling.
2) They deliver building stones for mitigation plans that should be available before any operational activity unfolds.

In hindsight it appears that the scenarios to consider are not particularly tortuous and do not involve a long chain of various FEPs. To drive the point home, below the most blatant examples in the Oltenia case are collected.

- If the consulted set of legal documents is not complete this may lead to omissions in the quest for a permit to go ahead with the operational phase. This will lead to time delay. In extremely unfortunate cases it might even lead to a "no go" decision that could have been foreseen otherwise!
- If it appears that the aquifers bordering the target area have not been mapped out well enough there is a "surprise" possibility that "bordering" aquifers become contaminated by the debris of the UCG, and even that the contaminants come into contact with potable waters.
- If the uncertainties in the geological properties of the target area are not properly addressed the geomechanical modeling may go astray. The predictions for the integrity may turn out to be wrong, with potentially disastrous consequences. More precisely, stratigraphy, faults and cracks and material properties must be sufficiently well-known to allow trustworthy geo-mechanical modeling on the integrity of the relatively unconsolidated target area.
- If the system of cracks and faults has not been mapped out well enough there is the "surprise" possibility that there exist non-identified gateways for polluted water and toxic gas into the outside world. Admittedly, appropriate monitoring can be helpful here from a risk management point of view, should leaks still occur. Nevertheless, one wishes to forego "surprise leaks".

The adverse scenarios in the Oltenia UCG project invariably seem of such a "short-chained" nature. This shows that the problems of the project are nicely compartmentalized; they are not "spaghetti-like". Had this been the case, *then* using Markovian methods to see how the total system might evolve, would have become virtually indispensable.

Conclusions from the Risk assessment workshop

From the Utrecht workshop of February 2nd and 3rd 2016 and the COAL2GAS project meeting of 7th June 2016 at DMT in Essen two main conclusions emerge.

The importance of obtaining site-specific data is borne out clearly by the example of the geo-mechanical modelling. However, it is clear from general in-depth considerations that UCG at larger depths is likely to be safer (= less risky) as far as roof stability is concerned. The possibility for such an alternative may exist at Oltenia.

Site-specific mitigation and monitoring plans must be made. After the UCG project has stopped, and the cavity has been cleaned-up monitoring must continue. There must be wells in place for monitoring and the removal of pollution / toxic substances.

Monitoring plans have to address what exactly has to be monitored, where to monitor, and how frequent the relevant parameters have to be measured.

These obligations will satisfy legal demands and deliver the scientific prerequisites for responsible and sound operations.

The COAL2GAS project meeting in Essen made it clear that the issue of roof stability is by far the dominant one. The modeling exercises on this issue are all-important; they provide indications whether UCG at shallow depths at Oltenia is at all possible in a safe and secure way. It is clear, as already mentioned, that (more) geological, stratigraphical and lithological (rock property) data are needed to perform numerical modeling that is trustworthy; modeling just with literature (= guessed) data will not do. These data shall have to be obtained.

A second issue is the continuity of the lignite seems. Well drilling may be necessary to ascertain this continuity, and to determine how much lignite there actually is at the target area.

Alternative option: Coal seam V

As a back-up scenario and to assess if deeper coal seams might be more suitable for a UCG application at the target site, an operation in coal seam V was also considered. From the risk assessment performed on seam V some general aspects were re-considered with respect to the properties and set-up of seam VIII. It should be mentioned that coal seam V was no subject of the detailed risk assessment workshop as reported above.

Coal seam V appeared to be a promising (back-up) option according to the available information. Based on the available geological profile it was expected at 115m depths and with a thickness of 4m and good lateral extension. The available geological profile also indicated that there might be a proper seal on top. However, the preliminary modelling in Task 4.4 indicated that the roof will also collapse as the result of the unconsolidated overlying formations. Again, the risk of loss of integrity of the target site and potential pollution of overlying aquifers (fluid) barriers was considered as high.

Principally, the overall risk aspects identified for seam VIII are also valid for coal seam V, which was confirmed by the new data and updated modelling.

Task 5.6 - Assess the calculated risks on the basis of legal requirements

For this task accessible sources have been reviewed for information related to relevant legislative framework applicable to UCG technology at EU level, in Romania and in COAL2GAS partner countries. Today UCG technology does not have dedicated laws and regulations, some countries applying the existing regulations in place for coal mining and/or natural gas production. But a clear statement whether UCG falls under regulations for coal mining or natural gas production should be made at European level.

On one side there are the EU directives and on the other side the national legislations which contain provisions for the permitting, operation and end-of-life planning for mining projects. In terms of environment protection or wastes handling, the main impact of policies and legislation can be derived from broader societal challenges, for instance related to permitting aspects, emissions, handling of hazardous materials and wastes, as well as health, safety and risk management aspects. At EU level the legal and regulatory framework needs updates, improvements and more UCG customized approach, all actions claiming for support from EC and EU/international bodies involved in environmental oriented policies and LCT development.

Some European countries, such as Poland and Slovenia, can boost the deployment of demonstration UCG projects, having favourable coal geology, an applicable legislative framework and political support, without strong opposition from local communities. However, for a successful UCG process integration into national strategies for further budget allocation and deployment, in situ research and testing should continue in particular with regard to environmental impact.

The development of an UCG project is conditioned by the development of the existing regulatory framework. As an EU Member State, Romania has to transpose the EU legislation, to harmonize the existing legislation with the EU acquits and to develop the institutional framework able to apply and monitor the legal provisions' implementation. Romanian legislation allows references to EU legislation, unless Romanian law is more restrictive than the European one.

The Romanian relevant laws include issues of Health, Safety and Environment (HSE), waste, land management, water management, fire-fighting, and formal administrative issues regarding licensing. The National Agency for Mineral Resources (ANRM), environmental authorities and local authorities may be seen as essential to the implementation of a UCG project. In Romania there are seven such authorities which play a well-defined role. A geological research methodology is also in effect, approved and imposed by ANRM, which has a direct influence on what has to be done in the risk assessement.

From the detailed review of available UCG configurations done in Task 4.1, L-CRIP (Figure 2.2.30) has been concluded as the UCG configuration most sustainable for the selected site in Oltenia. From the analysis of this configuration's characteristics and having in view potential risks related to UCG operation it was observed that in addition to the non-condensable gas produced directly from the coal conversion reactions, the liquids (condensable) produced during UCG derive from 5 main sources: 1) injected water (i.e. water injected via the injection well and production well); 2) naturally occurring groundwater infiltration; 3) non-aqueous-phase fluids produced during coal pyrolysis; 4) release of inherent water held within the coal; and 5) water produced by chemical reactions that occur during UCG. Containment of these fluids is essential to reduce environmental impacts and maximise resource utilisation. The management of the containment of fluids starts at the site selection stage and requires appropriate well engineering and management of UCG processes throughout a UCG module's lifetime. Essentially, a coal seam suitable for UCG should be a confined aquifer i.e. a coal seam surrounded by thick, water-saturated low permeability rocks (aquitards) that restrict both the migration of water into the coal seam and syngas out of the coal seam.

Based on the relationship between hydrostatic and reactor pressure, it should be clear that the reactor pressure should never exceed the hydrostatic pressure, because this will cause syngas to be forced out of the reactor. In addition to affecting the syngas yield at the production well, loss of syngas can lead to groundwater contamination in poorly selected sites because coal pyrolysis products can condense out of the syngas and be transported in the groundwater. Operating at pressures below hydrostatic pressure and ensuring flow only towards the reactor, however, will mitigate this risk because contaminants cannot be transported against the flow of groundwater.

The correct operation of the UCG reactor is essential during reactor shutdown. It will be necessary to use the "clean cavern" techniques that were tested during UCG trials in the USA and Australia. The clean cavern technique involves venting the reactor post-UCG, flushing the cavity with water/steam to reduce the temperature and stop pyrolysis and remove any compounds to the surface for treatment.

Detailed process well engineering has been addressed in Task 4.3. In essence, the processes of drilling and installing UCG wells can disturb the natural geological and hydrogeological conditions at a site such that fluids could escape via "preferential pathways" (i.e. low permeability zones) that may surround the boreholes. Furthermore, if well completions are inadequate, fluid may escape via cracks/poor joints between well casing/liners. It is therefore necessary to adopt appropriate drilling and well completion techniques to minimise the risk of developing preferential pathways.

The monitoring strategy depends on the type of UCG module configuration. Figure 2.2.39 shows the instrumentation deployment strategy around an L-CRIP module that was selected as suitable for a potential future UCG pilot project in Oltenia region.

Instrumentation can be deployed in the process wells, in monitoring wells drilled around the UCG well field or in surface equipment (e.g. in syngas flow-lines). In order to correctly and efficiently manage the UCG process and mitigate residual risks the following processes need to be attentively monitored:

- the in-situ reactor pressures and temperatures;
- the injection point retracting positions;
- the mass and energy balances around the control volume of the in-situ reactor control;
- the residence time distribution of syngas in the in-situ reactor and
- the gas and heat losses.

A customized analysis performed for the potential future UCG pilot project by screening the already identified risks, proposing adequate monitoring techniques and recommending appropriate extensions of the monitoring program in case irregularities are observed during the UCG test are presented below in Task 6.2.

Based on the evaluation of the experts' opinions and the discussions during the RA workshop the main possible risks have been identified (they have been described per phase in Task 5.5 above).

Considering the study of the proposed UCG configuration and the risk analysis the following types of risks have been identified as potentially possible to occur for the UCG pilot project at the site of Urdari - Valea cu Apa.

Risks related to the approval of mining activities:

- lack of an approved framework method for exploitation in accordance with the legal provisions in force;
- non-correlation of the framework method for exploitation with the concrete conditions of the mining perimeter;
- not meeting the operating parameters of designed UCG in legislation for water and environmental protection;
- drawing up specific technical documentation in accordance with legal provisions by using insufficient and / or unrealistic data;
- lack of ownership and / or concession of land related to the exploitation perimeter;

Risks related to the hydrological and geological conditions of the mining perimeter:

- insufficient information, low density and depth of drilling;
- unrealistic and / or badly executed research activity;
- faulty laboratory research activity;
- analyzing the areas in the immediate vicinity with correlations on the existing missing information;

Risks related to UCG design, type, technology, equipment dimensioning, etc.:

- lack of data, choice of an inappropriate UCG configuration;
- choosing an expensive technology that leads to unprofitable exploitation;

Risks related to reactor / gas generator design and operation:

- inappropriate operation (low gas flows, low syngas quality);
- major environmental impacts due to the reactor;
- impossibility of remedial action;
- system / network monitoring failure;

Risks deriving from the monitoring activity:

- non-correlation of accepted risks with additional monitoring measures;
- unhappy choice of unit and frequency measurement;
- acceptance of the acquisition

The identified risks have been evaluated based on the existing legal requirements and a risk – legal requirements matrix has been constructed. The matrix was structured according to the project stages of development (construction / operation / post-operation / decommissioning) and filled with information related to risk themes, risk assessment (general FEP and impact/probability range) and legal requirements.

The main recommendations that have been drawn on the treatment of residual risks, in terms of site characterisation and selection, monitoring and risk reduction measures, for the design of the pilot project in the selected mining test site in Romania are:

Site Selection

- A proper site selection management must be performed in order to generate less residual risks to cope with;
- Considering Oltenia lignite basin existence of several groundwater streams – when selecting the UCG pilot site we must observe the chosen engineering process characteristic of L-CRIP configuration; Rigorously adhering to the selection criteria and to the chosen UCG configuration design will contribute substantially to reducing the occurrence of residual risks;
- Right from the site selection stage of the project, the management of fluids containment must start;
- A key element for the UCG site selection criteria in Oltenia basin is to have low permeability rocks layers (aquitards) in order to avoid migration of water into and syngas out of the lignite seam.

Monitoring plan

- A special attention must be given to the following parameters monitoring: Roof fracturing and subsidence; Groundwater and surface water dynamics and quality; Gases flows temperatures and pressures; Soil quality and seismicity; Air quality and meteo data;
- The monitoring strategy must be developed according to the type of UCG module configuration and as suitable as possible with the future UCG pilot project in Oltenia region;
- A customised and well equipped monitoring process mitigates residual risks and efficiently manages the UCG process; A proper risk management and the design of suitable monitoring plans and mitigation/remediation actions will remove, as much as possible, uncertainties with respect to major risk in Oltenia basin – target zone integrity (subsidence, aquifers, faults);
- Additional monitoring techniques to be consider – InSAR; Increasing samplings number and frequency; Perform additional observation wells.

Risk reduction measures

- Eventually, in the future, deeper lignite seam(s) might be targeted, at other locations of the Oltenia mine;
- Potential risks can be substantially reduced by applying a good, preventive complete and site-specific Risk Assessment strategy, which pervades all activities: pre – (design-engineering, construction, pre-operation, commissioning), during – (operation and maintenance), and after – (post-operation and decommissioning; The unrolling of a thorough integrated risk assessment strategy (technical, operational, environmental & financial) has a tremendous importance;
- Launching a permitting procedure must be a priority of the planning stage of the project, considering the legislative issues which may lead to delays or even the rejection of permit applications;
- Compliance with the national laws / regulations / standards is a must; Periodic formal presentations to responsible authorities and good relations with the mining industry and related authorities are always welcome; in a pilot project the relevant authorities should be included to optimise the future rules.
- Updating the existing legal and regulatory framework for coal and coal-derived syngas, in order to strongly develop the coal chemical industry.

2.2.6. *WP6: Preparation of Pilot Project*

Task 6.1 - Final assessment of the most suitable site and design of site specific technologies

Within the preparatory work packages 2 - 5 and tasks, the acquisition of relevant information was achieved and outlines for preparation of a UCG were defined. Criteria for the selection of a suitable site were set up and applied. The data collected in WP2 on the Oltenia coal deposit served as a basis for this objective. Areas which belong to CEO were evaluated for their potential for UCG. From a number of sites, which were suggested by CEO, the application of the selection criteria showed, that in all sites the conditions with respect to the geology and accessibility of potentially suitable coal seams are principally similar and given. The knockout criterion that led to the selection of the site of the former Urdari Mine was the legal / landownership situation. In Urdari the opportunity to perform more detailed site investigation was given. At this selected site a thorough investigation campaign could be carried out. The initial phase included, after the process of de-classification of confidential data, the assessment and processing of the available data. This led to the set-up of a structural geologic 3D model and initial selection of potentially suitable coal seams – i.e. seams VIII and V. In the subsequent step, a detailed field exploration campaign was carried out. This included core drilling, laboratory testing of soil and coal samples with respect to coal qualities as well as geotechnical rock parameters, geophysical well logging, hydrologic investigations, etc. (see WP3). From the field campaign, valuable information on the site-specific conditions were acquired. These could be used then for the refinement of the geologic model, the construction of numerical models, and the development and definition of site-specific UCG layout and monitoring plans.

As a result of the site investigations, the definition of UCG technology and module configuration, constructed structural and numerical models and risk assessment, the site of Urdari can be regarded as principally suitable for a UCG test in lignite. Three coal seams (VIII, VI and V_{upper}) with suitable coal qualities and sufficient thickness and resources can be used for UCG.

The numerical models show that stability of a UCG cavity is more favourable in the upper seam VIII than in the deeper seam. Although the stability of the cavity is a concern, the model results are so far only indicative. Effects of heating and drying of the surrounding rock mass may increase the rock strength and have a positive impact on roof stability. As the soft rocks surrounding the coal are less beneficial with respect to the mechanical stability of any underground opening on the one hand, their positive effect is the plastic behaviour of the surrounding clay on the other hand. It will not react brittle like hard rocks, which break into the cavity and may be associated with fracturing of the roof rocks above the UCG georeactor, thus causing potential pathways and leakage of gas and fluids. Instead, the clay may behave much more ductile and restrict the migration of water, so maintaining the sealing properties for the UCG georeactor. Also the experiences made in Spain with the El Tremedal UCG trial show that the issue was not with the roof stability. At El Tremedal geologic conditions are comparable to the Oltenian coal strata. The test was also performed in low-grade coal with surrounding soft rocks. Only seams were dipping steeper and located at greater depth than in Urdari. The main problems during the UCG trial in Spain was not the roof stability, but the excessive water inflow and the underground pressure in the cavity during the gasification. A second problem was the heat loss.

As a result of these experiences, for a UCG test in Oltenia / Urdari the pressure in the UCG module should always be kept below hydrostatic pressure to prevent any losses, and the velocity of the gas flow and gasification rate should be increased.

As result of the risk assessment and with respect to environmental issues, it has to be concluded that thorough care has to be taken because of the groundwater situation in Urdari. The seams are located quite shallow (not deeper than 130 m below surface). Also the groundwater levels are not undisturbed, but influenced by pumping and nearby open cast mining activities. From an environmental point of view, it is generally recommended to conduct the gasification at a deeper seam, here seam V. Also the sealing potential of the surrounding rocks is regarded better than for seam VIII, where at the outer SE corner of the site in borehole CG-03 only a thin layer of clayey sediments is covering the coal roof. If UCG will be carried out in Urdari, much attention has to be paid on the environmental monitoring in order to prevent any negative impact of the gasification on the surrounding. A concept for monitoring was developed in this task.

As the structure of the seams as well as the surrounding rock strata is laterally not very consistent, a detailed assessment of the area outside the current site exploration will have to be made in case a further extension is planned.

In addition to the detailed study on Urdari with the development of site-specific techniques, the review of the information on the Oltenia coal basin as well as on other areas in the EU has shown additional potential for UCG.

Task 6.2 - Selection of monitoring techniques and design of monitoring plans

In this task the most suitable action plans for site specific monitoring of the intended UCG test trial were established in order to minimize environmental and economical adverse effects.

Generally, two monitoring aspects have been considered, namely monitoring of the gasification and mining progress and monitoring of the main environmental factors. In order to design a specific monitoring plan the panel layout and module configuration as outlined in Task 6.1., i.e. a northwest-southeast trending single-module UCG panel layout with the size of 250 x 80 m and L-CRIP configuration, has been taken as a basis.

The following process monitoring is suggested:

- continuous temperature recording using in-well thermocouples and/or fibre optic sensors (Distributed Temperature Sensors);
- continuous pressure monitoring at the process wellheads (injection and production);
- continuous monitoring of the injection point position using fibre optic sensors (Time Domain Reflectometry);
- continuous (intermittent for condensable liquid and particulates at production wellhead) monitoring of gas, liquid and solid composition (both injected gasification agents and produced syngas);
- continuous gas losses calculation (via nitrogen and/or rare gas mass balance);
- continuous mass and energy balance calculation based on monitoring results above, and subsequent calculation of the underground reactor control volume, which will in turn allow estimation of (a) gasification rate and efficiency; (b) water influx rate; and (c) char/coal ratio (pyrolysis indicator);
- continuous calculation of gasification equilibrium conditions (e.g. water-gas shift and methanation reactions). Intermittent measurement of the natural isotope (deuterium ^{2}H, ^{13}C) balance will also be used to predict the reacting water origin and confirm the previous equilibrium conditions; and
- underground syngas residence time distribution via intermittent tracer tests using ^{133}Xe and/or He.

In order to perceive any environmental risks associated with the underground gasification, the monitoring concept covers following aspects:

- Roof fracturing and subsidence
- Groundwater dynamics and quality in the mined area and future UCG panels
- Groundwater and surface water quality (downstream of the selected area)
- Occurrence of combustion gases in the soil or air
- Changes of air and water temperature
- Heating of water from drainage drillings
- On-site air quality
- Effects of UCG on surface vegetation above the reactor and in its perimeter
- Soil quality

For the environmental factors it is essential that adequate baseline data is determined in order to decipher impacts caused by the UCG test from naturally occurring irregularities in the monitored data, and to be able also to decipher expected from unexpected changes. Some reference samples of groundwater quality were obtained during the drill and logging campaign.

Particularly for the environmental factors a wealth of monitoring techniques is available. The suggested approach for the test site in Oltenia is summarized in Figure 2.2.51, Table 2.2.25 and Table 2.2.26.

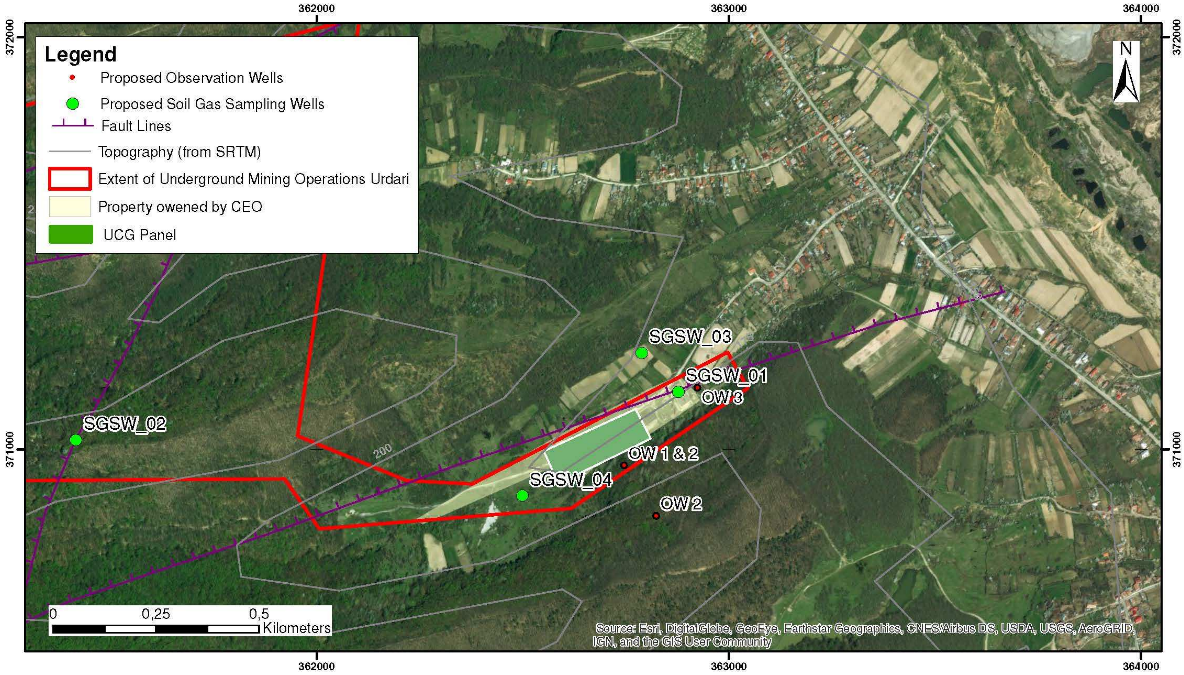


Figure 2.2.51: Map showing possible location of UCG test trial panel and proposed location of observation wells

Table 2.2.25: Potential risks and applicable monitoring techniques at the test site in Oltenia

Risk	Monitoring	Additional monitoring activities if irregularities are observed during UCG test
Groundwater contamination	- Min. 4 groundwater observation wells equipped with multi parameter data loggers - Hydro-geochemical analysis in observation wells - Hydro-geochemical analysis in surrounding wells within the catchment area	- Installation of additional observation wells to determine the extent - Increase of sampling frequency for hydro-geochemical analysis
Surface water contamination	- Spring and water course mapping - Detection of suitable measurement points for spring discharge and stream run-off - Hydro-geochemical analysis	- Increase of hydro-geochemical sampling frequency
Uncontrolled coal fire development	- Ground subsidence monitoring	- Continuation of measurements - Application of additional techniques e.g. InSAR - Microseismic monitoring
Air quality degradation	- Min. 4 soil gas wells - Soil gas analysis with portable gas chromatograph - Continuous monitoring of meteorological data, e.g. wind direction - Permanent CO and CO_2 monitoring with warning system on surface installations	- Increase of soil gas sampling wells over the entire UCG panel area with sampling spacing of approx. 25 m - Increase of soil gas sampling frequency
Soil quality degradation	- Soil sampling prior to UCG test at soil gas well locations - Repeated sampling during UCG test	- Continuation of soil sampling and analysis
Adverse impact on flora and fauna	- Review of protected species in the region - Assessment if further action (e.g. ecological survey) needs to be taken	- Not applicable

Table 2.2.26: Frequency of monitoring techniques of environmental factors

Parameter	Method	Frequency			Comment
		12 Months prior to UCG test	During UCG Test	12 Months subsequent to UCG test	
Ground Subsidence	Geodetic Levelling	monthly	monthly	monthly	
Ground Subsidence	GNSS/GPS Monitoring	daily	daily	daily	
Groundwater Level	Data Logger	hourly	hourly	hourly	Automatic, online
Groundwater Temperature, Eh/pH, O_2, Conductivity	Data Logger	hourly	hourly	hourly	Automatic, online
Groundwater Chemistry	Water Sampling	quarterly	weekly	quarterly	at observation wells
Groundwater Chemistry	Water Sampling	monthly	weekly	monthly	at drinking water wells
Groundwater Biogeochemistry	Water Sampling	monthly	monthly	monthly	at drinking water wells
Precipitation, Wind Direction, Wind Speed	Weather Station	daily	daily	daily	ideally up to 10 years of meteorological data should be assessed; automatic, online
Spring discharge	Water Sampling	monthly	monthly	monthly	
Eh/pH, O_2 and Conductivity at springs	Water Sampling	monthly	monthly	monthly	
Water Chemistry at Springs	Water Sampling	monthly	monthly	monthly	
Soil Chemistry	Laboratory Analysis	quarterly	quarterly	quarterly	
Soil Gas Analysis	Laboratory Analysis	quarterly	monthly	quarterly	
Air Quality (CO, CO_2, etc.)	Gas Chromatograph on Site	hourly	hourly	hourly	Automatic monitoring, with alarm function

In case that the initial monitoring program identifies any anomalous values, which can be related to the UCG test, the monitoring program will have to be extended and remediation actions have to be taken. Additional monitoring techniques are thought to be monitoring techniques applicable in the unlikely worst-case of the development of an uncontrolled coal fire with connection to the environment as an extreme scenario. As an extension of the proposed monitoring additional exploration and monitoring techniques have to be considered, like infrared mapping, microseismic monitoring, magnetic mapping or electrical resistance tomography.

Task 6.3 - Draft site-specific proposal for syngas utilization

In order to define and compare the most suitable options of using the UCG produced syngas, the generation costs and quantities were assessed. The levelised cost of syngas was considered as reference figure to compare the influence of syngas over the profitability of different possibilities of using syngas in technical applications. The levelised cost of syngas was computed over an 11 years period of analysis, based on data regarding the CAPEX and OPEX of syngas production (UCG) and treatment facilities, reaching a value of about 73 EUR/MWh.

The following options of using the potentially produced syngas by local applications were analysed: (i) using it for industrial applications in the chemistry sector, (ii) using it for fuelling residential consumers in the surrounding area, (iii) using syngas for power generation.

(i) Use of syngas for industrial applications in the chemistry sector

Syngas can be used in the production process to obtain various chemical compounds. One of the most important base chemicals that can result from processing syngas is methanol. Methanol is usually used as feedstock for production of formaldehydes, acetic acid, propylene and various esters, which are intermediate compounds for obtaining plastics, resins, pharmaceuticals, adhesives. Syngas may also be used to obtain ammonia the base for nitrogen fertilizers like ammonium, nitrate and urea. Ammonia is also used in the production of plastics, including nylon and polyurethane.

Because most of chemical products that can be made from coal gasification can in general also use feedstocks derived from natural gas and petroleum, the chemical industry tends to use whatever feedstock is most cost-effective.

Using the UCG produced syngas for chemical industry instead of natural gas, would result in increasing the cost of final product of this industry, having in view that the levelised cost of syngas is about 73 EUR/MWh while the final price of natural gas is almost three times less.

(ii) Use of syngas for fuelling residential consumers in the surrounding area

Using obtained syngas for fuelling residential consumers in the surrounding area could be an option if the cities around were connected to a gas network or had implemented a district heating system. Having in view that there is no gas network around, using syngas for fuelling the residential consumers in the surrounding area implies high investment costs in gas networks and connections. In the same time, the price of selling syngas that should be applied in order to cover the CAPEX and OPEX for both syngas production and syngas distribution is not affordable for the local community.

(iii) Use of syngas for power generation

Taking into consideration the location of the syngas production unit, the most appropriate use of syngas is for electricity generation. Therefore, the following alternatives were defined and analysed:

- Alternative 1 – Use of syngas by CEO in the existing power plants facilities instead of natural gas as additional fuel
- Alternative 2 – Use of syngas on site in a new facility (gas engine) for electricity generation

In order to compare the alternatives mentioned above, a simplified cost-benefit analysis was conducted, consisting in:

- Establishing the general assumptions regarding the analysis horizon, financial discount rate, possible financing sources, income tax, electricity price on the market, etc
- Establishing the technical assumptions regarding the syngas production, syngas treatment, HHV of syngas
- Assessment of CAPEX and OPEX for syngas production unit (UCG), syngas treatment units and power generation facilities
- Assessment of the annual generated revenues from electricity selling
- Financial modelling of profit and loss statement with gross profit and net profit evolution, net and cumulated financial cash flow, calculation of financial performance indicators (FNPV and FRR).

The financial performance of both alternatives was calculated for the following situations regarding the financial sources: (i) the investment is 100% covered by own sources and (ii) the investment for the UCG and syngas treatment facilities is covered by grant.

The results obtained for each alternative of electricity generation by using syngas, are presented below.

Alternative 1 – Use of syngas by CE Oltenia in the existing power plants facilities instead of natural gas as additional fuel

The investment financial cash flow evolution over the reference period is presented in Figure 2.2.52 below:

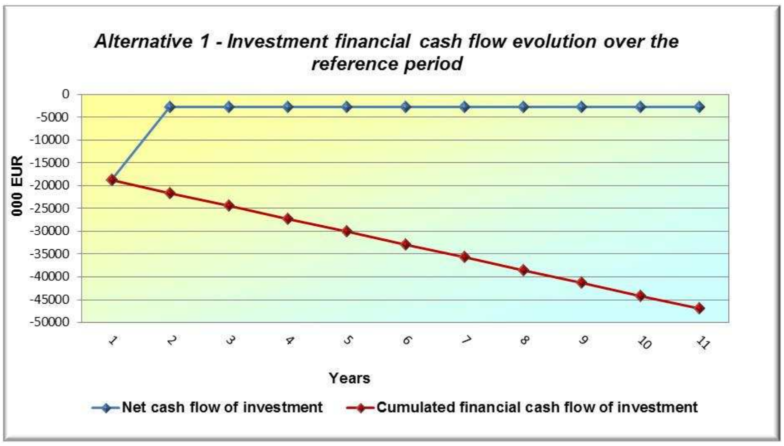


Figure 2.2.52: Investment financial cash flow evolution – Alternative 1

The obtained evolution shows that, for the estimated input data regarding CAPEX and OPEX of syngas production and treatment facilities and CAPEX for connecting the existing power generation facility to the syngas production facility and also taking into consideration the electricity average market price, the financial cash flow is negative throughout the entire analysis period. The FNPV of this alternative in the circumstances mentioned above is also negative with a value of EUR thd. (-)40,043. Normally these negative results are due to the high value of CAPEX and OPEX of syngas production and treatment facilities.

As a sensitivity analysis, the minimum electricity price ensuring a minimum FNPV=0 thus placing the project at the minimum profitability level was calculated. Therefore, for an average electricity price of about 248 EUR/MWh, the financial cash flow evolution (Figure 2.2.53) shows that net cash flow is positive throughout the whole operation period, while cumulated cash flow becomes positive starting with year 9 of operation.

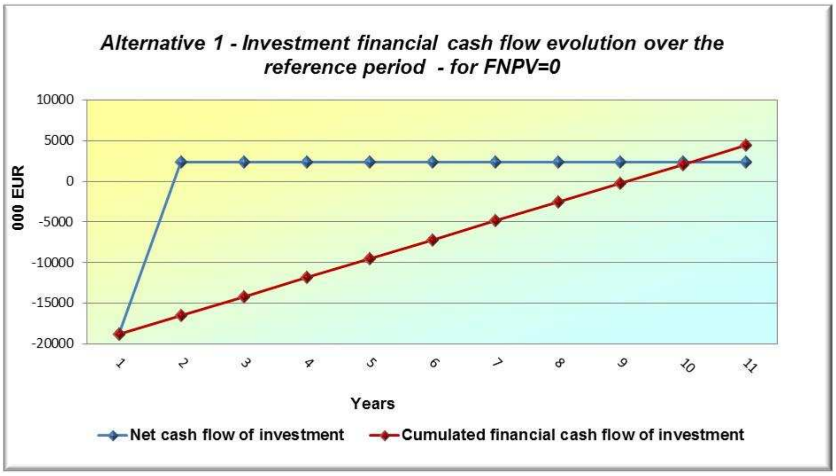


Figure 2.2.53: Investment financial cash flow evolution – Alternative 1 (FNPV=0)

If the CAPEX of syngas production and treatment facilities are covered by a grant, the financial cash flow evolution is improved (Figure 2.2.54), but still negative throughout the entire analysis period. In the same time, the FNPV value will increase with about 37% to a value of about EUR thd.(-) 25,985.

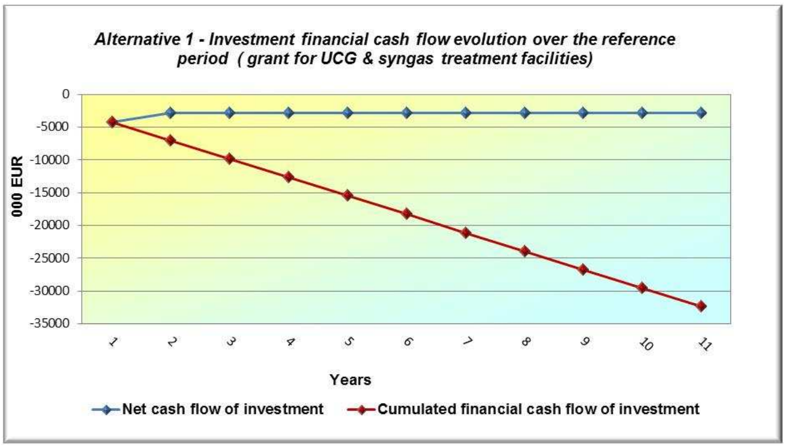


Figure 2.2.54: Financial cash flow evolution – Alternative 1 (grant for UCG &syngas treatment facilities)

As a sensitivity analysis, the minimum electricity price that ensures a minimum FNPV=0 was computed. Therefore, for an average electricity price of 175 EUR/MWh, the financial cash flow evolution (Figure 2.2.55) shows that net cash flow is positive throughout the whole operation period, while cumulated cash flow becomes positive starting with year 9 of operation.

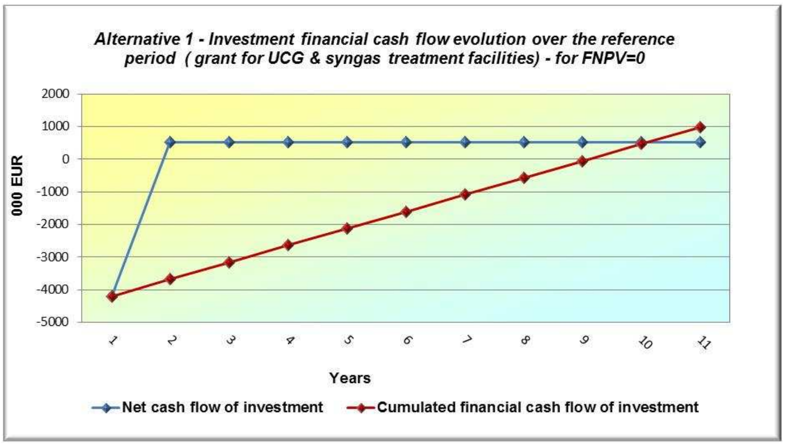


Figure 2.2.55: Investment financial cash flow evolution – Alternative 1 (grant for UCG &syngas treatment facilities – for FNPV=0)

Alternative 2 – Use of syngas on site in a new facility (gas engine) for electricity generation

The investment financial cash flow evolution over the reference period is presented in Figure 2.2.56 below:

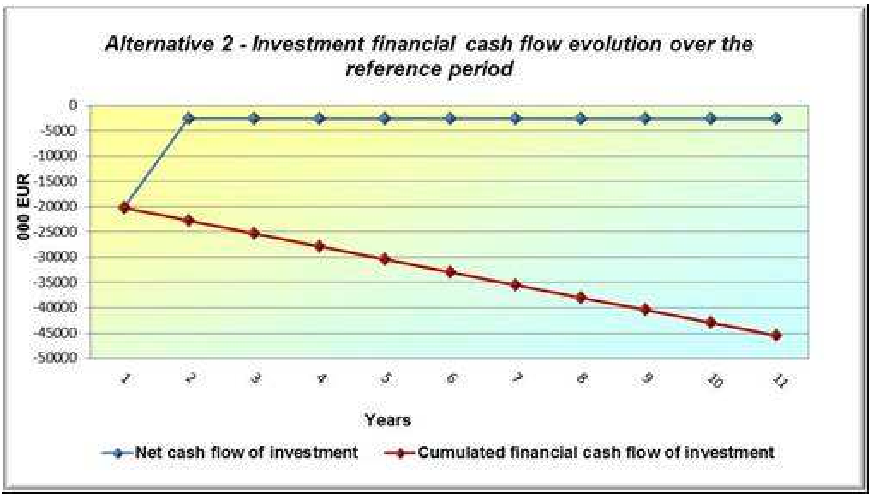


Figure 2.2.56: Investment financial cash flow evolution – Alternative 2

The obtained evolution shows that, for the estimated input data regarding CAPEX and OPEX of syngas production and treatment facilities and CAPEX for power plant equipped with gas engine, and also taking into consideration the electricity average market price, the financial cash flow is negative throughout the entire analysis period. The FNPV of this alternative in the circumstances mentioned above is also negative with a value of around EUR thd. (-)39,158. Normally these negative results are due to the high value of CAPEX and OPEX of syngas production and treatment facilities.

As a sensitivity analysis, the minimum electricity price ensuring a minimum FNPV=0 thus placing the project at the minimum profitability level was calculated. Therefore, for an average electricity price of 194 EUR/MWh, the financial cash flow evolution (Figure 2.2.57) shows that net cash flow is positive throughout the whole operation period, while cumulated cash flow becomes positive starting with year 9 of operation.

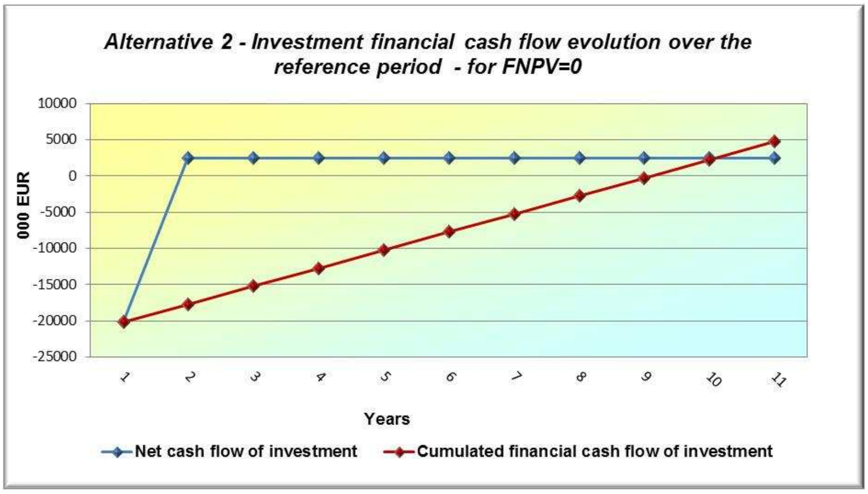


Figure 2.2.57: Investment financial cash flow evolution – Alternative 2 (FNPV=0)

If the CAPEX of syngas production and treatment facilities are covered by a grant, the financial cash flow evolution is improved (Figure 2.2.58), but still negative throughout the entire analysis period. In the same time, the FNPV value will increase with about 36% to a value of about EUR thd.(-)25,100.

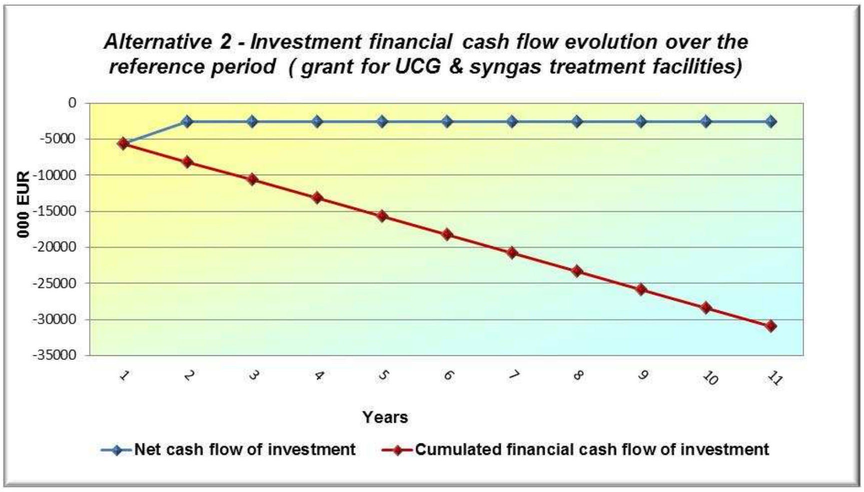


Figure 2.2.58: Financial cash flow evolution – Alternative 2 (grant for UCG &syngas treatment facilities)

As a sensitivity analysis, the minimum electricity price that ensures a minimum FNPV=0 was computed. Therefore, for an average electricity price of 140 EUR/MWh, the financial cash flow evolution (Figure 2.2.59) shows that net cash flow is positive throughout the whole operation period, while cumulated cash flow becomes positive starting with year 9 of operation.

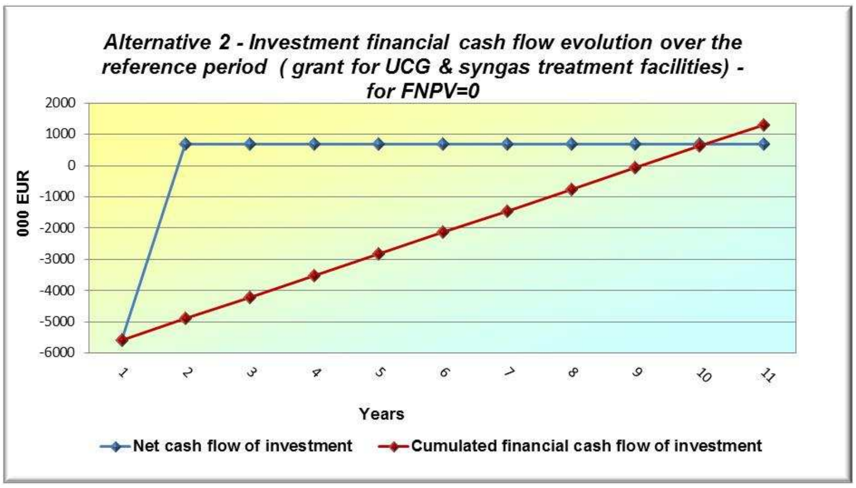


Figure 2.2.59: Investment financial cash flow evolution – Alternative 2 (grant for UCG &syngas treatment facilities – for FNPV=0)

Comparative overview of the results for the two alternatives

The results obtained for both alternatives of electricity generation by using syngas, are presented in the table below.

Table 2.2.27: Alternative 1 and Alternative 2 - Results of the financial analysis

	MU	Alternative 1	Alternative 2
Investment covered 100% by own sources			
Financial Net Present Value (FNPV)	k EUR	-40,043	-39,158
Financial Rate of Return (FRR)	%	-	-
Cost/Benefit Ratio (C/B)	-	0.18	0.21
Minimum electricity price ensuring a FNPV=0	EUR/MWh	248	194
Grant for UCG and syngas treatment facilities			
Financial Net Present Value (FNPV)	k EUR	-25,985	-25,100
Financial Rate of Return (FRR)	%	-	-
Cost/Benefit Ratio (C/B)	-	0.26	0.28
Minimum electricity price ensuring a FNPV=0	EUR/MWh	175	140

If the investment is 100% covered by own sources, the obtained performance indicators underline that both alternatives are not profitable. Considering that CAPEX of syngas production and treatment facilities are covered by a grant, the financial cash flow evolution is improved, but still negative throughout the entire analysis period for both alternatives.

The obtained result shows that the profitability of the projects does not depend only on the estimated CAPEX but also on the OPEX for UCG which is still too high and cannot be covered by the revenues from electricity sold.

However, having in view that the technology is not fully matured yet and the estimated CAPEX and OPEX are deeply dependent on the maturity degree of the technology, seems that the obtained results could be significantly improved when a commercial technology will be available.

The comparative overview of the two alternatives shows that **Alternative 2 – Use of syngas on site in a new facility (gas engine) for electricity generation** has a better result than *Alternative 1 – Use of syngas by CEO in the existing power plants facilities instead of natural gas as additional fuel*. In order to become profitable, Alternative 2 requires a minimum electricity price of 140 EUR/MWh which is 20% less than the required minimum electricity price for Alternative 1.

Task 6.4 - Preparation of necessary permit applications for a subsequent demonstration project

In this task the documentation needed for obtaining the required permits for a pilot UCG project in Romania have been identified. The stages for preparing the legal documentation for obtaining the necessary approvals are presented in Table 2.2.28.

Table 2.2.28: Stages for preparing the legal documentation for obtaining the necessary approvals for a UCG pilot project in Romania

Nr. Crt.	Stage/Order of obtaining approval from the competent authority	Aim of document	Comments
1.	Technical documentation for the delimitation and background of the exploitation perimeter (1)	Any mining perimeter entering in mining operation is necessary to be delineated in coordinates in order to be able to carry out the Mining Book by National Agency for Mineral Resources (ANRM). This document represents the transposition on the Romanian surface of the perimeters that are or have been in mining operation. The evidence is kept on mineral substances and the coordinates are defined by the topographic system “Stereo 70”.	According to ANRM order nr. 197 of November 13, 2003 for the approval of the Methodological Norms regarding the execution of the cadastral works specialized in mining extraction

2.	Framework Method for Coal Exploitation through Underground Gasification in Romania (OMRom-UCG) (2)	This documentation is prepared prior to the implementation of a mining operation in any mining perimeter. The documentation is approved by ANRM, the Ministry of Economy, INSEMEX and the Ministry of Labour and Social Justice. The documentation is the framework for the technical development and application of the exploitation method, containing description of the working methods and of the used technology, the economic, security and environment protection issues, and social implications. This documentation is the main document on which the proposed exploitation method will be applied in Romania.	According to ANRM order nr. 187 of 5 November 2002 for approving the criteria for the contents of documentation for exploitation methods frameworks in mines and quarries.
3.	Documentation regarding the evaluation of mineral resources and useful mineral reserves (3)	After the approval of the operational method framework (OMRom), the drawing of the exploitation perimeter, the resource / reserve calculation is made. The calculation is made on the exploitation parameter and on the technical conditions for its application. The methods for calculating the resources / reserves are set in the ANRM norms. The calculated resources are submitted for the approval by the ANRM and the approval is given on the basis of a specific conclusions document that will enter into the records of the National Geological Fund.	According to: - Mining Law No. 85 / 2003, art. 20 (1); - GD 1208 of 14 October 2003 regarding the approval of the Norms for the application of the Mining Law no. 85/2003, art. 103; - Technical Instruction no. 85-02 / 1998 ANRM on framework content for the documentation of mineral resources assessment and of mineral reserves of mineral materials.
4.	Feasibility study on mineral resources utilization and deposit protection (3)	This documentation, based on the OMRom, the approved exploitation perimeter and the reserves / resources evaluation approved by ANRM, will include: - technical analysis of the method implementation; - machinery and equipment that will be used; - analysis of the production capacity possible to be obtained in economic conditions of profitability; - safety parameters of the deposit and environment protection; - economic indicators proposed for exploitation of the mining perimeter with the chosen method of exploitation.	According to: - Mining Law no. 85 / 2003, art. 20 (1); - GD 1208 of 14 October 2003 regarding the approval of the Norms for the application of the Mining Law no. 85/2003, art 103.
5.	Mineral resources / reserves exploitation plan (3)	The exploitation development plan will show us the exact evolution of working points / abates, operating levels, areas. This diagram will define the working points, the development of the mining exploitation during the entire period for which exploitation permit was requested.	According to: - Mining Law no. 85 / 2003, art. 20 (1); - GD 1208 of 14 October 2003 regarding the approval of the Norms for the application of the Mining Law no. 85/2003, art 104.

6.	Environment restauration plan (3)	The plan and the technical project for environment rehabilitation will provide for the measures for monitoring and reducing the effects of the environmental factors throughout the exploitation period, and after the closure of the activity, and the rehabilitation measures for the affected environment. Based on this documentation the mining permit will be granted by the Ministry of Environment. The Ministry of Environment through the control and monitoring authorities (the Environmental Protection Agency and the Environmental Guard) will be permanently supervising the activities in the mining perimeter and will suspend the activity if the conditions for which the approvals / agreements were granted will not be respected.	According to: - Mining Law no. 85 / 2003, art. 20 (1); - GD 1208 of 14 October 2003 regarding the approval of the Norms for the application of the Mining Law no. 85/2003, art 105; - GD 445 of 8 April 2009 on the assessment of the impact of certain public and private projects on the environment - ANRM order no. 17 of 9 March 2005 for approving the Technical Guidelines regarding the Framework Content The Environmental Recovery Plan and the Environmental Recovery Technical Project.
7.	Social impact study (3)	Any activity that is developed must positively affect the community, or, at least not affect it in a negative way. The social impact is analysed before the operating permit is granted; local communities are consulted in all phases of project approval and development.	According to Mining Law nr. 85 / 2003, art. 20 (1),

The first step towards a specific legislation for UCG in Romania is the development of the operation framework method for underground coal gasification (OMRom-UCG) (no.2 in the table above). OMRom has been developed as a final outcome of the COAL2GAS project and is covering all stages of a UCG project - from concept - planning / design to construction, operation, post-operation and decommissioning.

OMRom has been prepared by following a structure imposed by the regulatory authority (ANRM) for mining activities, which considers the following important aspects of the UCG technology implementation: general data related to the mining method; site selection approach; operating method – design and engineering principles; works schedules; necessary underground and surface tools and equipment; monitoring plan; risk assessment and prevention measures.

This framework method is the document that needs to be submitted to and approved by the responsible authority, the National Agency for Mineral Resources (ANRM), prior to any documentation needed for issuing the legal permits for exploration, construction & commissioning, operation and decommissioning.

Task 6.5 – Development of site-specific framework method, as a guideline for similar future UCG projects

The site-specific framework method was developed as a guideline for similar projects in the future, on a worldwide basis and includes important aspects regarding the risk assessment methodology, mining plans and commercial deployment, legal and environmental requirements, coal supply chain, processing routes, and carbon capture and sequestration/utilisation.

As an introduction to the guidelines MCE has first summarised the lessons learnt from the detailed review of UCG trials with emphasis on the lessons learned from El Tremendal, the first trial in a framework of a community collaboration (SF/369/91; 1991-1997). The in-situ coal conversion experiment at El Tremedal (Spain) demonstrated the feasibility of carrying out in-situ coal conversion process at an intermediate depth (500 to 600m) from Sub-bituminous C (ASTM) soft coal very similar to the Oltenia coal (Lignite B coal) and the Velenje coal (Lignite A coal). The project established also the potential viability of using the linear CRIP technique. The geological/hydrogeological conditions of the overburden at El Tremedal site are also similar (at the exception of the depth) to the conditions encountered at the Oltenia site. The El Tremedal trial provided a number of essential lessons for future UCG trials regarding directional drilling, detailed engineering design of the underground components and the gasification operations.

From the detailed reviews of the available UCG configurations (see Task 4.1), it was concluded that L-CRIP (and SDB) is the most sustainable, reliable and efficient UCG configuration with the lowest environmental impact. This configuration is applicable to all coal seam dip angles, from horizontal to dip angles exceeding 60°, and is also applicable to all coal seam depths and types of coal.

Risk assessment methodology

This section develops the practical framework for the risk management and assessment of the UCG project lifecycle. The essential stages are: 1) site selection; 2) commissioning (subsurface and surface engineering) and production (including temporary shutdowns for maintenance and subsequent re-starts); 3) decommissioning the UCG reactor(s); and 4) site rehabilitation. Each of these stages consists of several smaller phases or operating modes, with multiple interconnections and relationships.

The risk analysis frame is based on the 'state-of-the-art' Layers of Protection Analysis (LOPA) and Safety Integrity Level (SIL) methodology integrated to the standard Hazard an Operability (HAZOP) study.

The general framework includes the following main layers of protection:

1. Site and technology selection and mining plans;
2. Sub-surface process design, monitoring and control;
3. Critical alarms and safety systems; and
4. Emergency plans.

The LOPA/SIL methodology is used to assess the environmental, technical and operational risks of UCG technology (principally sub-surface). The phase/gate review methodology is then applied in combination with UCG process/performance models integrated with financial models to assess the commercial risks of developing the UCG project to a commercial phase (see Figure 2.2.60).

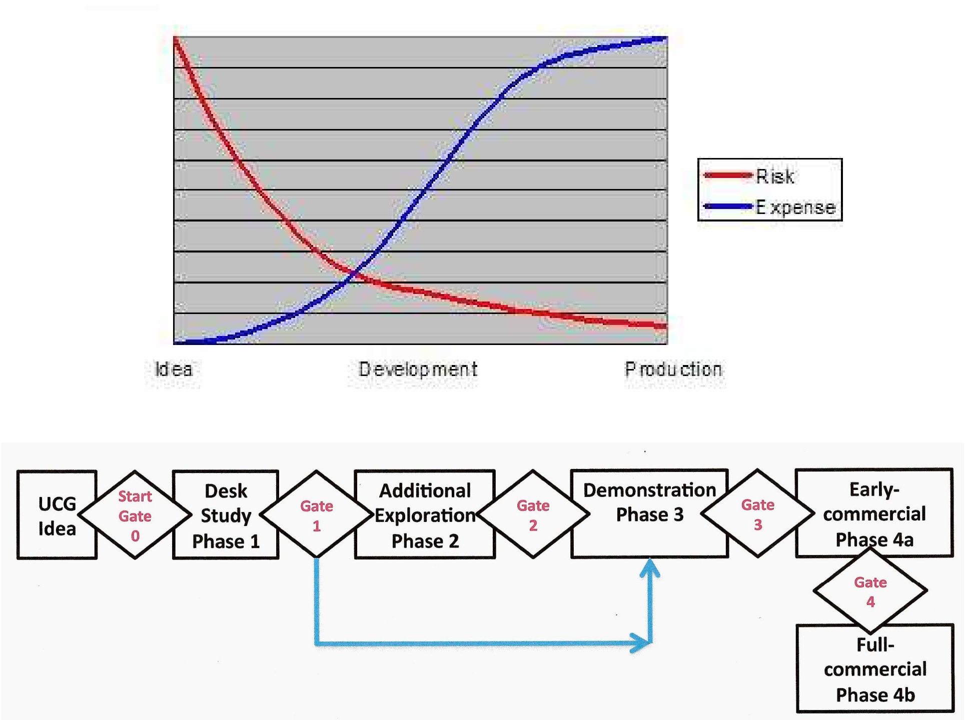


Figure 2.2.60: Phase/gate review methodology

The LOPA/SIL analysis is dedicated principally to the sub-surface systems. Standard HAZOP analysis applicable in the chemical industry will be added to the LOPA/SIL analysis for sub-surface and surface plant critical alarms and safety systems.

General methodology

The integrated assessment is generally initiated by calling a meeting (or session) usually comprising of the operating company, the engineering consultancy company (ies) (if this is a new project) and the HAZOP/LOPA/SIL facilitator(s) with his (their) scribe(s) (who is usually an independent third party). The team of engineers/scientists should definitely consist of chemical (or process) engineers, geo-scientists (geology, hydro-geology), mining engineers, well drilling and completion engineers, instrumentation and safety engineers. Other engineers or scientists are optional depending on their need during the course of the session.

HAZOP

A standard HAZOP is used to identify major process hazards or operability issues related to the process design. Major process hazards include the release of hazardous materials and/or energy (sub-surface and surface). The focus of the study is to address incidents, which may impact on public heath and safety in the workplace, economic loss, the environment, and the company's reputation. The inputs to the HAZOP are the Process and Instrumentation Diagram (PI&D), Cause and Effect charts (C&E) and the operating company's risk matrix (which is a matrix quantitying the risk level depending on the likelihood and severity). A typical risk matrix would look as given in Figure 2.2.46). The outputs from HAZOP are the risk ranking of each identified cause of process deviation and recommendations to lower the risk involved. These recommendations are given in the form of safeguards.

LOPA/SIL assessment

LOPA/SIL study is to assess the adequacy of the Safety Protection Layers (SPL) or Safeguards that are in place to mitigate, at different project phases, against hazardous events relating to major hazards, identify those safeguards that do not meet the required risk reduction for a particular hazard, and make reasonable recommendations where a hazard generates a residual risk that needs further risk reduction. This is done by defining the Tolerable Frequency (TF). The inputs to the LOPA/SIL assessment are the process deviations, causes, risk levels and safeguards identified during the HAZOP. The LOPA/SIL assessments recommend the Safety Protection Layers (SPL) to be designed to meet the process hazard.

The Features, Events & Processes (FEP) method

The so-called FEP method, as a SIL method (see here above), was integrated to the general risk assessment methodology (the method and risk factor screening is summarised in Task 5.1 of this report). The FEP risk matrix is presented in Figure 2.2.46.

UCG operability and reliability

When looking at operational reliability (with reduced risks), the main objectives during the active gasification phase of an UCG module to ensure safe and reliable production of syngas are:

- Performing controllable and reliable manoeuvres (ignition plus backward movement of injection point);
- Ensuring reliable injection and production well equipment (e.g. choosing suitable materials for the specific conditions associated with the sub-surface UCG environment - see also Task 4.3 here above);
- Installing reliable near-wellhead surface plant for single- and multi-module operations;
- Monitoring and controlling the module(s) to optimise the sub-surface processes and avoid contamination of groundwater;
- Managing UCG cavity collapse and subsidence; and
- Ensuring that water abstraction and injection and/or natural recharge are balanced in sub-surface.

Operational risks require management during the final linking and commissioning of UCG modules, the operation of UCG modules and during the post-gasification (decommissioning) phase.

Instrumentation and control deployment strategy, and process optimisation

A wide range of instrumentation is now available to modern UCG projects (see Task 4.2 in this report and Figure 2.2.39).

Reactor control volume

As direct observation of the reactor volume is not feasible during UCG, a combination of computational modelling, in-situ instrumentation and mass balance calculations are required to calculate UCG reactor volumes (see Task 4.2 of this report and Figure 2.2.36, Figure 2.2.37 and Figure 2.2.38).

Site selection

One of the most valuable conclusions drawn from previous UCG trials is the importance of selecting the correct site. Details are given in Task 4.1 of this report.

Mining plans and commercial deployment

A mining plan for a targeted coal resource should divide the well field into panels (the series of required panels are discussed Task 4.1 (section 4.3 of this report) and represented schematically in Figure 2.2.35).

As also described previously**,** near-wellhead surface equipment such as pumping units, gas and water analysis shelters will be skid-mounted and used multiple times on different modules. Other surface plant, however, will require careful planning to ensure the efficient transition from early- to full-commercial operations (see Figure 2.2.61). A complete list of surface plant depends on the end-use of the syngas e.g. ammonia plants require different syngas pre-end-use processing plants to others, such as electricity generation.

Another key element of surface plant is the air separation unit (ASU) to provide compressed oxygen and nitrogen to the well field. The design of the ASU should take into consideration the expected increase in output from the well field as it incrementally develops from early-commercial operations to the maximum commercial output.

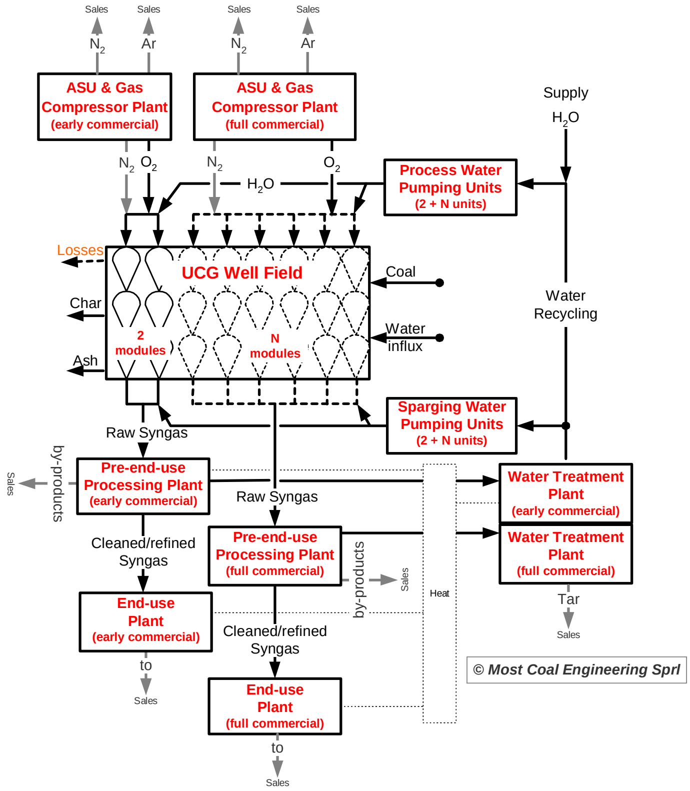


Figure 2.2.61 Scaling-up process to full-commercial deployment

Legal and environmental requirements

The development of the legal and environmental requirements for future UCG project is conditioned by the development and adaptation of the existing regulatory framework. As mentioned previously in the introduction Section 1 of this Task, UCG is a combination of (i) a mining process and (ii) a coal-gas chemical conversion process; both processes having their own efficiencies and environmental impacts. So the legal environmental requirements and adaptations will have to take it into account these facts.

In addition, the legal and environmental requirements should be based on (i) the essential construction/process stages identified here above (the site selection, the construction and commissioning of the sub-surface and surface processing units, the sub-surface production, the decommissioning of the UCG reactors and the site rehabilitation), (ii) the mining plans (the future expansion panel, the drilling panel, the gasification panel, the venting and cooling panel, and the depleted and decommissioned panel) and (iii) the recommended UCG phase/gate development (the desk study phase, the exploration phase, the demonstration phase, the early-commercial phase and the full-commercial phase).

Glossaries of UCG and mining terms were also developed to support adaptation of the existing regulatory framework.

<u>UCG mining project</u>

A UCG project is covering all activities carried out by the holder of the license or permit from prospection to environmental rehabilitation and mine closure. The essential construction/process stages are detailed in Figure 2.2.60 and the mining plans are detailed in Figure 2.2.35 in Task 4.1 here-above.

<u>Desk study phase (phase 1)</u>

This phase corresponds to the mining prospection defined in the mining glossary: all desk studies and surface prospection operations carried out to assess the suitability of a site for UCG and also identify areas where more information on aspects such as geology, hydrogeology, and environmental regulation is required (see Figure 2.2.60).

Exploration phase (phase 2)

This phase corresponds to the mining exploration defined in the mining glossary: all studies and activities performed for the identification of the mineral resource deposit, its quantitative and qualitative evaluation, as well as the assessment of the technical, operational, environmental and economical conditions for its use (see Figure 2.2.60).

Exploitation phase (phase 3 and phase 4)

This phase corresponds to the mining exploitation defined in the mining glossary: all activities performed at sub-surface and surface required extracting mineral coal resources, and processing and delivering them in specific end-product forms (see Figure 2.2.60).

Decommissioning modules & panels

The principal aim of decommissioning modules & panels is to continue to minimise risks from UCG after gasification operations (gasification panels) have ceased (details are given Task 4.1 of this report).

Public perception and the role of governments

Understanding public attitudes and the ways in which energy and technologies are themselves understood and used is vital for a technology to progress to commercialisation. Before a UCG project can be undertaken, it will clearly be essential to gain approval from the public. To improve public perception, it is recommended the following: (i) building trust between the developer, the regulator and the local community, (ii) ensuring greater transparency in regulatory and assessment processes, responsibilities and liabilities, (iii) providing more proactive community participation in site selection and monitoring, (iv) facilitating independent reviews of the submitted case for development and regulatory data and (v) establishing a site liaison committee with membership from the local community, regulators and site operators.

The importance of clear government support is inevitable. Government (and EU) support of UCG field trials is needed to grow our knowledge base, to gain more environmental data, and attract more private investment. Although it is recognised that investors have confidence in the long-term future of the UCG as an option for clean coal production, the technology needs to "derisk" from both economic and environmental perspectives in the near-medium term.

Coal supply chain, processing routes, and CCS&U

UCG, like all fossil fuel-based energy technologies, produces carbon dioxide. Carbon dioxide emissions will remain an important factor for coal and the new emerging clean coal technologies, like UCG, in the 21st century as the EU continue to reduce GHG emissions; UCG will have to limit carbon emissions to gain approval and not incur large financial penalties. The UCG industry in the world is currently adapting to this by investigating the potential for combined UCG and carbon dioxide capture and sequestration/utilisation (CCS&U), as well as the re-use of carbon dioxide by way of processes such as enhanced oil recovery (EOR) or enhanced coal bed methane (ECBM).

As UCG syngas is similar to other gases produces by the industry, the technologies for capturing carbon dioxide from syngas are in existence, well understood and widely available. Relatively little adaptation of these technologies to UCG syngas will be required. Although not a "magic bullet", UCG does offer some advantages compared with conventional technologies regarding CCS. UCG produces syngas relatively inexpensively and is undertaken close potential sequestration sites (such as deep saline aquifers or depleted oil/gas reservoirs), limiting then the cost impact of capture and sequestration. It may also be possible to inject carbon dioxide in the spent UCG reactors (with deep soft coals like lignite offering more potential storage than hard coals due to their intrinsic higher moisture content). As with other fossil-fuel technologies, the future of UCG is intimately associated with commercial development of carbon capture and sequestration/utilisation.

Figure 2.2.62 and Figure 2.2.63 are giving the different possible processing routes and CCS options from the UCG raw syngas produced.

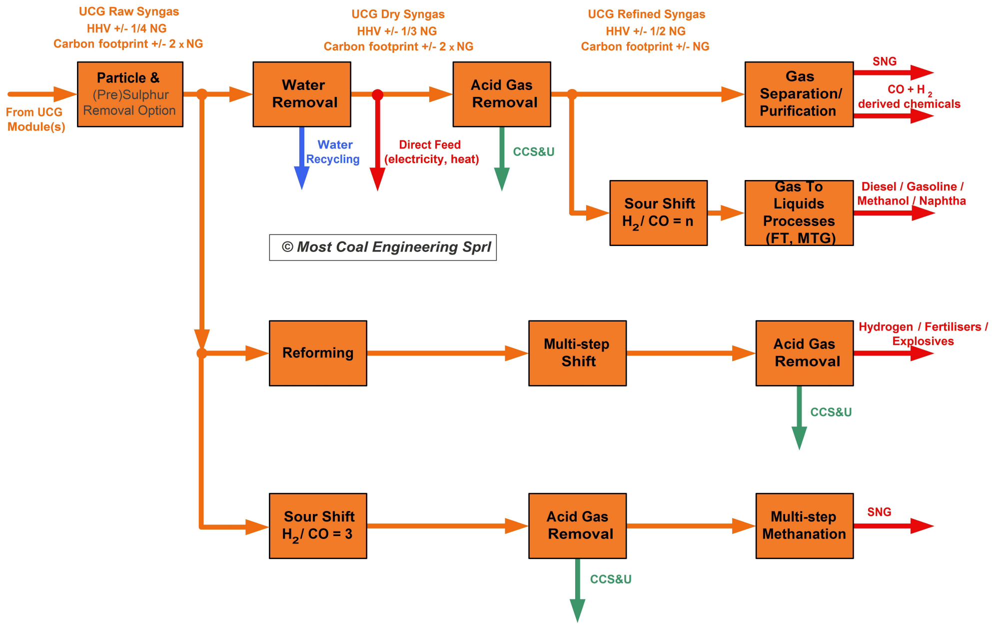


Figure 2.2.62: Standard processing routes of syngas

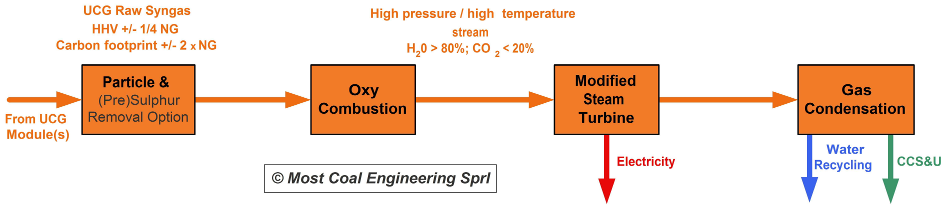


Figure 2.2.63: Oxy-combustion processing route of syngas

2.3. *Conclusions*

WP2: Data Analysis and Site Selection

The work in this WP covered data collection and analysis for the determination of the geological, tectonical, hydrogeological and mining conditions and parameters of the Oltenia deposit and to evaluate the suitability of the geological conditions in other European deposits. The work comprised: collection of data and analysis, set-up of 3D geological models, establishment of site selection criteria and site selection.

The data that was collected in this task about the Oltenia Coal Basin and the review of all available geologic, geotechnical and hydrogeological information allowed the characterization of the deposit. Based on this data and with respect to the site selection criteria defined in Task 2.3 a test site could be chosen close to the Urdari underground mine. The available data allowed construction of a 3D structural model of the selected site, which served as a basis for the further assessment and the numerical modeling. The initial 3D model could be refined when the drill results became available.

The study carried out in Task 2.2 showed that with respect to the recommended criteria for UCG operations referring to deposit thickness, minimal depth, deposit type and inclination in the countries under analysis (Poland, Greece, Slovenia, Romania, Germany), mining regions exist where these criteria can be met. However, a detailed site investigation is necessary in particular with respect to identification of single seams since the deposits frequently display complex seam structures and they are not homogenous in respect to physicochemical parameters such as moisture and ash content and calorific value.

However, not only technical criteria like geological characteristics or infrastructure need to be considered, but also legal aspects, as well as social and political acceptance. In none of the investigated countries, and also not at EU level, specific regulations and legislations for UCG exist. UCG is generally considered as a special kind of underground mining, and to smaller extent like natural gas exploitation. Therefore, it has to be handled and implemented based on the respective laws that exist for these more "conventional" production methods. At the national level there have been some attempts at regulating this process, but, in reality, only some regulations in legal acts concerning environment, geology, mining etc. can be used as reference for this process. The currently used approach, adopted by those countries performing any UCG research, piloting projects, as well as experiments and demonstrations is, thus, to refer to those EU directives which contain guidance on technical and environmental protection issues. These would include, for example, *the Environmental Impact Assessment Directive, the Mining Waste Directive, Environmental Liability Directive, Groundwater Directive, Water Framework Directive, Carbon Capture and Storage Directive, Large Combustion Plant Directive, Directive on Control of Major Accident Hazards, Strategic Environmental Assessment, Discharge of Pollutants Directive,* etc.

Despite the high interest in UCG among many of the EU and world countries, only few of them have national regulations which could be applied to the technology. Without any doubt, still the most advanced EU country, in this respect, is Hungary, where on the 1st January 2014 the UCG regulations entered into force. For this purpose the existing Hungarian mining law was used. The remaining countries in order to conduct UCG experiments use either the mining laws, the fuel related acts or the environmental protection acts.

From the reviewed four countries with attractive lignite deposits, Poland is the only country that has recent experience in conducting UCG demonstration projects. Two trials were made within the RFCS projects HUGE and HUGE2 close to the surface, another one at greater depth in an active underground mine, that was financed by a national Polish project. The Polish Government sees UCG as a method to exploit its coal reserves for power generation, and the public acceptance of coal mining and implementation of unconventional mining technologies, such as UCG, in Poland is still good. The positive public perception of UCG in Poland was additionally strengthened after a safe completion of the three underground trials conducted in recent years.

In Germany and Romania UCG tests were performed (even in Oltenia), but many years ago. So in the other countries except Poland, there are no experiences with applying for UCG under present legal conditions. Theoretically it would be possible to carry out a UCG project under the existing regulations in Germany. However, with respect to the current public and political acceptance of coal utilization and mining, and probably with the same for underground gasification, it is very unlikely to implement UCG in Germany at the moment or in the near future. Public debate on CCS and other underground activities like shale gas is overshadowing political position towards UCG. So far, however, politicians and regulators have refrained from touching this issue.

In Romania, legal and social acceptance of coal mining is still favorable. So if the legal and regulatory aspects will be handled, a successful UCG trial in Oltenia could probably lay the foundation for future UCG commercialization in Romania.

In order to boost the development of UCG technology in these countries the following activities are needed:

- to ensure adequate legal regulations, their clarification for the purpose of development of the technologies, in particular the UCG (including the regulations strictly related to the application, issuing licences, wok safety and the protection of the environment),
- to further test, conduct pilot, demonstration projects as well as in the end commercial projects which will eliminate the uncertainty of investments in these technologies,
- to broaden the social awareness and to obtain social acceptance for the UCG technology.

The most valuable lesson learned from the review of previous UCG projects is that selection of the correct site for UCG is essential to reach technical and economic success and reduce environmental risk. Numerous factors, of which many are interrelated, need to be considered in the process of site selection for the success of a UCG project. Not many well-documented examples with similar conditions like in Oltenia, i.e. shallow lignite, exist. And as conditions – both geological / technical and legal / regulatory – are always different, site selection criteria have to be developed and adapted site-specifically.

The analysis lead to the conclusion that the possibility of obtaining additional exploration results and to conduct later on a UCG trial due to the license situation is the driving factor towards site selection in the Oltenia region.

The study of naturally occurring coal fires yielded some valuable information concerning monitoring techniques, which ensure a safe and efficient production of syngas during a UCG operation.

WP3: Testing and Drilling

This WP was dedicated to experimental work aiming at collecting more data. Ex situ laboratory UCG simulations on large bulk coal samples, extracted from Oltenia and Velenje mines, at amospheric and high pressure conditions have been performed and lab tests were carried out on samples provided from the drilling campaign at the selected site Urdari.

The following geotechnical underground and laboratory tests were performed in the WP: geotechnical core logging; proximate – ultimate analysis; porosimetry; coal petrography; porosity and density; moisture/ water content; shear and brasilian tests; grain size distribution; consistency limits; Ignition loss; penetrometer tests; water permeability. The laboratory analyses were conducted on both coal samples and on the surrounding rock strata.

The coal characterisation showed that both coal samples used for the experiments are characterized by relatively high moisture content, i.e. 31.6% and 45.6% for the Velenje and Oltenia lignites respectively. Due to the high moisture contents in the low grade lignites (especially in ortho-lignites), the issue of their suitability for UCG process was questionable at the beginning of the gasification campaign.

The ex-situ simulations of UCG using large samples of Polish ortho-lignites, conducted formerly by GIG, revealed that the coal moisture content is one of the crucial parameters determining the gasification conditions, the quality and amounts of the products, as well as the suitability of lignite for UCG. The high moisture content considerably affects the coal calorific value and as a consequence, the energy density of the coal volume to be gasified.

The experimental campaign conducted demonstrated that the physicochemical properties of the feed lignite considerably affect the UCG process. For the similar process conditions (coal seam dimensions, oxygen supply rates) gasification of Velenje lignite resulted in much better gas quality and process performance both in atmospheric and high-pressure gasification regime. The moisture content in coal is regarded as the main parameter affecting gas quality (calorific value) and process energy efficiency. The overall energy efficiencies, expressed as a ratio of energy in the produced gas to the energy in the coal feed consumed, in each experiment with Velenje lignite were significantly higher compared to Oltenia trials. Nevertheless, the maximum obtained energy efficiency of approximately 45% during the atmospheric gasification of Velenje lignite was still much less than the values characteristic for UCG of hard coals, i.e. 60-70%.

The results obtained indicate that UCG may be a feasible option for exploitation of lignite deposits, especially in the case of the Velenje lignite. The over-stoichiometric water content in the lignite seam eliminates the need for supplying of additional reagent water, at least at the early stages of the gasification process. The excessive water, however, may result in a decrease in the gasification efficiency due to considerable heat loss for the evaporation of coal moisture. The obtained results suggest that the key issue for the improvement of process performance in lignite deposits may be an appropriate length of the gasification channels, especially for the high pressure gasification when gas self-combustion phenomena may occur. The proper reactor configuration promotes the process of steam condensation underground, leading to the recovery of thermal energy and making it available for the process (heating up of the unreacted coal). Recuperation of the physical heat of gas on the surface is another option that can be considered for the improvement of the overall process performance. This issue could be especially important in the case of the Oltenia lignite, for which lower process efficiencies were obtained both under atmospheric and high pressure regime.

Taking into account the scale and specific conditions of the ex situ gasification experiments, the obtained results should be considered as tentative. One should be aware that the actual conditions of the gasification plant in natural conditions due to the scale and a number of significant natural factors can significantly affect the gasification process. The results should rather be used as data for a comparative analysis of coals subjected to gasification in respect of gas composition gas production rates and yields and properties of UCG-derived by-products, depending on gasification reagent used and gasification conditions. Because the UCG trials in natural conditions are money, labor and time intensive activities, the UCG studies are frequently supported by laboratory UCG simulations. Such information can give significant recommendations for the underground works and can be helpful in the design of surface infrastructure based on the following:

- information on the temperature profiles in the reacting coal seam; the temperature distribution contours at different gasification time allow to visualize the evolution of UCG cavity in time,
- high accuracy balance data (material and energy) can be obtained since the input and output material and energy streams can be measured, including the coal seam weight before and after experiment,
- quantitative and qualitative characteristics of gasification by-products like post-processing waters and tars can be carried out in real time, which makes it possible to predict their production rates depending not only on the type of coal used, but also on the phase of the gasification run (initiation, gasification, termination),
- possibility of obtaining many UCG by-products for assessment of potential environmental impact of the technology (leaching of contaminants from char and ash) as well for prediction of changes in mechanical properties of overlying rock strata with respect to possible land subsidence resulting from UCG.

To acquire detailed information about the selected test site and improve the site specific data base, a drilling program was carried out. Five boreholes with a total length of 461 m were drilled to intersect the target coal seams. By drilling, samples of lignite and host rock were obtained for geochemical and geotechnical lab analysis. Drilling and the results enabled the verification of the historic exploration data and refinement of the geologic model as well as the final assessment of suitability for UCG.

From the boreholes drilled in Task 3.3 a thorough investigation program was performed both on the recovered drill core material and inside the boreholes. Geologic and geotechnical core logging, direct testing of the rocks and coal and core scanning, in combination with geophysical downhole logging, provided detailed insight into the underground of the test site and improved the data base. Borehole logging enabled to analyse the conditions in-situ. The structure and thickness of the target seams are quite variable. The logging results delivered exact data that were implemented into the models and the assessment of suitability for UCG. The acquired data also document the initial situation and establish a base line case for the UCG monitoring.

WP4: Panel and Well Design & Engineering for Integrity and Safety / Surface Plant Assessment

The work in this WP covered (i) the UCG technology review and update on a worldwide basis, (ii) the UCG-module performance comparison and recommendation applicable for the COAL2GAS project and the EU, (iii) the selection of the suitable process operations and monitoring techniques for the Oltenia coalfield, (iv) the well design and engineering recommendations for the selected site Urdari, and (v) the thermal-hydro-mechanical-chemical impacts of UCG operations on surrounding rocks in the selected area.

The main achievements obtained from the UCG technology update are the lessons learned on a worldwide basis and the first guidelines for future UCG project in the EU. From the detailed review of the available configurations, it was concluded that L-CRIP and SDB are the most sustainable, reliable and efficient UCG configuration with the lowest environmental impact. This configuration is applicable to all coal seam dip angles, from horizontal to dip angles exceeding 60°, and is also applicable to all coal seam depths and types of coals. Additional guidelines are: (i) during active gasification, the counter-pressure of the underground reactor(s) should always be maintained at pressures significantly less than the minimum hydrostatic pressure of the underground UCG system, (ii) the design and built of each module should ensure that, in each module, the injection point is positioned low in the coal seam as possible, and (iii) an integrated risk assessment methodology (technical, operational, environmental and financial) based on "state-of-the-art" risk assessment methodologies applicable in sub-surface resource production technologies (conventional and non-conventional) and surface chemical plants should be applied from inception to commercial deployment of the UCG mining project.

For the Oltenia selected site the L-CRIP configuration was considered as the best option and the module performance was estimated for three case studies representative of the coal seam conditions in the Oltenia coalfield.

A discussion was also on the potential impacts (geology, hydro-geology and reactor environment surroundings) of the L-CRIP reactor/module growth, and how these effects could be monitored in the field and computer-modelled using "state-of-the-art technologies. The principals of UCG L-CRIP modules including (i) the control volume concept, (ii) the process instrumentation, control and optimisation, (iii) the water ingress and gas/energy leakage controls, and (iv) the management of the UCG reactors post-gasification were also analysed/assessed.

The specific achievement was to estimate how an L-CRIP module would perform (process operations and monitoring plans) under conditions relevant to the Oltenia coalfield in preparation of WP6.

In WP4 the guidelines and the pre-design/engineering of a potential future pilot-scale project adapted to the specific conditions of the Urdari selected site were also developed. The pre-design and engineering were established by (i) defining the stratigraphy units (and sub-units) and the hydrogeological conditions of the site, (ii) defining the sequence of process phases (and sub-phases) applicable, (iii) defining the well configurations and well positioning (injection, production and tranverse water wells). Others aspects to be considered like (i) the principals of the underground reactor(s), (ii) the well specialised design and (iii) the in-well control and monitoring required techniques were also developed.

The main achievement was to prepare the well design (including the in-well instrumentation required) and engineering for the integrity and safety of L-CRIP modules in the Urdari selected area (also in preparation of WP6). The design and engineering developed in COAL2GAS project is applicable for future similar projects.

The mechanical modelling revealed instable cavities for the foreseen operations in seams V and seam VIII for all scenarios investigated. These results can only be seen as indications as relevant parameters could not be established on a site-specific level. However, the results imply that (more) relevant site-specific geological and geomechanical data need to be collected and evaluated before a final decision on an UCG location at the site investigated should be made.

WP5: Risk Analysis, Environmental Issues and Legislative Background

The work in this WP provided a risk assessment methodology and a risk analysis of environmental impacts of UCG activities, exemplified by the selected pilot UCG site in Targu Jiu, Romania. This work included the identification environmental issues by large-scale lab-test and considered legal requirements for UCG in the EU and Romania.

Risk analysis is a task that precedes UCG activities, but also accompanies it. It starts in a qualitative fashion at first, but modelling activities designed to (further) reduce uncertainties are needed. When the UCG activities have begun new incoming data (by operational experience) are to be used. Good RA is transparent, updatable and strives at completeness. It observes the requirements imposed by EU-law and Romanian legislation.

Remediation plans and monitoring plans should be based upon the results of RA. In principle, they may be updated as well, when operational results so demand.

Communication issues play a role that should never be underestimated:

- Contacts with the authorities, formal and informal, are important.
- Timely contacts with other stakeholders are crucial as well.
- Regular contacts between the experts from different disciplines are also crucial. This holds at the first, qualitative stage, but certainly also in a phase when modelling prevails.

The study on the formation and release of UCG-related contaminations was carried out during the four large scale UCG experiments (WP3). It was found that values of the measured physicochemical parameters in the post-processing UCG effluents significantly varied over the time of gasification for the particular experiments. These variations reflected changes in the gasification conditions (temperature) and development of oxidation and pyrolysis zone over the experiments. An effect of lignite used and gasification conditions on the values of physicochemical parameters of the wastewaters was evident. It was found that the increase in gasification pressure led to decrease in concentrations of organic compounds due to intensification of tar cracking phenomena. Environmental risk in the post-gasification phase was assessed based on physicochemical characterisation of solid UCG by-products and elution tests conducted in laboratory quasi-static–dynamic conditions. The study shown that composition of UCG wastewaters significantly varied over the time of the particular experiments, which reflected changes in the gasification thermodynamic conditions and development of oxidation and pyrolysis zones. The effect on lignite properties and gasification pressure was also confirmed in the study. The elution tests carried out for char residues from both gasification trials shown that the elements with the highest mobility into the aqueous phase were As, B, Zn, Al, Mn, Fe and, to a lower extent Mo and Se. Therefore these elements may be regarded to be of greatest concern for the groundwater environment in the post gasification phase. Another observation was that the metal elution potential to a larger extent related to the physicochemical properties of UCG residues than to the content of specimens in the eluted material. The possible negative environmental effects due to release of organics from UCG char was found negligible for lignites under study.

In WP5 the base data and the context for the risk assessment were also defined. The types of risk for the Oltenia demo project concern risks of an environmental nature, risks regarding the technological and operational feasibility, and risks concerning the legal situation. The required site-specific information for the identified risks were compiled and were provided as basis for the subsequent risk assessment. The key performance parameters for UCG were identified based on an extensive literature review. The coal seams at the test site are flat lying, so the L-CRIP configuration was determined to be the most suitable UCG concept. The injection point within the module(s) shall be positioned in the seam as low as possible. This method has been shown by previous UCG trials to be the most reliable, efficient UCG configuration and consequently with the lowest environmental impact. For the containment of fluids it will be essential that the reactor pressure will always be lower than the surrounding hydrostatic pressure during UCG. During shut-down, it will be necessary to use the “clean cavern” techniques that were tested during UCG trials in the USA and Australia.

Based upon the general risk assessment framework established in Task 5.1 a comprehensive risk parameter database has been developed to screen and evaluate any related risk with (shallow) UCG applications. The risk database can be used as questionnaire for experts going through and assessing the identified risks of a given operation. It became obvious during the application of the database in the course of the project that the risk parameters and the related questionnaire are of great help to the experts to screen, discuss and evaluate risks related to UCG process (at Oltenia).

As a result of the application during the project and the feedback of the experts involved, the database was improved by some minor modifications after first usage. It became obvious that it is of utmost importance to clearly defined and specify each risk factor and how to rank them. This should also include specific definitions of the different phases, e.g. when does the decommissioning phases starts exactly but also all site-specific information relevant for each parameter, such as monitoring plans.

One of the main outcomes of WP5, the definition of risk scenarios, strongly depends on the risk assessment workhop that was the main activity in this task. An expert panel screens, discusses and ranks all identified risk given in the risk factor database and using the procedure developed in Task 5.1 and Task 5.3 to evaluate relevant risk based on operational and site-specific information.

In general the following main conclusions can be drawn from the performed risk assessment:

1) The depths of the envisaged target seams VIII and alternative seam V are shallower than previously reported (34-37 m and 103-108 m respectively) what puts risks related to shallow location (e.g. subsidence, roof collapse or loss of containment) even more into focus, particular for target seam V.
2) The thickness and continuation of the seams and the (unconsolidated) sealing layers vary strongly, which confirms the high risks of uncertainties related to the structural set-up and the integrity of the site, for target seam VIII and also for alternative option seam V.
3) Coal seam VIII sample analysis revealed that the seam is stiffer than expected, which has a positive effect on the integrity, but still the (updated) geomechanically modelling shows risks for the containment of pollutants
4) Overall the numerical simulations indicate significant risks of cavity collapse and loss of integrity for both target seams which were already reflected in the outcomes of the risk assessment workshop.

After the drilling campaign, when more information on the geological, hydrological and mechanical properties of the target site became available, the mechanical modelling and, subsequently, general risk aspects were re-considered towards the end of the project to include all relevant, available data. The new data demonstrated that the previous results of the risk assessment and identified, evaluated and ranked risk scenarios are (still) valid and accurate, and do actually underline the findings. The generated site–specific data could help to reduce the uncertainty of several scenarios; however, the main risks remain. The unconsolidated and very shallow target seam appears to be not well-suited for UCG operations, at least at the site investigated. Considering the unconsolidated overlaying formations, and consequently the risk of roof failure and loss of containment at the investigated location (at least above ~110 m depths) it could be worthwhile to investigate a site (in the vicinity) where the geological set-up appears to be more ideal using the issues identified in this study. However, more (geomechanical) data or targeting deeper seams could lead to a reduction (of the uncertain) of the identified risks related to UCG operations at this location. Thus, more relevant data should be collected to make a final, informed decision and update the current risk assessment.

When assesing the identified risks based on the existing legal requirements one of the main conclusions that can be taken is that monitoring is one of the most important issues not only during the operational phase, but also during exploration and post-mining phases. A special attention must be given to the following monitoring parameters: roof fracturing and subsidence, groundwater and surface water dynamics and quality, gases flows temperatures and pressures, soil quality and seismicity, air quality and meteo data. The monitoring strategy must be developed according to the type of UCG module configuration and as suitable as possible with the future UCG pilot project in Oltenia region. A customised and well-equipped monitoring process can mitigate residual risks and can efficiently manage the UCG process. A proper risk management and the design of suitable monitoring plans and mitigation/remediation actions will remove, as much as possible, uncertainties with respect to major risk in Oltenia basin – target zone integrity (subsidence, aquifers, faults).

WP6: Preparation of Pilot Project

Based on the investigations on the Oltenia deposit and the results of modelling and testing, the coal seams and the selected site can be regarded as generally suitable for conducting a UCG test. The recommended UCG concept (L-CRIP) and technologies e.g. for process control will allow a state-of-the-art UCG operation. As result of the risk assessment, the main concern is associated with the shallow depth of the seams and the groundwater, and to limited extent to cavity stabilty. Although the clay cap rocks are soft and possess low strength, they are beneficial with respect to their sealing capacity. To prevent any harm to the environment, thorough and consequent monitoring has to be performed during all phases – from the acquisition of baseline data until site decommissioning. In addition to the detailed study on Urdari with the development of site-specific techniques, the review of the information on the Oltenia coal basin as well as on other areas in the EU has shown additional potential for the implementation of UCG.

A concept and action plan for the site-specific monitoring was developed for a UCG test at the Urdari site. Two aspects for monitoring were distinguished, i.e. environmental and process monitoring. The objectives are to minimize the environmental risks and to optimize the performance of the UCG operation. The process monitoring focuses on aspects like the testing and control of temperatures, injection point position, pressures and gas, and matching with calculations of e.g. mass and energy balance, gas losses or gasification equilibrium conditions. Environmental monitoring mainly covers aspects like subsidence, ground and surface water dynamics, temperature and quality, soil gas and air composition, and effects on the vegetation. It is essential that reliable base line data are acquired before the gasification, to be able to distinguish normal variances from abnormal data.

For the Urdari site a minimum of four multi-level groundwater observation wells equipped with data loggers and at least four soil gas wells are recommended. In addition, a comprehensive monitoring program containing geodetic levelling and GNSS/GPS monitoring, a weather station, as well as sampling and analysing surface waters, soil and air (gas chromatograph) is suggested.

Based on the simplified cost-benefit analyses performed for the identified options of using syngas, it appears that at this point of UCG estimated development costs, the most suitable option could be, in certain conditions, the use of syngas on site in a new facility for electricity generation.

The obtained results show that the profitability of the project does not depend only on the estimated CAPEX but also on the OPEX for UCG, which is still too high and cannot be covered by the revenues from electricity sold. However, having in view that the technology is not fully matured yet and the estimated CAPEX and OPEX are deeply dependent on the maturity degree of the technology, it seems that the obtained results could be significantly improved when a commercial technology will be available.

The conditions in which the option of using syngas for electricity generation can be sustainable are related to: (i) financing of syngas production and treatment facilities from grants, (ii) decreasing of OPEX of syngas production and treatment facilities which can occur along with the maturity of the technology and (iii) supporting scheme for this kind of projects. The supporting scheme should include feed-in tariff for electricity, grants for OPEX of UCG facility.

One of the most important outcomes of WP6 is the practical site-specific guidelines that were developed by integrating the lessons learnt as a guide to the designing, planning, construction, operation and decommissioning of future UCG mining projects, the "state-of-the-art" risk management applicable to the UCG mining project lifecycle, and legal requirements applicable for mosthly Romania and the EU. The content of the complete integrated guidelines developed are: (i) the lessons learned from previous UCG trials, (ii) the recommended mining plans and commercial deployment, (iii) the necessary legal and environmental requirements, (v) the potential optimisation of the EU coal supply chain and (vi) the potential processing and recycling routes of the raw syngas produced at the module(s) wellhead(s).

2.4. *Exploitation and Impact of the Research Results*

WP2: Data analysis and Site Selection

UCG can be a method that is feasible for the extraction of coal resources and alternative energy generation from currently not economically mineable deposits in Europe. The extensive set of data that has been collected about lignite deposits in countries like Germany, Poland, Greece and Romania and especially the information on the Oltenia coal basin provides a sound database for the assessment of additional UCG potential in Europe. The application of site selection criteria and first screening of some major lignite deposits provides an overview and a first ranking and assessment of potentially attractive areas. It lays the ground for the next more regional / local study phase and future development of UCG, and provides a basis to other countries and interested stakeholders. It allows comparison and selection of suitable places not only within the described deposits, but can also be used as a reference for other deposits in Europe.

The elaborated site selection criteria could be used in future feasibility studies for UCG. The criteria that were set up for Oltenia may be used also as a basis for other UCG projects in similar deposits of shallow lignite. Screening of potential sites in Europe that were identified in Task 2.2 may be carried out applying the here developed set of criteria. For the evaluation an assessment of type, quality and quantity of (geological) data may be performed in an analogous way to the reporting of coal resources and reserves as outlined e.g. in the JORC code, in combination with an assessment based on the confidence levels of the available geological data.

WP3: Testing and Drilling

An extensive borehole and drill core investigation program was completed in order to gain a detailed understanding of the proposed UCG test site in Romania. The program included geophysical well logging, hydrogeological testing, geologic and geotechnical core logging and field testing, topographic surveying of collar positions and sampling of coal and surrounding rocks for subsequent geomechanical and coal quality analyses.

The data and results obtained from the drill campaign served for verification and refinement of geologic and numerical underground models and the assessment of suitability of the lignite deposit for UCG. These results were supported by the large scale laboratory UCG simulations conducted by GIG. Apart from typical process parameters, the gasification experiments provided a valuable and universal data on qualitative and quantitative characteristics of UCG by-products and possible negative environmental impact of the technology. The obtained detailed information on the Urdari site provides a valuable database for any subsequent UCG test in Romanian lignite deposits and in similar deposits elsewhere in Europe.

The investigation concept for the underground coal gasification test in lignite seams was presented at the "Second International Conference Mining in Europe", which took place between 06 and 08 June 2017 in Aachen, Germany (S. Peters; T. Gorka, B. Teigler: Site investigation for an underground coal gasification (UCG) test in Lignite seams - an Example in Romania). As a result of the proposed site investigation another two presentations/papers were prepared:

- T. Gorka, S. Peters: "Initial investigations for the in-situ gasification of lignite seams - A case study of a Romanian deposit"; the 8th International Freiberg Conference on IGCC & XtL Technologies: Innovative Coal Value Chains; 12-16 June 2016 Köln, Germany.
- T. Gorka, S. Peters, M. Mostade, K. Kapusta, C. Vasile, J. Wollenweber: In-situ gasification of shallow lignite: Results of an EU study for a potential demonstration site in Romania; the 9th International Freiberg Conference on IGCC & XtL Technologies: Closing the Carbon Cycle; 3-8 June 2018 - Berlin, Germany (accepted for publication).

As a result of the UCG tests conducted, the following presentations/papers were prepared:

- K. Kapusta, K. Stańczyk, A. Solschi, S. Završek, S. Bălăcescu. Large scale experimental simulations of underground coal gasification (UCG) process with selected European lignites, in the International Freiberg Conference 2016 – Cologne, Germany.
- M. Wiatowski, K. Kapusta, K. Stańczyk, K. Stańczyk. High-pressure ex situ experimental simulations of underground gasification of ortho- and meta-lignite: A comparison study; Submitted to FUEL journal (Impact Factor 4.601) (under review).

WP4: Panel and Well Design & Engineering for Integrity and Safety / Surface Plant Assessment

The designs and solutions developed here as a practical example for the Urdari coal site demonstrate the up-to-date and most promising techniques for UCG operation in shallow depth. With these methods, underground coal gasification can be applied as an alternative use for currently not economically mineable shallow lignite deposits. They ensure the safe operation of UCG as well as the decommissioning and site abandonment.

The basis of the guidelines that were prepared and used for the pre-design and engineering of a future pilot-scale project at the Urdari selected site are not only applicable in the Oltenia coalfield but also in other potential UCG mining projects elsewhere in the EU.

This WP (and more generally the COAL2GAS project) was also further participating to the collaboration, and sharing of expertise and knowledge between people, projects and governments with experience in UCG in view of the future commercialisation of the technology in the EU (see details in "V. Sarhosis, S. Lavis, M. Mostade, H.R. Thomas. "Towards commercialising underground coal gasification in the EU – ICE 2016").

The 2D and 3D geomechanical models developed for the chosen site investigated in Oltenia have shown their importance to gain some indications on the feasibility and the evolution of a UCG operation at certain conditions and location and are therefore key input for the risk assessment. Naturally, outcomes and accuracy of the simulations depend strongly on the availability and quality of the site-specific data set. The models present a guidance which site-specific data needs to be collected and can be used for future investigation, also of other UCG sites. The models are readily available at certh and TNO for future shallow UCG investigation and can easily be transformed into models for deep UCG, if required.

WP5: Risk Analysis, Environmental Issues and Legislative Background

With the developed and applied comprehensive risk assessment procedure for UCG operations a powerful "tool" has been created for future feasibility studies of foreseen UCG sites. The risk factor database can be used for shallow and deep UCG likewise as it was constructed in a generic, comprehensive and updatable way. With some smaller modifications it can also be used to perform a risk assessment for other geo-energy activities like (enhanced) coal bed methane.

The discussions in WP5 clearly showed that such a detailed methodology is required to identify and rank all possible risk related to a UCG operation and can help to point towards uncertain or problematic scenarios and indicate any missing, relevant data that should be collected. It helps to tailor and specify the UCG operation itself towards a safe and reliable operation. Therefore the tool has the potential to be used in future site assessment studies, including any additional potential research at the Oltenia site.

The large-scale lab tests demonstrated the importance for the assessment with respect to contaminants and their transport behavior. This directly supports the risk assessment to derive proper scenarios and come to an informed conclusion on potential risk related to pollutants generated during the UCG operation. The gained lab test results can be seen as representative for comparable coal seems and can be used for risk management of other potential UCG sites.

Additionally, the results from WP5 of COAL2GAS project enhance the know-how of European partners in UCG application in shallow, as well as deep, mining environments. The developed risk assessment procedure has been designed so that it can be easily adapted to various conditions of potential UCG operations in other countries, inside or outside of European Union.

WP6: Preparation of Pilot Project

The investigated Urdari site and analysed seams and coal provide generally potential for conducting a UCG test. Consequently, the acquired data and developed plans would allow continuing with the next step that is an actual in-situ test. Nevertheless, due to the environmental risks associated with the shallow depth and nearby mining, careful monitoring has to be guaranteed. The assessment of the site can serve as reference and guideline for the search for suitable UCG sites elsewhere in the EU.

The presented monitoring methods reflect state-of-the art techniques for modern UCG control. The suggested concept for the Urdari site may be transferred to other areas of shallow lignite and serve as guidance for an environmentally safe and cost effective approach. The monitoring plans and concepts could serve as an important part of the application process for the regulators and will be required for any UCG test according the environmental regulations. As no specific regulations yet exist and UCG is considered somewhere in-between conventional mining and gas exploitation, this method of coal utilisation has to be considered as a special form of mining, applying the Romanian mining law and corresponding regulations. To develop new regulations for UCG in Romania, a UCG demonstration test with full engagement of the state authorities will be required.

The framework method for coal exploitation through UCG (OMRom-UCG) that has been drafted in Task 6.4 is the statement paper for UCG application in Romania that needs to be submitted to and approved by the National Agency for Mineral Resources (ANRM), prior to any documentation needed for issuing the legal permits for exploration, construction & commissioning, operation and decommissioning. This is the first step towards a specific legislation for UCG in Romania that once approved it could open the gate for UCG projects.

The complete and integrated guidelines that were developed during COAL2GAS project could be applicable to (i) the future development and adaptation of the existing EU mining regulatory framework to the UCG technology, (ii) the UCG site and technology selection, (iii) the UCG mining plans, (iv) the commercial deployment and (v) the sub-surface and surface process design, monitoring and control. Task 6.5 is also integrating the "state-of-the-art" risk assessment methodology applicable to future UCG mining project in the EU.

3. LIST OF FIGURES

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5. ACRONYMS AND ABBREVIATIONS

°C	Celsius degree
ANRM	National Agency for Mineral Resources
ASTM	American Society for Testing and Materials
Bar	Barometric pressure
BET	Brunauer-Emmett-Teller
BJH	Barrett-Joyner-Halenda
BTEX	Benzene, Toluene, Ethyl-xylene, Xylene
C/B	Cost/Benefit Ratio
CAPEX	CAPital Expenditures
CBA	Cost Benefit Analysis
CEO	Complexul Energetic Oltenia
CH_4	Methane
CO	Carbon Monoxide
CCS&U	Carbon Capture and Sequestration/Utilisation
C&E	Cause and Effect charts
CRIP	Controlled retracting injection point
DHS	District Heating System
DSC	Differential Scanning Calorimetry
EC	European Commission
ECBM	Enhanced Coal Bed Methane
ELVW	Enhanced Linked Vertical Well configuration
EOR	Enhanced Oil Recovery
EU	European Union
FEP	Features, Events and Processes
FIA	Flow Injection Analysis
FDR	Financial Discount Rate
FNPV	Financial Net Present Value
FRR	Financial rate of Return
L-CRIP	Linear Controlled Retracting Injection Point configuration
HAZOP	Hazard operation analysis
HHV	High Heating Value
LOPA	Layers of protection analysis
LVW	Linked Vertical Well configuration
MU	Measuring Unit
OPEX	Operation Expenditures
PAH	Polycyclic Aromatic Hydrocarbons
P-CRIP	Paralell Controlled Retracting Injection Point configuration
PI&D	Process and Instrumentation Diagram
RA	Risk Assessment
SDB	Steeply Deeping Bed configuration
SIL	Safety Integrity Level
SPL	Safety Protection Layers
TGA	Thermogravimetric Analysis
TOC	Total Organic Carbon
UCG	Underground Coal Gasification

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The present report summarises the achievements of the RFCS project COAL2GAS: Enhanced Coal Exploitation through Underground Coal Gasification in European Lignite Mines (RFCR-CT-2014-00003). The COAL2GAS project aimed at evaluating the feasibility of UCG in shallow lignite seams having in view geological, technical and environmental aspects. Experimental work and modelling have advanced the state-of-the-art in the areas of how UCG can be used to access and exploit resources that cannot be mined economically with other technologies.

Based on the analysis of geological, hydrogeological, coal and mining parameters of deposits in the partner countries, with main focus on the Romanian Oltenia deposit, a geological model was created. Site selection criteria have been established, potentially suitable areas for a UCG pilot in the Oltenia deposit have been assessed and the exploration site has been selected.

High-quality experimental data were obtained from large-scale gasification tests conducted in artificial coal seams under atmospheric and high pressure (35 bar) regimes, analysis of UCG-related contaminants and laboratory tests of drill samples.

Based on the obtained data the suitable process operation and monitoring techniques were selected, well design and engineering were developed and a numerical modelling of UCG operations impact on surrounding soil layers and rocks was performed.

COAL2GAS also provided a risk assessment (RA) procedure for UCG operations, a powerful tool for future feasibility studies of foreseen UCG sites that, with few modifications, can also be used to perform RA for other geo-energy activities like (enhanced) coal bed methane.

The results obtained during the project were gathered in a site-specific framework method that was developed as complete and integrated guidelines for similar future UCG projects in shallow lignite seams.

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