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# A quantitative assessment of the environmental sustainability of UCG and CO2 storage

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**Abstract**
In this study, an innovative numerical model was developed to quantify the environmental sustainability situation of in situ underground coal gasification (UCG) and the CO2 storage process, which is expressed in terms of the environmental sustainability index (ESI). This approach is based on four environmental indicators: rock and soil, groundwater, surface water, and atmosphere. Based on the ESI values, the methodology proposed herein is used to classify the environmental sustainability state of the UCG process and its corresponding threshold limit value. Finally, the developed mathematical model was applied to possible European coal deposits, specifically in a Bulgarian coal basin. Research efforts have focused on the development of a mathematical model for environmental impact assessments to pave the way for full-scale trial and commercial applications.

*Keywords*: underground coal gasification; environmental sustainability index; sustainability condition.

# Evaluación cuantitativa de la sostenibilidad ambiental de UCG y almacenamiento de CO2

**Resumen**
En este estudio, se desarrolla un modelo numérico innovador para cuantificar la situación de sostenibilidad ambiental de la gasificación subterránea de carbón *in situ* (UCG) y el proceso de almacenamiento de CO2 que se expresa en términos del Índice de Sostenibilidad Ambiental (ESI). Este enfoque se basa en cuatro indicadores ambientales, a saber: roca y suelo, agua subterránea, agua superficial y atmósfera. Basado en los valores de ESI, aquí se propone una metodología para clasificar el estado de sostenibilidad ambiental del proceso UCG, así como su valor límite admisible correspondiente. Finalmente, el modelo matemático se ha desarrollado y aplicado a posibles depósitos de carbón europeos, específicamente en una cuenca de carbón de Bulgaria. Los esfuerzos de investigación se han centrado en el desarrollo de un modelo matemático de evaluación de impactos ambientales con el fin de buscar el camino para una prueba a gran escala y aplicaciones comerciales.

*Palabras clave*: gasificación subterránea de carbón; índice de sostenibilidad ambiental; condición de sostenibilidad.

## 1. Introduction

Underground coal gasification (UCG) developed in Russia during the 1930s, consisting of the opening of vertical drill holes to intersect a coal seam at a certain depth, then injecting air or oxygen and/or steam at a high temperature to cause underground combustion. The resulting gases were extracted from the combustion chamber through other boreholes, thus resulting in “in situ” coal gasification to produce CO and H at high pressure for electricity-generating plants or the production of chemicals. UCG is integrated with a combined gas turbine (CCGT) and carbon capture and sequestration (CCS) to produce a coupled UCG-CCGT-CCS system (Fig. 1).

The advantages of this technique are related to its high efficiency because it makes possible the tripling or quadrupling of exploitable coal reserves, thus preventing a decline in reserves of other mineral fuels such as oil and gas.

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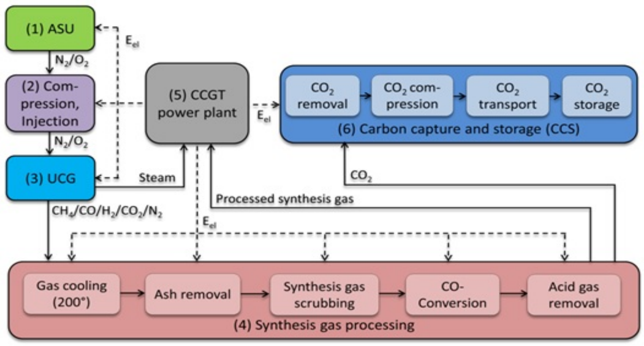

Figure 1. Coupled UCG-CCGT-CCS process.
Source: Nakaten, N. et al, 2013.

It is particularly suitable for low-quality coals, such as lignite and bituminous coal, which produce less heat during combustion than other coal types due to their high ash content and cause greater pollution in conventional plants.

Several processes are used for UCG process control, such as the controlled retraction injection point (CRIP) process, developed by the Lawrence Livermore National Laboratory (LLNL) for shallow coal seams and used in the European deep-coal trials.

## 2. Characterization of environmental indicators in the UCG process

The analysis of physical and chemical interactions during the UCG process indicates that it may cause changes in the surrounding rock mass due to the occurrence of contaminants at the reactor site and the surrounding rock mass and induce subsidence potential and various forms of pollution in the groundwater, surface water and atmosphere (Fig. 2).

The potential for subsidence during the UCG process will be quite small compared to that associated with underground mining, as exemplified in Centralia and Chinchilla (Australia), where negligible subsidence was predicted to occur [3]. However, a risk of subsidence is present, as demonstrated by numerical modeling results, showing important displacement around UCG cavities [4].

After the removal of the coal seam from within the cavity, the stresses in the immediate vicinity of the cavity change, and new stresses are induced. As the induced stresses overcome the tensile or compressive rock mass strength, the

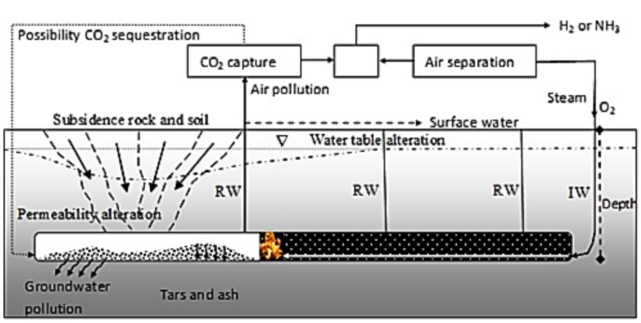

Figure 2. Summary of UCG/environment interactions.
Source: Da Gama C. D. et al, 2010.

failure and potential horizontal or vertical rise of the cavity can occur and may lead to subsidence above the cavity [5] [6].

The main pollutants of groundwater associated with UCG result from coal burning processes. Such pollutants include benzene, ethylbenzene, xylenes (BTX), toluene, phenols, coal ash, tars, aromatic hydrocarbons and sulfides, NH3, NOx, cyanide, boron, H2S and CO [7]. Phenol leachate is the most significant environmental hazard due to its high water solubility and high affinity for UCG [8].

During the UCG process, syngas leakage may be generated from i) organic materials such as phenols, benzenes and PAHs; ii) inorganic materials such as sulfate and boron, and iii) metalloids and metals such as mercury, arsenic and selenium, causing groundwater pollution [9]. Volatile elements such as mercury, arsenic and selenium are likely to be released as a gas and contaminate the air [10].

The lithology, mineralogy and impurities in the adjacent rock mass associated with the coal seam gasification process are influenced by ground water and atmospheric air pollution [11].

### *2.1. Surface water pollution*

The potential for the pollution of the surface water as a result of UCG is extremely low, and the common pollutants are phenols, ammonia, and sulfides, and the chemical oxygen demand (COD), pH, and conductivity can be negatively affected. The surface water can be affected by groundwater pumping and drilling operations, and in a Spanish trial, the water pumped to the surface was polluted with phenols (500 ppm) [12].

### *2.2. Atmospheric contamination*

The major components of the gas resulting from the UCG process are CO2, $H_2$, $CH_4$, and CO. In an example of a UCG trial, bituminous coal having sulfur, nitrogen and chlorine contents of 2.0%, 0.2% and 0.8% in weight, respectively, resulted in a gas emission product consisting of 22.7% $H_2O$, 46.1% CO2, 19.2% CO, 9.4% $CH_4$, 1.6% $H_2$ and 1.0% other components ($H_2S$, HCl, and $N_2$).

In terms of air quality, however, the unused gases are not dispersed into the atmosphere; instead, these processes end with gas clean-up and then combustion. It therefore seems that the environmental impact should be assessed on the basis of the amounts of contaminants that are emitted after utilization, and since these contaminants are controlled by emission legislation for SOx, NOx, etc., abated plants will always meet the current standards. In terms of control actions, CO2 emissions are penalized by payment of the carbon tax [13].

## 3. Development of a mathematical model to assess the environmental sustainability of UCG CO2 storage

The main purpose of the UCG process is to obtain a sustainable energy source. This process should be aimed at achieving an adequate balance among financial, environmental and social factors during the energy generation process. As a scientific contribution to the effective sustainable environmental management of the UCG process, an innovative numerical model was developed (expressed in terms of an environmental sustainability index (ESI)) to quantify the environmental sustainability situation of the in situ UCG process with CO2 storage. In a given time and space, this parameter allows the definition of an environmental sustainability standard or a minimum permissible level of sustainability for future projects. This approach is based on four environmental indicators: (i) atmosphere quality, (ii) rock and soil subsidence, (iii) groundwater quality and (iv) surface water quality. The main purposes of this index are the establishment of acceptability criteria for new underground coal gasification projects and the optimization of studies for existing installations [14].

The developed quantitative model for the ESI is a function of 4 component indexes: the subsidence sustainability index (SSI), groundwater sustainability index (GWSI), surface water sustainability index (SWSI) and atmosphere sustainability index (ASI). The calculation of these indexes considers the sustainability condition for each pollutant based on threshold limit values given by the existing standards.

The basic equation used for the calculation of the ESI of UCG/CCS is

$$ESI_{UCG} = 0{,}25(SSI + GWSI + SWSI + ASI) \quad (1)$$

A graphical representation of the results is given in Fig. 3.

To calculate the sustainability index (SI) of each component (the SSI, GWSI, SWSI and ASI), the mathematical model uses the condition of sustainability for each element (X and/or X’) based on the standard of sustainability or life quality given for the norms. Three sustainability criteria are used, considering the state of the local environmental conditions (Fig. 4).

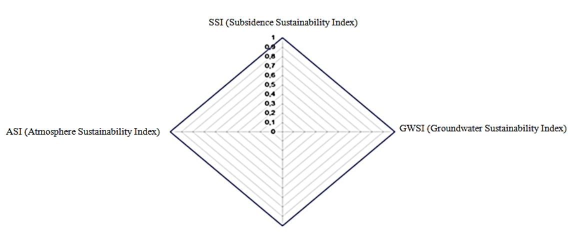


Figure 3. Structure of the environmental sustainability index of UCG.
Source: The Author.

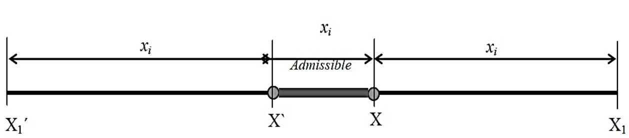


Figure 4. Sustainability criteria.
Source: Navarro Torres V. F. et al, 2012.

Table 1.
Proposals of ESI UCG and ESICO2 for sustainability conditions.

| Sustainability level | Color | Condition based on $ESI_{UCG}$ |
|---|---|---|
| Very Good | | $ESI_{UCG} = 1.00$ |
| Good | | $0.75 < ESI_{UCG} < 1.00$ |
| Moderate | | $0.50 < ESI_{UCG} \leq 0.75$ |
| Low | | $0.25 < ESI_{UCG} \leq 0.50$ |
| Very Low | | $0.0 < ESI_{UCG} \leq 0.25$ |

Source: Navarro Torres V. F. et al, 2011

Sustainability criteria: $X' \leq xi \leq X$ are admissible values, $xi \geq X$ and $xi = X1$ represent unsustainable situations, and $xi \leq X'$ and $xi = X1'$ are unsustainable.

The permissible minimum level of the ESI for UCG and CO2 storage is proposed in Table 1. As the quality of the 4 environmental indicators (subsidence, groundwater, surface water and atmosphere) varies with time, the ESI for UCG and CO2 will also vary.

## 4. Results of the application of the developed model to possible coal deposits

The developed ESI model was applied to real coal deposits, such as in a study of the Dobrudzha area in Bulgaria, the Florina basin in Greece and the Spanish coal deposit El Tremedal (Teruel). Real coal data obtained from each studied area were incorporated into the environmental model, thus improving and enriching the previously created basic ESI model. The four environmental indicators (SSI, GWSI, SWSI and ASI) were calculated for the specific case of the study area considering the condition of the sustainability of each pollutant based on the threshold limit values determined according to the existing standards. The permissible minimum level of the ESI for UCG and CO2 storage was also determined.

It was not possible to find scientific publications on the topic for the purpose of comparison with the results of the present case study because this article is new and innovative.

### *4.1. Subsidence Sustainability Index (SSI)*

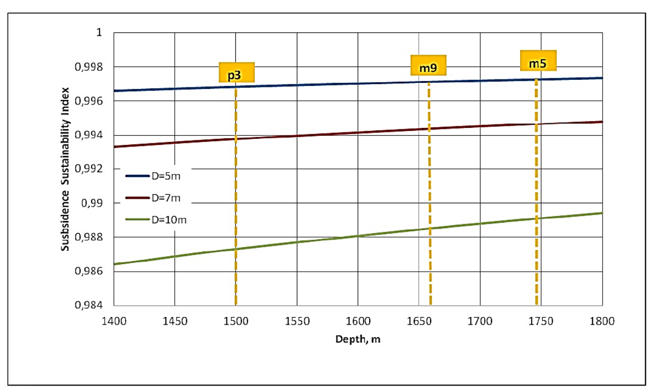


Figure 5. Scenarios of the subsidence sustainability index in the study area for the three selected coal seams and for different cavity diameters (5 m, 7 m and 10 m).
Source: Navarro Torres V. F. et al, 2012.

Considering the particular depth of the study areas, the SSI value is illustrated for different scenarios of cavity diameter (Fig. 6). The results show that the SSI varies from 0.986 to 0.997 (the SSI is practically equivalent to 1), which means that subsidence in the study area will be negligible according to the proposed minimum permissible level of the ESI for UCG and CO2 storage (Fig. 5).

In the room-and-pillar underground Panasqueira Portuguese mine, the simulation results for the geotechnical sustainability index were near 0.90, similar to the results of the present study, which showed higher values because of the better rock mass quality and small rooms [15].

### *4.2. Groundwater Sustainability Index (GWSI)*

The GWSI for the study area was simulated based on six typical environmental indicators associated with UCG processes (n=6): sulfates (SO4), ammonia (NH3), phenols (C6H5OH), polycyclic aromatic hydrocarbons (P.A.H.s), pH, and calcium (Ca2+), and the groundwater quality standard as per Bulgarian regulation N°1 of 10 October 2007 on the basis of the exploration was used. The index was calculated for two cases: (a) for pH values <6.5 and unsustainable pH=0 and (b) for pH values >9.5 and unsustainable pH=14. The results from the simulations of GWSI behavior illustrate the great variability and sensitivity of diverse pollutants of groundwater. Therefore, it is important to apply preventive measures in the study area because of the aquifers it contains.

### *4.3. Surface Water Sustainability Index (SWSI)*

While there is no significant presence of rivers at the surface in the study area, appropriate preventive measures should be used mainly because of the occurrence of the recharge areas of the aquifers. The SWSI values are assumed to have very good performance (with mean values near 1).

### *4.4. Atmosphere Sustainability Index (ASI)*

The ASI behavior for hypothetical UCG in the study area was simulated based on four environmental indicators (r=4) using average atmospheric quality standard values. The ASI was calculated for two cases: (a) for $H_2$<4% and $CH_4$<5% and unsustainable $H_2$=0 and $CH_4$=0 and (b) for $H_2$>74.2% and $CH_4$>14% and unsustainable $H_2$=100 and $CH_4$=100. The simulation results for ASI behavior for $CO_2$ gas variation of 0 to 8000 ppm for $H_2$=3% and $CH_4$=0 and for $CH_4$=4 and CO=25 ppm are shown in Fig. 6a. The simulation results for ASI behavior for CO gas variation of 0 to 100 ppm for $CH_4$=25% and $H_2$=74.2% and for H2=100% and $CO_2$=1000 ppm are shown in Fig. 6b.

Applying the ESI model to the selected sites shows that subsidence in the study area will be negligible, the GWSI value will be high, and the SWSI value should be very good (due to the absence of surface waters in the area) and that the ASI behavior associated with several environmental pollutants shows high sensitivity to an increase in $CO_2$

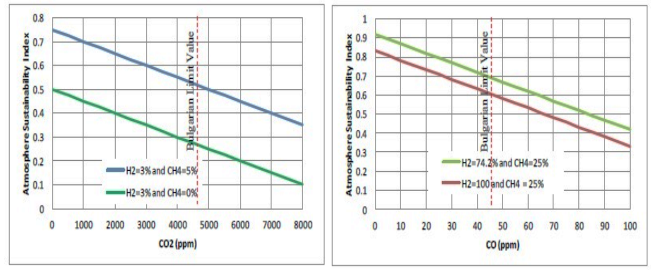


Figure 6. (a) ASI behavior for $CO_2$ and $H_2$=3% and for $CH_4$=0 and $CH_4$=5% when CO=25 ppm; (b) ASI behavior for CO under $CH_4$=25% and $H_2$=74.2% and under $CH_4$=25% and $H_2$=100% when $CO_2$=1000 ppm.
Source: Navarro Torres V. F. et al, 2012.

concentration when compared to that associated with an increase in CO emissions.

These results indicate that the mathematical model developed for ESI has excellent applicability for quantitative sustainability assessment of the UCG and $CO_2$ storage process. However, to improve the quality of such evaluations, there is a need to introduce additional information not only from bibliographic sources but also from field data collected in accordance with the requirements of the sustainability analysis.

## 5. Conclusions

The application of the mathematical model developed for the quantification of the environmental sustainability of a mining operation showed excellent adaptability and results for the assessment of sustainability in the mineral industry and particularly under UCG.

The developed mathematical model was applied for the analysis of the sensitivity of the ESI in association with UCG and CCS in a study of the Dobrudzha coal basin in Bulgaria.

The results of this application for this coal basin were very good in terms of geotechnical sustainability (ESI ~1), there were no significant impacts to surface water or groundwater ($_{\text{ESI}}$ ~1), and low to moderate atmospheric sustainability was demonstrated (ESI ~0.3 to 0.7), indicating the need for combination with $CO_2$ storage information to facilitate the reduction of greenhouse gas emissions.

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