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Assessment of an Environmental Sustainability Index for the Underground Coal Gasification Process by Using Numerical Analysis

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ASSESSMENT OF AN ENVIRONMENTAL SUSTAINABILITY INDEX FOR THE UNDERGROUND COAL GASIFICATION PROCESS BY USING NUMERICAL ANALYSIS

Vidal Navarro Torres[1], Anthony Steven Atkins[2] and Raghu Nath Singh[3]

ABSTRACT: In this study, an innovative numerical model is developed to quantify the environmental sustainability situation of an in-situ underground coal gasification (UCG) process which is expressed in terms of an Environmental Sustainability Index (ESI). This approach is based on four environmental indicators, namely: (i) rock and soil subsidence, (ii) groundwater quality, (iii) surface water quality and (iv) atmospheric quality, respectively. Based on the ESI values, this paper proposes a methodology for classifying the environmental sustainability state of the underground coal gasification (UCG) process and also proposes the corresponding Threshold Limit Value. Finally, a mathematical model is developed which is applied to El Tremedal Spanish trial.

INTRODUCTION

The Underground Coal Gasification (UCG) technique is an environmentally friendly process of extracting thermal energy compared to conventional underground and surface coal mining operations. The UCG process produces gas suitable for high-efficiency power generation by providing high-pressure product gas which can be easily treated to eliminate solid waste discharge and also has fewer particulates such as NOx and SOx. The UCG cavity is a potential for CO2 sequestration locations and a source of low-carbon hydrogen for transport and other applications. In spite of these potential benefits, the process still creates environmental risks.

The UCG process, involves air or oxygen pumped into an underground coal seam through an injection well. The introduction of an oxidizing gas produces heat, which partially combusts the coal in-situ and creates the synthesis gas (syngas) product Friedman(2009), primarily composed of hydrogen, carbon monoxide, and smaller amounts of carbon dioxide and methane Friedman (2009), Stephen *et al*. (1985). The syngas is extracted from the UCG burn cavity by a production well, which brings the gas product to the surface for energy or power station utilization.

A review of the world´s historical UCG sites in the former Soviet Union, Europe, United States, New Zealand, Australia and China between 1974 and 2002 revealed a limited number of pilot projects and full-scale operations, suggesting two main environmental risks associated with UCG processes.

Firstly there is a risk of groundwater contamination and organic contaminants such as Polycyclic Aromatic Hydrocarbons (PAHs) may be generated during combustion of coal, and trace metals in the coal may be released through geochemical reactions induced by the UCG process. Contaminants may also be released from adjacent geological formations and these organic and metal contaminants could migrate and contaminate groundwater aquifers. Secondly, because the *in situ* burning of coal creates cavities in the subsurface, there is a risk of ground subsidence, whereby the overlying rock layers partially collapse into the newly created void space. Subsidence creates a hazard for any surface infrastructure that might be present above the UCG zone, and may create detrimental changes in surface or groundwater hydrology above the cavity (Sury, *et al*., 2004, Walter, 2007).

Another potential environmental impact risk in UCG constitutes the atmosphere air pollution following gas utilization and surface water pollution. These UCG environmental situations need to be managed on the basis of sustainability. In this context, the research focuses on the Environmental Sustainability Index and will be an important contribution to sustainable UCG. Currently there are no standard references for the assessment of sustainability levels and this paper makes an attempt to quantitatively

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assess by developing and Environmental Sustainability Index (ESI) for UCG (Navarro Torres, Singh and Pathan, 2008), based on four main environmental indicators: atmosphere quality, surface water quality, rock and soil subsidence, and groundwater quality.

The quantitative model to calculate the environmental sustainability condition developed by the first author (Navarro Torres) was first applied to underground mines in 2006 having been introduced to model three environmental indicators: geotechnical, groundwater and underground atmosphere (Navarro and Dinis, 2006). Based on these encouraging results, in 2008 this was applied to mine water environmental assessment considering three environmental indicators: physic-chemical properties, toxic components and other components (Navarro, *et al*., 2008).

In both cases the results were excellent, so it was decided to apply this concept and develop the numerical model of the environmental sustainability in UCG process based on the Environmental Sustainability Index (ESI).

POTENTIAL OF ENVIRONMENTAL IMPACT IN UCG

Environmental interactions in the UCG process

In the UCG process the physic-chemical interactions changes the natural stress state in the surrounding rock mass, influencing in contaminants formations in the UCG reactor and through the surrounding ground, as well as inducing potential subsidence and pollutions of the groundwater, surface water and atmospheric Quality (Figure 1).

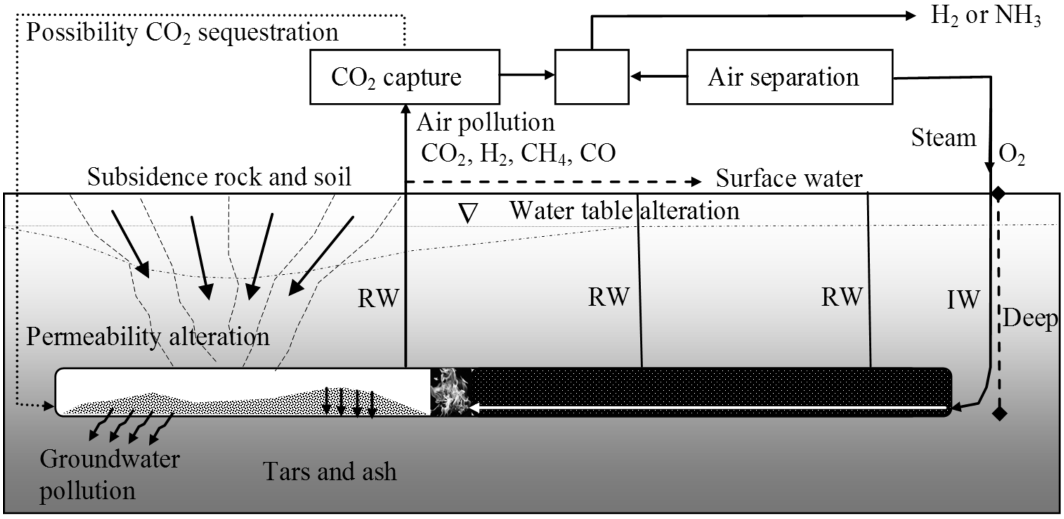

Figure 1 - Summary of UCG vs. environment interactions

Drilling and gasification actions would cause important alteration in the rock mass and in the virgin water table. These alterations would adversely influence the effects of subsidence. The gasification cavities of the coal seams are sources of gaseous and liquid pollutants and they constitute some environmental risks to groundwater in the adjacent strata, depending on whether the contaminants can migrate beyond the immediate UCG reactor zone.

Characterisation of the environmental indicators in the UCG process

Subsidence

In the UCG process, the potential of subsidence will be quite small compared to underground mining, as exemplified in Centralia and Chinchilla where negligible subsidence was experienced (Friedman and Upadhye, 2004). However, subsidence risk is present, as demonstrated by numerical modelling results (Ren, *et al*., 2003), while observed important displacements occurred around UCG cavities. In the UCG process an underground cavity is opened from coal seam burning into a stressed rock mass and the stresses in the vicinity of the new opening are re-distributed.

Before the cavity is opened, *in situ* stresses are uniformly distributed in the area of rock under consideration. After removal of the coal seam from within the cavity, the stresses in the immediate vicinity of the cavity are changed and new stresses are induced. The stresses values are varied depending of depth, the structural and geotechnical properties of the rock mass surrounding UCG cavity. As the induced stresses overcome the tensile or compressive rock mass strength this will cause failure and a potential horizontal or vertical extension of the cavity and may ultimately lead to a subsidence above cavity (Hoek, 2000, Navarro, *et al*., 2011).

Ground water contamination

The main pollutants of groundwater quality in UCG are results of the coal burning processes; these could include benzene, toluene, ethyl-benzene, and xylenes (BTEX), phenols, coal ash and tars, aromatic hydrocarbons and sulphides, NO_X, NH_3, boron, cyanide, CO and H_2S (Creedy, *et al*., 2001) (Table 1). Phenol leachate is regarded as the most significant environmental hazard due to its high water solubility and high affinity to gasification (Shuquin and Jun-hua, 2002).

Uncontrolled migration and leakage of the syngas itself could result in contamination of overlying aquifers. In addition, bye-products, such as organic contaminants (PAHs, phenols, and benzene), as well as inorganics (sulphate, boron, and metals and metalloids such as mercury, arsenic, and selenium), may be inadvertently generated from the coal during the UCG process (Sury, *et al*., 2004; Liu, *et al*., 2006). Mercury, arsenic, and selenium are volatile, and they can also be released as gases during the UCG process . Their liberation could possibly negatively affect the underground water and air qualities.

Table 1 - Main groundwater pollutants found in Texas UCG pilot sites (Creedy, *et al*., 2001)

Chemical constituent		Before burn	After burn	Increase	
Name	Symbol	(mg/l)	(mg/l)	(mg/l)	%
Hydrogen sulphide	H_2S	4	1150	1146	28650
Ammonia	NH_3	1	100	99	9900
Phenols	C_6H_5OH	0.1	20	19.9	19900
Acidity	pH	-	7.6	-	-

Rock masses, the mineralogy and trace impurities, immediately adjacent to the targeted coal seam will also likely be influenced by UCG operations, and thus, oxidation and other geochemical processes in the surrounding rock could also result in the release of contaminants (Stratus Consulting Inc. 2010).

Surface water contaminations

The potential pollution of surface water in UCG is extremely low, and the common pollutants are phenols, ammonia, chemical oxygen demand (COD), pH, conductivity and sulphides (Sury, *et al*., 2004). 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 phenol (500 ppm) (Green, 1999).

Atmosphere contamination

The major constituents of the product gas from UCG are CO2, H2, CH4, and CO. An example for UCG trial process for bituminous coal with sulphur, chlorine and nitrogen contents of 2.0%, 0.8% and 0.2% in weight respectively give a product gases emission which was 22.7% of H2O, 46.1% of CO2, 19.2% of CO, 9.4% of CH4, 1.6% of H2 and 1.0% of others (H2S, HCl, N2).

For air quality, however, the unused gases are not put into the atmosphere, but this process end by gas clean-up and then combustion. It seems therefore, that the environmental impact should be assessed on the amount of contamination that is emitted after utilization, and since these are controlled by emissions legislation for SOx, NOx, etc, the abated plant will always meet the current standards. For control action the CO2 emissions are penalised by payment of the carbon tax (Green, 1999).

MATHEMATICAL MODEL TO ASSESS AN ENVIRONMENTAL SUSTAINABILITY INDEX FOR UCG

Structure of Environmental Sustainability Index of UCG

The key for sustainable development of UCG will comprise of three "basic pillars": economic, social and environmental. In the present paper a quantitative model is developed to assess the environmental component of UCG process, which is called the Environmental Sustainability Index (ESI_{UCG}) (Figure 2).

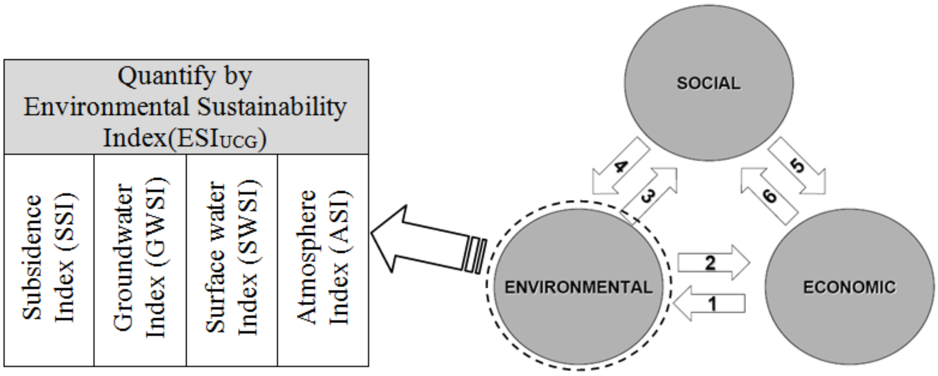

Figure 2 - Pillars of UCG sustainable development and quantification of the environmental components by environmental sustainability index

The global quantitative expression of sustainable development (SD) in UCG is a complex task since it involves a large numbers of parameters (6 shown in Figure 2) and data involved throughout the life cycle of the UCG process. In the proposed model the expression of the SD by Sustainability Index that is an innovative and important method, because it allows a quantification of SD and enables efficient management of SD, compared with admissible sustainability values previously defined.

The proposed ESI_{UCG}, is a composite of a four dimensional structure as shown in Figure 3, that is formed by indicators which have many sub-indicators depending on the type, dimension, location and other characteristics of the UCG operations.

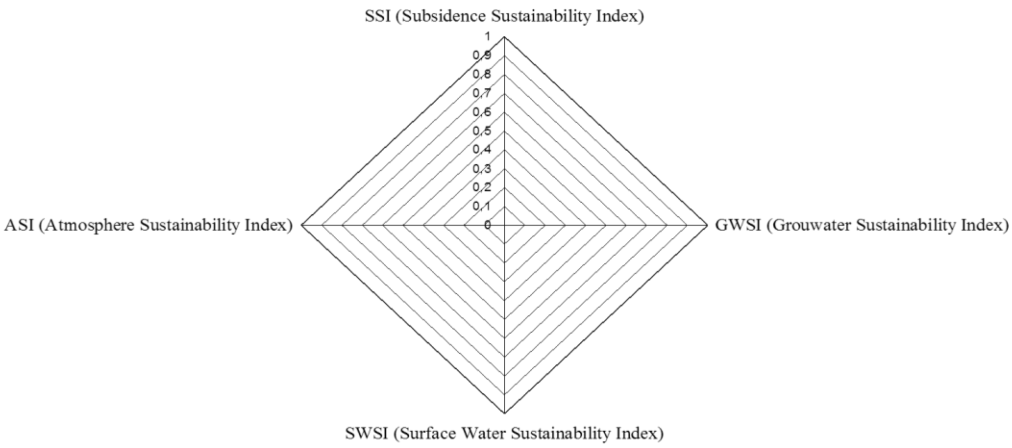

Figure 3 - Structure of Environmental Sustainability Index for UCG

The relationship between the four SD indicators of the potential environmental impact and the Environmental Sustainability Index of the UCG (ESI_{UCG}) is given by equation (1), which is a function of a Subsidence Sustainability Index (SSI), Groundwater Sustainability Index (GWSI), Surface Water Sustainability Index (SWSI) and Atmosphere Sustainability Index (ASI).

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

Equation (1) expresses the Environmental Sustainability Index of the UCG process based on the criterion of equal weighting of the four environmental indicators. Section 2.2 i of this paper shows that in the UCG process, where contamination of groundwater and subsidence are major environmental hazards and the pollution of surface and atmosphere have only a few incidences there is still a potential risk. This difference in size or occurrence of each of the four environmental indicators are considered in their specific mathematical models and presented as follow.

To calculate the sustainability index (SI) of each component, the condition of sustainability of each pollutant is based on environmental standards given for the norms. Three criteria are taken considering the local environmental condition with variable xi:

1) When the sustainability is $x_i \leq X$, when X is maximum standard
2) When the sustainability is $x_i \geq Y$, when Y is minimum standard
3) When the sustainability is $Y \leq x_i \leq X$, when Y and X are minimum and maximum standards.

Considering the conditions of criterion 1, the SI can be calculated using the equation (2), based on condition $x_i \leq X$. In this criterion when x_i values are less the sustainability is high. In this case X is a maximum standard (Figure 5).

$$SI = 1 - \left| \frac{x_i}{X} \right| \tag{2}$$

Incorporating the following two conditions:

1) If $x_i = X$ or $x_i > X$ $\rightarrow$ SI = 0
2) If $x_i = 0$ $\rightarrow$ SI = 1

In the conditions of criterion 2, the SI can be calculated using the equation (3), based on condition $xi \geq Y$ where high values of xi generate high values of sustainability. In this case X corresponds to a minimum standard (Figure 6).

$$SI = \left| \frac{x_i}{Y} \right| \tag{3}$$

Incorporating the following two conditions:

1) If $x_i = Y$ or $x_i > Y$ $\rightarrow$ SI = 1
2) If $x_i = 0$ $\rightarrow$ SI = 0

Considering the criterion 3 for minimum and maximum admissible standards values, the SI can be calculated using equation (4) when $x_i \geq X$ and when $xi = X_1$ is unsustainable and, also considering the criterion 3, the SI can be calculated by equation (5) when $xi \leq Y$ and $xi = Y_1$ is unsustainable.

If

$$x_i \geq X \rightarrow SI = 1 - \frac{x_i - X}{X_1 - X} \tag{4}$$

Incorporating the following two conditions:

1) If $Y < x_i < X$ or $x_i = X \rightarrow$ SI = 1
2) If $x_i = X_1 \rightarrow$ SI = 0

If $x_i < Y \rightarrow SI = 1 - \frac{Y - xi}{Y - Y_1}$ (5)

Incorporating the following two conditions:

1) If $Y < x_i < X$ or $x_i = Y \rightarrow$ SI = 1
2) If $x_i = Y_1 \rightarrow$ SI = 0

Subsidence Sustainability Index (SSI)

Reactor cavities formed during UCG process may affects the surface and subsurface structures (such as landscapes, surface water, water table, etc.), but their presence also alters ground movement around these cavities. The terms defining the geometry and settlement and the coordinate system which will be adopted throughout this paper are defined in Figure 4.

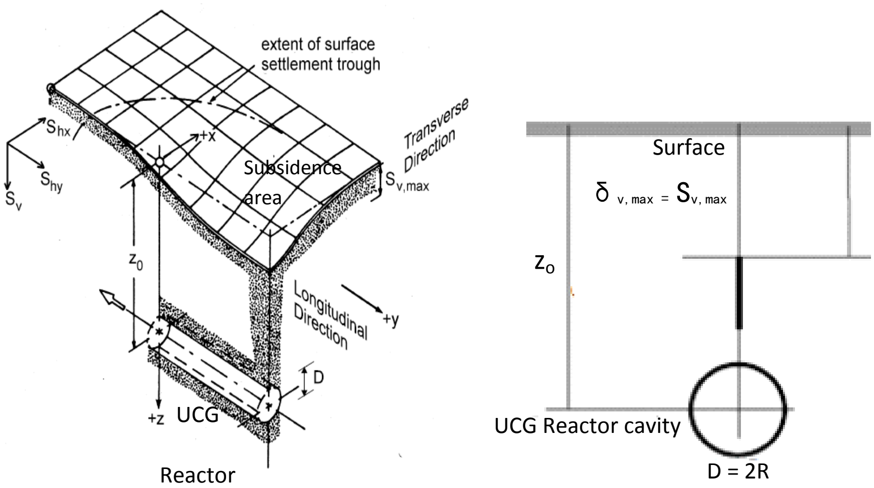

Figure 4 - Subsidence model of UCG process and parameters influencing ESI_{UCG}

Building risk damage from subsidence classification is based in horizontal tensile strain in five categories:

- categories 0 to 2 (εh = 0 – 0.15%) correspond to aesthetical damage,
- serviceability damage occurs in categories 3 and 4 (εh = 0.15 – 0.3%)
- stability of the structure is affected by damage of category 5 (εh>0.3%) (17).

Horizontal tensile strain develops as a change in length *over* the corresponding length.

The mathematical model for obtaining SSI is based on the limiting horizontal tensile strain as given in Table 2, where εh > 0.15. Using the limiting values of the potential damage to the modern infrastructures (buildings) in equation (2), the subsidence sustainability index (SSI) can be calculated by using equation (6) as follows:

$$SSI = 1 - \frac{\varepsilon_h}{\varepsilon_{h(L)}} = 1 - 6.67\varepsilon_h \quad (6)$$

where,

ε_h, horizontal soil displacement (%) as calculated by equation (7), and
$\varepsilon_{h(L)}$ is the admissible horizontal soil displacement (0.15%).

Note : $\varepsilon_{h\,(L)}$: Limiting Tensile strain

$$\varepsilon_h = \frac{\delta_{v,\max}}{z_o}\left(\frac{x^2}{i^2{}_x} - 1\right) \tag{7}$$

In Equation (3) $\delta_{v,\max}$ is the maximum vertical settlement above the reactor cavity axis and can be calculated by equation (8), z_o is the depth of the cavity axis below the surface, x that denotes the distance from the tunnel centre line in the transverse direction and i_x is the distance of cavity axis to the point of inflection in Gauss curve as shown in Figure 4.

Table 2 - Subsidence standard based in the limiting tensile strain (Burland, 1995)

Category of Damage	Normal Degree of Severity	Limit Value- $\varepsilon_{h(L)}$(%)
0	Negligible	0-0.05
1	Very slight	0.05-0.075
2	Slight	0.075-0.15
3	Moderate	0.15-0.3
4 to 5	Severe to Very severe	>0.3

$$\delta_{v,\max} = \sqrt{\frac{\pi}{2}}\frac{V_L D^2}{4i_x} e^{\frac{x^2}{i^2{}_x}} \tag{8}$$

where V_L is the volume loss calculated by equation (9) based on Borms and Bennemark proposals(9) and D is the reactor cavity diameter (Figure 5).

$$V_L = 1.33\left(\frac{P_t - P_s}{\sigma_t}\right) - 1.4 \tag{9}$$

where,

P_t is the total overburden pressure at tunnel axis level (including any surcharges);

P_s is the cavity pressure (if present), and

σ_t is the un-drained shear strength of rock or soil.

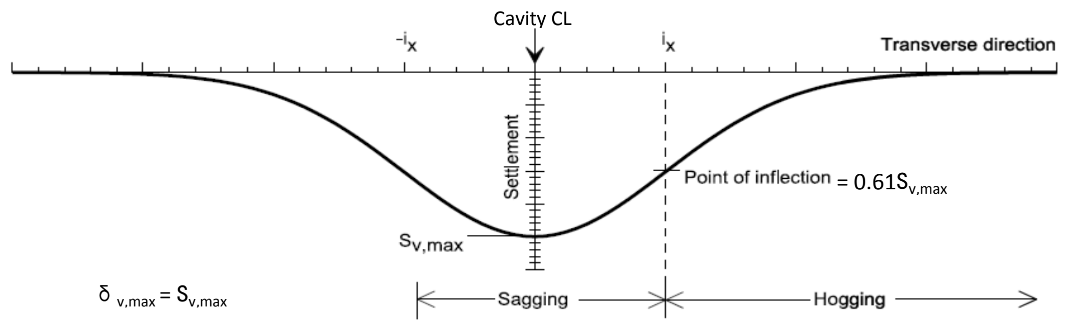

Figure 5 - Gauss curve of displacements in transverse direction

Groundwater Sustainability Index (GWSI)

The groundwater sustainability index (GWSI) can be calculated by using equation (10).

$$GWSI = \frac{1}{n}\left(n - \frac{\sum_{i=1}^{l_1} GW_{1(i)}}{l_1.LV_1} - \frac{\sum_{i=1}^{L_2} GW_{2(i)}}{l_2.LV_2} - \frac{\sum_{i=1}^{l_3} GW_{3(i)}}{l_3.LV_3} - .... - \frac{\sum_{i=1}^{l_n} GW_{n(i)}}{l_n.LV_n} \right) \tag{10}$$

where,

n is the number of groundwater pollutants,

$l_1, l_2, l_3, \ldots l_n$ are local quantities,

$GW_1, GW_2, GW_3, \ldots, GW_n$ are groundwater pollutants and

$LV_1, LV_2, LV_3, \ldots, LV_n$ are limit values of the groundwater quality standard.

For six environmental indicators number (n=6), when pollutants are Hydrogen sulphide (H_2S), Ammonia (NH_3), Phenols (C_6H_5OH), pH, conductivity (C) and Benzene (C_6H_6), using the average Groundwater Quality Standards (Table 3) and applying equation (2), the groundwater sustainability index (GWSI) can be calculated for the following two conditions:

(a) For the pH values <6 and unsustainable pH=0, applying equation (4) results in equation (11);

(b) For pH>9 and unsustainable pH=14, applying equation (5) results in equation (12).

Thus, for pH<6 and unsustainable pH=0:

$$GWSI = 0.8 - 2.86H_2S - 8NH_3 - 0.0033C_6H_5OH - 0.04C_6H_6 - 0.0002C + 0.03pH \quad (11)$$

For pH>9 and unsustainable pH=14:

$$GWSI = 1.3 - 2.86H_2S - 8NH_3 - 0.0033C_6H_5OH - 0.04C_6H_6 - 0.0002C - 0.04pH \quad (12)$$

Table 3 - Groundwater quality standards (Wisconsin Natural Resource Board, 2008; State Water control Board, 2004)

Pollutant	Limit Value	Institution	Application
H_2S	0.07 mg/kg	US – EPA, 2004	Human health
NH_3 (N_2)	0.025 mg/l	Virginia State, US, 2004	Public health or welfare
C_6H_5OH	6 mg/l	Wisconsin State, US, 2008	Public Health
pH	6 – 9	Virginia State - US , 2004	Public health or welfare
C_6H_6	5 µg/l	Pennsylvania State, US, 2001	Public health
Conductivity	1000µS/cm	European quality at 20 ºC	Public health

It is well known that the pH scale ranges from 0 to 14 and it measures the acidity for values less than 7; with a pH value of 7 is neutral and a pH greater than 7 is basic. The pH=0 and pH=14 are unsustainable values, because they represent the extreme acidic and basic conditions.

Surface Water Sustainability Index (SWSI)

The surface water sustainability index (SWSI) can be calculated by using equation (13) as follows:

$$SWSI = \frac{1}{m}\left(m - \frac{\sum_{i=1}^{l_1} SW_{1(i)}}{l_1.VL_1} - \frac{\sum_{i=1}^{L_2} SW_{2(i)}}{l_2.VL_2} - \frac{\sum_{i=1}^{l_3} SW_{3(i)}}{l_3.VL_3} - \text{........} - \frac{\sum_{i=1}^{l_m} SW_{m(i)}}{l_m.VL_m} \right) \quad (13)$$

where,

m is the surface water pollutants quantity;
$l_1, l_2, l_3, \ldots l_m$ are local quantity;
$SW_1, SW_2, SW_3, \ldots, SW_m$ are surface water pollutants and
$LV_1, LV_2, LV_3, \ldots, LV_m$ are limit values of surface water quality standard.

For the following four environmental indicator (m=4): Phenols (C_6H_5OH), Ammonia (NH_3), pH and Conductivity using the Surface Water Quality Standards (Table 4 and applying equation (2) for pH values between 6 to 9, the surface water sustainability index (SWSI) can be calculated for the following two conditions:

(a) Applying equation (4) when pH<6 and unsustainable when pH=0, and results in equation (14) as follows.

$$SWSI = 1 - 250C6H5OH - 10NH_3 - 0.00025Conduct + 0.042pH \quad (14)$$

(b) For pH>9 and unsustainable pH=14: results are given by equation (15)

$$SWSI = 1.45 - 250C6H5OH - 10NH_3 - 0.00025Conduct - 0.05pH \tag{15}$$

Table 4 - European surface water quality standards

Pollutant	Limit Value	Application
C_6H_5OH	0.001 mg/l	Human
NH_3 (N_2)	0.025 mg/l	Fish
pH	5.5 – 9.0	Human
Conductivity	1000 to μS/cm at 20 ºC	Human

Atmosphere Sustainability Index (ASI)

The Atmosphere Sustainability Index (ASI) in UCG process will be calculated by equation (16) where *s* is the number of atmosphere pollutants; *l* is the local quantity around the emission points.

$$ASI = \frac{1}{p}\left(p - \frac{\sum_{i=1}^{l_1} A_{1(i)}}{l_1.VL_1} - \frac{\sum_{i=1}^{l_2} A_{2(i)}}{l_2.VL_2} - \frac{\sum_{i=1}^{l_3} A_{3(i)}}{l_3.VL_3} - .... - \frac{\sum_{i=1}^{l_p} A_{p(i)}}{l_p.VL_p} \right) \tag{16}$$

where,

p is the atmosphere pollutants quantity;
$l_1, l_2, l_3, \ldots l_p$ are local quantity and ASI;
$A_1, A_2, A_3, \ldots, A_n$ are groundwater pollutants and
$LV_1, LV_2, LV_3, \ldots, LV_p$ are limiting values of air quality standard.

For four environmental indicators (r=4), using average values of Atmospheric Quality Standards (Table 5 and applying equation (16) for CO_2 and equation (2) for CO, and equations (4) and (5) for H_2 and CH_4 gases respectively, results in equations (17) and (18). The H_2 standard varies from 4% to 74.2% and CH_4 from 5% to 14%.

(a) For H_2<4% and CH_4<5% and unsustainable H_2=0 and CH_4=0: equation (17) gives:

$$ASI = 0.5 - 0.00005CO_2 + 0.063H_2 + 0.05CH_4 - 0.005CO \tag{17}$$

(b) For H_2>74.2% and CH_4>14% and unsustainable H_2=100 and CH_4=100: equation (18) represents:

$$ASI = 1.76 - 0.00005CO_2 - 0.0097H_2 - 0.0029CH_4 - 0.005CO \tag{18}$$

Table 5 - Atmosphere quality standard (Navarro, 2006)

Pollutant	Limit Value	Institution
CO_2	5000 ppm	Mine Safety and Health Administration - USA
H_2	4% - 74.2%	Bureau of Mines Diagram - USA
CH_4	5% - 14%	Bureau of Mines Diagram - USA
CO	50 ppm	Mine Safety and Health Administration - USA

The environmental pollutant quantities (n, m, s) depend upon geological, hydro-geological, physicochemical, operational conditions, etc. of UCG process.

PROPOSED PERMISSIBLE MINIMUM LEVEL OF ESI $_{UCG}$

Proposed ESI_{UCG} levels and sustainability criteria

The proposals of ESI_{UCG} for standardizing the permissible minimum level of SD in UCG are expressed by coefficients varying between 0 and 1, Table 6.

Table 6 - Proposals of ESI_{UCG} for permissible minimum level assessment

ESI_{UCG}	ESI_{UCG}	ESI_{UCG}	ESI_{UCG}	ESI_{UCG}
0.0 ≤0.25	0.25 ≤0.50	0.50 ≤0.75	0.70 ≤1.00	1.00
Very Low	Low	Moderate	Good	Very Good

The UCG sustainability will vary when subsidence, groundwater, surface water, and atmosphere quality vary with time. The permissible sustainability is obtained when ESI_{UCG} is 1 (Figure 6).

Environmental quality standards

The UCG subsidence assessment can be used to evaluate the type of damage to landscape, or buildings, etc. In this paper, a typical example of possible building damage is based on the tensile strain (Wisconsin Natural Resource Board Rules, 2008) (Table 2).

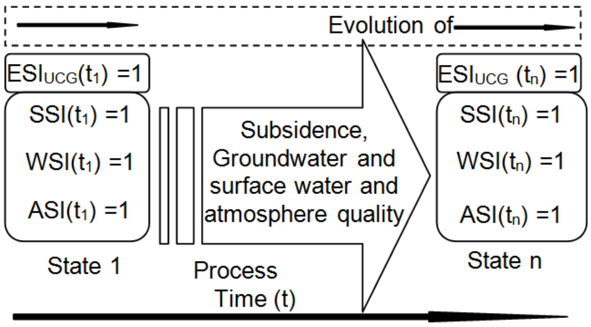

Figure 6 - Permissible level of Environmental Sustainability Index of UCG

Normally each region or countries have the groundwater quality standards for substances of public health or environmental goal (Navarro, 2006; El Tremedal, Final Summary Report, 1999) (Tables 3).

Based on the main potential pollutants for surface water as phenols, ammonia, chemical oxygen demand (COD), pH and conductivity, as an example are shown in the Table 4, the European surface water quality standard. As discussed earlier, the major and main potential pollutant gases emitted in the UCG process are CO_2, H_2, CH_4, and CO. The atmospheric air quality standard is presented in Table 5.

NUMERICAL MODEL APPLICATION TO THE EL TREMEDAL SPANISH CASE-HISTORY

Technical data of El Tremedal Spanish trial

The mathematical model developed above was applied to the El Tremedal trial of UCG in the Province of Teruel, Spain, with the following site characteristics:

- two dipping coal seams separated by 7 to 14 metres of limestone,
- depth of 500-700 metres and
- a seam thickness varies between 1.9 and 7.0 metres with
- a thin layer of carbonaceous clay lays under both coal seams and
- an area of continuous coal seam is at least 200 metres from any significant faults (Figure 7).

The following conditions are assumed for the measured environmental indicators in the El Tremedal trial:

- measured pollutants concentrations would be similar with hypothetical production at commercial level; measured pollutants values used any after remedial action.

- In a hypothetical production at commercial level applied to the CO_2 capture and underground sequestration technique; in local atmospheric air velocity the CO gas dilution even 50 meters surrounding emission point at average 40 ppm.

9Main environmental results

In El Tremedal UCG Spanish trials there is no report on the soil or rock subsidence because the site condition is not favourable for potential subsidence.

For the El Tremedal trial, excess water is produced during gasification and the main pollutants show in Table 7. The product gas composition in the 1^{st} and 2^{nd} gasification period was 14% of CO_2, 12.8% of CO, 24.8% of H_2, 13.2% of CH_4 and 8.3% of H_2S (Table 8 and Figure 8) (El Tremedal, Final Report 1999).

In the El Tremedal UCS trial project the environmental impact observed on the surface facilities and the plant operations including surface water are shown in Tables 7 and 8 (Skousan, *et al*., 2000).

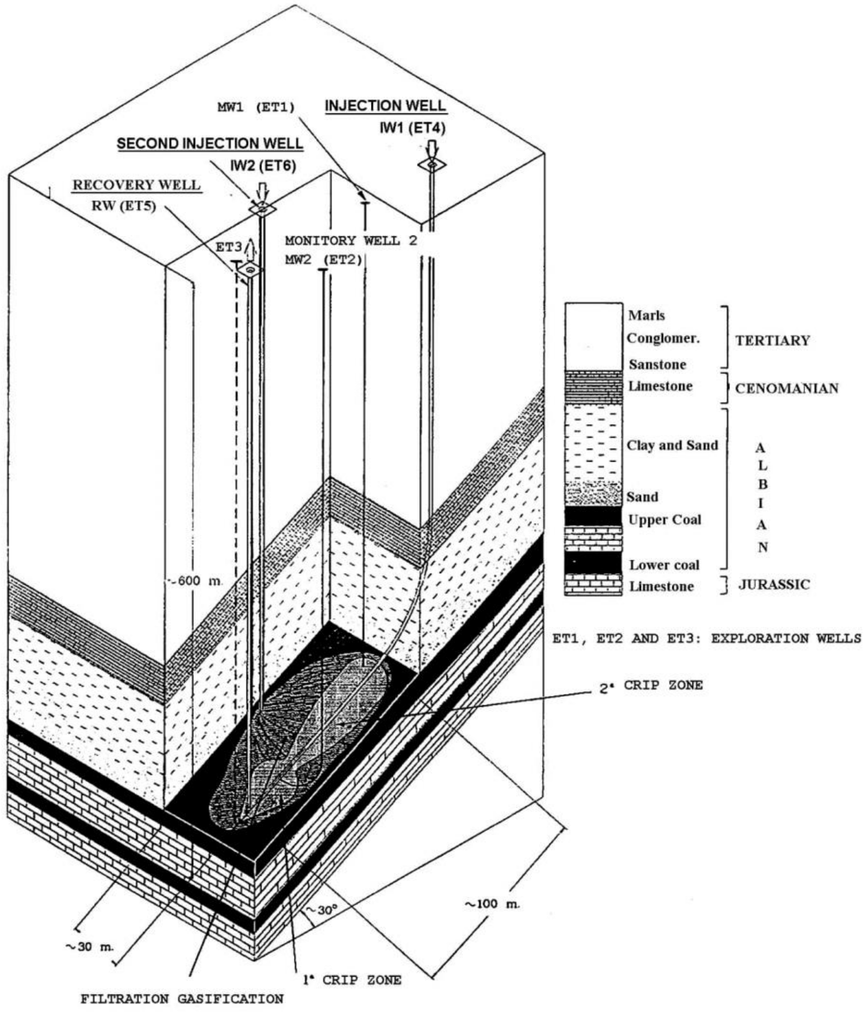

Figure 7 - Geological and well layout of El Tremedal UCG trial (Skousen, *et al*., 2000)

Table 7 - El Tremedal wastewater record concentrations (Sury, *et al*., 2004)

Pollutants	Record Concentrations	Pollutants	Record Concentrations
Phenols	2.6 - 575 ppm (0.26 – 57.5 mg/l)	Conductivity	1410 – 5640 μ S/cm
Ammonia	5.9 - 1080 ppm (0.59 – 108 mg/l)	COD	102 – 5880 ppm
Sulphurs	0.94 - 148 ppm (0.095 – 14.8 mg/l)	pH	8.4 – 7.6

Table 8 - Product Gas Composition in El Tremedal Trial (El Tremedal Final Report, 1999)

Product Gas	Gasification Period		Total	
	I[st]	2[nd]	%	ppm
CO_2	43.4%	39.4%	41.0	410000
CO	8.7%	15.6%	12.8	128000
H_2	24.9%	24.7%	24.8	248000
CH_4	14.3%	12.4%	13.2	132000
H_2S	8.8%	7.9%	8.3	83000

Environmental Sustainability of El Tremedal UCS trial

Calculation of SSI

The subsidence sustainability index (SSI) is calculated by using equation 6, taking the horizontal soil displacement $\varepsilon_{h(L)}$ as 0 that is negligible according to the standard quality adopted, and
SSI= 1- $\varepsilon_{h/}\,\varepsilon_{h(L)}$= 1- 6.67 x 0+ 1

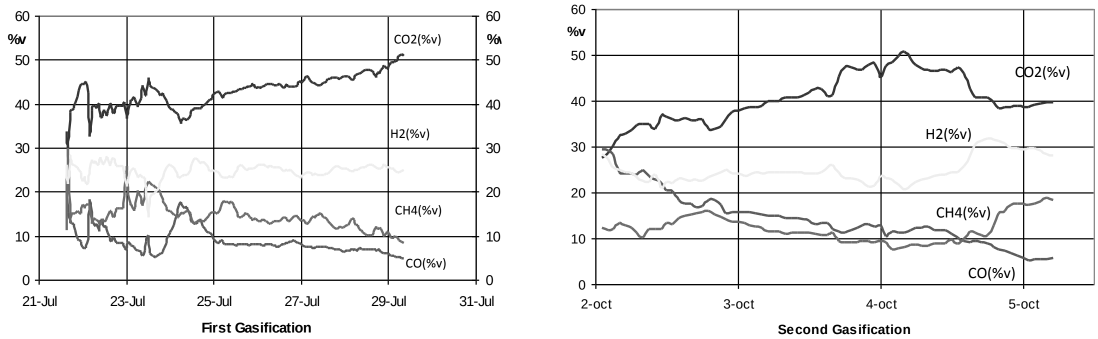

Figure 8 - Gas Composition on Dry N_2 Free – 1[st] Gasification and 2[nd] gasification period (Skousan, *et al*., 2000)

Calculation of GWSI

For calculating the Ground Water Sustainability Index (GWSI), it is necessary to analyse pH as a measured pollutant that varies between the permissive limits of Groundwater Quality Standard between7.6 and 8.4, therefore the sustainability index of this pollutant is 1. Based on this result, with groundwater standards presented in Table 3 (H_2S=0.07 mg/kg, NH_3=0.025 mg/l, C_6H_5OH=6 mg/l, Conductivity=1000 μs/cm-1) are applied to equations (2), (4) and (5) resulting in equation (10) as follows:

$$GWSI = \frac{1}{5}\left(1-\frac{H_2S}{0.07}+1-\frac{NH_3}{0.025}+1-\frac{C_6H_5OH}{6}+1-\frac{C}{1000}+1\right)$$

However, the four environmental groundwater indicators measured in El Tremedal as shown in Table 8 are greater than groundwater quality standards (Table 4) except pH. For these situations applying four pollutants values (H_2S, NH_3, C_6H_5OH and Conductivity) to equation (10) and equation (2), the ground water sustainability Index is calculated, using

$x_i = X$ or $x_i > X \quad \rightarrow$ SI = 0 , as follows:

$$GWSI = \frac{1}{5}\left(0+0+0++0+1\right) = 0.25$$

Appling equation (13) to the condition of equation (2) for SWSI calculation, with SI_{pH}=1 for Surface Water Quality Standard, the general equation for the main pollutants result in the following equation:

$$SWSI = \frac{1}{4}\left(1-\frac{C_6H_5OH}{0.001}+1-\frac{NH_3}{0.025}+1-\frac{C}{1000}+1\right)$$

In El Tremedal UCG trial no report of surface water pollution was obtained. Therefore, the pollutant value is taken as zero and the SWSI result is as follows:

$$SWSI = \frac{1}{4}(1+1+1+1) = 1$$

Calculation of ASI

Finally, in order to calculate atmospheric Sustainability Index (ASI) air pollutants CO_2, H_2, CH_4 and CO are measured in El Tremedal trial. Concentrations of pollutants H_2 and CH_4 are 24.8% and 13.2%, respectively, applying to Equations 16 and equation (2) and CH_4 which is applying the equation (16) and equation (2) results in the following equation:

$$ASI = \frac{1}{4}\left(1 - \frac{CO_2}{5000} + 1 + 1 + 1 - \frac{CO}{50}\right)$$

The gases obtained from the El Tremedal trial production well (CO_2=410000 ppm and CO=128000 ppm), are processed for utilization and after which there are air pollution potential risk, so that, for purposes of developed model application, assumes a CO_2 and CO of 5000 ppm and 40 ppm, respectively, to about 50 meters from the emission source for atmospheric local air velocity condition. For this assumed condition the Atmospheric Sustainability Index results in the following equation:

$$ASI = \frac{1}{4}\left(1 - \frac{5000}{5000} + 1 + 1 + 1 - \frac{40}{50}\right) = 0.60$$

If it is assumed that all CO_2 gas is captured and sequestered in underground cavern, the sustainability for CO_2 gas result 1. The CO gas assumed 40 ppm concentration above 50 meters for certain atmospheric local air velocity condition, the ASI of El Tremedal UCG trial result:

$$ASI = \frac{1}{4}\left(1 + 1 + 1 + 1 - \frac{40}{50}\right) = 0.80$$

The result of application the quantitative ESI model with measured and assumed environmental indicator in El Tremedal Spanish UCG trial assessment by proposal sustainability levels for UCG process (Table 6) shows the sustainability due subsidence and surface water is very good, due to atmosphere pollution is good and due groundwater is extremely low.

Applying equation (1) the ESI results in 0.74 and globally environmental sustainability of El Tremedal UCG trial as shown in Figure 9 is good.

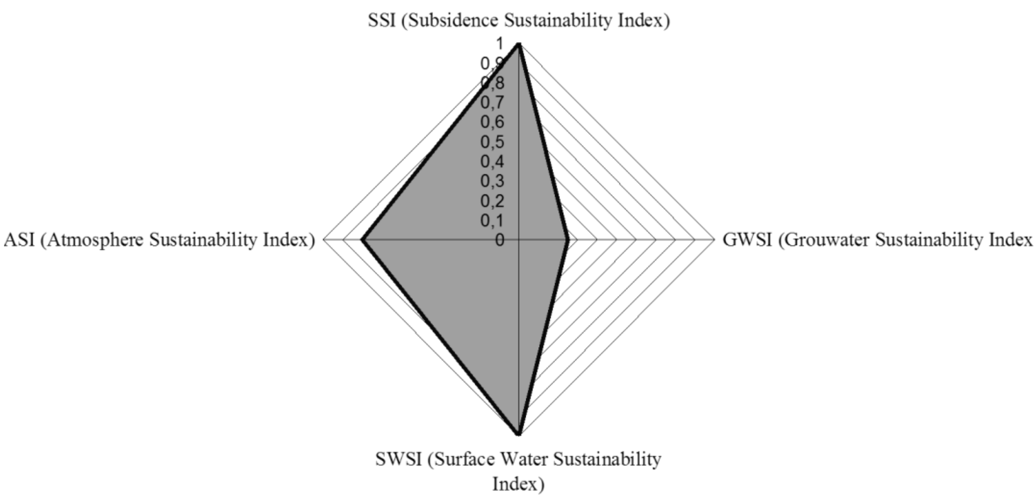

Figure 9 - Environmental Sustainability Index of El Tremedal UCG trial

The ESI determination process and the results demonstrate that the implementation of remediation action is needed for reducing ground water pollutants (H_2S, NH_3, C_6H_5OH and Conductivity) to

permissible levels. The ESI is very useful index for indicating remediation actions and applications of the Management of Sustainable UCG Practices.

DISCUSSION OF RESULTS

In the quantitative assessment of the Environmental Sustainability Index of the UCG process, for most of the environmental pollution components (H_2S, NH_3, C_6H_5OH, pH, C_6H_6, CO, CO_2, SO_x, NO_x, phenols, conductivity, etc.) are applied to the mathematical model and conditions of sustainability criterion 1 (equation 2) based on their minimum standards.

For only subsidence then the mathematical model and conditions of sustainability criterion 2 based on the maximum standards (admissible horizontal tensile), and for pH, CH_4 and H_2 applies the mathematical models and conditions of sustainability criterion 3 (equations 4 and 5) based on a permissible range from a low to a high standard.

Table 9 shows the calculated Environmental Sustainability Index for El Tremedal Underground Coal Gasification trial, as compared to those for underground tungsten mining in Portugal (6) and surface water And groundwater sustainability index in underground mining showing close resemblance of results with reference to GWSI and other Environmental Indicators.

Table 9 - Environmental Sustainability Index (ESI) of El Tremedal UCG trial compared with underground mining and mine water

Sustainability Index	El Tremedal UCG trial	Panasqueira Portuguese mine(5, 6]	
		Underground mining	Mine water
SSI	1		
GWSI	0.25	0.27	0.35
SWSI	1		
ASI	0.70		
GSI		0.98	
UASI		0.54	
ESI	0.74(high)	0.45(Low)	0.35(low)
SSI: Subsidence Sustainability Index; GWSI: Groundwater Sustainability Index; SWSI: Surface Water Sustainability Index; ASI: Exterior Atmosphere Sustainability Index; GSI: Geotechnical Sustainability Index; UASI: Underground Atmosphere Sustainability Index			

Table 9 also indicates that the ESI result 0.74, equivalent to *good* level according to (Table 6);Compared with ESI=0.45 for underground tungsten mining (d] and equivalent to *low* level and ESI=0.35 for mine water (Stephan et. al. 1985), also equivalent to *low* level.

During assessment of the environmental sustainability of El Tremedal UCG trial, low sustainability of groundwater (GWSI = 0.25) greatly reduces the global Environmental sustainability Index (ASI), this behavior is also observed in the case of mining underground (GWSI = 0.27) and even for mine water (GWSI = 0.35).

CONCLUSIONS

Underground coal gasification, in the future, will be an important activity for human development, but the future projects must be implemented based on acceptable environmental sustainability.

The environmental sustainability of underground coal gasification can be quantified by calculating the Environmental Sustainability Index through the developed mathematical model.

The numerical model presented in this paper opens a way for analysis, assessment, remediation and contribution to effective Sustainable management of the underground coal gasification process.

The Environmental Sustainability Index, calculated by the developed model, is a quantitative indicator of the environmental sustainability of an UCG project. In the future, this index will be able to standardize the minimum level of sustainability of UCG process.

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