EUROPEAN COMMISSION

Directorate-General for Research
Directorate K - Energy

Research Fund for Coal & Steel

UCG&CO2 STORAGE Project

Funded under the Research Program of the RFCS, Coal RTD

Grant Agreement No. RFCR-CT-2010-00003

WP 6: Environmental Assessment of UCG - CO_2 Storage

MONITORING AND APPLICATION OF PROACTIVE ACTIONS FOR IMPROVING THE ENVIRONMENTAL SUSTAINABILITY OF UCG AND CO_2 STORAGE

(Deliverable 6.1, Task 6.4 – Review report)

Beneficiaries responsible for the Deliverable:

1. IST Lisbon group: Instituto Superior Técnico of Technical University of Lisbon (IST), Cais Digital Instrumentação e Sistemas de Informação, Lda. (CDISI), Tecninvest 2 - Estudos de Desenvolvimento, Tecnologia e Inovacao, Lda. (TECNINVEST)
2. Geological Institute- Bulgarian Academy of Sciences (GI-BAN)
3. University of LEEDS (UNIVLEEDS)
4. Centre for Research and Technology Hellas/ Institute for Solid and Fuel Technology Applications, Greece (CERTH/ISFTA)

Authors:
1. Antonio Coimbra (Tecninvest 2, sub-contractor Lisbon group)

WP 6: Environmental Assessment of UCG - CO_2 Storage

Task 6.4 – Monitoring and application of proactive actions for improving the environmental sustainability of UCG and CO_2 storage.

TABLE OF CONTENTS

TASK 6.4 - Monitoring and application of proactive actions for improving the environmental sustainability of UCG and CO2 storage.

Main topic:

- Demonstrate how monitoring programmes contribute to sustainability.

ABSTRACT

In the last decades Underground Coal Gasification (UCG) come to be considered a promising energy technology able to extend the world coal reserves for several hundred years. If combined with carbon dioxide (CO_2) geological storage, it has the potential to be a cost-effective, near-zero-carbon energy source. Though most of the technologies used in the UCG + CO_2 storage are already mastered by the industry and many successful trials have been carried out around the world, the overall process is not yet a mature and commercially available group of technologies. Thus an UCG project requires a thorough and reliable measuring, monitoring and verification system to control all variables critical to operation and environmental performance and to deal with unexpected hazards. Such programme will also help in providing a transparent and independent measurement and verification of the project, which is instrumental for gaining social acceptance by local communities and the public at large.

1. UCG AND CO_2 STORAGE

A key objective of contemporary energy strategies is to guarantee diversified, secure, safe, and affordable energy systems. Due to the worldwide trend of increasing electricity demand, such systems will need to incorporate new power stations, electricity networks and other infrastructure to provide new supplies of energy. This is mostly to be attained by expanding the generation of energy of low carbon sources, such as solar plants, wind farms and other renewable energy sources as there is now a consensus that the global climate changes are a result, at least partially, of raised atmospheric concentration of greenhouse gases.

In spite of many attempts to develop new technologies enabling the large scale use of sustainable energy sources, the world will continue to depend substantially on fossil fuels, especially coal, which is an abundant and globally distributed resource. The challenge now is to develop technologies that can effectively bridge the transition period required to further develop and implement sustainable sources of energy, keeping industrial competitiveness in global markets, without putting additional pressure on the environment (Chandel 2009).

Although the earth is an abundant source of coal, a significant amount is currently unrecoverable as only 15% to 20% of the total coal resources can be recovered by conventional technologies. It is currently considered that the world coal reserve[1] is close to 1,000 billion tonnes or 150 years while world coal resources are being estimated in the range of 6,000 billion tonnes (Burton 2006; Younger 2010; Self 2012).

UCG

Underground Coal Gasification ('UCG') is an in-situ gasification process where underground coal seams are converted into Synthesis Gas or 'syngas' through the injection of oxidants via an injection well. This process, which recovers approximately 70-95% of the coal's energy, is controlled remotely and does not require human access or other costly infrastructure in comparison with traditional mining methods. Even though the coal gasification process has existed for more than 150 years, it did not achieve widespread utilisation. The only exception was USSR, where UCG trials began in the 1930s, several pilot plants and five industrial UCG[2] plants were deployed since then, until the discovery of significant natural gas reserves in Siberia in the 1960s reduced interest in this technology (Moorhouse 2010).

In the last decades the potential of UCG technologies to grow and replace or complement traditional methods for coal mining became more extensively considered worldwide. Currently there are more than 30 countries undertaking UCG activities, including a wide diversity of trials and pilot projects (Brand 2012).

Directional drilling techniques, which already had a good efficiency record in coal mining, are ready for UCG usage (Kravits 1994). Only in North America more than 4,000 horizontal wells have been drilled since 1995 with excellent results (Browen 2008). Its application to

[1] Including only recoverable resources using conventional mining as the typical method of extracting coal.

[2] In Angren, Uzbekistan a commercial UCG plant has been successfully operated for more than 50 years– supplying UCG syngas for power generation.
Source: http://www.lincenergy.com/investor_linc.php?articleId=69

UCG enhances the potential of this technology by reaching reservoirs not located directly beneath the drilling rig and allowing a better utilisation of the gases. This, together with other recent technology developments, such as in the three-dimensional (3D) seismic technology, allowing more accurate target identification and enhanced drilling, is positioning UCG as the best technology in the unconventional gas market.

Studies carried out in 2004 and 2005, based on data from IGCC[3] and SCPC[4] plants in Australia (Dalton 2004) and from Ergo Exergy UCG based IGCC plant in South Africa (Blindermann 2006), suggested that the Cost of Electricity[5] of UCG based power plants will be 25 to 50% lower than conventional power plants and the introduction of a globally competitive UCG can expand the current coal reserve for several hundred years. Yet, a gap of uncertainty will remain as to its economic performance, until undertakings with sizable magnitude come into stream (Bowen 2008).

CCS

Carbon capture and storage (CCS) prevents the release of large quantities of CO_2 into the atmosphere by capturing CO_2 and pumping it into underground geologic formations to securely store it away from the atmosphere. It is considered a potential means of mitigating the impact of fossil fuel emissions on the environment and ultimately in global climate changes. The long term storage of CO_2 is a relatively new concept; the first commercial application was established some ten years ago in Weyburn-Midale CO_2 storage site, Saskatchewan, Canada[6]. Another 4 full-scale projects demonstrating CCS from high-purity sources are currently operating: three natural gas processing projects with storage in saline formations (1 in Algeria and 2 in Norway) and one in Colorado, USA. There is one under construction in Western Australia that will store CO_2 in saline formations (IEA 2011).

---

3 Integrated Gasification Combined Cycle

4 SuperCritical Pulverised Coal

5 The cost of electricity or COE (typically measured in Euro/kWh, Euro/MWh) generated by different technologies is a calculation of the cost of generating electricity at the point of connection to a load or electricity grid. It includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance. It is also named the 'levelised' cost electricity

6 According to the Petroleum Technology Research Centre (PTRC) of Canada, in spite of the fact that since July 2000 about 5,000 tonnes/day of 95% pure CO2 have been injected continuously into the storage facility at Weyburn-Midale, "PTRC has never identified a leak of CO2 into the biosphere or soil in the Weyburn-Midale field area, nor in selected sample locations beyond it." Source: 'Statement by the Petroleum Technology Research Centre on the allegations of a CO_2 leak at the Weyburn-Midale CO_2 storage site', 12/01/2011.
http://www.zeroemissionsplatform.eu/component/downloads/downloads/725.html. Accessed September 2012.

Coupling UCG and CCS allows the capturing, compressing and re-injecting of post-combustion CO_2 on-site into the highly permeable rock created during the burning process and around it. This way coal extraction and conversion methods are combined into a single process that avoids many of the challenges associated with conventional mining practices. Basically, UCG combined with CCS could provide a cost-effective, near-zero-carbon, energy source through the use of a self-contained system with a closed carbon loop (Self 2012).

In summary: UCG + CO_2 storage although promising, as many of its individual segments are based on proven technologies that have been used in industry for years, is not yet a mature, commercially available group of technologies. Upscaling and integrating these diverse technologies still requires additional research effort. According to recent reviews of the knowledge base of UCG and CO2 storage projects, some of the areas where research needs are felt the most are: strength reduction and failure of caprock under the combined effects of high pressure and high temperature, modelling for some components is underdeveloped (e.g.: vadose zone of the groundwater, surface water bodies, etc.), integration of individual models and of multiple data streams of the monitoring activities (Shukla 2010; Koornneef 2012).

2. ENVIRONMENTAL IMPACT

UCG enjoys the reputation of (potentially) being the most safe and environmentally friendly coal mining technology, allowing more environmental benefits when compared to traditional fossil fuel energy techniques. Among its many advantages are the minimisation or elimination of sources of risks of negative impacts: no stockpiles of coal, no coal dust, no ash handling at surface, reduced noise due to coal transportation and offloading, lower emission of greenhouse gases and other contaminants, lesser water consumption, reduced surface use and disruption, etc.. In addition, UCG projects offer opportunities for carbon storage or sequestration, which is seen as the major road to CO_2 reduction in this century (Sury 2004; Friedman 2009a; Sheng 2011).

Undoubtedly UCG has the potential to access significant energy reserves and can generate electricity with less impact than traditional coal plants. However there are several outstanding risks associated with UCG that must be addressed (Sury 2004; Gama 2011).

Some risks that are intrinsic to the process and have a direct effect on technical performance of the overall industrial facility may impair significantly the economics of the project and, ultimately, render it unprofitable; these risks may have also negative effects in the environment. Other risks, though not affecting significantly the technical and economic performance of the project, may represent severe threats to the environment.

These risks can be briefly categorised along the following lines (Moorhouse 2010):

Groundwater contamination

Groundwater contamination is considered the most environmentally significant risk[7]. During the gasification process a number of compounds are created such as phenols, polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia, sulphides, etc. A detailed list of such potential contaminants is depicted in tables 1 through 3, pp. 9-11 of the review report of Task 6.2 of this project (Gama 2011). These contaminants can migrate from the combustion area to the surrounding groundwater (ibid., pp. 4-6).

In a survey of pilot projects in North America, 2 out of 34 have resulted in groundwater contamination, attributable to gross operator errors, and required considerable remediation efforts. Studies conducted in USSR in the 60's showed severe contamination in more than one location (Liu 2007).

Groundwater contamination risk can be mitigated through appropriate site selection, good assessment of potential drilling sites, and good operational and shutdown practices (Moorhouse 2010, Younger 2011). Actually most of the UCG operations did not generate any significant environmental consequences and in Europe and Australia all relevant trials were concluded without any contamination during the operation phase or 5 years thereafter (Burton 2006; Liu 2007; Moorhouse 2010).

Subsidence

[7] There is a strong consensus to this respect in the literature (Humenick 1978; Sury 2004; Blinderman 2006; PriceWaterhouseCoopers 2008; Friedman 2009; Moorhouse 2010; Younger 2011; Gama 2011; Gama 2012; Brown 2012)

Subsidence of surface regions is a major risk of UCG projects. Usually results in height decrease of the coal seam affecting the land directly above the gasified area and its extension and seriousness depends on many factors (seam thickness, caprock strength, and other geological properties). It can impact surface water flows, shallow aquifers and any above ground infrastructure. Two of the U.S. pilot projects experienced subsidence (Burton 2006; Moorhouse 2010; Powers 2010).

Subsidence is manageable when approached by a well-planned strategy as it is done in many conventional underground mining operations. Subsidence is a site-specific issue; careful site selection together with specifically designed proactive measures (e.g.: creation of buffers around surface occurrences, such as lakes, rivers, roads and other major infrastructure elements) are fundamental conditions to minimize subsidence risk and its impacts (Friedman, 2009a; Moorhouse 2010). Still, more and improved techniques aiming at managing and reducing surface subsidence are needed in the context of UCG (Powers 2010).

Surface water and soil

The gas generated underground by the partial oxidation of coal contains chemical components that may contaminate surface water and soil. These contaminants are similar to the ones occurring in the ‘producer gas’ from the fixed surface gasifiers of the biomass gasification industry, which exists for more than 2 centuries. For more than 60 years this industry is routinely treating the contaminants by filtration, scrubbing, adsorption, condensation, cooling and other techniques so as to meet stringent environmental standards (Moorhouse 2010; Burton 2012).

Air quality

The combustion of syngas, like the combustion of natural gas, will generate air emissions with associated environmental and health concerns. However, the emission of air contaminants (such as sulphur dioxide, nitrogen oxides and particulate matter) per unit of electricity are expected to be significantly lower than in a conventional coal power plant and to comply with present and future air emissions standards. Naturally, the treatment of air emissions will depend on the combined sources of emissions in the region and the pollution control standard to which the facility is to be designed (Moorhouse 2010).

Land use

Though minimal when compared to surface gasification plants, UCG will entail some surface disturbance and visual impact. To mitigate these negative effects it is essential to ensure that land planning complies with the proper protection of the environment and the local community. It would be appropriate to assess the sensitivity of the ex-ante environment and the magnitude of the potential impact in order to arrive at suitable solutions in terms of landscape, forest cover and its ecology, surface water and groundwater, land quality, cultural heritage, transportation and other infrastructure, socio-economics system and pollution (Bhuyan 2012).

Operational risk

Many serious operational risks can occur if UCG projects are not properly designed and operated. These risks range from uncontrollable fires and explosions to the creation of fissures and fractures due to ignition of methane, failure of equipment, and other causes and may lead to serious impairment of the technical performance of the project or even to the shutdown of the plant. These risks will also produce environmental impacts such as surface, groundwater and soil contamination, harmful air emissions and other environmental disruptions or disturbances (Burton 2006; Shafirovich 2009; Lauder 2011).

As already indicated, all the above risks can be minimized or excluded with well-planned and managed UCG projects, including a comprehensive and meticulous site selection, in-depth, deliberate and timely risk management and control systems and an integrated and continuous oversight of contractors.

3. MONITORING

When UCG is located, designed and operated properly, it can be a very effective technology with considerable potential for power generation, industrial applications and petrochemical feedstock. The technology has been progressively overcoming barriers to commercial development, notably as regards environmental concerns, where detailed and comprehensive environmental impact of surface and subsurface operations are paramount to minimise risks, provide amelioration methods and prepare contingency action plans for remediating unforeseeable disturbances.

However, if the above conditions are not met, UCG may not reach its expected efficiency and/or environmental performance. It is therefore essential to examine in detail each operation and ensure that site-specific performance goals are well defined and environmental criteria and standards are being met.

Environmental, operational and societal risks

As it is difficult to find sufficient public data on UCG facilities operating at a continuous rate for long periods of time to demonstrate the industrial and environmental reliability of the process, there are diffused concerns as to the level of certainty of operational and environmental safety. This, together with the general awareness of the harmful consequences of conventional coal mining, particularly in old coal mining districts, tends to amplify the perception of risk by the public.

Research conducted in various countries identified a relatively consistent range of worries of local stakeholders, namely in the UK (at Silverdale, where locals had concerns regarding safety, noise, waste, property values, and the environment in general), Sweden (where scepticism and opposition to the CCS technology among NGOs and politicians contrasted with favourable attitudes from industry and scientists), the US (where concerns about the economic, environmental, and aesthetic impacts were identified) and Australia (at Kingaroy, where groundwater contamination and transparency concerns related to UCG were strongly felt[8]) (Shackley 2004; Hansson 2005; Ag Mohamed 2011; James 2012).

[8] This plant was not open by decision of local authorities in spite of scientific evidence that the Kingaroy UCG facility operations "posed no threat to the environment". According to Ergo Exergy, the technology provider of the Kingaroy project, the project owner, Cougar Energy, "has commenced legal proceedings against the Queensland Government and three of its officials over their decision to halt the company's flagship UCG development in Kingaroy, Queensland. Seeking damages of more than AU$34Mil, Cougar Energy alleges negligence and breach of statutory duties in the Bligh Labour Government's administration of the Queensland Environmental Protection Act. Cougar Energy has received legal advice that the Government's closure of the Kingaroy project was unreasonable and compounded by the defendants' continued refusal to allow the re-opening of the plant despite a wealth of scientific evidence that its operations posed no threat to the environment. Over the course of more than 15 months, Cougar Energy have attempted to resolve the forced close-down of the Kingaroy UCG plant but have been essentially stone-walled by the Queensland Government throughout this time. Despite the Government's own test results revealing no evidence of groundwater contamination, they have continued the unjustified and unreasonable stance of keeping the Kingaroy plant closed.» October 17, 2011. http://www.ergoexergy.com/. Accessed September 2012

Preliminary efforts to develop a conceptual framework to consider the multiplicity of factors that influence social learning of complex demonstration projects such as the ones that have been deployed in recent years in Europe, in the Americas and Asia, enhanced the role the "way in which alignment of interests is achieved, mechanisms for communication among stakeholders, project framing, governance structures and the national contexts within which projects are designed and implemented" plays in influencing cognitive processes and attitudinal changes of the concerned population and the public at large (Markusson 2011).

Therefore, besides the essential requirement of ensuring that UCG + CO_2 storage projects are planned and conducted in accordance with stringent operational and environmental criteria, there is the critical need of avoiding public resistance and local hostility based on misconceptions, information gaps or other factors.

Public resistance to large or 'sensitive' infrastructural and industrial projects has intensified in the last decades, particularly in OECD countries. Object of increasing attention by policy makers in democratic countries, this collective behaviour is also being investigated extensively by academia and research institutions. While the difficulties of handling public acceptance of large projects is clearly a matter that depends on the region/country and contextual factors of the project location, there is growing agreement that there are some requisites and conditions that make more likely for this type of projects to succeed in gaining public acceptance (Dröge 2012):

- Transparency since the onset of the project is key to success: to gain stakeholder acceptance results of the project should be produced in an open and transparent manner so that implications for ecosystems and human health can be fully addressed.
- Involvement of local people in the decision making process will increase the understanding of the issues at stake.
- Measurement and appraisal conducted on an impartial basis by independent organisations increase the credibility of data needed to inform the various constituencies of the benefits and limitations of the project.
- In many cases some in-kind compensation not directly related to project may be offered. However the outcome of such approach is not assured and, if tackled tactlessly, may well backfire and make the acceptance more difficult; or the cost of the desired compensation may be too high to be reasonably considered.

Monitoring, a trusted constituent of engineering projects

Monitoring is a well-established element in the engineering practice as a fundamental component of project execution and appraisal. It serves to bring up to date reviews of the parameters of project implementation by providing the planners, project managers, wider decision makers and other stakeholders with information as to how predicted effects are being realised and managed. The benefits of monitoring include identifying and tracking unforeseen effects should they arise, enhancing an understanding of how the base structure/scheme and its environment is changing as a result of the execution of the project, assessing the effectiveness of measures designed to mitigate undesirable effects and identifying whether operational and strategic actions are necessary to enhance or reduce identified negative effects (Nikander 2001; Al-Jibouri 2003; Kazimieras 2010).

Since long, project monitoring, mitigation and verification (MMV[9]) programmes are considered to be critical requirements for delivering robust and reliable decision-making frameworks confirming that complex undertakings, such as the CO2 geologic sequestration projects, perform up to required operational and environmental goals. These programmes have to be capable of addressing uncertainties of the physical and chemical processes and of the hydrogeological and geomechanical properties of the strata complex, thus incorporating all potential factors that determine the long term sustainability of the project (Klara 2003; Deel 2006; Deel 2007; Feeley 2010). MMV programmes are also viewed as an essential part of the requirements for legal and regulatory purposes of the geological sequestration of CO_2 (Solomon 2007; Feeley 2010).

Monitoring UCG and CO_2 storage projects

The same basic principles and rationale that justify the importance of using MMV programmes in the preparation and implementation of CO_2 storage projects clearly apply to coupled UCG + CO_2 storage projects. These MMV programmes have to be adjusted by including the operational phase of coal gasification in the overall setting. MMV activities should also include triggering control measures that prevent or correct any major deviation from specifications or standards before significant impacts occur.

[9] The acronym MMV usually means ‘measurement, monitoring and verification’ or ‘monitoring, mitigation and verification’ (as used by the US National Energy Technology Laboratory's Sequestration Programme: http://www.netl.doe.gov/).

There are currently many proven techniques with a technology readiness level that enable their application in MMV programmes needed for UCG + CO_2 storage projects. Many have been used routinely for many years (e.g.: CO_2 detectors or tilt meters for surface or near surface monitoring; electrical resistance tomography for subsurface monitoring), others have been demonstrated only in an operational environment. Lists of available monitoring technologies are provided in 2 of the references appended to this report (Spectra 2012; Bianchini 2009).

In general, it is recognised that there are many multi-monitoring techniques that can be applied for both surface and subsurface monitoring of UCG + CO_2 storage projects, their operation and management face site-specific, ever changing challenges and that new or improved monitoring technologies are continuously becoming available (WorleyParsons 2010). Thus the effort should be put in developing best practices of monitoring programmes and some ‘horizontal’ areas that need to be further addressed, such as:

- The integration of the results of measurements of the MMV programmes, which is considered to be still a major gap in current monitoring capabilities and understanding (Ansolabehere 2007).
- Integrated risk assessment, which is seen by some to be «urgently needed» for CO_2 geological storage (Orlowsky 2010). The systematic risk assessment of the whole chain of risks is instrumental to allow the design of effective safeguards based on geology, engineering and MMV performance targets. The current approaches to environmental protection are now routinely based on environmental risk-based decision-making (RBDM). Its use is recommended for siting and design of UCG operations by quantifying risk for various potential scenarios and identifying the conditions necessary to meet an acceptable level of risk. This is based on a sufficiently robust technical framework that can reliably predict contaminant generation, behaviour, and human/environmental exposure pathways (Burton 2006).

4. CONCLUSIONS

Monitoring, through the application of a MMV programme, is a critical component of a UCG + CO_2 storage project and a major contributor to its sustainability by avoiding and mitigating most of the technical risks of the undertaking, either operational or environmental. Furthermore, a well-designed MMV programme will also provide the basis for a transparent and independent measurement and verification of the project, which is instrumental for gaining social acceptance by local communities and the public at large.

5. REFERENCES

Ag Mohamed, A et all. 2011. *Viability of Underground Coal Gasification with Carbon Capture and Storage in Indiana*. Spring 2011 Capstone, Bloomington School of Public and Environmental Affairs, Indiana University. May 4, 2011. http://www.indiana.edu/. Accessed September 2012

Al-Jibouri, S. 2003. *Monitoring systems and their effectiveness for project cost control in construction*. International Journal of Project Management. Volume 21, Issue 2, February 2003, pp. 145–154

Ansolabehere, S. et all. 2007. *The Future of Coal. An Interdisciplinary MIT Study*. Massachusetts Institute of Technology. 2007, p. 48

Bhuyan, P. et all. 2011. *Site Selection – A key to Underground Coal Gasification (UCG)*. The 2nd South Asian Geoscience Conference and Exhibition,GEOIndia2011, 12-14th Jan, 2011,Gearter Noida, New Delhi, India. http://www.apgindia.org/pdf/529.pdf. Accessed September 2012.

Bianchini, R. 2009. *Aspectos ambientais e MMV*. "Produção regional de combustíveis limpos a partir do carvão no RS". 4 de Março de 2009.

Blinderman, M. and S. Friedmann. 2006. *Underground coal gasification and carbon capture and storage: Technologies and synergies for low-cost, low-carbon syngas and secure storage*. Lawrence Livermore National Laboratory. 2006

Bowen, C. 2008. *A Review & Future of UCG, Underground Coal Gasification*. Energy Center at Discovery Park, Purdue University. 2008. http://www.purdue.edu/discoverypark/energy/.Accessed July 2012.

Brand, J. 2012. *Underground Coal Gasification (UCG)*. Wildhorse Energy. June 2012. http://www.wildhorse.com.au/en/ucg-overview. Accessed July 2012.

Brown, K. 2012. *In Situ Coal Gasification: An Emerging Technology*. National Meeting of the American Society of Mining and Reclamation, June 8/15, 2012.www.asmr.us/Meetings/2012/Abstracts2/0051-Brown-CO.pdf. Accessed August 2012

Burton, E, S. Friedmann, and R. Upadhye. 2006. *Best Practices in Underground Coal Gasification*. Lawrence Livermore National Laboratory. 2006. http://www.purdue.edu/discoverypark/energy/assets/pdfs/cctr/BestPracticesinUCG-draft.pdf. Assessed July 2012.

Buscheck, T., J. Morris and E. Burton. 2009. *Thermal-Hydrological Sensitivity Analysis of Underground Coal Gasification*. 2009 International Pittsburgh Coal Conference, Pittsburgh, PA, United States. September 20/23 2009.

Chandel, S and E. Williams. 2009. *Synthetic Natural Gas (SNG): Technology, Environmental Implications, and Economics*. Climate Change Policy Partnership, Duke University. January 2009

Dalton, S. 2004. *Cost Comparison IGCC and Advanced Coal*. Roundtable on Deploying Advanced Clean Coal Plants. Electric Power Research Institute. July 2004. http://www.climatevision.gov/. Accessed August 2012

Deel, D. 2007. *Summary of DOE's Monitoring, Mitigation, and Verification Program and Modeling Program*. National Energy Technology Laboratory. 26 September 2007

Deel, D. and C. Mahoney. 2006. *Risk Assessment and Management for Long-Term Storage of CO_2 in Geologic Formations*. Proceedings of The 10th World Multi-Conference on Systemics, Cybernetics and Informatics. July 16-19, 2006.

DeStefano, H et all. 2008. *Evaluation Of the Environmental Requirements To Construct and Operate a Coal-To-Liquids Plant*. Science Applications International Corporation, Indiana Operations Center. February 2008. http://www.saic.com/. Accessed September 2012.

Dröge, P. and P. Messer. 2012. *European power struggles. Can public resistance be overcome?* Special Report – Energy Technologies. Parliaments and civil society in Technology Assessment (PACITA) Project. 09 January 2012. http://www.pacitaproject.eu/. Accessed September 2012.

Evans, D. 2009. *A review of underground fuel storage events and putting risk into perspective with other areas of the energy supply chain*. The Geological Society of London. 2009. http://sp.lyellcollection.org/content/313/1/173.short. Accessed August 2012.

Feeley, T. and all. 2010. DOE's Carbon Capture and Sequestration R&D Program. National Energy Technology Laboratory. 2010

Friedman, S. 2009a. *Low-impact fossil energy: Keystone to sustainability*. Lawrence Livermore National Laboratory. December 2009. http://www.bu.edu/energy/files/2009/12/4BU_LIFE_Dec09.pdf. Accessed July 2012.

Friedman, S. et all. 2009b. *Carbon Management and Underground Coal Gasification*. Lawrence Livermore National Laboratory. December 2009. http://www.bu.edu/energy/files/2009/12/4BU_LIFE_Dec09.pdf. Accessed July 2012.

Gama, C. et all, 2012b. *Report on the Application of the ESI Model to Possible Coal Deposits in the DCD (Bulgaria), Florina Basin (Greece) and El Tremedal (Teruel, Spain)*. UCG&CO2 STORAGE Project. WP 6. Task 6.3

Gama, C. et all. 2011. *Potential Environmental Impacts of UCG and UCG with CO_2 Storage*. UCG&CO2 STORAGE Project. WP 6. Task 6.1

Gama, C. et all. 2012. *Development of Models to Assess the Environmental Index of UCG + Co2 Storage and Minimum Levels of the ESI*. UCG&CO2 STORAGE Project. WP 6. Task 6.2

Hansson A. and Bryngelsson, M. 2005. *Attitudes regarding CO2 Capture and Storage from a Swedish perspective*. Proceedings of the Fourth Annual Conference on Carbon Capture and Sequestration DOE/NETL. May 2-5, 2005

Humenick, M. and C. Mattox. 1978. *Groundwater Pollutants from Underground Coal Gasification*. Water Research Vol 12 pgs 463-469.

James, M. et all. 2012. *How Australians value water. Results from a literature review*. Global CCS Institute. June 2012.

Kazimieras, E. et all. 2010. *Risk assessment of construction projects*. Journal of Civil Engineering and Management. Volume 16, Issue 1, 2010, pp. 33-46

Klara, S. and all. 2003. *Integrated collaborative technology development program for CO_2 sequestration in geologic formations*. Energy Conversion and Management 44 (2003), pp. 2699-2712.

Koornneef, J. and all. 2012. *The environmental impact and risk assessment of CO_2 capture, transport and storage – An evaluation of the knowledge base*. Progress in Energy and Combustion Science. 28 (2012), pp.62-86.

Kravits, S, and Jeffrey J. Schwoebel. 1994. *Directional Drilling Techniques for Exploration In-advance of Mining*. World Mining Equipment, January 1994.

Lauder, J. 2011. *Introduction to Underground Coal Gasification. A Clean, Safe, Indigenous Energy Supply*. UCG Association. UCGA Training Course, London 21st – 22nd March 2011. http://repository.icse.utah.edu/. Accessed September 2012.

Litynski, J. 2012. *Best Practices for Monitoring, Verification, and Accounting of CO2 Stored in Deep Geologic Formations – 2012 Update*. National Energy Technology Laboratory. October 2012.

Liu, S. et all. 2007. *Groundwater Pollution from Underground Coal Gasification*. Journal of China University of Mining and Technology, Volume 17, Issue 4. December 2007. Pp. 467–472.

Markusson, N. and all. 2011. The social and political complexities of learning in carbon capture and storage demonstration projects. Global Environmental Change. Volume 21, Issue 2, May 2011, pp. 293–302.

Moorhouse, J, M. Huot and M. McCulloch. 2010. *Underground Coal Gasification - Environmental Risks and Benefits*. The Pembina Institute. May 2010

Nikander, I and E. Eloranta. 2001. Project management by early warnings. International Journal of Project Management. Volume 19, Issue 7, October 2001, pp 385–399

Orlowsky, D. 2010. *Aims and Objectives*. Geophysical Aspects of CO_2 -Storage – Challenges and Strategies. DGG/SEG CCS-Workshop. Bochum, March 19th, 2010, p. 48

Piessens, K and M. Dusar. 2003. *CO2-sequestration in abandoned coal mines*. Royal Belgian Institute for Natural Sciences, Geological Survey of Belgium. Proceedings of the 2003 International Coalbed Methane Symposium, Tuscaloosa, paper 0346.

Powers, B. 2010. *Technical and Cost Issues Associated with CIRI Underground Coal Gasification Project*. Powers Engineering. February 2010. http://www.groundtruthtrekking.org/. Accessed August 2012.

PriceWaterhouseCoopers. 2008. *Industry Review and an Assessment of the Potential of UCG and UCG Value Added Products*. PriceWaterhouseCoopers. May 2008

Ryan, B. 2010. *Underground Coal Gasification UCG or In-situ Coal Gasification ISCG: a very unconventional gas*. British Columbia Government Consultant. Posted September 2010. http://www.docstoc.com/docs/54594743/Slide-1---BC-Government-Home---P. Accessed August 2012.

Schreck, B. 2011. *Technology Roadmap: Carbon Capture and Storage in Industrial Applications*. OECD/International Energy Agency and United Nations Industrial Development Organization. 2011

Self, S B. Reddy and M Rosen. 2012. *Review of underground coal gasification technologies and carbon capture*. International Journal of Energy and Environmental Engineering 2012, 3:16. 31 August 2012. http://www.journal-ijeee.com/content/3/1/16. Accessed September 2012.

Shackley, S. et all. 2004. *The Public Perceptions of Underground Coal Gasification (UCG): A Pilot Study*. Tyndall Centre Working Papers. Working Paper 57. 2004. http://www.tyndall.ac.uk/. Accessed August 2012.

Shafirovich, E and A. Varma. 2009. *Underground Coal Gasification: A Brief Review of Current Status*. Industrial Engineering Chemical Research Journal, Vol. 48, 2009, pp. 7865-7875.

Sheng, Y. 2011. *New life for old coal*. January 2011. Institute of Resilient Infrustructures, School of Civil Engineering, University of Leeds. http://www.engineering.leeds.ac.uk/. Accessed August 2012

Shukla, R. and all. 2010. *A review of studies om CO2 sequestration and caprock integrity*. Fuel 89 (2010), pp. 2651-2664.

Solomon, S. et all. 2007. *A Proposal of Regulatory Framework for Carbon Dioxide Storage in Geological Formations*. International Risk Governance Workshop. March 15-16, 2007.

Spectra. 2012. *Fort Nelson Carbon Capture and Storage Feasibility Project*.

Sury, M et all. 2004. *Review of Environmental Issues of Underground Coal Gasification*. WS Atkins Consultants Ltd. Report No. COAL R272. DTI/Pub URN 04/1880. http://www.dti.gov.uk/files/file19154.pdf. Accessed July 2012.

Walker, L. 2007. *The Development and Future of Underground Coal Gasification in the Australasian Region*. International Conference on Underground Coal Gasification. Houston, Texas. June 2007. http://www.cougarenergy.com.au/pdf/PapertoHoustonUCGConferenceJune2007Final.pdf. Accessed September 2012.

WorleyParsons consortium. 2010. *Strategic Analysis of the Global Status of Carbon Capture and Storage. Report 4: Existing Carbon Capture and Storage Research and Development Networks around the World*. e Global CCS Institute. 2010.

Younger, P. 2010. *King coal: restoring the monarchy by underground gasification coupled to CCS*. Geological Society. London. Petroleum Geology Conference series. January 1, 2010. V. 7, pp. 1155-1163.

Younger, P. 2011. *Hydrogeological and Geomechanical Aspects of Underground Coal Gasification and its Direct Coupling to Carbon Capture and Storage*. Mine Water and the Environment, Volume 30, Number 2 (2011)