Evaluating the costs and achievable benefits of extending technologies for uneconomical coal resources in South Africa: the case of underground coal gasification

M Zieleniewski
Graduate School of Technology Management, University of Pretoria

A C Brent
Graduate School of Technology Management, University of Pretoria; and Sustainable Energy Futures, Natural Resources and the Environment, CSIR

Abstract

As the South African economy relies heavily on its coal resources, these resources should be utilised and managed in the best possible manner. Underground coal gasification (UCG) is one of the leading technologies used where conventional mining techniques are uneconomical. UCG delivers gas suitable for synthesis, production of fuels and electricity, or for home usage. The method is perceived as being environmentally friendly and safer than traditional mining. The study summarised in this paper was conducted so as to create a simple model that would allow for the evaluation of UCG process-related costs versus expected benefits in a wider context and under different circumstances. The parameters of the model are: feasibility definition, i.e. maximum possible gas calorific value, based on geological surveys and gasification agents for a pre-defined need; direct process-related costs that are derived from the expected capital and operational expenditures and compared to the value and volume of the gas produced; and assessment of externality costs, i.e. the indirect economic value of environmental, safety and health benefits. The externalities concept should encourage governmental agencies to consider further investment in UCG technology as a vehicle for delivering, potentially, high savings in terms of the reduction in the costs of environmental damage resulting from gaseous emissions into the atmosphere, specifically expenditure on national health.

Keywords: underground coal gasification (UCG), externalities, cost benefit model

1. Introduction

In view of the likely slow but steady increase in the price of crude oil, South African coal has to be considered as the best available alternative source of gas, chemicals, and smokeless fuels in the interim period, between the present crude oil-dominated liquid fuels era and completely new types of fuels. Since South Africa has the seventh largest coal resources in the world, of about 50 billion tonnes (US DOE, 2005), coal-based options seem to be well justified for the short- to medium-term development of energy production facilities for the fuel and chemical conversion industry. However, as Lloyd (2006) remarks: 'there is a big difference between a resource and a reserve (…) the resource is normally very large and unlikely to be used in its totality, while reserves are constantly changing in response to price'. The commonly accepted period of 150 to 200 years of coal availability in South Africa has become a source of serious misconceptions and overly optimistic forecasts. The recoverable South African coal resources, being true reserves, may only total between 27 and 29 billion tonnes (Prevost, 2004). The most pessimistic prediction suggests that by the year 2040 there will be only 7 billion tonnes remaining, assuming the present consumption rate of 302 Mt/a and an approximately 5% increase in production levels.

The realisation of this status quo prompts the consideration of other, alternative solutions to the energy shortage problem. Underground coal gasification (UCG) is among the most promising technologies and, to an acceptable degree, the proven feasible one (Walker *et al.*, 2001; Ergo Exergy, 2005; Shoko *et al.*, 2006; Shackley *et al.,* 2006). This method (Creedy *et al.*, 2001; UK DTI, 2004) is suitable primarily for areas of complex geophysical
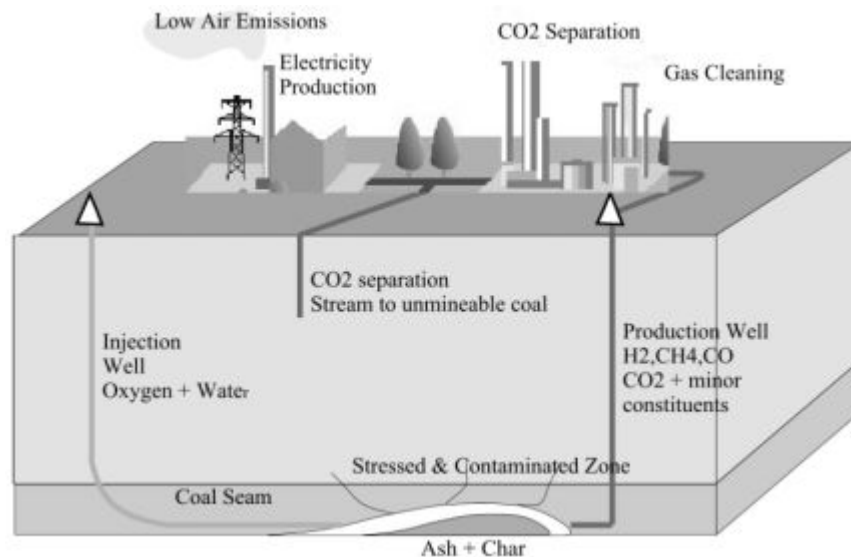
Figure 1: The main components of a commercial UCG site for power generation
Source: www.coal-ucg.com/concept2.html

structure, for which traditional mining methods prove to be economically unviable.

Zieleniewski (2006) and Burton *et al.* (2006) provide historical overviews of the method and tests that have been conducted around the world. In principle, the process enables a coal-to-gas conversion using underground coal seams with surrounding mineral layers forming the natural vessel walls, i.*e.* exactly where the coal is found. The operational depth for UCG is relatively flexible and can vary from 80 to 1 200 m. The minimum coal seam thickness required for the process is approximately 0.35 m. Figure 1 illustrates the UCG process collated with electricity generation.

Typical converting media such as air, oxygen, or their blend with high-pressure steam or hydrogen are pumped through a piping system into the coal seams. Reaction takes place, propagating along the seam. The created synthesized gas is evacuated to the surface through a dedicated pipe grid and utilised in several possible applications such as:
- steam production;
- electricity generation;
- chemical synthesis;
- hydrocarbon-based synthesis; and
- communal use (household heating and/or cooking).

The gas type is determined by the coal seam depth, thickness, and ash content, and its composition can be controlled by the type of gasification media used. Ash, the solid process residue, remains in the post-reaction cavity, filling approximately one-quarter to one-third of the original coal volume (Perkins, 2004). The process does not require mining operations and enables the penetration of areas not economically justifiable for classic mining methods.

1.1 Objectives of the paper
The UCG method appears to offer a considerable degree of flexibility in terms of different types of coal and depths, using various methods. By selecting gasification media and operational conditions, it is possible to achieve the expected composition and the desired volume of gases. The existing technology enables the processing of by-products of underground gasification, resulting in marketable commodities and, by the same token, preventing environmental pollution. Storing areas for ash or discard, inevitable in the case of traditional coal processing units, are virtually non-existent with the use of UCG (Shackley *et al.*, 2006).

The extent to which all the advantages can be claimed as real benefits depends firmly on the economics of a planned project. As in any other case, the final balance between profit and expenditure will be the decisive factor. A logical conclusion therefore emerges from a reflection upon the development of UCG and its potential on the one hand, and the South African resources and needs on the other. If any serious and longer-term attempts to utilise the UCG method are to be carried out in South Africa, such projects will call for a benefits evaluation method that is universal enough to be used in preliminary business cases.

Presently, a comprehensive and systematic evaluation model of the benefits derived from the UCG technique is practically non-existent in South Africa. Aiming at the formulation of such a model, the following questions must be answered:
- What cost determinants emerge from the available literature?
- What degree of similarity exists between classic gasification and UCG?
- Which identified criteria can be used for benefit

and cost estimation under South African circumstances?

- What are the specific South African concerns inherent in the selected benefit and cost criteria?
- What kind of UCG products can be economically achievable under local circumstances?
- What is the order of importance for the utilization of UCG products in South Africa (energy production, chemical synthesis, communal usage, etc.) for each separate case?

By answering the above research questions, the objective of the study summarised in this paper was to structure, propose and test a method suitable for the estimation of process-related costs and achievable benefits through the application of UCG on uneconomical coal resources in South Africa.

2. Proposed model

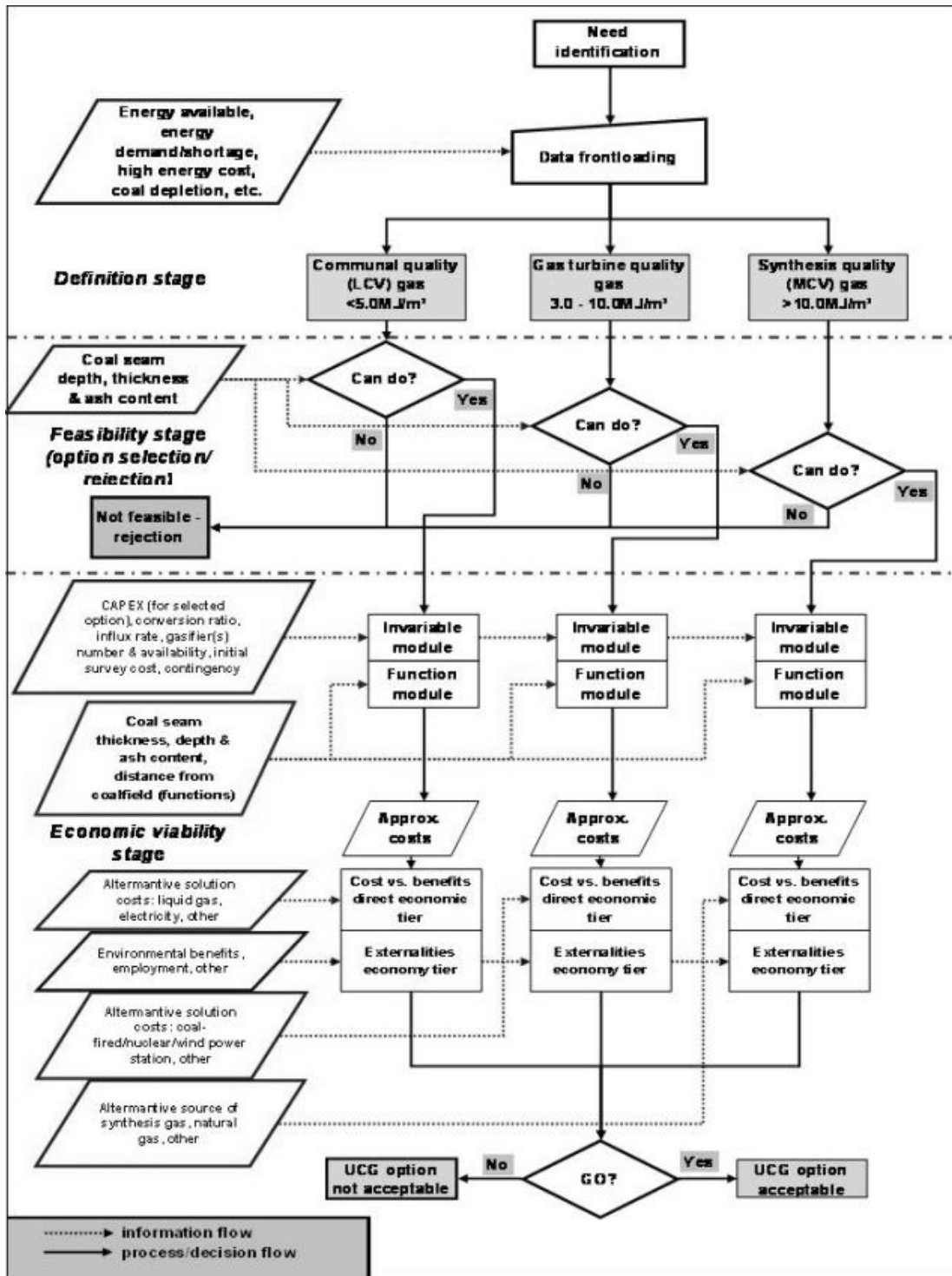The proposed model is summarised in Figure 2 (Zieleniewski, 2006). Some of the process relation-

Figure 2: Schematic diagram of the UCG benefits estimation model
Source: Zieleniewski (2006)

ships for the proposed method were derived from British and Belgian UCG test runs (Simeons, 1978). There are, however, considerable limitations in the usefulness of the experimental data, caused by the nearly three-decade time gap between their origin and the present. Still, certain relationships and functions drawn from the past observations can be verified under South African conditions and therefore be adopted into the proposed benefits model.

Another significant impact on the degree of reliability of the intended model emerged from the conclusions of Jie (2003), Perkins (2004) and Brand (2006) that point to the similarities of the UCG technology and classic industrial gasification processes. As the latter has been well established in South Africa for a half century, its economics and *modus operandi* are well-known and documented.

Finally, the best corroborated portion of the model's input consists of the geological information on coalfields of South Africa (Sparrow, 2006; Venter, 2006; Makwakwa & van der Merwe, 2003), capital expenditure of the implemented infrastructure, operational costs related to the gasifying media production, and synthesized gas transfer and processing. The adopted generic technical assumptions are provided elsewhere (Zieleniewski, 2006). Capital expenditures (CAPEX), including geological surveys, depend on the selected UCG option, i.e. air or oxygen as the gasifying agent (Brand, 2006). The equations applied by the model are summarised in the Appendix.

3. Research methodology
The following techniques were used in the study:
- Input data gathering, including South African coalfields geophysical characteristics;
- Economic data gathering in terms of infrastructure (CAPEX) approximations, installation costs, and energy conversion and transfer costs;
- Formulation and selection of process relationships (technical feasibility relations/functions) based on literature, interviews and Lurgi Gasification process data;
- Generic comparison of the trends found for South African and European Union common ground relationships;
- Selection of functions presenting sufficient trend resemblance;
- Sensitivity analysis for the selected border conditions with manipulation of these conditions;
- Validation and/or rejection of certain model elements;
- Validation and/or rejection of the entire model; and
- Running the model on selected potential South African cases.

3.1 Sources of data and data gathering methods
For the proposed model sensitivity verification runs and the entire model real-case validation, a wide spectrum of information sources had to be engaged. The required knowledge ranges from basic geological information on the selected coalfields, geological surveys and drilling costs, capital expenditure for necessary infrastructure (air/oxygen supply and compression, gas processing and transfer), through to the energy generation and capacity installation costs for different energy sources.

Additional information on the UCG process itself was obtained from available literature, mostly on the basis of classic, fixed bed gasification and underground technique similarities. The utilised sources are listed in Table 1, with their recognised areas of expertise.

No less important than finding the information sources, is the credibility of sources themselves, which meant that the experience and intellectual capital of the sources had to be evaluated. The selected sources, and associated input functions for the model, were presented to UCG experts, for re-evaluation and prioritization. The evaluation questionnaires were designed to provide quantifying numerical responses in only two categories ('priority' and 'impact') and for nine selected relationships. Three experts participated, two South African and one Polish, and contributed to the further verification and validation of the model; as described by Zieleniewski (2006). In three out of the nine listed questionnaire items, their priority indication was almost identical. The cost impact priorities, i.e. the strongest factors influencing gas unit costs that must feature in the model, were subsequently identified in the following order:
- Type of the gasifying medium (air, oxygen…);
- Production borehole spacing (grid);
- Depth of the coal seam (subsequently also the maximum recommended operational pressure).

3.2 Indirect economic costs – externalities estimation
The lower, subjective tier of the model is possibly of equal importance to the direct process-related costs, but has far reaching consequences. In some cases it is now possible to quantify, in financial terms, these ostensibly intangible or, at least elusive, costs, due to initiatives such as the European Extern-E Project (PDC, 2003). Extern-E is an acronym for 'externalities of energy':

> … numerous environmental and social problems, such as the health effects of pollution of air, water and soil, ecological disturbance and species loss, and landscape damage. Such damages are referred to as external costs, as they have typically not been reflected in the market

Table 1: Sources of model input information

Source	Expertise	Research stage[a]
Sasol Technology OPI	Capital expenditure estimation: piping, oxygen plant design, gas transfer costs, infrastructure costing, direct involvement in the UCG test planning, consulting of the Eskom test at Majuba Power Station	Stage II & IV
MANAIR Ltd (Pty)	Capital expenditures of high capacity air compressors (production and rental of variety of air compressing units)	Stage III
Sasol Geological Service	Geological techniques costs (vertical and directional drilling), South African coalfields characteristics, water table dynamics, coal seam behaviour	Stage II & III
Sasol Business Development	Business cases (BC) approach – environmental elements of BC, CAPEX for the infrastructure, cost amortisation, PIBIT[b]	Stage III & IV
Eskom Holdings	Energy production and capacity installation costing, traditional and alternative fuels solutions unit costs, Mpumalanga coal fields stratigraphy	Stage III & IV
Sasol SHERQ (Sasol Secunda Shared Services)	Environmental issues in the coal conversion industry, financial implications of non-adherence to the standards	Stage III & IV
Gemecs Ltd (Pty)	Geological expertise on coalfields of South Africa, safety aspects of UCG, geophysical limitations to the UCG technology	Stage III & IV
Ergo Exergy Technologies, Inc.	Comprehensive database on UCG technology, findings and relationships	Stage I & II
Anglo Coal Geological Service	Generic characteristic of selected South African coal fields in Mpumalanga, Limpopo and Orange Free State Provinces	Stage II & III
Kumba Coal	Specific geophysical information on Waterberg coal resources	Stage II & III
Majuba Power Station (Eskom Holding)	Experience of personnel directly involved in the UCG test planning and running	Stage II – IV
Sasol Synfuels – Gasification	Practical knowledge of the Lurgi fixed bed gasifiers process and parameters, relationships	Stage II – IV

Notes:

a   As per the detailed research methodology described in Zieleniewski (2006):

   Stage I – preparatory (initial stage)

   Stage II – extended selection/verification stage

   Stage III – model elements validation

   Stage IV – generic model validation

   Stage V – reporting stage

b   Profit before interest tax.

price of energy, or considered by energy planners, and consequently have tended to be ignored. … The purpose of externalities research is to quantify damages in order to allow rational decisions to be made that weigh the benefits of actions to reduce externalities against the costs of doing so. (PDC, 2003: 12).

Although still a contentious issue, the methodological steps and examples of externalities estimation can be found in literature (PDC, 2003) and has been applied to South Africa (Brent et al., 2006; 2007; Nyoka and Brent, 2006).

For the 'subjective' tier of the model, the estimation provides a common denominator with the upper, strictly economic layer. In 2003, the Provincial Development Council (PDC, 2003) estimated the external costs of electricity production as R75 billion to R120 billion per annum, based on two major fuel cycles in South Africa, i.e. coal and

uranium (in weighted ratio of 93:7; hydro energy was not included for its contribution and was below 1%). Table 2 presents three main categories of the external costs of electricity production (as per the 2003 year).

Table 2: Approximate external costs in damage category
Source: PDC (2003:15-16)

Exemplary damage cost range*	
Mine accidents	R0.006 /MJ
Health problems due to air pollution	R0.0625 /MJ
Global warming	R0.010–0.353 /MJ

Note:
* Based on an European Union study and an exchange rate of ZAR 9/Euro

A comparison of the main energy sources in South Africa (excluding diesel and petrol) has revealed that the highest external cost per energy

unit utilised lies with illuminating paraffin, used widely in households for the purpose of cooking, heating and illumination (see Table 3). Extremely high societal expenses, caused mainly by deaths, burns and ingestions (mostly among children), are estimated as exceeding R100 billion yearly (PDC, 2003). The costs of medical treatment constitute the majority of this estimate.

Table 3: Approximate external cost per fuel cycle
Source: PDC (2003: 15-19)

Cost of estimated externalities[*]	
Coal	R0.120 – 0.193 /MJ
Nuclear	R0.005 – 0.010 /MJ
Electricity	R0.011 – 0.018 /MJ
Paraffin (excluding deaths)	R0.450 /MJ
Paraffin (including deaths)	R9.485 /MJ

Note:
* Based on an European Union study and an exchange rate of ZAR 9/Euro

The expected function of the benefits evaluation model is to calculate and emphasize the advantages of the availability of cheap gas, not only from the strictly financial point of view, but also from a much more human and ecological perspective. The Extern-E findings allow combining both evaluation tiers.

4. Results

The results obtained during the process of model development and testing can be grouped in the fol-
lowing order:
- Initial project feasibility equation (simplified but workable go-no-go step);
- Formulation of oxygen (air) consumption per energy unit of produced gas;
- Tested model reactivity to changing initial border conditions; and
- Comparison of gas unit cost (R/MJ) with conventionally generated energy unit costs, with and without energy externalities.

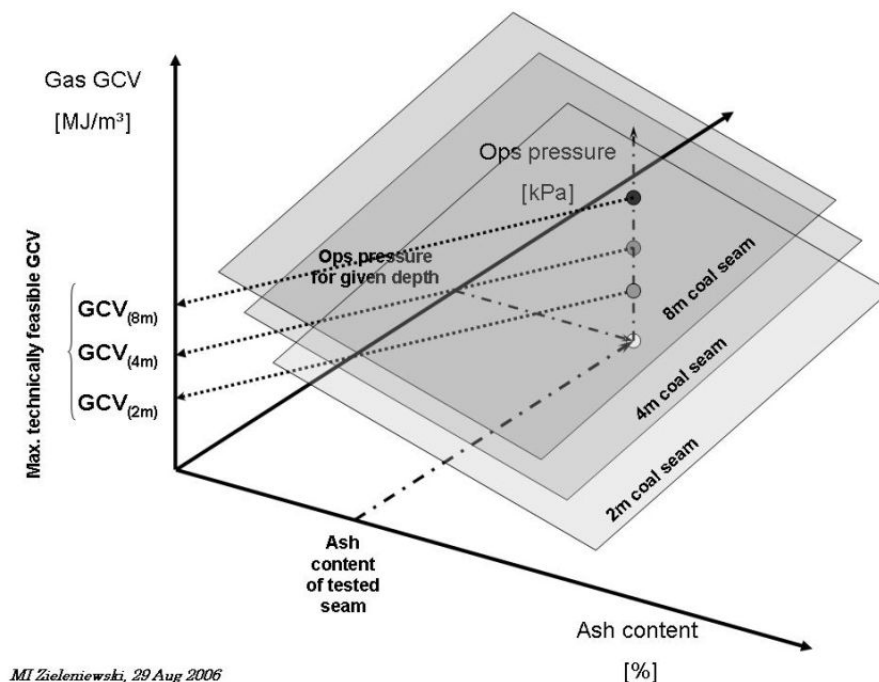### 4.1 Option affirmation or rejection tool

The feasibility stage equation is a function of three geological variables (Zieleniewski, 2006):
- Coal ash content A^{ad};
- Maximum allowable operational pressure P_{tmo} (being the function of the coal seam depth d_s); and
- Coal seam thickness h.

The result is reported as the maximum technically expected gross calorific value GCV_{tmx} of the produced gas. For the adopted input data ranges, the selected functions were simplified into linear equations and combined into equation 1 of the Appendix, which is graphically presented in Figure 3.

4.2 Gasification agent demand estimation

Brand (2006) adopted the coal-to-gas conversion ratio of 1350 m^3n/tonne of coal ROM, i.e. measured on a run-of-mine basis, described also as an as-received (ar) basis. Such a value is used as a constant for the final calculation of the volume of oxygen necessary to produce the demanded volume of gas (see equation 4 of the Appendix).

Figure 3: Relationships of feasibility stage test (GCV$_{tmx}$ finding)
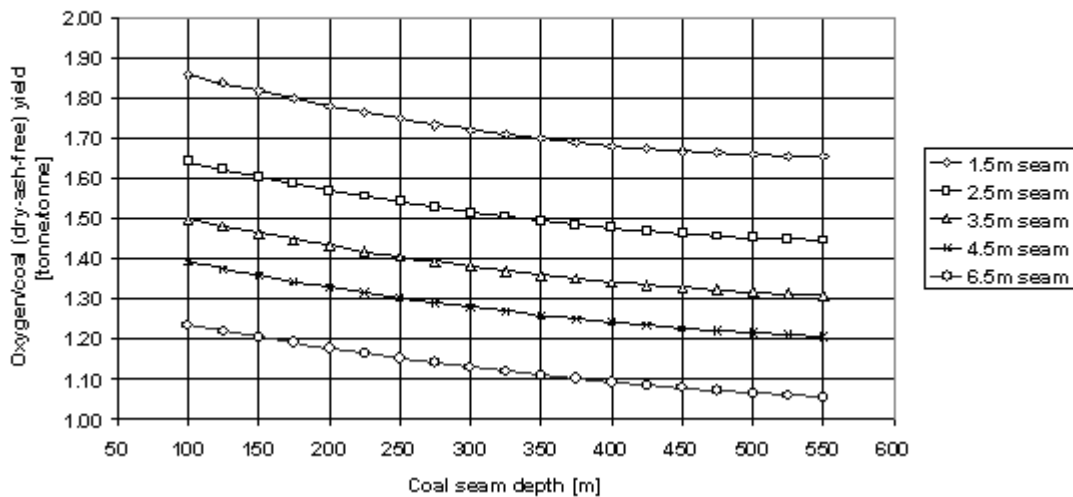*Source: Zieleniewski (2006)*

Figure 4: Expected oxygen/coal (dry-ash-free basis) yield vs coal seam depth and thickness

Recalculating the oxygen/coalar yield from tonne/tonne units into the m³/tonne is necessary for the final matching of the gas demand with the oxygen volume necessary for the production. The standard density ñ of technically pure oxygen, i.e. 98.5% pure, is 1.434×10-3 tonne/m³. Assuming the gas/coalar conversion ratio î = 1365 m³/tonne, it becomes possible to estimate the quantity of oxygen Vox necessary for the sustained production of the required gas volume VUCG (see Figure 4).

4.3 Sensitivity test of input factors
For the model to be used with a reasonable degree of certainty, initial testing is required, which includes manipulation of the input variables within their assumed value range. Border values of the three geological input variables were as follows (Makwakwa, 2003; Spurr, 2006; Venter, 2006; Council for Geoscience, 2008; see Table 4):
- Coal seam depth: 100 to 550m;
- Coal seam thickness: 0.5 to 11m; and
- Coal seam ash content: 15 to 35% (air dry basis).

The sensitivity test was performed as 'small' cases, in which only one of the input parameters was altered while the remaining two were constant and averaged. The test verified the initial assumptions. For instance, for a ten year operation comparison basis to achieve energy unit costs = R10/MJ, the following border conditions should be considered:

Table 4: Selected coal seams of South African coalfields

Sources: Makwakwa et al. (2003:7-11), Pinchero et al. (1999:66-81), Sparrow (2003:9-19), Spurr (2006:20-48)

Coalfield	Seam	Depth	Thickness	Ash [ad] *
Highveld	No 2	30 – 240m (N – SW)	4.75 – 10m (N – W)	22 – 29%
	No 3	170 – 185m	0.5 – 1.0m	22 – 25%
	No 4	15 – 300m (N – S)	1.2 – 4.5m (N – S)	18 – 42%
Witbank West	Seam 2	95 – 105m	5 – 7m	20 – 25%
Utrecht	Dundas	260 – 265m	0.7 – 2.6m	
	Gus	250 –260m	1.0 – 3.3m	
	Alfred (Moss)	225 – 230m	1.9 – 3.8m	15 – 22%
	Cokina	275 – 285m	0.3 – 1.5m	
Klip River	No 3	94 – 96m	Up to 1.3m	23 – 25%
Limpopo	Main	245 – 255m	10 –11m	20 –27%
Waterberg	No 1	300 – 305m	0.7 – 1.0m	20 – 24%
	No 2	290 – 295m	3.5 – 4.0m	
	No 3	280 – 292m	8 – 9m with mudstone interlayer	
	No 4	265 – 270m	0.7 – 0.8m	

Note:
*   Except the Highveld area, ash content of coal seams is estimated based on the washed product data.

- For A^{ad} = 25% and h = 3.5m → seam depth no lower than 145m;
- For A^{ad} = 25% and h = 2.0m → seam depth no lower than 230m;
- For A^{ad} = 25% and d_s = 300m → seam thickness no less than 1.2m; and
- For A^{ad} = 25% and d_s = 200m → seam thickness no less than 2.5m.

4.4 Direct energy unit costs comparison

Following the Eskom method of the electricity unit cost estimation, it is necessary to apply so-called life cycle levelled costs estimates, which couple the total cost of energy generation over the expected lifespan of the power station with capital expenditure. Depending on the type of energy provided, the unit cost range is as follows (Fick, 2006):

- For coal-fired power stations: about 28 R/MWh, i.e. 7.8 R/GJ;
- For nuclear power stations: about 34 R/MWh, i.e. 9.4 R/GJ; and
- For gas fuelled power stations: about 37 R/MWh, i.e. 10.3 R/GJ.

In the case of UCG, the amount of coal processed is determined by the reserves volume, and therefore shapes the final energy unit cost. Longevity of the UCG complex causes the CAPEX percentage to diminish, while operating costs are overtaken by accumulating calorific value of the produced gas (see Figure 5). Assuming ten years of operation and 10Mt of coal processed, the life cycle levelled cost would be as follows:

- 'average' case (A^{ad}=25%, d_s=250m, h=3.5m) → 8.1 R/GJ;
- 'best' case (A^{ad}=15%, d_s=550m, h=11m) → 4.1 R/GJ; and
- 'worst' case (A^{ad}=35%, d_s=100m, h=0.5m) → 26.6 R/GJ.

The inclusion of the lower tier energy externality costs of the model supports the business case. For the selected case of the Waterberg basin in the Limpopo Province of South Africa (coal seam depth, d_s: 290m, seam thickness, h: 3.5m and ash, A^{ad}: 24%) the application of UCG gas instead of widely used illuminating paraffin in the area, seems to be logical (see Table 5). The costs are derived from the discussion in section 3.2, and considering severe aspects of paraffin usage, e.g. fires and explosions often occur, resulting in injuries or even deaths and significant damage to property, and also the effects of indoor air pollution such as headaches, eye irritation, coughs and bad smells (PDC, 2003). These environmental aspects cannot be neglected, e.g. large quantities of CO (1.9 g/MJ) and CH_4 (0.03 g/MJ) are emitted from paraffin stoves with efficiencies of approximately 50%; the US EPA (as cited in PDC, 2003: 123) provide gas emission estimates.

Table 5: Total energy unit costs comparison, in R/MJ

Source: Zieleniewski (2006)

	Illuminating paraffin	UCG gas (R2 bln OPEX)	UCG (10 bln OPEX)
Direct economic cost (retail price)	0.330	0.050	0.150
UCG externalities		0.055a	0.045*
Paraffin externalities (excl. deaths)	0.450		
Paraffin externalities (incl. deaths)	8.485		
Total unit cost	0.780 / 8.815	0.105	0.195

Note:
* Estimated, from Table 3, as lower than coal (0.1-0.2 R/MJ) but within electricity range (0.01-0.02 R/MJ)

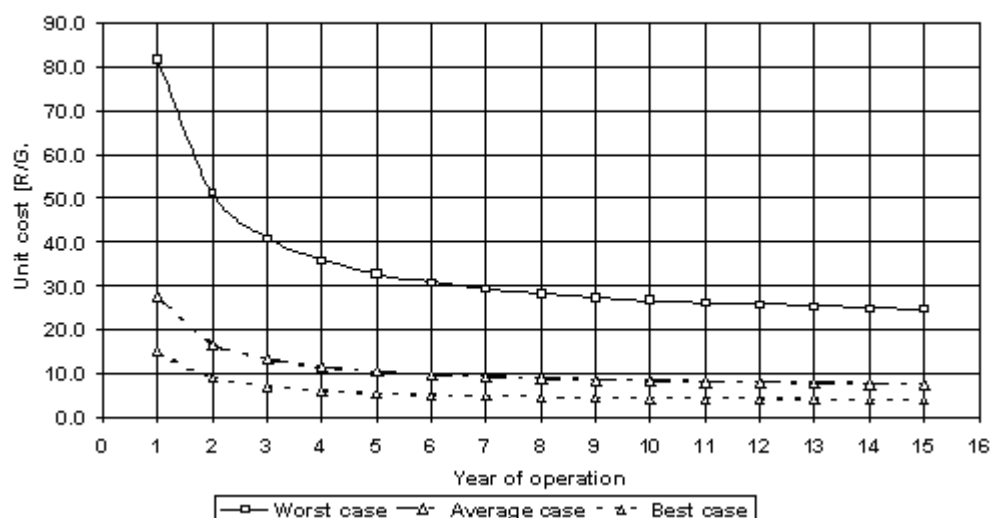Energy unit cost for 1Mt/annum coal extraction UCG case.

Figure 5: Influence of the operation time span on energy unit cost

5. Conclusions and recommendations

This paper introduces a functional benefit estimating model, which is capable of exposing limitations of considered UCG options, while at the same time, providing an idea of its maximum potential, at least theoretically.

The proposed approach, emphasised in the externality tier of the model, seems to be well tailored for the consideration of South African governmental agencies. The Extern-E equations allow the expression of environmental and national health losses expressed in monetary terms. Any intended UCG undertaking in terms of the economics then becomes far more encouraging as an investment. Even if the 'upper tier' direct economy were to present a payback time of longer than five or seven years, additional benefits would appear in the form of declining medical and ecological expenditures. In view of steeply growing medical and environmental costs, any modern state should embrace opportunities, which could lead to their reduction. Such considerations may justify taxation incentives to encourage non-governmental investment, although this fell outside the scope of this study. Regardless, present and future energy demands, as well as steadily rising prices of conventionally used agents, could well make UCG more competitive through market forces.

The model in its present, simplified form can already be used in an initial pre-feasibility study for any entity contemplating an investment in this form of energy conversion and distribution. The model can be further developed in order to yield a more precise estimation of costs versus benefits. To this end, it is recommended to improve the model's functionality further as follows:

- Replace the linear function ($GCV = f(A^{ad})$) by a polynomial type in order to include the ash content range beyond 40% (possibly up to 60%);
- Include equations that enable the estimation of the physical enthalpy of the produced gas as an additional benefit, which would reduce the energy unit cost for the electricity produced (for other applications, the cost could be reduced through recovery of the enthalpy by, for instance, the production of steam or hot water);
- Investigate the possibility and, if feasible, include the correcting module for geological anomalies, which can devalue the R2 of the function $P_{tmo} = f(d_s)$; and
- Specify the function of the energy unit cost versus the planned transfer distance for non-local applications of the produced gas.

Another suggested direction for further study could be an expansion of the benefit base beyond the gas calorific value and into more precise gas composition forecasts, which is essential in the case of synthetic gas substitution in the chemical and petrochemical industry.

References

Brand, J., 2006. Secunda Underground Coal Gasification (UCG) Cost. Preliminary feasibility study presentation, Sasol, South Africa.

Brent, A.C., van Erck, R.P.G., Labuschagne, C., 2006. Sustainability Cost Accounting: Part 1 – A monetary procedure to evaluate the sustainability of technologies in the South African process industry. *South African Journal of Industrial Engineering*, 17(2): 35-51.

Brent, A.C., van Erck, R.P.G., Labuschagne, C. 2007. Sustainability Cost Accounting: Part 2 – A case study to demonstrate and assess the introduced monetary procedure to evaluate the sustainability of technologies in the South African process industry. *South African Journal of Industrial Engineering*, 18(1): 1-17.

Burton, E., Friedmann, J., Upadhye, R., 2006. Best practices in underground coal gasification. Lawrence Livermore National Laboratory (LLNL), US DoE contract no. W-7405-Eng-48, https://eed.llnl.gov/co2/pdf/BestPracticesinUCG-draft.pdf, accessed 22 October 2008.

Council for Geoscience, 2008. South African Coal Database. Available from: www.geoscience.org.za.

Creedy, D.P., Garner, K., Holloway, S., Jones, N., Ren, T.X. 2001. Review of underground coal gasification technological advancements. UK DTI Cleaner Coal Technology Transfer Programme, Report No. COAL R211 DTI/Pub URN 01/1041, www.berr.gov.uk/files/file18660.pdf, accessed 22 October 2008.

Ergo Exergy Technology Inc., 2005. UCG history. www.ergoexergy.com/eUCG_his.htm, accessed 8 Aug 2006.

Fick, N., 2006. Personal communication.

Jie, L., 2003. An overview of the Chinese program on UCG. Study report, Underground Gasification Engineering Research Centre of the Coal Industry, Beijing, Peoples Republic of China.

Lloyd, P., 2006. South African energy reserves and the future. Presentation at GSSA DPP South African Energy Resources and the Future, Johannesburg, South Africa.

Makwakwa, Z., van der Merwe, K., 2003. Coal fields of South Africa: Depositional characteristics, exploitation, and markets. Highveld coal field: structural-geological features and the distribution of coal seams, Presentation at Sasol Synfuels, Secunda, South Africa.

Nyoka, M., Brent, A.C., 2007. Application of an environmental valuation approach to incorporate externality costs in the metallurgical sector. *Journal of the South African Institute of Mining and Metallurgy*, 107(10): 663-669.

Perkins, G., 2004. Underground Coal Gasification modelling. University of New South Wales, Australia.

Pinchero, H.J., Pretorius, C.C., Boshoff, H.P., 1999. Analyses of coal product samples of South African collieries 1998-1999. Bulletin 113, South African Bureau of Standards (SABS) Coal and Mineral Services, Pretoria.

Prevost, X.M., 2004. SA coal reserves, after the act. Presentation at the Fossil Fuel Foundation 10th Southern African Conference on Coal Science and Technology, Sandton, South Africa.

Provincial Development Council (PDC), 2003. Review of the effectiveness of energy subsidies and related taxation policies in South Africa. PDC in co-operation with Science Consultancy Enterprises, www.pasasa.org/pasasa/research/Review%20of%20the%20effectiveness%20of%20energy%20subsidies%20and%20related%20.pdf, accessed 7 September 2006.

Shackley, S., Mander, S., Reiche, A., 2006. Public perceptions of underground coal gasification in the United Kingdom. *Energy Policy,* 34(18): 3423-3433.

Shoko, E., McLellan, B., Dicks, A.L., Diniz da Costa, J.C., 2006. Hydrogen from coal: Production and utilisation technologies. *International Journal of Coal Geology*, 65(3-4): 213-222.

Simeons, C., 1978. Coal: Its role in tomorrow's technology. Pergamon Press, Oxford, UK.

Sparrow, J., 2006, Personal communication.

Spurr, M., 2006 The coalfields of South Africa. Presentation at GSSA DPP South African Energy Resources and the Future, Johannesburg, South Africa.

Sury, M., White, M., Kirton, J., Carr, P., Woodbridge, R., Mostade, M., Chappell, R., Hartwell, D., Hunt, D., Rendell, N. 2004. Review of environmental issues of underground coal gasification. UK DTI Cleaner Coal Technology Transfer Programme, Report No. COAL R272 DTI/Pub URN 04/1880, www.berr.gov.uk/files/file19154.pdf, accessed 22 October 2008.

Venter, E., 2006. Waterberg coal. *Quo vadis?* Presentation at GSSA DPP South African Energy Resources and the Future, Johannesburg, South Africa.

Walker, L.K., Blinderman, M. S., Brun, K., 2001. An IGCC Project at Chinchilla, Australia based on underground coal gasification (UCG). Paper presented at the 2001 Gasification Technologies Conference, San Francisco, USA.

UK Department of Trade and Industry (DTI), 2004. Review of the feasibility of underground coal gasification in UK. Cleaner Fossil Fuels Programme, http://www.berr.gov.uk/files/file19143.pdf, accessed 22 October 2008.

US Department of Energy (US DOE), 2005. Energy Information Administration. South Africa Country Analysis Briefs. www.eia.doe.gov/emeu/cabs/safrica.html, accessed 31 March 2006.

Zieleniewski, M., 2006. Selection and deployment of a method to evaluate the achievable benefits of extending technologies for uneconomical coal resources in South Africa. Masters project, Graduate School of Technology Management, University of Pretoria, South Africa, Available from: www.up.ac.za/dspace/handle/2263/4005, and alan.brent@up.ac.za.

Appendix

As a provision for inevitable gas quality variability, a 10% uncertainty margin is adopted in the decision-making process. The feasibility equation is therefore:

$$GCV_{dbn} = GCV_{tmx} * 1.1 \tag{1}$$
$$GCV_{tmx} = (-0.002083A^{ad} - 0.0125)h^2 + (0.0275A^{ad} - 0.475)h + 0.003149p_{tmo} + 9.481 \tag{2}$$
$$p_{tmo} = 7.55\, d_s \tag{3}$$

Where:
GCV_{dbn} = demanded gross calorific value of gas [MJ/m³]
GCV_{tmx} = maximum technically possible gross calorific value [MJ/m³]
A^{ad} = ash content of coal (analytical i.e. air dry basis) [mass %]
h = coal seam thickness [m]
p_{tmo} = maximum theoretic operational pressure [kPa]
d_s = coal seam depth [m]

Oxygen consumption per tonne of coal is the bi-variate equation:

$$Oxygen/coal^{daf} = [(-28.854*10^{-8}ln(h) + 104.44*10^{-8})d_s^2 + (226.022*10^{-6}ln(h) - 1147.778*10^{-6})d_s - 445792.77*10^{-6}ln(h) + 2.137] \tag{4}$$

$$coal^{daf} = coal^{ar} *[1 - (A^{ar} + M)/100] \tag{5}$$
$$A^{ar} = A^{ad} *(100 - M)/ (100 - m) \tag{6}$$

Where:
$coal^{daf}$ = coal mass measured on dry-ash-free basis [tonne]
$coal^{ar}$ = coal mass measured on as-received (ROM) basis [tonne]
h = coal seam thickness [m]
d_s = coal seam depth [m]

A^{ad} = *ash of coal measured on air-dry basis [mass%]*
A^{ar} = *ash of coal measured on as-received basis [mass%]*
M = *total moisture of coal [mass%]*
m = *inherent moisture of coal [mass%]*

For in-seam coal, M and m can be assumed to be almost equal; therefore A^{ad} ˜ A^{ar}. Coal^{daf} is then specified as:

$$Coal^{daf} \sim coal^{ar} * [1 - (A^{ad} + m)/100] \tag{7}$$

The DAF factor daf$_f$ is described as follows:

$$daf_f = Coal^{daf} / Coal^{ar} \tag{8}$$

Therefore:

$$Oxygen/coal_{ar} = (Oxygen/coal_{daf}) / daf_f \tag{9}$$
$$V_{ox} = V_{UCG} * oxygen/coal_{ar} / (\xi * \rho * 0.985) \tag{10}$$

Where:
V_{ox} = *oxygen volumetric flow [m³/h]*
V_{UCG} = *demanded gas volumetric flow [m³/h]*
oxygen/coal^{ar}   = *oxygen yield per coal on as-received basis [tonne/tonne]*
ξ = *gas yield from coal on as-received basis [m³/tonne]*
ρ = *technical purity oxygen density [kg/m³]*

The table below shows all the basic cost groups and units costs, such as drilling expenditures, which are quoted per meter. The Oxygen Plant (used as an example) includes both capital and operational costs, the latter being a function of the demanded oxygen volume.

Exemplary cost breakdown for input variable sensitivity test (for 1Mt of coal/anum)				
Specification	Unit	Item cost	Item	Total cost
Initial costs:	[R*1,000]	35,000		35,000
In seam (DD) drilling	[R*1,000]	4,000		40,000
Well connecting piping	[R*1,000/m]	9.5	2500 m	237,500
Monitoring well drilling	[R*1,000/m]	0.3	16 wells	9,600
Vertical production wells	[R*1,000/m]	0.3	115 wells	57,500
Vertical injection wells	[R*1,000/m]	0.3	5 wells	2,500
Oxygen Plant capex & opex	[R*1,000]	1,122,643	1 plant	1,122,643
Total cost:	[R*1,000]			**1,504,743**
Oxygen/coal^{daf} yield	[m³/tonne]	1,095.9		
DAF factor *daf$_f$*	[1]	0.705		
Oxygen/coal^{ar} yield	[m³/tonne]	772.6	**Expected years:**	**10**
Total oxygen volume	[m³*1,000]	7,726,434		
Oxygen unit cost	[R/m³]	0.10		
Coal seam depth d_s	[m]	200	**Constant used:**	
Coal seam thickness h	[m]	2.5	ξ - gas/coal conversion =	
Coal ash A^{ad}	[%]	25.0	= 1,365 m³/tonne	
Max.expected gas GCV_{tmx}	[MJ/m³]	11.07	ρ - technical oxygen density =	
Expected gas volume V_{UCG}	[m³]	1.37E+10	= 1.434 kg/m³ @98.5% purity	
Total GCV (ex 1Mt coal)	[GJ]	1.51E+08		
Rand gas unit cost	*[R/GJ]*	*10.0*		