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Review on the Existing and Developing Underground Coal Gasification Techniques in Abandoned Coal Seam Gas Blocks: Australia and Global Context

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Abstract: Coal is the major energy source which provides about 40% of the total electricity generation of the world. For Australia it is nearly 80%. For meeting global demand with less greenhouse gas emission (GHG), Australia is pursuing for alternative eco-friendly renewable energy sources. In Australia, there are huge ranges of coal resources, especially deep seated coal deposits, which are difficult to extract with conventional mining and the policy makers are practicing "clean coal" policy for further usages of the resources. Coal seam gas (CSG) and underground coal gasification (UCG) is identified technology for exploiting those coal deposits. The UCG is much more effective process for energy exploitation (theoretically greater than 15-20 times) compared to CSG process. Demonstration of UCG projects and development of these technology received momentum as one of the successful pilot project at Chinchilla, Queensland, Australia, which operated successfully from 1997 to 2003 for demonstration power generation and till dated for GTL(gas to liquid) commercial production from the gasification products . Last few years there was a debate for choosing priority policy for CSG / UCG. Australian local entrepreneur and global international oil companies (IOC) sought for massive scale CSG extraction and presently this industry is in booming stage. Apparently it is seen from the industry trend that UCG operation is behind the race compared to CSG activity, however the long term prospect of UCG is brighter as there are not much CSG left in the coal body for exploiting. The ideal conditions of the coal body have been deviated while CSG operation is being done. Only minor amount of hydro-carbon (with in-situ natural gases) are extracted but major share of the coal deposit are left over at deep geological formation. Review on the existing and developing sophisticated technology for next phase of abandoned CSG fields is a potential area for further research and development (R&D). This paper reviews history and methods of UCG both in Australia & global context. The issues related to UCG in abandoned CSG blocks are identified and discussed. Finally the study recommended the scopes of future study. The success of this effort can enlighten the black coal towards "Cleanest and Greenest" source of energy for next generation Hydrogen fuel.

Keywords: Coal Seam Gas, Underground Coal Gasification, Hydro-fracking, Depleted coal body, Carbon capture & storage.

1. Introduction

Coals were formed 100-400 Million years ago and their quality depends on the formation process, temperature, pressure as well as materials, where geological condition plays the main role. Coals are exploited by conventional mining (underground/open pit stripping) where the geological condition, depth of deposit, environment and ecological impacts are viable in respect of return and cost effective operation. But coal reserves in deeper position are not suitable for conventional mining. The diversified methods for exploiting hydro-carbon from those deep coal reserves are as :

- Coal Seam Gas (CSG) operation
- Underground Coal Gasification (UCG) operation
- Biotechnology in coal reserve (R & D stage)
- Borehole Mining (research stage) etc.

The coals are used as major energy source; but never been treated as prime choice of energy sources because of hazardous & risky extraction procedures as well as environmental pollution. However the coals are still using as bulk source of energy for electricity generation. Sulphur, Nitrogen Oxides, Carboneus products can be minimized using clean coal technologies (such as Fluidized Bed Combustion, Oxy fuel pre-post combustion etc.) at the combustion stages. Other technologies such as coal gasification are adopted for producing synthesis gas from the coal before reaching the burning state. The synthesis gases are processed for further application as burning fuel, or chemical products.

UCG is a gasification process , where the gas conversion chamber is constructed within the coal body at underground [1]. This technology originated with German engineer William Siemens in 1860s [2]. William Ramsay conducted the successful experiment at Durham coalfield in northern England. In 1939 the former Soviet Union had successfully begun operating a UCG plant at Ukraine, which was later shut down by German occupation. Later on they introduced UCG project in1960s, at Angren, Uzbekistan for running a power station (figure - 1) which is still operating and producing about a million standard cubic feet of syngas per hour [3]. Unfortunately this project and their practices are not treated as standard procedure to the global context.

More than 30 UCG pilot test projects conducted in United States of America. In the late 1970s and 1980s, the U.S. government instituted several research projects and trials of UCG (Hanna I, II,III & IV and The Rocky Mountain- I) trial demonstrated the gasification of about 30,000 tons of coal [2]. In South Africa, an UCG pilot project at the Majuba coal field, Johannesburg achieved ignition in January 2007 for supplying gas for a 4,200 MW power plant but the field was found severely faulted with volcanic intrusions. The authority is in progression for a 1,200 MW integrated gasification combined cycle (IGCC) plant [4].

Huge range of proven coal reserves (especially coals are not exploitable with conventional mining) in Australia. Massive activities are running in Australia especially in Queensland, New South Wales, South Australia and Western Australia for extraction and processing of in-situ Methane resides inside the porous coal formation, which are unminable due to deep geological position. Coal Seam Gas (CSG) extraction through low head pressure well , accumulated with gathering pipelines to the step up compressor station, then transport to the liquefied natural gas (LNG) plant for shipment. On the other hand there is an established technology for developing the facility of “Gasifier Chamber” inside the coal body, for producing raw synthesis gas which can be used as flue gas for direct power generation. Otherwise the synthesis gas property can be controlled for further extraction of commercial by-products.

For choosing policy, implementation of UCG would be a better exploitation strategy for the deeper coal deposits (200-1500 m, below the surface). R&D initiatives are running in pace throughout other continents especially Europe, North America, China, South Africa, India, New Zealand and Australia to establish the UCG technology & sustainable operation. Researcher and technologists are working on this area for shaping the uncontrolled activity, development of new concept. In the competitive energy market, UCG should pass the threshold barrier. Implementing the ability of UGC requires extensive feasibility study and long term effort considering the economic values, less emission of GHG, trapping and storage of the major carbon products of pre/post combustion activity. In addition to this the experts are seeking provision for permanent storage of carboneus material in leftover deep firing chambers of the coal seam area.

This study presents a review on UCG projects in Australia & other areas, identified issues on UCG technology also presented. Finally the scope and future study is recommended.

2. UCG in Australia

UCG projects initiated in Australia in (1980- 1990) and Linc Energy started the UCG project at Chinchilla, Queensland (coal seam depth 140 m and thickness 10 m, air injection as oxidant) and conducted the feasibility study, which is treated as standard example to the global perspectives (Figure

-1). Over than 35,000 tons of coals were gasified (output pressure apx. 10 bar, temperature 300^{o} C 100% availability, 1999-2002) with no observed subsidence or contamination of groundwater. The project achieved 95% recovery of the coal resource, 75% recovery of the total energy and a controlled shutdown. Carbon Energy conducted the pilot project (nearby Dalby, Queensland) in associated with Commonwealth Scientific and Industrial Research Organization (CSIRO) [5, 6]. Cougar Energy also planned to build a 400 MW electricity generation from a UCG plant at Kingaroy, Queensland [7]. The Queensland government approved three UCG trial sites to evaluate various technical and environmental factors and the prospects & future management.

Figure 1. (left) Angren, Uzbekistan, UCG co-fired 100 MW (steam Turbine) power station [3] and (right) UCG plant at Chinchilla, Australia .

Groundwater contamination with benzene (pyrolysis product of gasification process) was observed at two sites at UCG trials in USA [8]. In May'2010, it was reported presence of Benzene (2 ppb) and Toluene leached in two samples from a single monitoring bore near the Cougar Energy's plant .In 2011, the Queensland authorities shut down Cougar's operations at Kingaroy [7, 9]. In June'2013, the Independent Scientific Panel (ISP) formed by the state government reviewed vetoed commercial operations by Linc and Carbon Energy until the companies could "demonstrate safe decommissioning by extinguishing the fires, shutting off reactions and preventing groundwater contamination" [9, 10]. This statement disappointed those pioneer entrepreneurs and they are planning for moving outside Australia. Linc Energy announced that they are shutting their Chinchilla project and moving to China and the USA. Carbon Energy engaged in China, Argentina and Chile and Cougar Energy has shifted their attention to Indonesia. Michael Blinderman (Exergy UCG Technology) disagreed with the decision made against Cougar Energy's Kingaroy project shutdown. He mentioned that the trace of Benzene was due to laboratory error, where 17,000 analyses of ground water undertaken with no contamination found [11].

3. Identified Issues

3.1.CSG Operation

Coal seam gas became an important energy source in USA, Canada, Australia and other countries. The estimated CSG reserve in Australia is around 33 TCF [12] . Coal is an assorted and anisotropic permeable medium. The micro pore, void & cleats, fracture, fissures are the influencing parameters of permeability, which is a function of pressure. Gas resides within coal seam as (a) coal matrix (major portion) due to adsorption mechanism (b) small amount as free gas with in the micro pores of coal body and (c) Minor amount as dissolved gas in the connate brine in the cleats/voids.

The gas concentration and deposit depends on various factors particularly geology of the coal formation. The construction of the production well and strategy prepared based on the geological formation of the coal deposits. In the coal boundary/sub-surface, the cleats are generally filled with water. The productivity and life of the coal block depends on the following properties:

- Type of the coal
- Depth and thickness of the coal body
- Adsorption capacity of the coal
- Permeability, presence of fracture & fissure
- Water contents

For extraction of in-situ gases the following external activity executed for gas exploitation as:

- Production well drilling (vertical)
- Hydraulic fracking of coal seam for creating openings of fissures, fractures for connecting the gas deposit area to the production well. In addition placement of fracking agent (mainly sand) within the coal body (provisional).
- Inter linking the production well gas inlet port by means of horizontal bore hole loop and controlled blasting (provisional)
- Dewatering of the coal body

3.2.After Effects of CSG Extraction

Dewatering of coal seam releases the stress state and allows dissociation of the coal matrix. Gas production and life expectancy of a CSG block is a function of dewatering rate over several years. In Queensland, the average dewatering of a well is around 20,000 liters of water/day. The CSG extraction process and coal structure can be understand from the figure -2 [13].

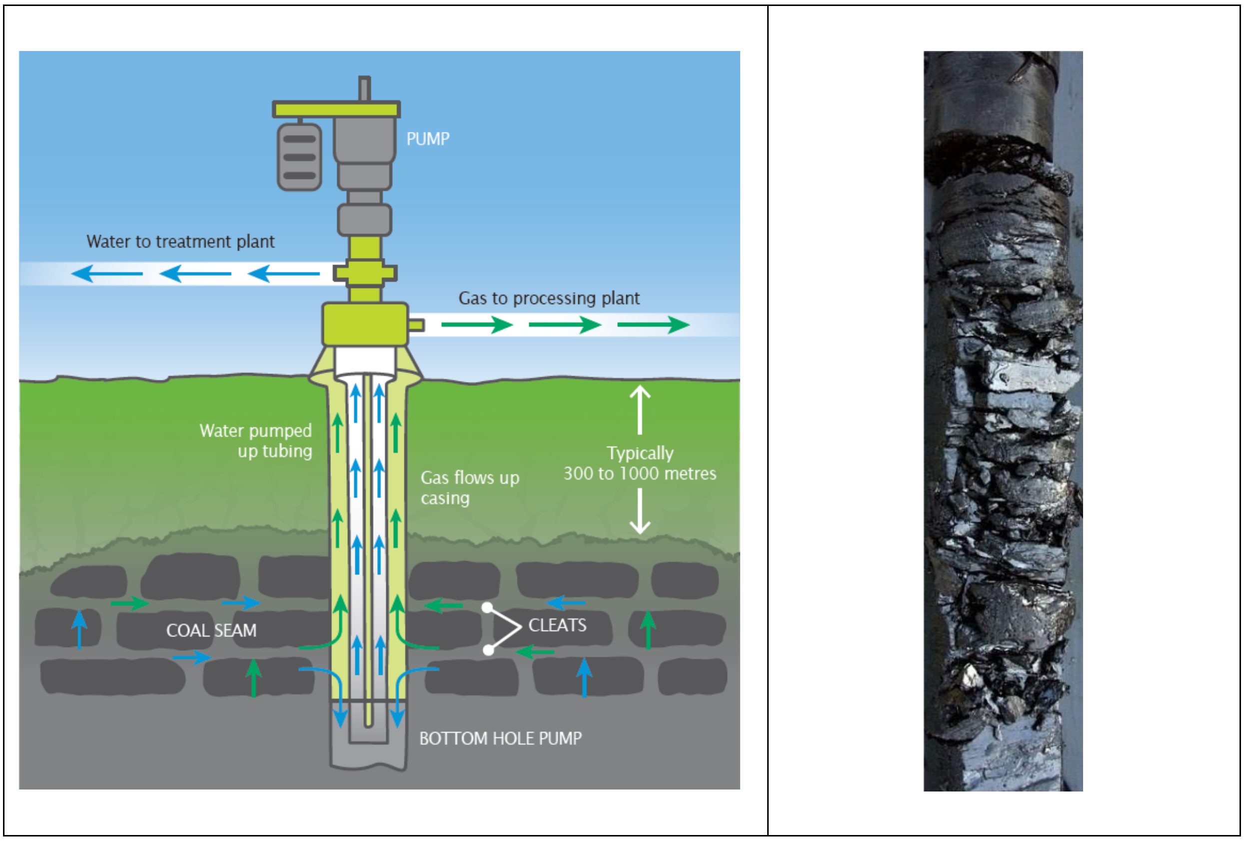

Figure 2. (a)Schematic diagram of Coal Seam Gas extraction process [www. csiro.au, April 2012] and (b) a typical core sample of coal body.

The gas production rate of a CSG field attained in a stable state while major portion of the waters are extracted from the coal body (presented in Figure-3). This happens due to release of pressure from the micro pores, cleats. Decline phase of gas flow refers to minimization of water incoming rate, which assumed due to closing of openings of the coal body [14] .

Work over activity of the CSG well is carried out based on the well-head production rate. Further drilling and hydro fracking stimulation activity are executed on the basis of the economic return and geological prospecting. This is a decision making phase for further extension or permanent sealing of the well.

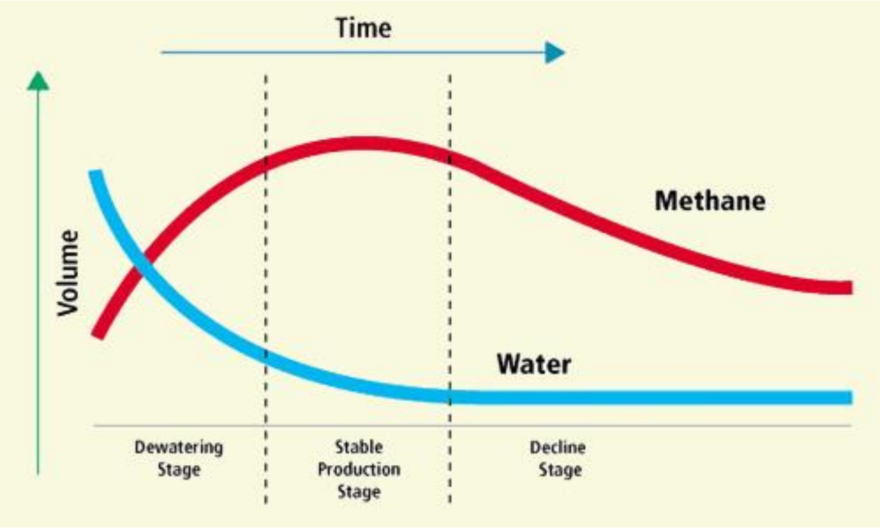

Figure 3. Stages of gas and water production from coal life expectancy and gas production rate based on dewatering operation. [14]

3.3. Carbon Sequestration within Deep Seated Coal Body

The global carbon emissions from coal is approximately 2.5 Gt C and it can be raised to 9 Gt carbon (C) in future based on the demand [15]. For GHG reductions, deep geological storage are deployed, where carbon dioxide are isolated from the combustion product through physical, chemical, biological or engineered processes. The most promising reservoirs are porous and permeable rock bodies, generally at depths around 1(one) km at a pressure and temperature where CO_2 would be in a supercritical phase [15]. Apart from the other geological formation, the deep seated coal deposits (normally 700-800 m, but better option more than 1000 m) which are exploited by UCG operation, can be a potential carbon sequestration.

3.4. Underground Coal Gasification at Deep Seated Coal Seam

Underground coal gasification process and technology is well understood through extensive laboratory studies [16, 17], model & simulation [18-26] and feasibility study through execution of pilot projects [4, 27, 28]. A deeper UCG pilot test is successfully conducted at depth of 1400 m in Swan Hills, Alberta, Canada and ready for commercial production [29]. UCG facilities can be developed at deep seated coal seam in combination with standard directional and horizontal drilling techniques. A numbers of vertical wells are drilled up to the coal body and linked up within the coal body through directional drilling/hydraulic fracturing and scape way of produced gas through vertical producer. *CRIP (Continuous Retraction Injection Point) and "e-UCG"* are the proven techniques for linking up the injection well and production well. The CRIP process retracts the combined steam and oxygen injection point to control the location of the combustion front [19].

Oxidants (air, oxygen or steam) are injected to ignite and fuel the underground combustion process. The high pressure (4-10 bar.) combustion is conducted at a temperature of 700–900 °C (1,290–1,650 °F) ; but it may reach up to 1,500 °C (2,730 °F). The process decomposes coal and generates carbon dioxide (CO_2), hydrogen (H_2), carbon monoxide (CO) and small quantities of methane (CH_4) and hydrogen sulphide (H_2S). The overall gasification processes is well understood and the important reactions in the coal gasification process are summarized in table -1.

Table 1. The reactions involved in coal gasification

a)	Heterogeneous water gas shift reaction (Exothermic)	$C + H_2O = H_2 + CO$	$\Delta H = +118.5$ kJ /mol
b)	Shift conversion (Endothermic)	$CO + H_2O = H_2 + CO_2$	$\Delta H = -42.3$ kJ / mol
c)	Methanation (Endothermic)	$CO + 3H_2 = CH_4 + H_2O$	$\Delta H = -206.0$ kJ /mol
d)	Hydrogenating gasification (Endothermic)	$C + 2H_2 = CH_4$	$\Delta H = -87.5$ kJ /mol
e)	Partial oxidation (Endothermic)	$C + \frac{1}{2}O_2 = CO$	$\Delta H = -123.1$ kJ/ mol
f)	Oxidation (Endothermic)	$C + O_2 = CO_2$	$\Delta H = -406.0$ kJ /mol
g)	Boudouard reaction(Exothermic)	$C + CO_2 = 2CO$	$\Delta H = +159.9$ kJ/ mol

UGC process involved several distinct multi-physical /chemical process domains, including the cavity, the cavity wall zone contacting coal body, the wall zone contacting rock and rubble zone (Figure - 4). The first step is ignition of the coal by injection of air/air enriched with oxygen. The combustion converts the C to CO_2 and provides heat for subsequent reactions in which the CO_2 reacts with steam to produce H_2, CO, and CH_4. Second stage of gasification starts (both permeable bed gasification and natural convection driven surface gasification). Firing of coal produce environment for further gasification of the surrounding coals.

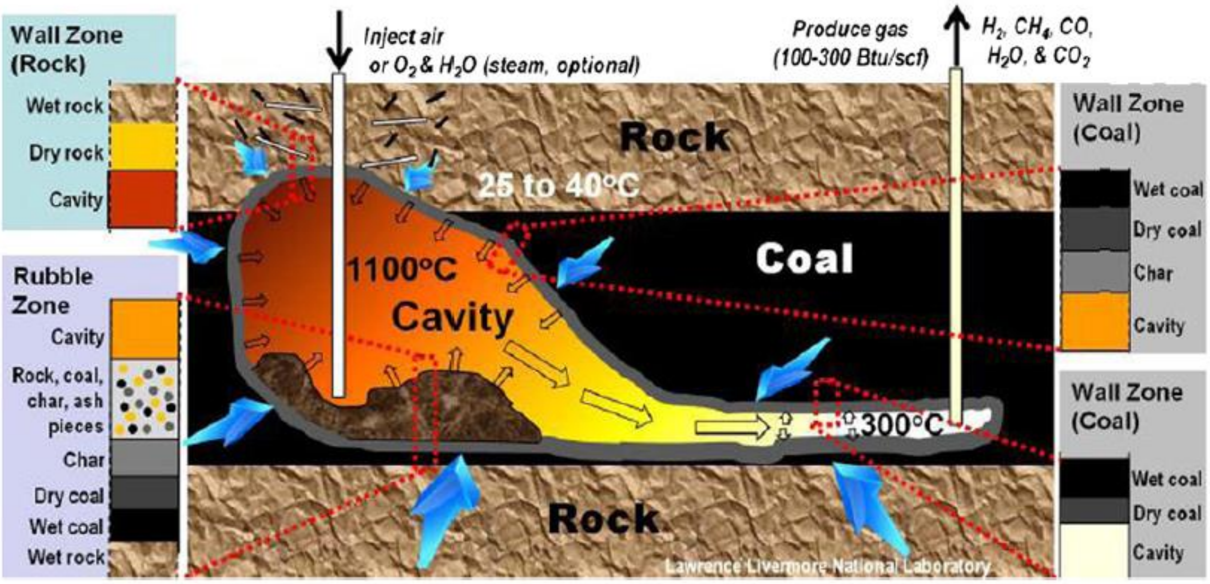

Figure 4. A typical cavity configuration and coal gasification reaction zones[18]

The overall process can be sub divided into 3 zones as (a) Oxidation zone (b) Reduction zone and (c) Gasification/Dry distillation zone. UCG is a self-contained complex thermo-chemical gasification process. The property of the final product can be controlled through injection charge quality, pressure etc. The influencing factors of the underground coal gasification are mainly as :

- Temperature
- Type and composition of the Coal
- Thickness of Coal seam
- Water incoming rate towards the gasification chamber
- Quantity and quality of Air Blasting
- Operational Pressure
- Length and section of the gasification channel

3.5 Economic and Environmental Issues

From observation and findings, UCG is considered as a viable unconventional coal extraction engineering process. For electricity generation, the integrated gasification combined cycle (IGCC) systems give increased efficiencies by using waste heat from the product gas. IGCC systems also produce less solid waste and lower emissions of SO_2, NO_x and CO_2. Combination of UCG and IGCC is technically feasible. Gasification at deep seated coal body is a new challenge. Deeper seams require higher drilling costs as well as higher injection and operating pressure and increase the cost of any subsequent activity.

Subsidence is a major problem for Shallow depth coal gasification activity. It is observed that the subsidence decreases with increasing of depth. Deeper seams are less likely to be linked with aquifers and reduced probability of contamination with pyrolysis products. In additional the UCG cavities at depths of more than 800 m could be used for CO_2 sequestration, where cap rock and overburden layer can restrain with in the depleted geological coal formation.

The cost effective operation of a plant based on unconventional deep seated coal extraction process which is still under observation. The value added each steps of the process make the final product cost effective while decisions are taken considering optimization. The commercialization of the UCG technology would be a sustainable adoptable concept, while best practices are adopted for extraction of the resources. CSG, UCG and CO_2 sequestration are individual operations and added values to the service, which are being demonstrated in global projects. The concept of integrated operation and their implementation may open a new horizon to the energy conservation sector. Clean energy practices along with minimum GHG emission is the current policy of the developed countries. Among the fossil fuel, Natural Gas is the lowest emitter of GHG. Electricity generation with UCG is 25% (apx.) lower than that of conventional coal fired plant ; but 75% higher than that of Natural gas fired plant [30]. With adopting appropriate UCG technology, the cost of the gas per unit of energy is much lower than natural gas. When compared to current coal fired power generation , these factors combined to provide a competitive cost of power at a scale with lower Co_2 emission, leaving solid products at deep cavity [31].

3.6 Provision of Deep Seated Coal Gasification and Optimization

CSG operation is a proven commercial industry in Australia, USA and other area of the world. UCG activity can be executed as post CSG operation, which would be cost-effective and sustainable engineering activity, where existing well can be used for further operation. In addition the cost of the surveying and assessment, dewatering of the coal body (dry coal is better choice for UCG), hydro-fracking operation (improving permeability of the production wells) could be added as capital investment. The optimal benefits can be achieved if UCG operation as post CSG activity, integrated with permanent storage of CO_2 (which may be transported from other areas or post combustion CO_2 separation from the gas process plant/electricity generation station) injected into post-UCG geological structure via the existing production wells. The CO_2 would be stored permanently in to the coal cavities along with the ‘Char and combustion product’. This CSG-UCG-CCS program will play a significant role on the electricity production costs and meet up the international climate protection targets of Co_2 emission levels.

A comprehensive cost model of coal gasification (depth of 1000-5000 m deposits in Germany) and power generation (European context) including with post carbon sequestration integrated program is presented in figure -5. The power generation costs without CCS is the lowest but for 50% CO_2 capture and storage is achieved the power generation costs about 24 % lower and the CO_2 emission rate about 12% lower than the natural gas-fired combined cycle power station. If the CCS capacity raised from 50% to achievable target 86% the power generation costs of the UCG-CCPP-CCS process are about 36 % lower , where combined cycle power plant (CCPP) is one of the best option for maximum thermal efficiency [32] .

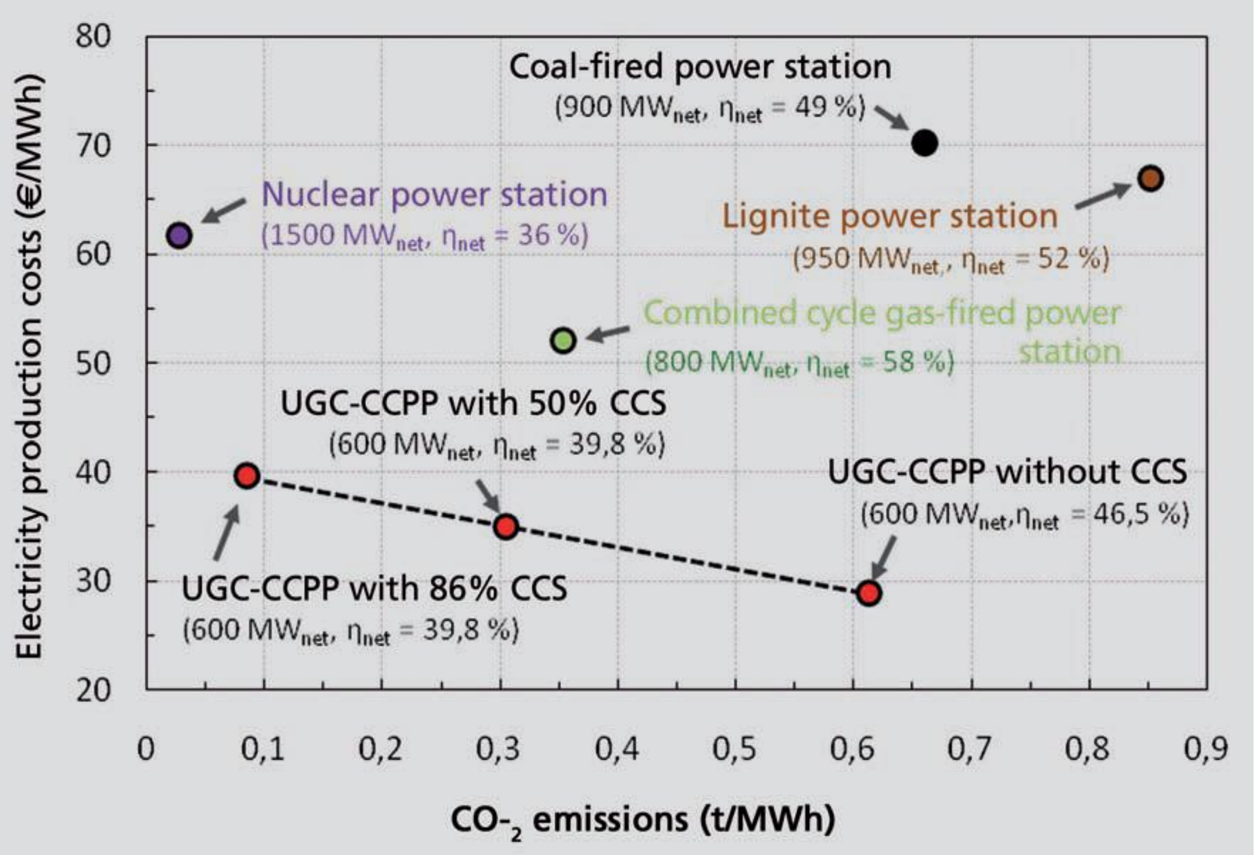

Figure 5. Electricity generation costs in respect of CO_2 emission for UCG-CCPP-CCS process on the basis of EU perspective [32]

UCG activity has the similar impact of subsidence like as underground long wall mining for shallower depth operation. In general subsidence depth is equivalent to one-third of the vertical thickness of the coal seam and would only affects land directly above the gasified coal seam. But this effect can be insignificant for deep seated coal gasification. Besides this the gasification occurs in a deeper position, the scope of aquifer contamination is very much low than that of the operation for shallow depth [1]. In Queensland the discovered reserves and geological survey report (Figure - 6) shows that the coal deposits of Bowen Basin, Surat Basin, Gallilee Basin having potential prospect for deeper coal exploitation operation [33].

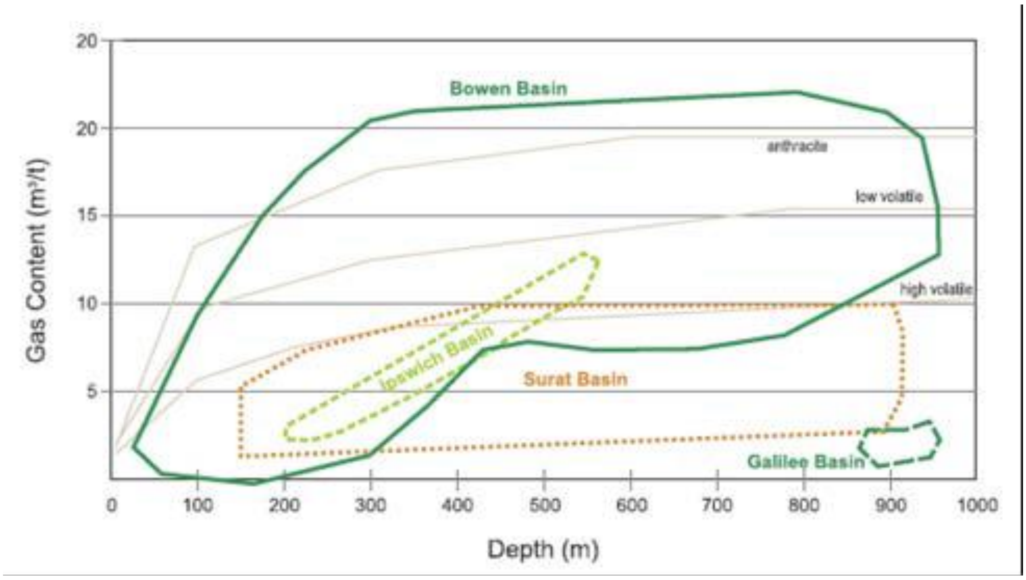

Figure 6. Properties of Australian Coal deposits mainly in Queensland [33]

4. Discussion

Adopting the sustainable policy, CSG industry gained momentum in Australian economy. Australia shows zero tolerance for adopting engineering action, which does not satisfy the standards, safety issues compliance to national regulation & act as well as global standards. The observation and recommendations from the Independent Scientific Panel, formed by the Queensland State Government has set "Threshold Barrier" as principal recommendations for further steps on commercial UCG operation [9]. That technical committee also recommended for establishing two new entities for supporting the UCG industry. The proposed regulatory bodies for screening the UCG activity in view of environmentally, socially and economically viable as :

- Queensland UCG Independent Assessment, Evaluation and Advisory Group.
- The Queensland UCG R&D Network.

Underground Coal Gasification Association (UCGA) considered the environmental issues and seeking coal gasification operation at deeper coal bodies such as Alberta's Swan Hills Synfuels pilot project to commercial operation (1400 m deep) [11]. A group of skilled and dedicated entrepreneur are seeking the pathways for exploitation of deep seated hydrocarbon within a safe engineering framework and bringing the global UCG projects under the same umbrella. Australian experts especially worked in Chinchilla project(1999 till dated) achieved their demonstrated skills for commercialization of UCG technology. They have operated 5 successive UCG activity, running the GTL(gas to liquid) plant for producing fuels and other chemical products from Syngas product, development facilities for controlling process & shut down practices as well as validation of numerical results scientifically.

Unfortunately those experts who had spent their toil & moil for nourishing the “Western world’s leading practice in UCG” demonstration for commercial production (Chinchilla UCG plant) are being stalling at the verge of the hurdle. They are planning to move other areas like India, China, Pakistan, Indonesia, South Africa etc. where exists energy draught.

Although, UCG has a history of 100 years of efforts & investment; but still is in crippling stage. On the other hand CSG industry embarked with billion dollar investment from the pronounced IOC and local investors. But another prospecting UCG byproduct (H_2) can be a potential player for progression of UCG in Australia. FCV (Fuel Cell Vehicle) Hydrogen cars(Figure - 7) would be the premier choice in respect of most environment friendly zero emission GHG vehicle within very short time in global market [34]. Australia would be in front line for drive away this new generation vehicle, where Hydrogen by-product of UCG is treated as a burden [35].

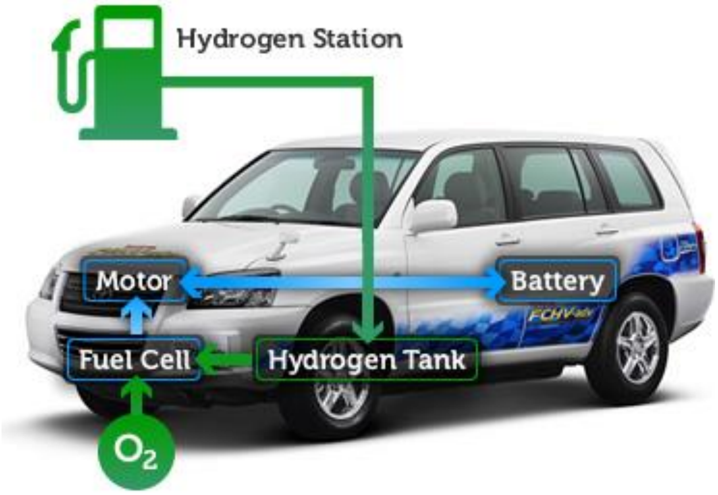

Figure 7. H_2 fuel cell drive vehicle [www.toyota-global.com/./fuelcell_vehicle]

Coupling the gasification process to subsequent CO_2 storage in post CSG deposits, can open up new possibilities for the eco-friendly exploitation of the deep seated coal deposit. In this context an engineering concept/approach is presented in the paper, where UCG draws the most priority and focus. A fore step engineering approach (presented in Figure-8) is adopted for:

- Seeking provision for UCG operation in the depleted CSG blocks
- Carbon sequestration after event exploitation
- Simultaneous operation of both activity (CSG and CSG) in the same block
- Open door for H_2 drive vehicle and engine

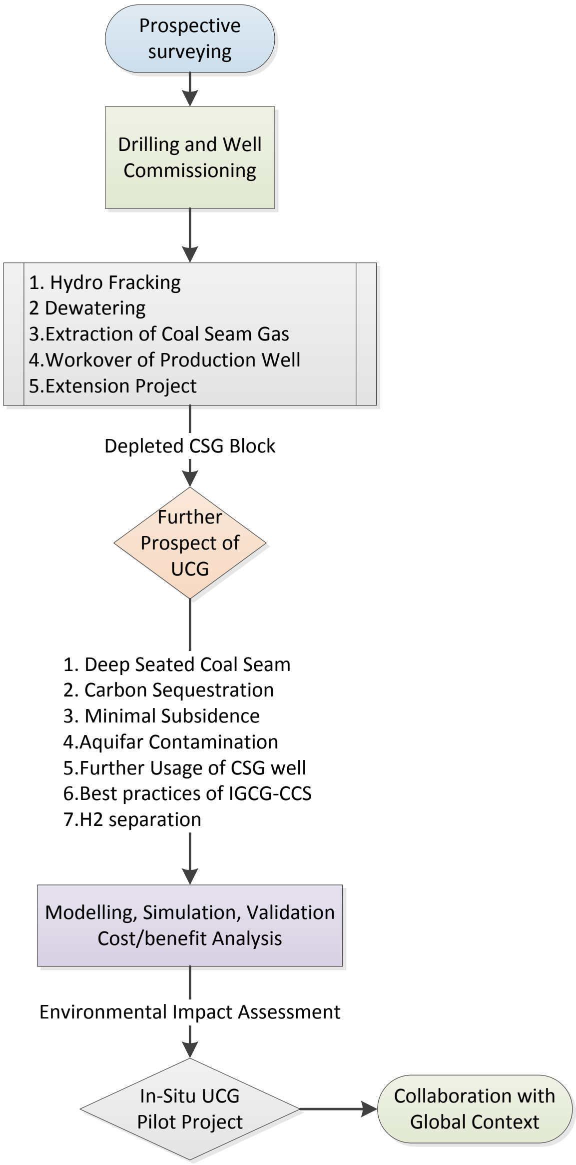

Figure 8. Flow diagram of prospective UGC activity in Depleted CSG fields.

4. Conclusion & Recommendations

The term "In-Situ" are using instead of conventional term UCG, as it is pointing towards a cutting edge technology for best practices of energy exploitation strategy as; in-situ coal seam gas ,later on development of reaction facilities in-situ coal resources and finally permanent sequestration of Carboneus products in-situ cavity formed at deeper formation. Assess the provision of UCG activity next to end of the economic life of the CSG field, would be a potential area of research & development. The frame work of the further work should focused on the following issues:

- State and nature of the fractured coal body (for deeper position) with embedded water.

- The distribution of reactants and nature of gasification process for such favorable condition (as the coal body already been fractured).
- What will be the impact of water (presence inside the cracked area of porous coal) and incoming flow control strategies.
- Nature of caving and growth rate of the cavity in advancement of the gasification course.
- Provision for CCS inside the porous caving area.

These identified issues can be addressed within an engineering framework for further proceedings. The skilled group and experts may create space for running the UCG program parallel with the CSG operations. In Australia there is a very good prospect for UCG development in the abandoned /exploited CSG fields specially deep seated coal seams, where environmental issues like the ground water contamination, subsidence can be omitted along with permanent CCS.

Conflicts of Interest

There is no conflict of interest.

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