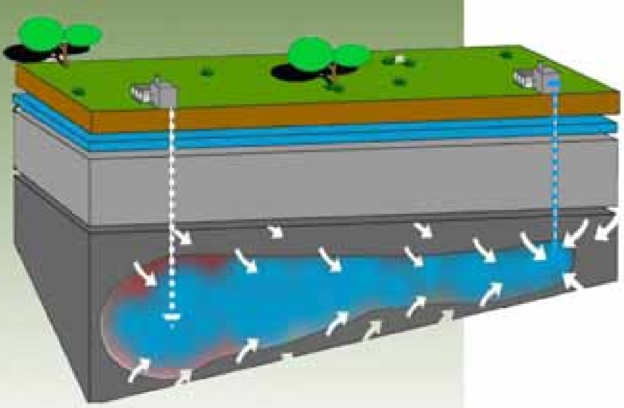
Underground Coal Gasification

Environmental Risks and Benefits

A Preliminary Review by the Pembina Institute



Jeremy Moorhouse • Marc Huot • Matt McCulloch

the PEMBINA institute
25 years of Sustainable Energy Solutions

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May 2010

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Underground Coal Gasification: Environmental Risks and Benefits
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About the Pembina Institute

The Pembina Institute is a national non-profit think tank that advances sustainable energy solutions through research, education, consulting and advocacy. It promotes environmental, social and economic sustainability in the public interest by developing practical solutions for communities, individuals, governments and businesses. The Pembina Institute provides policy research leadership and education on climate change, energy issues, green economics, energy efficiency and conservation, renewable energy, and environmental governance. For more information about the Pembina Institute, visit www.pembina.org or contact info@pembina.org.

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Pembina Corporate Consulting (PCC) helps to advance the sustainability performance of business leaders in Canada. Our service areas focus on corporate sustainability initiatives, progressive climate strategies, and technology evaluation and deployment. Our approaches range from providing strategic insights and facilitating decision making to detailed technical analyses and creating a culture of sustainability through organizational change tactics. Our desired outcome is to help progressive businesses turn a profit while reducing environmental and social impact. As a not-for-profit consultancy that is part of a leading Canadian environmental NGO focused on advancing sustainable energy solutions, PCC is able to offer a unique perspective to our clients.

Acknowledgements

The Pembina Institute would like to acknowledge the assistance of several individuals that assisted in the development of this report. They do not necessarily endorse the results of this analysis and did not review the report at any time.

Table 1: List of individuals interviewed during the preparation of this report

Name	Organization
Jolene Shannon	Pembina Agricultural Projection Association
Dr. Evgeny Shafirovich	University of Texas El Paso
Dr. S. Julio Friedmann	Lawrence Livermore National Lab
Dr. Michael S. Blinderman	Ergo Exergy Technologies Inc.
Mike Fowler	Clean Air Task Force – United States
Simon Maev, Lynn Mcneil	Laurus Energy Canada Inc.
Rob Sturgess, Gord MacMillan	Matrix Solutions Inc.

Executive Summary

The Alberta Energy Resources Conservation Board (ERCB) estimates that all of Alberta's approximate four trillion tonnes of underground coal resources could be utilized by underground coal gasification (UCG). It is estimated that these coal reserves could provide electricity in Alberta for more than 150,000 years at current usage; however, coal power's heavy environmental impact including both mercury and greenhouse gas emissions are limiting factors in the long-term use of this resource. Many UCG proponents claim that UCG has the potential to produce this energy resource in a less damaging manner than current coal technologies. The technology is not yet commercial, although there are several pilot projects in North America. Laurus Energy Canada Inc. (Laurus) is one of the companies attempting to commercialize UCG. It has licensed its technology from Ergo Exergy for implementation in the North American market. Laurus is currently developing two demonstration projects in North America: one in Alberta's Drayton Valley and the other in Wyoming. It is also in discussions with Cook Inlet Region Inc. to build a UCG facility in Alaska.

These projects aim to demonstrate UCG as a "clean, safe and economically viable method for producing synthesis gas (syngas)"[1]. Ergo Exergy will be providing expertise throughout the project, including designing the mine plan, training operators, technical support over the life of the project and a global technical sharing network where Laurus can access the innovations of Ergo Exergy's other UCG projects. Ergo Exergy's portfolio includes projects in South Africa, Canada, the United States, Australia and New Zealand.

What is UCG? Instead of removing coal from the ground and transporting it to a power plant to be combusted and turned into electricity, UCG operators hope to convert the coal locked underground into a gas, known as synthesis gas or syngas, that can be extracted at the site without mining. The syngas can then be used in similar applications to natural gas, like producing electricity or as an ingredient in chemical manufacturing. Converting coal into gas is not new — what is new is producing the gas underground at a commercial facility. At the most basic level, UCG projects are developed by drilling two wells into the underground coal seam and creating a connection between them. One of the wells injects oxygen or air while the other extracts the gas. A connection between the injector and extractor is normally created by hydrofracturing, where high pressure water (hy-

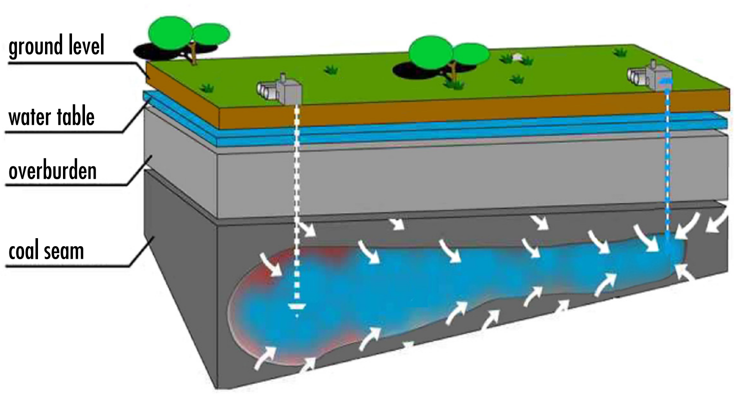

Figure 1: Underground coal gasification scheme
Source: Courtesy of Ergo Exergy[2]

dro) is used to break up (fracture) the rock. Once the two wells are connected, the operator ignites the coal and then controls its gasification by varying the amount of air let in and the amount of gas that exits. Figure 1 depicts the gasification process.

For the purposes of this report we assume the gas is cleaned at the surface and then used to produce electricity, much like the way natural gas is currently used to produce electricity.

Laurus contracted the Pembina Institute's consulting team to review its UCG technology and provide a summary of the environmental risks and benefits associated with the technology including the perspective of members of Pembina's policy team. Our research approach was guided by the following:

- **Information Sources:** All the information in this report came from public literature sources, interviews with UCG experts and in some places Pembina's policy team's perspective on the technology. Laurus also provided information on its technology; however, any information they provided Pembina is also available in the public domain.
- **Types of Information:** The information provided in this report is primarily qualitative. For example, this report discusses potential groundwater impacts based on other UCG operations. It does not provide specific information on the concentrations of contaminants or the probability of issues arising.
- **General UCG Technology Review:** While Laurus proposes to use one specific UCG (Exergy UCG) technology and approach for its facility, the focus of this report is on the common environmental risks and benefits of operating a UCG facility regardless of Laurus' specific approach. To the extent we do comment specifically on Laurus, the comments focus on facts about Laurus and the opinion of the interviewees.
- **Regional versus Local Impacts:** Like many large projects, the environmental impacts can be considered from a regional scale and a local scale. This report attempts to view the impacts of UCG from both the regional and local perspectives whenever possible.
- **Social and Economic Considerations:** This report does not focus on the economic cost or the social risks or benefits of this technology. In some instances costs are discussed, but only when relevant to the environmental focus of the report.

The literature and interviewees indicate that UCG has the potential to access significant energy reserves, is approaching commercialization and can produce electricity with less impact than coal generation. However, there are several outstanding risks associated with UCG that must be addressed before considering commercial projects. The issues identified and reviewed along with respective conclusions are summarized below.

Groundwater

Local groundwater contamination is the most serious risk associated with UCG. Two UCG pilots out of 34 pilots conducted in North America have resulted in groundwater contamination. These two projects required considerable remediation efforts. Groundwater contamination risk can be mitigated through appropriate site selection, and good operational and abandonment practices. Mitigating this risk also requires operator expertise that is not widely available. Widespread commercialization in Alberta will require development of this expertise and regulations to ensure appropriate site selection, and operation and abandonment practices. Laurus appears to be one of the few companies with access to this expertise and the pilot project will assist in developing this expertise further.

CO_2 Emissions and Carbon Capture and Storage (CCS)

UCG with electricity generation will likely result in GHG emissions 25% lower than conventional coal electricity generation, but 75% higher than natural gas electricity generation. UCG can also integrate CCS, where carbon dioxide (CO_2) is captured and then transported via pipeline and either sequestered or used to enhance oil recovery, into its operation to achieve more significant GHG emissions reductions. Current CCS costs indicate that integrating CCS into UCG operations will be less costly in comparison with other electricity-generating technologies because capturing the CO_2 stream is easier and doesn't require the same capital investments as other technologies. With integrated CCS, UCG should have a GHG intensity lower than natural gas combined-cycle generation but higher than coal with CCS, energy conservation, energy efficiency and low-impact renewable energy sources like wind. However, Alberta does not have a CO_2 pipeline and Canada does not have policies or regulations to drive widescale deployment of this technology. From a local perspective the primary impact would be additional infrastructure, such as CO_2 pipelines and concerns of transport and storage safety.

Ground Subsidence

UCG creates cavities underground similar to other long wall underground mining activities. Eventually the rock and other materials that are no longer supported by the coal that the UCG process has removed will fill the cavities. On the surface, the land will gradually settle or subside as the underground cavities are filled over a period ranging from months to years. This subsidence can impact surface water flows, shallow aquifers and any above ground infrastructure like roads and pipelines. These impacts will have to be managed as done in other underground mining operations. Those living near a UCG operation would be most affected if poorly managed subsidence were to take place. However, UCG operators, knowing subsidence will happen, can manage it by providing buffers around surface features such as lakes, rivers and roads to minimize impact.The literature reviewed for this report and comments from interviewees indicate that subsidence is manageable and when managed properly, has resulted in minimal local impact. Subsidence is also not unique to this technology and is common for conventional underground mining.

Land Use Impacts

UCG operators must perform a thorough assessment of the underground environment at the selected site, including geology, hydrogeology and rock mechanics. The tools for this assessment may include geological mapping, core samples and analysis, seismic surveys and aquifer pressure/hydrogeological modelling. Once operating, a single commercial facility would actively disturb one half-section of land (1.3 km^2). From a regional perspective, if UCG eliminated the need for a new coal mine it would lead to fewer land impacts. From a local perspective, the surface impacts of UCG developments will depend largely on location and the intensity of the operation. A large UCG development in a relatively undeveloped environment will still lead to habitat fragmentation issues similar to in situ oil sands development. Large or multiple UCG developments should therefore be considered in the context of cumulative impacts and regional land use planning.

Air Emissions

The combustion of syngas, like the combustion of natural gas, will generate air emissions with associated environmental and health concerns like acid rain. 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 a conventional coal power plant. Nonetheless, air emission concerns will depend on the combined sources of emissions in the region and the pollution control standard to which the facility is designed. A UCG facility will lead to incremental increases in air emissions wherever constructed, unless it replaces a facility with higher emission intensities.

Additional Research Required

As with any new technology, there is little publicly available information on commercial facilities. There are no operating commercial-scale UCG operations in North America, so any assessment of environmental benefits and issues is uncertain. Additional research and development of this technology is needed, especially regarding monitoring ground water and subsidence requirements, and environmental management practices to reduce risk. Pilot projects such as Laurus' are essential to learn more about the technology, its potential, its risks and how the risks can be managed.

Current State of Regulations

The current regulatory structure in Alberta is also uncertain and it is not possible to determine whether it is sufficient to manage the unique environmental risks of this technology. Pilot projects will help regulators design effective regulation; however, for those located next to a pilot project, the current regulatory framework and legislative uncertainty regarding UCG is concerning. Should the pilot result in unexpected impacts, the ERCB and Alberta Environment may be unclear on who holds jurisdiction. The ERCB created a multidisciplinary committee in January 2009 to develop a legislative framework for UCG projects to address this uncertainty. Alberta Energy and Alberta Environment established similar committees in 2010. If the legislation is passed by the Alberta government it will clarify many of the uncertainties regarding UCG development.

Implications for Alberta's Electricity Grid

The Alberta Electric System Operator (AESO) expects Alberta's electricity demand to almost double over the next 20 years. Based on preliminary review of several environmental metrics, the order in which electricity sources should be developed in Alberta to minimize environmental impacts is: energy conservation and efficiency; low-impact renewables including run-of-river hydro; and natural gas technologies. Once those sources of electricity production have been developed, UCG with CCS could be an alternative to conventional coal-fired electricity production with or without CCS. Alberta has significant coal reserves that could be accessed using UCG in a less damaging manner than current coal technologies. Once fully proven effective and safe, UCG with CCS has the potential to have similar impacts to natural gas electricity generation. In this scenario UCG would help Alberta reduce land use impacts, GHG emissions and air emissions associated with electricity production. However, consistently realizing these benefits while managing the risks of UCG will require operators with expertise in UCG

— expertise that is currently limited. Laurus has access, through Ergo Exergy, to some of the most experienced UCG operators available and plans to develop this expertise further with its pilot project.

Based on the information in this report, the potential of UCG technology implementation in Alberta should be investigated further and a pilot project seems like a necessary next step to better understand how to mitigate the risks of the technology and determine if the considerable benefits can be realized. In addition, based on the comments of the interviewees and available literature sources, it appears that Laurus and Laurus' technology provider, Ergo Exergy, have some of the most experience operating UCG facilities around the globe. A follow-up review based on the results of the pilot project would more accurately assess the commercial potential of the technology especially in the Alberta context. However, as with any large project it must have support of the local community.

▲ *Ergo Exergy's Operating Underground Gasifier, surface pipeworks, 2009.*
Courtesy of Ergo Exergy

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1 Introduction

Laurus Energy Canada Inc. (Laurus) has licensed Ergo Exergy's[3] underground coal gasification (UCG) technology for implementation in the North American market. Ergo Exergy will assist Laurus during all phases of the project, including: providing expertise during the design phase, training operators, designing 30-year production plans and providing ongoing support throughout the life of the project. Ergo Exergy is considered by those interviewed to be the best suited company to develop UCG because of its significant experience with the technology. Laurus is currently developing two demonstration projects in North America: one in Alberta and the other in Wyoming. It is also in discussions with Cook Inlet Region Inc. to build a UCG facility in Alaska.[4] "These projects aim to demonstrate UCG as a clean, safe and economically viable method for producing synthesis gas (syngas)"[5]. Syngas is versatile fuel composed of primarily nitrogen, hydrogen, carbon dioxide and carbon monoxide. It can be used for a number of purposes such as driving turbines, generating electricity, or producing synthetic natural gas for heat or chemical products.

Laurus has submitted an application for approval of the demonstration project with the Alberta Energy Resources and Conservation Board (ERCB) and Alberta Environment. The demonstration project will be located in Parkland County, roughly 15 kilometres northeast of Drayton Valley. The project plans to produce 70,000 m^3/d of syngas over a period of one year from the Ardley coal seam. The ERCB, based on its current understanding of UCG, considers the Ardley coal seam a good candidate for UCG in Alberta.[6] The purpose of the demonstration project is to determine the composition and characteristics of the syngas to be produced based on site-specific coal properties and to measure and evaluate environmental responses to the project. The information gained during the demonstration project will be used to design a commercial-scale gasification facility in the region.

Laurus engaged the Pembina Institute's (Pembina) consulting team to review its UCG technology and provide a summary of the system-wide risks and benefits associated with the technology. This assessment focuses on the implications of wide-scale commercialization of the UCG technology rather than focusing on the potential impacts of the demonstration project alone. For the purposes of this report, syngas produced during the UCG process is used to generate electricity in a combined cycle power plant, one that includes a gas turbine and a steam turbine; considered a likely scenario for the proposed project given future electricity demand projections. The review does not focus on the specific location of the pilot or Laurus' proposed commercial facility.

Pembina's review methodology included the following:

- Identifying preliminary environmental risks and benefits associated with UCG in general through literature sources and several interviews with UCG experts in North America.
- Briefing and acquiring feedback from Pembina policy staff. This included a presentation and discussion with Laurus.
- Preliminary comparison of UCG with electricity generation with other electricity generating technologies and evaluation of its potential contribution to

electricity generation development in Alberta.

- Understanding the applicable regulatory framework in Alberta and determining additional research on select environmental issues and benefits.

The information presented in this report summarizes the results of thereview and provides context for UCG development in Alberta and the technology in general. While the interviewees provided valuable input to this report, they did not review this report and do not necessarily support its conclusions or perspectives.

▲ *Monitoring well drilling at a UCG site in Alberta, 2009.*
Courtesy of Laurus Energy Canada

2 Technology Overview

The UCG process has existed for more than 100 years but has failed to achieve widespread commercialization. The theory behind UCG was developed in the late 1800s and trials began in the 1930s in the former U.S.S.R. The U.S.S.R. continued developing the technology from the 1930s until discovery of significant natural gas reserves in Siberia in the 1960s reduced interest in the technology.[7] However, a few facilities continued to operate including one in Angren, Uzbekistan. The United States also experimented with the technology during the 1970s and 80s. The combination of low energy prices and significant environmental issues at two of the test sites limited further investment in the technology.[8] Alberta also experimented with the technology in 1976.[9] Although interest in UCG waned at the end of the 1970s, there were still 30 pilot projects internationally between 1975 and 1996.[10]

Increasing energy costs and energy demand have renewed global interest in the technology.[11] A 2008 PriceWaterhouseCoopers review of the technology noted that "today, the technology is potentially at the transition point to mainstream commercial implementation."[12] Globally, there are 14 proposed pilot projects. Of these 14 projects, two are planned for Alberta: Laurus' project and Swan Hill Synfuels. The Province of Alberta has executed a letter of intent with Swan Hills Synfuels to provide a $285 million grant to support CCS development with the project. In addition Alberta's Energy and Resource Conservation Board is in the process of developing legislation and a new directive to regulate demonstration and commercial UCG developments. Table 2 provides a list of important UCG projects in chronological order.

Table 2: Summary of UCG projects

Source: Underground Coal Gasification: A Brief Review of Current Status[13]

Country	Company / Project Name	Date of Operation	Findings, Comments, Concerns
USSR (Russia, Ukraine & Uzbekistan)		1930s, 1955-1996	Research & development 5 UCG plants produced gas for boilers. Production peaked in the 1970s Very large scale – gasified over 300 times the total amount of coal in all U.S. & Austrian projects
United States		1940s-1950s	Initial UCG tests in Alabama.
United States	Hoe Creek	1970s	Tests resulted in significant ground water contamination.
United States		1972-1989	30 experiments conducted in Wyoming, Texas, Washington.
France		1980-1981, 1983	Failed tests – poor hydraulic connection.
United States	Rocky Mountain I	1980s	Most successful UCG venture in U.S. Plans for a commercial scale operation were cancelled due to lack of support.
China		1980s	Trials carried out using galleries of abandoned coal mines.
Belgium-German (joint)		1982	Unsuccessful tests.

Country	Company / Project Name	Date of Operation	Findings, Comments, Concerns
Spain	El Tremedal	1990s	Tested depths greater than 500m project ended when reactor failed Three attempts to create UCG process. Malfunction during the third test led to a methane explosion.
China		1991-present	China currently has the largest UCG program with16 UCG pilot projects carried out.
New Zealand		1994	13 day trial. Full gasification was not achieved.
Australia	Linc, Chinchilla	1999-2002	Stands out for its successful siting, operation, and environmental management efforts but not for its commercial success. Also demonstrated feasibility of control for UCG process, shutdown, and startup. (Ergo Exergy technology)
South Africa	Eskom, Majuba	2007	Test successful, plans to build 2100 MW power plant (Ergo Exergy technology)
China	ENN, Wulanchabu	2007-present	
Australia	Carbon Energy, Bloodwood Creek	2008-present	
Australia	Cougar, Kingaroy	TBD	(Ergo Exergy technology)
Canada	Laurus	TBD	(Ergo Exergy technology)
Canada	Swan Hills LLC	TBD	Completed first demonstration phase in July 2009. Gasification occurs at 1,400 metres. Has $285 million funding from the Carbon Capture and Storage Fund.
China	ENN, Tongliao	TBD	
New Zealand	Solid Energy, Huntley	TBD	(Ergo Exergy technology)
South Africa	Sasol	TBD	
United States	GasTech	TBD	(Ergo Exergy technology)
United States	Laurus	TBD	(Ergo Exergy technology)

2.1 Technology Potential

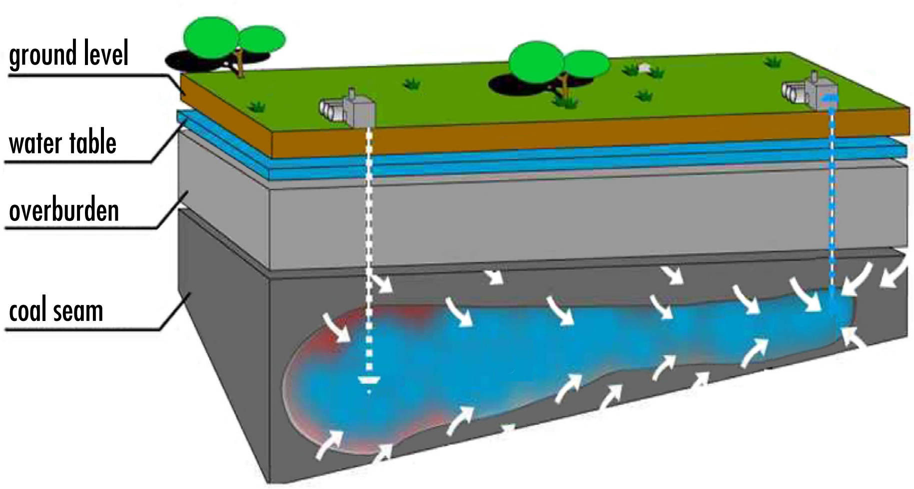
One of the main advantages of UCG is its ability to access coal that is too deep to recover using traditional means. The ERCB estimates that all of Alberta's estimated four trillion tonnes[14] of underground coal resources could potentially be utilized by UCG.[15] That is 370 times what is considered recoverable by surface mining methods in Alberta.[16] Global recoverable coal resources would also expand significantly if UCG were successful. However, the potential of UCG is largely speculative. An accurate assessment of the potential for UCG in Alberta will require experimentation and a better understanding of the technical limits of UCG developments and site specific issues.

2.2 Technology Description

At their most basic level, UCG projects are developed by drilling two wells into the coal seam and creating a connection between them. One of the wells is the injector and the other the producer. Communication between the injector and producer is normally created by hydro-fracturing process.[17] An oxidant, typically oxygen, or in Laurus' case, air, is injected into the seam and ignited. The gasification chamber created within the coal seam is maintained by controlling the amount of air injected. Syngas which is expected to be primarily composed of nitrogen, hydrogen, carbon dioxide, and carbon monoxide is produced to surface through the producing well.[18] Figure 1 depicts the gasification process.

For Laurus' potential commercial facility water, hydrogen sulfide and particulate matter will be removed from the syngas at surface facilities near the coal seam. The CO_2 portion of the syngas, 15% by molar mass, will also be removed at the surface facility and transported to enhanced oil recovery schemes. The cleaned syngas would then be transported to a combined cycle (gas turbine and steam turbine) power plant to produce electricity, or to another potential industrial customer. Laurus does not anticipate requiring any flue gas treatment for power generation applications. Technical details pertaining to specific environmental issue areas are discussed in more detail below.

Figure 1: Underground coal gasification scheme
Source: Courtesy of Ergo Exergy[19]



3 Environmental Risks and Benefits

3.1 Ground Water

Groundwater contamination is considered "the most significant [environmental] risk related to UCG."[20] The gasification process creates a number of compounds in the coal seam, including phenols and polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia and sulphide.[21] These compounds can migrate from the gasification zone and contaminate surrounding ground water. For example, studies in the Soviet Union in the 1960s revealed that UCG could result in widespread groundwater contamination.[22] Most groundwater concerns are a result of two trials in the U.S., at Hanna and Hoe Creek (both in Wyoming), where groundwater remediation was required. The shallow depth, poor site choice and, in the case of Hoe Creek, the transmission of pollutants through overburden fractures into other aquifers, resulted in significant groundwater impacts.[23]

One interviewee noted that "both trials involved serious operator error that resulted in the contamination and do not reflect on the environmental credentials of the technology itself … the sites themselves were high risk locations." Based on this, it is clear that operator expertise and proper site selection are crucial elements in reducing or eliminating environmental risk.

Looking at the broader context, most UCG operations have not produced any significant environmental consequences.[24] For example, European trials were completed with no environmental contamination detected during operation or within five years after operation.[25] Similarly, a UCG test site in Chinchilla, Australia did not result in ground water contamination.[26]

3.1.1 Mitigation

UCG researchers and operators have developed measures to mitigate the risk of groundwater contamination. These mitigation measures are broadly grouped into three categories: site selection, operational practices and abandonment procedures.

- **Site selection** – Appropriate site selection is the most important mitigation measure and is essential to minimize potential groundwater contamination. Operators should ensure the site is well characterized and that the coal seam has limited connectivity with other water sources.[27] According to discussion with Laurus, the selection of regions where the overburden is expected to deform plastically reduces the concern that shearing will occur. Shearing can result in vertical propagating fractures that allow for fluid communication between the gasification zone and surrounding groundwater.
- **Operational practices** – There are inherent aspects of UCG that help reduce the contamination potential of UCG projects. During operation, a steam barrier or "steam jacket" is created that surrounds and contains the process and helps prevent leakage.[28] Operators should maintain the gasification chamber below hydrostatic pressure in the surrounding aquifer to ensure that all groundwater flow in the area is directed inward, towards the gasification chamber.[29] UCG operators must also invest in groundwater monitoring around the facility to ensure contaminants are not migrating from the gasification chamber.
- **Abandonment practices** – According to dialogue with Laurus, the appropriate shutdown process is a controlled shut down in which the gasification zone is allowed

to cool slowly. During this time, the operator should continue extracting gas until the gasification process stops completely. In this way contaminants can be evacuated out of the gasification zone before the site is abandoned. Operators should also monitor groundwater for contaminants for a period of time after the site is abandoned. The actual duration of monitoring will depend of the specific site.

3.1.2 Laurus and Alberta

The ERCB has determined which Alberta coal seams would be suitable for UCG developments. It notes that the Ardley seam, in which Laurus' demonstration project and potential commercial project is located, "is within the groundwater protection interval defined by a maximum concentration of dissolved solids of 4g/L" yet there is a "concern for the Ardley zone regarding groundwater contamination" that will require "vigilant simulation and monitoring processes during operation."[30]

Laurus appears to have an intimate understanding of the groundwater issues and the knowledge to appropriately select a site, operate the facility and abandon a site so as to limit the potential of groundwater contamination.[31] However, the results of the demonstration project will be the best indication of Laurus' ability to manage this issue.

3.2 Surface Water

The gas solution produced by UCG contains a component of liquid or vaporized water (produced water) which is removed from the gas before the gas is combusted in a power plant.[32] This water contains residual hydrocarbons, benzenes and possibly phenols and polycyclic aromatic hydrocarbons, but it is expected to be fully treatable.[33] One of the interviewees noted that the syngas and the produced water from UCG produce a similar gas solution as the common (above-ground) fixed-bed coal gasifiers, and that industries have been treating those products for roughly 60 years.

3.3 Subsidence

Subsidence is the sinking or lowering of a surface region relative to the surrounding region. It occurs as a result of the removal of material from the underground coal formation. According to one of the interviewees, subsidence can typically be avoided in short-life pilot projects; however, larger commercial UCG operations will cause subsidence. In general, UCG subsidence results in height decrease equivalent to one-third of the vertical thickness of the coal seam and would only affect land directly above the gasified coal seam. The magnitude and characteristics of subsidence depends on many factors including the seam depth, rock stiffness and yield strength, disposition of seam, the stress resulting from the gasification, and other geological properties.[34] Subsidence typically results in a uniform lowering of the region as opposed to abrupt potholes.[35] According to the specific experience of the interviewee, the majority (up to 98%) of this height loss occurs within the first seven months, with the rest occurring over the next five years. The primary concern with subsidence is the effect it can have on re-routing surface waters, and local impacts on shallow aquifers and infrastructure likes roads and pipelines.

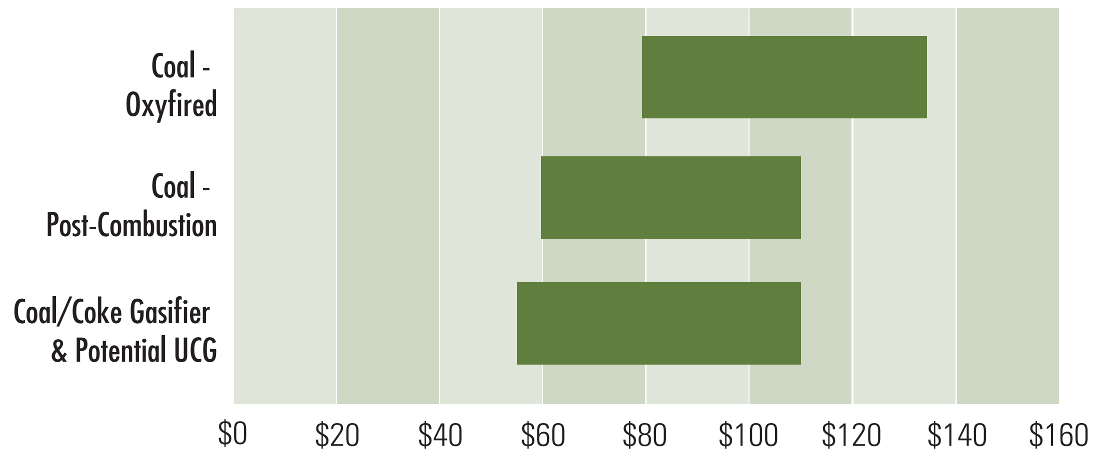
As surface subsidence is to be expected,[36] UCG operators should first understand the site surface and geology to anticipate the effects it may have. As such, the operator can avoid serious surface manifestations by ensuring that "surface infrastructure and natural features (such as rivers) are deliberately not undermined."[37] If surface hydrology is to be affected by UCG operations, measures can be taken to maintain proper flow directions. In all cases, the site should be actively monitored to determine the rate and extent of surface subsidence during operation of the facility.

In general, subsidence appears to be a site-specific issue. With proper site selection and operational management, it should be possible to avoid significant impacts to surface waters, road and industry infrastructure and buildings by avoiding regions most sensitive to surface level changes.

3.4 CO_2 Emissions and Carbon Capture

UCG combined with power generation is expected to be 25% less greenhouse gas intensive on a per MWh basis then a supercritical coal plant when both are operated without post-combustion carbon capture and storage (CCS).[38,39] However, the real potential of UCG is that it produces a syngas that is amenable to pre-combustion carbon capture.[40] UCG offers a CO_2 stream that will have capture costs estimated in the range of $50 to $110 per tonne of CO_2 abated.[41] Figure 2 shows the range of CCS costs for coal (oxyfired and post combustion) and gasification. UCG is likely in the gasification price range. This is the lowest carbon capture cost range for all power production and capture technologies that can only be matched by above ground gasifiers. However, unlike above ground gasifiers UCG does not require a constructed gasifier, as the gasification chamber is created in the coal seam. For these two reasons, relatively low capture cost without the capital cost of a gasifier, UCG will likely have one of the lowest carbon capture costs of any power generation facility.

Figure 2: Carbon capture cost range for coal (oxyfired and post combustion) and gasification
Source: Accelerating Carbon Capture and Storage Implementation in Alberta [42]



Laurus hopes to further reduce costs by selling the captured CO_2 for enhanced oil recovery (EOR). The current CO_2 price for EOR is approximately $20 per tonne. However, this price ultimately depends on oil prices. Oil prices between $50/bbl and $125/bbl can support CO_2 prices from $10 to $60 per tonne.[43] Laurus may be able to achieve cost-neutral CO_2 recovery.

Laurus anticipates a CO_2 intensity of 330 kg CO_2eq/MWhr at its commercial facility when carbon capture is installed. For comparison, a combined cycle natural gas facility has a lifecycle GHG intensity of approximately 500 kg CO_2eq/MWhr, wind turbines range from 1 to 42 kg CO_2eq/MWhr when accounting for lifecycle emissions and coal electricity generating facility with CCS are expected to have an intensity of 180 kg CO_2eq/MWhr.[44] However, these emission reductions are contingent on the development of CCS networks.

More generally, most sites suitable for UCG are usually near potential sequestration sites. A study of North American previous, current or planned UCG pilots found that more than 75% of the projects were within 50 kilometres of potential saline aquifers, depleted oil and gas fields and EOR schemes.[45]

CO_2 could also be stored in the cavity created by UCG. However, there "remains substantial scientific uncertainty in the environmental risks and fate of CO_2 stored this way."[46]

3.5 Operational Risk

Proper site selection and appropriate operation management practices are essential to reduce the risk of serious environmental impacts. The following section describes risks that may be associated with UCG in a worst case scenario.

3.5.1 Catastrophic Failure Scenario

When asked how a catastrophic failure may occur and what form it may take, one of the interviewees noted that the most likely scenarios have already take place — catastrophic groundwater contamination at Hoe Creek (Wyoming) and an underground explosion at a European trial site (Spain).

At Hoe Creek, the influx of water toward the gasification zone was above expected levels and was reducing operational efficiency. In order to counteract this effect, operators increased pressure in the gasification zone above the pressure of the surrounding groundwater. Contaminants then migrated from the gasification zone and lead to massive groundwater contamination.[47] The situation at Hoe Creek was worsened by fractures created during the coal seam collapse that interconnected multiple aquifers, allowing contamination to spread. The over-pressurization of the gasification chamber was a direct result of operator actions. Properly trained operators and an appropriately chosen site would have avoided this scenario. One of the interviewees also supported this conclusion and noted that site selection was poor at Hoe Creek and the operator did nearly everything wrong when a problem was first perceived.

During tests in Spain in the 1990s, technical problems occurred when attempting to restart a UCG operation that had been shut down. A malfunction in the ignition system and failure of the temperature measurement system resulted in the accumulation of methane gas underground, causing an explosion that damaged the injection well.[48] The interviewee added that, when following proper procedure for re-injection, he has had no experience of this sort in 25 years of operation.

In both of these cases, the accidents could have been prevented by following proper operating procedures and through improved site selection.[49]

3.5.2 Operability

In terms of operability and control of processes, the Chinchilla project "demonstrated the feasibility of controlling the UCG process, including shutdown and restart, and resulted in successful environmental performance according to independent audit reports."[50] However, one report does note that UCG is much more difficult to control than conventional gasification as many of the variables (rate of water influx, distribution of reactants in the gasification zone, growth rate of cavity) cannot be controlled.[51] The pressure in the underground gasification zone is primarily controlled by the rate of air/oxygen injection and the corresponding rate of extraction.[52] A difference between these two rates allows the operator the ability to vary the pressure. The directional travel of a UCG operation along a coal seam can also be controlled. This is accomplished by strategically locating the injection and extraction wells. Once two wells are interconnected, the negative pressure created as gas leaves the extraction well will draw the gasification reaction toward the exit well.

3.5.3 Operational Risk Summary

When considering the information described in the sections above and throughout the report, it is clear that many serious environmental risks can occur if UCG projects are not properly designed or carefully operated. Conversely, with the appropriate level of expertise, it is possible for a well-managed UCG project to avoid these types of failures.

According to the perspective of several interviewees, Ergo Exergy is one of the leading companies with the most experience and best track record in UCG. This is encouraging as they will be working with Laurus on the design of their project and will be providing extensive training and site supervision for several years of operation. This in turn helps to provide assurance that the Laurus site will be properly managed and should be able to reduce the risk associated with groundwater contamination and subsidence.

However, if a UCG industry develops and expands across the province, there is no certainty that the operators of those projects will be equally qualified. Alberta must further develop a regulatory framework that addresses environmental issues unique to UCG developments to ensure mismanagement-related environmental impacts are avoided.

3.6 Air Quality

The majority of air quality concerns associated with UCG result from syngas combustion. In Laurus' case the syngas will be incinerated on site during the pilot phase and likely combusted at a combined cycle power generation facility for the proposed commercial facility. Laurus will clean the syngas at surface facilities near the UCG site to reduce air emissions. The cleaned gas will then be transported via pipeline to the power generation facility. With UCG, there are essentially two categories of non-GHG air emissions: criteria air contaminants (e.g., nitrogen oxides, sulphur dioxide, particulate matter) and volatile trace elements (e.g., mercury, arsenic, selenium).[53,54] Laurus plans to use traditional gas cleaning technologies like acid gas removal for H_2S and baghouses for PM removal to reduce air emissions to within regulated limits.

UCG offers some inherent air emission benefits relative to conventional coal. During UCG, a significant portion of volatile trace elements like mercury, arsenic and selenium as well as sulphur remain in the underground cavity. In coal combustion, these compounds must be recovered from the flue gas at relatively higher cost. Combustion of syngas should also result in fewer NO_x emissions because the combustion occurs at lower temperature than coal combustion.[55]

3.7 Land Use Impacts

UCG land use constitutes a series of wells drilled into a coal seam with connecting roads and pipelines on the surface as well as any surface facilities required to process the syngas.

UCG operators must perform a thorough assessment of the underground environment at the selected site, including geology, hydrogeology and rock mechanics. The tools for this assessment may include geological mapping, core samples and analysis, 3-D seismic surveys, and aquifer pressure/hydrogeological modelling. All of these activities have some level of land impact. In the case of the Laurus demonstration facility, exploration well numbers were reduced by making multiple uses from the same wells.[56]

While the pilot project will have a minimal number of wells drilled during operation, the commercial scale will occupy approximately two to three sections (one section = 2.6 km^2) of land over its lifetime and will include a few hundred wells spaced 30 to 100 m apart.[57] The 300MW commercial facility is anticipated to operate for 30 years. UCG operations progress along the coal seam exhausting one panel (300m across) before starting a new one. At any given time the operation will actively disturb approximately one half-section, while the previous regions that no longer have active operations will be progressively reclaimed as needed. According to Laurus, reclamation consists of well decommissioning as topsoils are not being impacted by their operations (except for roads and buildings).

UCG is often compared to coal mining and favoured for its decreased land impacts; however, it should be noted that the two technologies are not competing for the same reserves of coal. UCG operations are targeted at deeper sections of coal seams that are otherwise un-mineable. The land benefits of UCG would only be realized if replacing or avoiding the need for new coal mining facilities.

3.8 Other Potential Issues

- **Communication with other wells**: Numerous wells (e.g., water, gas, oil) have already been drilled into the Ardley coal seam that Laurus plans to gasify. If connections were created with these wells, theoretically, UCG gases could contaminate them; or, the other wells could become a secondary source of oxygen underground reducing the control operators have over the UCG process. According to Laurus, the ERCB database of wells was reviewed during site exploration to ensure that no wells were in conflict with their operation.[58] Furthermore, it was noted that the sensitive mass/energy balance of UCG (where inputs and outputs are known and should be in balance) would indicate very quickly if gas is being lost or air is being added through unknown communication channels. Laurus also added that their use of fully cased wells should also reduce the risk of any unexpected communication with other wells.
- **Communication with other sour gas wells**: When asked about possible com-

munication with sour gas wells, Laurus clarified that the difference in depth between UCG and sour gas wells made the probability of this occurring very low.[59] Their UCG wells would be at a depth of 200 m and fully cased, whereas local sour gas wells are at a depth closer to 2,000 m and either are or will be filled with cement when abandoned.

- **Consistent syngas supply**: UCG "is inherently an unsteady-state process, and both the flow rate and the heating value of the product gas will vary over time. Any operating plant must take this factor into consideration."[60] Other operational difficulties can occur if gasification temperatures drop. This results in the formation of tar which can plug tubing or degrade equipment if not properly treated.[61] These issues are particularly relevant in an application where the UCG products are being used to provide syngas for electricity generation purposes. There is some concern that a disparity between the rate of syngas production and syngas demand may result in the following: deliberate pressure increases in the gasification chamber above external pressure to maintain production rates, intermittency of electricity generation, or flaring/incineration of large quantities of syngas when excess syngas is produced and electricity demands are low. According to Laurus, the Exergy UCG process is more appropriately labelled as a quasi-steady state process as they do have some ability to regulate the rate and quality of syngas production. However, it is difficult to find quality, public data on UCG facilities operating at a continuous rate for long periods of time to demonstrate reliability in syngas production rates, particularly at a commercial scale.

In summary, many of the interviewees acknowledged that when UCG is located, designed and operated properly, it can be a very effective technology. However, they also cautioned that when those conditions are not ensured, a facility may not reach its expected efficiency, recovery rates or environmental performance. It is therefore essential to examine each operation independently and ensure that site-specific performance objectives are being met.

4 Current State of Regulations

The following is a summary of the ERCB Proposed Legislative Framework for In Situ Coal Development.[62] The ERCB approved a UCG project as an experimental gas scheme under the Oil and Gas Conservation Act in 2008 and as an exploration scheme in 2009. However, the ERCB's legislative authority and requirements remain unclear. The ERCB created a multidisciplinary committee in January 2009 to develop a legislative framework for UCG projects. The committee reviewed other jurisdictions with UCG requirements such as the United States, South Africa and Australia but found their regulations too dissimilar for application in Alberta. The ERCB's current plan is to amend the Coal Conservation Act, Coal Conservation Regulations, Oil and Gas Conservation Act, Oil and Gas Conservation Regulations, the Pipeline Act, the Pipeline Regulations and the Security Management Regulation.

Under this plan the coal development itself would fall under the Coal Conservation Act and the Coal Conservation Regulations. Wells, facilities and pipelines would fall under the Oil and Gas Conservation Act, the Oil and Gas Conservation Regulations, the Pipeline Act and the Pipeline Regulations.

Project applications would fall under Directive 56 (Energy Development Applications and Schedules). To avoid conflicts for holders of different resource rights, operators would have to obtain rights to coal, petroleum and natural gas for the coal seam and all lithologic units above the targeted coal seam.

UCG schemes would also fall under Alberta Environment's designation. Alberta Environment has amended the Activities Designation Regulation to add a syngas plant, a component of a UCG development, that would require Environmental Protection and Enhancement Act Approval. This change ensures that syngas developments are reviewed by Alberta Environment. Alberta Environment can also request an Environmental Impact Assessment for a UCG scheme. UCG schemes may also require application under the Water Act for water use and withdrawal.

There are several specific requirements that have yet to be developed under this plan. For example, geological data requirements under the Oil and Gas Conservation Regulations or the Conservation of Coal Regulations are insufficient to assess the potential for a UCG project and will need to be enhanced. In addition Directive 20 (Well Abandonment Guide) will apply to well suspension and abandonment at UCG operations; however, "at this time there is limited available information on subsidence, fluid containment and chamber abandonment. These will be developed in the future."

Should the pilot result in unexpected impacts, the ERCB and Alberta Environment may be unclear on who holds jurisdiction. The ERCB created a multidisciplinary committee in January 2009 to develop a legislative framework for UCG projects to address this uncertainty. Alberta Energy and Alberta Environment established similar committees in 2010. The legislation, if passed by the Alberta Government, will clarify many of the uncertainties regarding UCG development.

5 Implications for Alberta's Electricity Grid

The previous sections of this report outlined the environmental issues and benefits associated with the UCG technology in isolation. However it is also important to consider its environmental performance in the broader context of Alberta's potential future electricity supply mix. The following sections compare UCG to other electricity-generating technologies and describe Alberta's current electricity supply, current estimates to meet future demand and Pembina's assessment of how Alberta could meet future demand with lower impact electricity sources. These sections are followed by a summary of UCG's potential to reduce the environmental impact of Alberta's electricity supply.

5.1 Relative Technology Comparison in Alberta

There is limited analysis comparing the impacts of UCG to other technologies in the public domain; particularly, using broader environmental impact categories that include water consumption, land impacts, air emissions, greenhouse gas emissions, long-term liabilities and risks. To satisfy this gap, Pembina completed a preliminary relative comparison of UCG's environmental performance to other power-generating technologies ranging from conventional fossil fuel systems to renewable energy systems in the Alberta context. All of the following technologies exist or are being considered for addition Alberta's electricity generati natural gas cogeneration

- natural gas combined cycle
- coal with carbon capture and storage
- integrated gasification combined cycle
- pulverized supercritical coal
- energy efficiency
- large scale wind turbines
- roof-mounted photovoltaics
- run of the river hydro
- biomass from waste sources

Pembina compared the alternative electricity generating technologies using a number of environmental indicators. The quantitative and qualitative values for each indicator and technology were sourced from public literature sources, based on discussions with UCG experts and from previous research completed by Pembina.

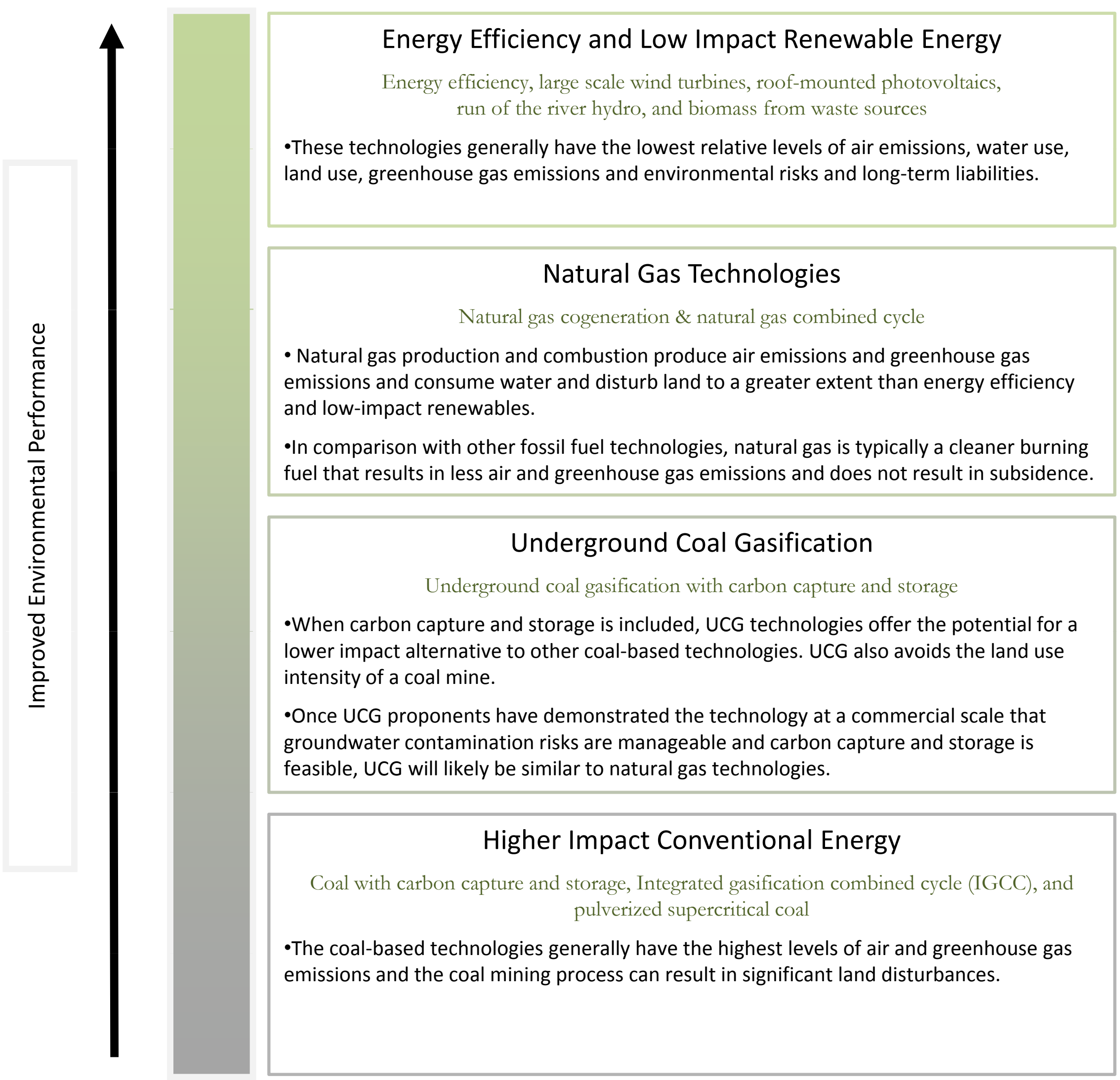
Table 3 lists the environmental indicators.

Table 3: List of indicators and comparison metric

Indicator	Quantitative or qualitative metric
Greenhouse gas emissions	tonnes CO_2/ GWh
Air emissions (NO_x and SO_2)	kg/GWh
Land use	m^2/GWh
Severity of disturbance	Qualitative degree to which a given area is altered
Water consumption	Qualitative (due to lack of information)
Severity of water quality impacts	Qualitative degree to which surface or ground water sources may become contaminated, disrupted or depleted.
Risks and long-term liability	Qualitative degree of risks and long-term liability associated with the technology
Severity of worst case scenario	Qualitative severity of worst case scenario

The quantitative data and qualitative assessments for each of the indicators are available in the Appendix. Pembina used this data to inform and develop three main technology groupings: higher impact conventional technologies, natural gas technologies, and energy efficiency and lower impact renewables. UCG is placed as its own separate category. Because this analysis is only preliminary, the data available in the appendix were considered as representative of each technology type. In reality, each technology type should be considered on a case-by-case basis considering specific environmental information and unique aspects of the project. Figure 3 summarizes the assessment of the relative environmental performance of different electricity-generating technologies and highlights the main determining factors for placement of the technology groupings. Nuclear electricity was omitted from the list because there are no facilities currently operating in Alberta. This figure is intended as a hierarchy like "reduce, reuse, recycle" — while there are exceptions, in general reduction has the lowest environmental impact followed by reuse and then recycle.

Figure 3: Relative environmental performance comparison of power generating technologies



The grouping and positioning of different electricity types is based on the data available in the Appendix. It does not include economic, technical or social considerations, and is a generic hierarchy provided for illustration purposes. Although economic costs are provided in the appendix for context, they were not used to determine the above. In general, energy efficiency and low impact renewable electricity generation technologies generate fewer environmental risks and impacts than other electricity sources. Energy efficiency and renewables are followed by natural gas fired facilities. The combustion of natural gas is generally less carbon and air emission-intensive than coal-fired electricity, with fewer land impacts that both UCG and coal. UCG with CCS is placed between high-impact conventional technologies and natural gas technologies. In this sense UCG with CCS is viewed as a clear improvement over conventional coal generation but still falls below natural gas electricity generation. This positioning is primarily due to uncertainty regarding the technology at this time. There are no commercial power-generating facilities for which data is readily available and there is a potential for significant ground water impacts. In addition, CCS is still under development in Alberta. If UCG operators can demonstrate environmental performance that matches current expected performance, UCG could be similar to natural gas production.

While the potential benefits of UCG are significant, the data suggests that electricity developers interested in low impact electricity production should first maximize energy efficiency and renewable energy opportunities followed by natural gas production before considering other options. UCG with power generation and CCS is preferable to conventional coal or coal with CCS. If environmental risks associated with the technology are demonstrated to be manageable, UCG would likely present environmental risks and impact on par with natural gas technologies including lower GHG intensity if CCS is incorporated.

5.2 The Alberta Electricity Grid

The section above clearly shows an environmental hierarchy to electricity generation technologies. However, understanding the Alberta context and the potential of each technology type requires an assessment of current and future energy needs in Alberta. This section presents Alberta's electricity grid under business-as-usual and maximum renewable energy integration scenarios. The information, assumptions and analysis used to develop the following graphs are from the Pembina Institute's *Greening the Grid* report and are not restated here.[63] Electricity generation from high impact conventional energy sources supply the majority of Alberta's electricity needs. Only a small percentage is generated through energy efficiency and low-impact renewables.

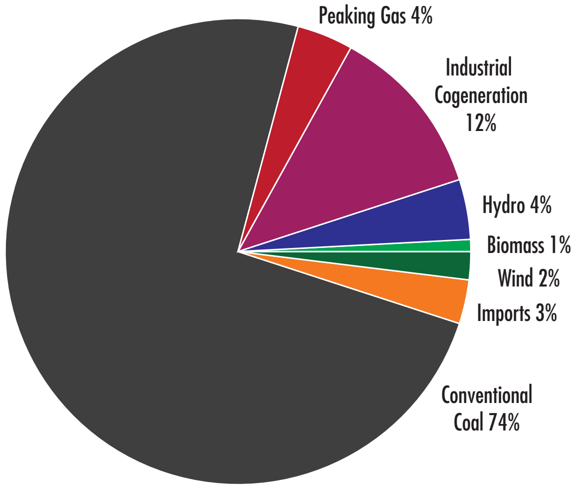
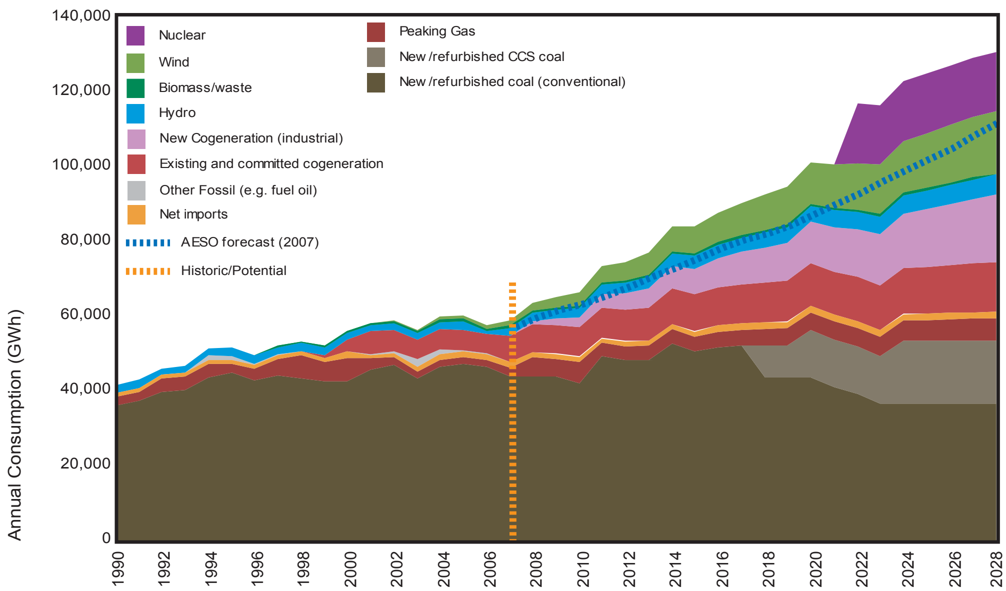


Figure 4: Alberta's current electricity generating mix
Source: Greening the Grid[64]

From an environmental perspective, Alberta's electricity generation mix is composed of primarily high-impact sources. The Alberta Electric System Operator expects Alberta's power demand to more than double over the next ten years. Figure 5 illustrates the expected growth in electricity generation mix to meet future demand; it is titled the "business-as-usual scenario." This scenario combines several AESO generation scenarios.[65]

These projections show new investments in coal, coal with CCS, cogeneration, wind and nuclear meeting future demand. Under the business-as-usual scenario, there is a clear role for UCG to replace coal generation to improve the environmental performance of Alberta's electricity system. UCG with electricity generation would also provide similar grid services to coal generation. It would likely be best suited to base load power generation. Coal generates just under 60,000 GWh of base load electricity in this development scenario.

Figure 5: Business-as-usual portfolio to meet electricity demand
Source: Greening the Grid[66]



However, the business-as-usual scenario does not fit with the environmental hierarchy presented in Figure 3. Figure 6 demonstrates how Alberta's growing electricity demand could be met by relatively low-impact energy options — primarily, wind, cogeneration and energy efficiency — while phasing out conventional coal plants, in line with the environmental hierarchy.[67]

Energy efficiency, low-impact renewables and natural gas technologies produce the majority of electricity generation in this scenario. Conventional coal is phased out and coal with CCS provides a small portion of total electricity generation. This scenario is based on peak load modelling and doesn't include any additions to the Alberta electricity grid like smart metering or power storage. The modelling exercise demon-

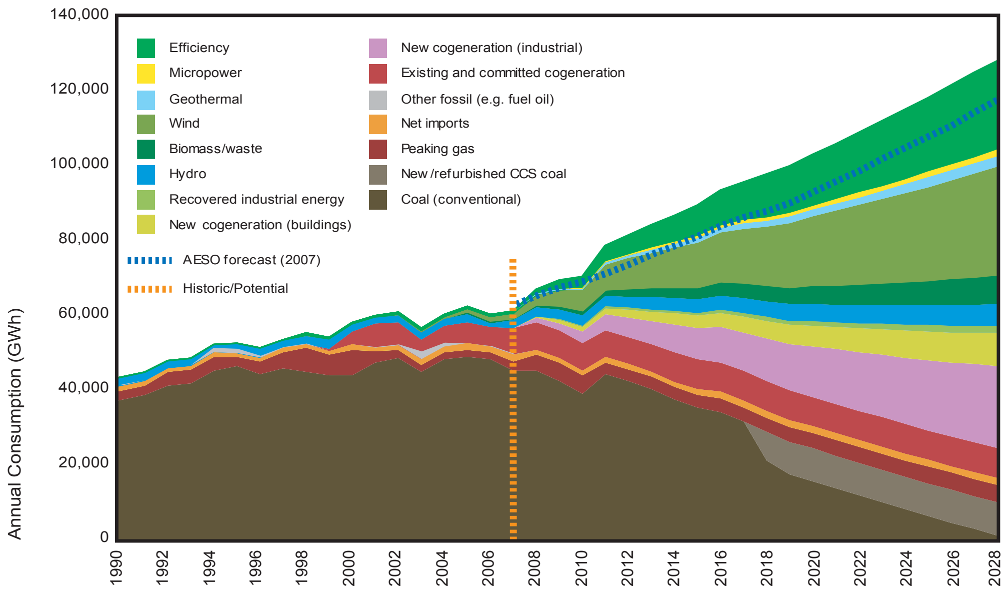


Figure 6: Greening the Grid's "Green" scenario of electricity generation showing a phase-out of coal.

Source: Greening the Grid[68]

strated that at low wind speeds and high demand, the mix of technologies in this scenario would supply all of Alberta's power requirements with a supply margin of 13% under a worst-case scenario. For detailed information on assumptions and modeling, see *Greening the Grid: Powering Alberta's Future with Renewable Energy*.[69] In this scenario, UCG would still be preferable to coal with CCS and could assist in reducing the environmental impact of the grid.

5.3 Summary

When comparing UCG with other electricity generating technologies in its capacity to reduce the environmental impact of Alberta's current and projected electricity supply mix, this analysis concludes the following:

- Energy efficiency and low-impact renewable and natural gas technologies are likely lower impact than UCG-derived power.
- UCG with CCS is considered an improvement over conventional coal technologies and coal with CCS.
- In both the business as usual and green electricity development scenarios there is a clear opportunity for UCG to help Alberta meet its future electricity demand while reducing the impact of the Alberta's electricity grid.

If UCG is able to demonstrate environmental performance in line with industry expectations, decreasing environmental risks associated with the technology, it would be comparable to the environmental performance of natural gas electricity generation technologies. In this scenario UCG would help Alberta reduce land use impacts, GHG emissions and air emissions associated with electricity production. UCG may also be preferable to natural gas for electricity generation because natural gas has other important uses such as residential heating.

6 Conclusions

UCG with combined electricity production has the potential to access the vast energy reserves locked in coal deposits that are uneconomic to mine using current technology. The technology may also be able to develop these resources with fewer environmental impacts than conventional coal mining and coal-fired generation. The technology is not yet commercial but there are fourteen pilot projects globally and two in Alberta that plan to demonstrate the commercial viability of the technology. This report focused on the environmental risks and benefits of UCG in general, with some specific comments on UCG potential in Alberta and on Laurus' pilot project. In reviewing literature sources, interviewing UCG experts in Alberta, speaking with Laurus staff and building off Pembina's analysis of electricity growth in the province, this report finds the following:

Groundwater

Local groundwater contamination is the most serious risk associated with UCG. Only two UCG pilots out of 34 pilots conducted in North America have resulted in groundwater contamination; however, those two required considerable remediation efforts. Groundwater contamination risk can be mitigated through appropriate site selection, and good operational and abandonment practices. Mitigating this risk requires operator expertise that is not widely available. Widespread commercialization in Alberta will require development of this expertise and regulations to ensure appropriate site selection, and operation and abandonment practices. Laurus appears to be one of the few companies with access to this expertise and the pilot project will assist in developing this expertise further.

CO_2 Emissions and Carbon Capture and Storage

UCG with electricity generation will likely result in GHG emissions 25% lower than conventional coal electricity generation, but 75% higher than natural gas electricity generation. UCG can also integrate CCS, where carbon dioxide is captured and then transported via pipeline and either sequestered or used to enhance oil recover, into its operation to achieve more significant GHG emissions reductions. With integrated CCS, UCG should have a GHG intensity lower than natural gas combined cycle generation but higher than coal with CCS, energy conservation, energy efficiency and low-impact renewable energy sources like wind. Current CCS costs indicate that integrating CCS into UCG operations will be less costly in comparison with other electricity-generating technologies because capturing the CO_2 stream is easier t and doesn't require the same capital investments as other technologies. However, Alberta does not have a CO_2 pipeline and Canada does not have policies or regulations to drive widescale deployment of this technology. From a local perspective the primary impact would be additional infrastructure, such as CO_2 pipelines and concerns of transport and storage safety.

Ground Subsidence

UCG creates cavities underground similar to other long wall underground mining activities. Eventually the rock and other materials that are no longer supported by the coal that the UCG process has removed will fill the cavities. On the surface, the land will gradually settle or subside as the underground cavities are filled over a period ranging from months to years. This subsidence can impact surface water flows, shallow aquifers and any above ground infrastructure like roads and pipelines. These impacts will have to be managed as done in other underground mining operations. Those living near a UCG operation would be most affected if poorly managed subsidence were to take place. However, UCG operators, knowing subsidence will happen, can manage it by providing buffers around surface features such as lakes, rivers and roads to minimize impact.The literature reviewed for this report and comments from interviewees indicate that subsidence is manageable and when managed properly, has resulted in minimal local impact. Subsidence is also not unique to this technology and is common for conventional underground mining.

Land Use Impacts

UCG operators must perform a thorough assessment of the underground environment at the selected site, including geology, hydrogeology and rock mechanics. The tools for this assessment may include geological mapping, core samples and analysis, 3-D seismic surveys and aquifer pressure/hydrogeological modelling. Once operating, a single commercial facility would actively disturb one half-section of land (1.3 km^2). From a regional perspective, if UCG eliminated the need for a new coal mine it would lead to fewer land impacts. From a local perspective, the surface impacts of UCG developments will depend largely on location and the intensity of the operation. A large UCG development in a relatively undeveloped environment will still lead to habitat fragmentation issues similar to in situ oil sands development. Large or multiple UCG developments should therefore be considered in the context of cumulative impacts and regional land use planning.

Air Emissions

The combustion of syngas, like the combustion of natural gas, will generate air emissions with associated environmental and health concerns like acid rain. 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 a conventional coal power plant. Nonetheless, air emission concerns will depend on the combined sources of emissions in the region and the pollution control standard to which the facility is designed. A UCG facility will lead to incremental increases in air emissions wherever constructed, unless it replaces a facility with higher emission intensities.

Additional Research Required

As with any new technology, there is little publicly available information on commercial facilities. There are no operating commercial-scale UCG operations in North America, so any assessment of environmental benefits and issues is uncertain. Additional research and development of this technology is needed, especially regarding monitoring ground water and subsidence requirements, and environmental management practices to reduce risk. Pilot projects such as Laurus' are essential to learn more about the technology, its potential, its risks and how the risks can be managed.

Current State of Regulations

The current regulatory structure in Alberta is also uncertain and it is not possible to determine whether it is sufficient to manage the unique environmental risks of this technology. Pilot projects will help regulators design effective regulation; however, for those located next to a pilot project, the current regulatory framework and legislative uncertainty regarding UCG development is concerning. Should the pilot result in unexpected impacts, the ERCB and Alberta Environment may be unclear on who holds jurisdiction. The ERCB has created a multidisciplinary committee in January 2009 to develop a legislative framework for UCG projects to address this uncertainty. Alberta Energy and Alberta Environment established similar committees in 2010. If the legislation is passed by the Alberta government it will clarify many of the uncertainties regarding UCG development.

Implications for Alberta's Electricity Grid

The Alberta Electric System Operator (AESO) expects Alberta's electricity demand to almost double over the next 20 years. Based on preliminary review of several environmental metrics, the order in which electricity sources should be developed in Alberta to minimize environmental impacts is: energy conservation and efficiency; low-impact renewables including run-of-river hydro; and natural gas technologies. Once those sources of electricity production have been developed, UCG with CCS could be an alternative to conventional coal-fired electricity production with or without CCS. Alberta has significant coal reserves that could be accessed using UCG in a less damaging manner than current coal technologies. Once fully proven effective and safe, UCG with CCS has the potential to have similar impacts to natural gas electricity generation. In this scenario UCG would help Alberta reduce land use impacts, GHG emissions and air emissions associated with electricity production. However, consistently realizing these benefits, while managing the risks of UCG will require operators with expertise in UCG — expertise that is currently limited. Laurus has access, through Ergo Exergy, to some of the most experienced UCG operators available and plans to develop this expertise further with its pilot project.

Based on the information in this report, the potential of UCG technology implementation in Alberta should be investigated further and a pilot project seems like a necessary next step to better understand how to mitigate the risks of the technology and determine if the considerable benefits can be realized. In addition, based on the comments of the interviewees and available literature sources, it appears that Laurus and Laurus' technology provider, Ergo Exergy, have the most experience operating UCG facilities around the globe. A follow-up review based on the results of the pilot project would more accurately assess the commercial potential of the technology especially in the Alberta context. However, as with any large project it must have support of the local community.

7 Glossary

Alberta Electric System Operator (AESO): This is an not-for-profit entity responsible for the safe, reliable and economic planning and operation of the Alberta Interconnected Electric System.

Ammonia (NH_3): Ammonia is a naturally occurring, colourless, acrid-smelling gas. It is widely used in a variety of manufacturing processes, but is mostly used as a fertilizer. Much of the ammonia in air results from the decomposition of organic matter and other biological activities. Air readily dilutes and degrades ammonia so it does not stay airborne for more than a week.

Ammonia vapour is an irritant to the eyes and the respiratory tract. Damage to the bronchial epithelium and the alveolar membrane have been documented at high concentrations while severe acute over-exposure can lead to death within minutes.

Benzene: Benzene, an aromatic hydrocarbon, is a clear, usually colourless liquid with a gasoline-like odour. Benzene is classified as a known human carcinogen. Benzene is considered a "non-threshold toxicant," where adverse effects may occur at any level of exposure.[70] Benzene does not persist in water or soil because it biodegrades and volatizes rapidly to the atmosphere.[71]

Biomass: Biological material derived from living, or recently living organisms; for example, wood chips and animal waste.

Carbon Capture and Storage (CCS): A process whereby carbon dioxide (CO_2) is captured and then transported via pipeline and either sequestered or used to enhance oil recovery.

Carbon Dioxide (CO_2): A colourless, ordorless, non-poisonous gas that is a normal part of Earth's atmosphere. Carbon dioxide is a product of fossil-fuel comsubtion as well as other processes. It is considered a greenhouse gas as it traps heat radiated into the atmosphere and thereby contributes to the potential for global warming.[72]

Communication between wells: In the oil and gas industry, a term describing the connection between two wells.

Criteria Air Contaminants: These are a group of pollutants that cause air issues such as smog and acid rain. They include sulphur oxides, nitrogen oxides, particulate matter, volatile organic compounds, carbon monoxide, ammonia, ground-level ozone and secondary particulate matter.[73]

Energy Resources and Conservation Board (ERCB): The ERCB is an independent, quasi-judicial agency of the Government of Alberta. It regulates the safe, responsible, and efficient development of Alberta's energy resources: oil, natural gas, oil sands, coal, and pipelines. Its mission is to ensure that the discovery, development and delivery of Alberta's energy resources take place in a manner that is fair, responsible and in the public interest.

Gasification: Conversion of solid material such as coal into a gas for use as a fuel.

Integrated Gasification Combined Cycle: Coal or other fuel is gasified in a gasification chamber and the resultant syngas is used to generate electricity. The syngas is first combusted in a gas turbine and the waste heat is used to heat water to turn a steam turbine. The rotary motion from each turbine is used to generate electricity.

Natural Gas Cogeneration: When natural gas is combusted to produce electricity and the waste heat is used for other processes, such as district heating.

Natural Gas Combined Cycle: A natural gas powerplant with two types of turbines. The natural gas is first combusted in a gas turbine and then the waste heat is used to heat water to turn a steam turbine.

Nitrogen Oxides (NO_x): NO_x is a by-product of combustion. It contributes to acid deposition leading to impacts on soils, lakes, forests, crops and buildings. When present with VOCs, NO_x is also a contributing factor to ground level ozone, which can cause adverse effects on humans, including lowered lung function and the development of chronic respiratory diseases. Ground-level ozone also has significant impact on reducing the productivity of agricultural crops and forests. NO_x has approximately 70% the acidifying potential of SO_2. See VOCs below for more information on ground-level ozone.

Particulate Matter (PM): Particulate matter is tiny pieces of solid and liquid matter small enough to be suspended in the air. The finest of these particulates are primarily soot and exhaust combustion products that may irritate the respiratory tract and contribute to smog formation. Secondary sources of PM result from SO_2, NO_x, and VOC emissions that act as precursors to PM formation in the atmosphere. Of particular concern are PM_{10} and $PM_{2.5}$ particulates – fine particulates smaller than 10 and 2.5 microns in size that can penetrate deep into the lungs. These particulates can have a serious effect on respiratory function and have been linked to cancer, especially those particulates from diesel exhaust that contain carcinogenic fuel combustion products.[74]

Phenols: Phenols are a manufactured class of weakly acidic water-soluble chemical compounds related to the organic chemical compound phenol naturally present in most foods. Phenols are readily absorbed following inhalation, ingestion or skin contact, and are widely distributed in the body. Some phenols are endocrine disruptors (disrupt normal hormone behavior in the human body).

Polycyclic Aromatic Hydrocarbons (PAHs): PAHs are a large group of organic compounds with two or more fused aromatic rings. They have relatively low solubility in water, but are highly lipophilic (fat soluable). PAHs primarily result from incomplete combustion such as in a UCG chamber. PAHs have known carcinogenic effects on humans.[75]

Pulverized Supercritical Coal (PSC): In a PSC plant the coal is first ground to a fine powder (pulverized) and then combusted to heat water and create steam. At a supercritical facility the steam reaches pressures of 30 MPa at 600˚C. These facilities can achieve higher efficiencies at this temperature and pressure (38%-45%) compared to 33% for subcritical facilities.[76]

Section (of Land): A section is an area of land measuring 1 mile by 1 mile, or 2.6 km^2.

Seismic: An exploration method used by industry to gather information about underground rock formations. It involves creating shock waves (low-frequency sound waves) that pass through deep underground rock formations, and then interpreting the waves that are reflected back to the Earth's surface.[77]

Sour gas: Sour gas is natural gas that contains measurable amounts of hydrogen sulphide (H_2S), a colourless substance that is poisonous to humans and animals. It is recognizable by its rotten egg smell at very low concentrations (0.01–0.3 parts per million), although there is no perceptible odour at higher concentrations as the chemical affects a person's sense of smell. Exposure to high concentrations of H_2S (150–750 parts per million) can cause loss of consciousness and even death.[78]

Subsidence: The sinking or lowering of a surface region relative to the surrounding region. With UCG it occurs as a result of the removal of material from the underground coal formation.

Sulphur Dioxide (SO_2): Sulphur dioxide (SO_2) is a colorless gas that smells like burnt matches. It can be chemically transformed into acidic pollutants such as sulphuric acid and sulphates (sulphates are a major component of fine particles). SO_2 is generally a byproduct of industrial processes and burning of fossil fuels. Ore smelting, coal-fired power generators and natural gas processing are the main contributors. Sulphur dioxide is also the main cause of acid rain, which can damage crops, forests and whole ecosystems.[79]

Synthesis Gas (Syngas): Syngas contains primarily hydrogen and carbon monoxide and can be produced from the gasification of coal. The gas is flammable and can be used for energy generation or as a building block for other processes.

Hydrogeology investigation (pumping well drilling) at a UCG site in Alberta, 2009.
Courtesy of Laurus Energy Canada

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Appendix 1

Table 4: List of quantitative and qualitative environmental indicators

Technology (Levelized Unit Electricity Cost $/MWh)[a]	CO_{2e} emissions	NO_X emissions	SO_2 emissions	Footprint	Magnitude of disturbance	Water consumption	Water/ground water impacts	Long term unknowns/liabilities	Worst Case Scenario
	t/GWh	kg/GWh	kg/GWh	m^2/GWh	(qual.)	(qual.)	(qual.)	(qual.)	(qual.)
Energy Efficiency (application dependent)	0[b]	0[c]	0[c]	Low[d]	Low[d]	Low[d]	Low[d]	Low[d]	Low[d]
Large Scale Wind (80–108 $/MWh)	17[e]	35[e]	35[e]	1,576[f]	Low[g]	Low[d]	Low[d]	Low[d]	Low[h]
Solar PV (roof) (160–800 $/MWh)	59[i]	248[i]	512[i]	41[f]	Low[j]	Low[d]	Low[d]	Low[d]	Low[d]
Hydro (run of river) (50–180 $/MWh)	Low[k]	Low[k]	Low[k]	Low[l]	Low[l]	Low[m]	Low[b]	Low[d]	Low[d]
Biomass (waste) (47–66 $/MWh)	Low[n]	Variable[o]	Variable[o]	Low[p]	Low[p]	Med[q]	Low[d]	Low[d]	Low[d]
Natural Gas Cogeneration (55–86 $/MWh)	427[r]	802[r]	311[r]	263[r]	Med[s]	Med[q]	Low[d]	Low[d]	Med[t]
Natural Gas Combined Cycle (55–86 $/MWh)	534[u]	1,504[u]	584[u]	329[f]	Med[s]	Med[q]	Low[d]	Low[d]	Med[t]
UCG with CCS (48.5–87 $/MWh)[v]	**330**[w]	**280**[x]	**60**[x]	**99**[y]	**Med**[z]	**Med**[aa]	**High**[bb]	**High**[cc]	**High**[dd]
Coal with CCS (113–114 $/MWh)	197[ee]	888[ee]	65[ee]	434[ff]	High[gg]	Med[hh]	Med[ii]	Med[ii]	High[dd]
IGCC (40 $/MWh)[kk]	800[ll]	410[mm]	70[mm]	434[nn]	High[gg]	Med[q]	Low[d]	Low[d]	Med[t]
Pulverized Supercritical Coal (39–56 $/MWh)	986[oo]	2,247[oo]	2,581[oo]	434[nn]	High[gg]	Med[q]	Low[d]	Low[d]	Med[t]

Table 4 notes

[a] All cost values (unless stated otherwise) from:

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[b] Jeff Bell and Tim Weis, *Greening the Grid: Powering Alberta's Future with Renewable Energy* (Pembina Institute, 2009) http://pubs.pembina.org/reports/greeningthegrid-report.pdf.

[c] Assumed to be negligible.

[d] Not applicable or assumed to be negligible.

[e] Number derived from the average of data from the following sources:

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International Energy Agency, *Hydropower and the Environment: Present Context and Guidelines for Future Action* (IEA, 2000): 188.

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[g] Wind turbines do not require mining operations or other intensive land use. Assumed that minimal land impacts will remain over the long term.

[h] Catastrophic failure of a wind turbine would likely have no direct human impacts given low population density in very close proximity to turbine.

[i] United States Department of Energy, *The Potential Benefits Of Distributed Generation And Rate-Related Issues That May Impede Their Expansion, A Study Pursuant To Section 1817 Of The Energy Policy Act Of 2005* (DOE, February 2007) www.ferc.gov/legal/fed-sta/exp-study.pdf.

[j] Roof-mounting takes advantage of a surface area that is already being used for other purposes.

[k] Assumed to have low or negligible emissions levels, only associated with construction & materials production.

[l] Assumed to be small or negligible in contrast to power output.

[m] Run of the river hydro does not require a dam and had low impact or river flow. Bell and Weis, Greening the Grid.

[n] Assumed that biomass energy can achieve close to net-zero GHG emissions.

[o] Depends upon type of biomass, conversion technology, and mitigation technologies included with the system.

[p] Biomass collected from waste sources will not result in any new surface or land impacts with the exception of possible transportation infrastructure and conversion facility.

[q] May require moderate volumes of water for thermal cycles, air emissions management, cooling, etc.

[r] Value was approximated based on NGCC — assumption that NG cogen will result in less emissions than NGCC due to increased efficiency and allocation of a portion of the emissions to the heat user. Approximated by multiplying by a factor of 0.8.

[s] In addition to facility, land use must also include the impacts associated with the procurement of natural gas — impacts consisting of wells, pipelines, other infrastructure — assumed to have moderate relative intensity.

[t] Worst case scenario could include human health impacts from fossil fuel related air emissions, catastrophic plant failure.

[u] Number derived from the average of data from the following sources:

McCulloch and Vadgama, *Life Cycle Evaluation of GHG Emissions and Land Change Related to Selected Power Generation Options in Manitoba.*

IEA, *Hydropower and the Environment.*

Rich Wong and Ed Whittingham, *A Comparison of Combustion Technologies for Electricity Generation* (The Pembina Institute, 2006): 37, http://pubs.pembina.org/reports/Combustion_CCS_Final.pdf.

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[w] Laurus anticipates a CO_2 intensity of 330 kg CO_{2eq}/MWhr at its commercial facility when carbon capture is installed.

[x] Value based on UCG IGCC (does not include CCS) from: Mark van der Riet, "Underground Coal Gasification," (presented at the SAIEE Generation Conference, South Africa, February 19, 2008) www.eepublishers.co.za/images/upload/Eskom%20coal%20gasification.pdf

[y] Calculated based on information provided by Laurus: 1 section of land (2.6 km^2) per 10 years for a 300MW capacity plant. Value does not include area required for CCS infrastructure.

[z] Land use intensity is moderate resulting from wells and subsidence — assume that with proper management, long-term impacts on land should be only moderate. Does not include an open pit mine.

[aa] May require moderate volumes of water for thermal cycles, air emissions management, cooling, carbon capture, etc. UCG also directly consumed ground water.

[bb] Risk of ground water impact resulting, see discussion in report. Additional risk associated with unknown levels of impacts that may results from CCS interactions with groundwater.

[cc] Many unknowns surrounding the operation of UCG technologies. Long-term liability to ensure that ground water contamination does not occur. Additional long-term unknowns or liabilities associated with CCS.

[dd] Worst case scenario could include catastrophic ground water contamination, surface water disruption or other impacts from subsidence. CCS worst case scenario could include release or large quantities of carbon dioxide.

[ee] Number derived from the average of data from the following sources:

Wong and Whittingham, *A Comparison of Combustion Technologies for Electricity Generation.*

Weisser "A Guide to Life-Cycle Greenhouse Gas (GHG) Emissions from Electric Supply Technologies."

Odeh and Cockerill, "Life Cycle GHG Assessment of Fossil Fuel Power Plants with Carbon Capture and Storage."

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Bergerson and Lave, "The Long-Term Life Cycle Private and External Costs of High Coal Usage in the US."

Martin Pehnt and Johannes Henkel, "Life Cycle Assessment of Carbon Dioxide Capture and Storage from Lignite Power Plants," *International Journal of Greenhouse Gas Control* 3, (2009): 17.

[ff] (value based on coal power, does not include CCS requirements) Fthenakis and Kim, "Land use and electricity generation."

[gg] Assumed high impact to land resulting from open pit coal mining.

[hh] May require moderate volumes of water for thermal cycles, air emissions management, cooling, carbon capture, etc.

[ii] Risk associated with unknown levels of impacts that may results from CCS interactions with groundwater.

[jj] Long-term liability associated with CCS — monitoring to ensure safety and effectiveness of storage.

[kk] GE Power Systems, Ergo Exergy Technologies, "Coal: A New Horizon." Assuming no carbon capture and storage.

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[mm] van der Riet, "Underground Coal Gasification."

[nn] (value based on coal power) Fthenakis and Kim, "Land use and electricity generation."

[oo] Number derived from the average of data from the following sources:

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