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Prepared for

Brown Coal Innovation Australia (BCIA)

NEXT GENERATION LOWER EMISSIONS GASIFICATION SYSTEMS R&D – PRODUCTS AND POWER:
STATE-OF-THE-ART REVIEW

Report No: HLC/2011/458
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by
HRL Technology

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Executive Summary

Overview of the Work Program

HRL Technology Pty Ltd, in collaboration with Monash University and the CO2CRC, have completed an extensive world-wide study into state-of-the-art gasification systems for the production of chemicals and fuels from brown coal syngas and power using advanced fuel-cell systems. The work is the first part of a much larger three phase program, which is required to develop a chemicals industry based on gasification of Victorian brown coal.

The work was extensive and included a range of technical, capacity building and commercial aspects including:

- A review of the technical literature to determine state-of–the-art for syngas production, gas conditioning and chemical production systems;
- The identification of specific technical requirements to achieve quantum leaps in processes to reduce carbon dioxide emissions and plant costs;
- A preliminary market survey to determine potential commercial opportunities for various chemicals and fuels;
- Identification of current political drivers and how these are directing research efforts around the globe;
- Identification of the major research institutes around the world, their facilities and research programs;
- Study tours to Europe, North America and China to liaise with key researchers in the field, to inspect their facilities and discuss technical aspects of gasification and gas processing research;
- Determine the status of next generation advanced power generation systems research using Integrated Gasification Fuel Cell (IGFC) systems;
- The development of technical research capacity of young engineers for the future viability of the brown coal industry;
- The identification of potential products and processes based on brown coal gasification that could be developed into commercial businesses;
- Identification of established and recent developments in coal syngas cleaning systems;
- The establishment of a viable pathway to move forward with future product development.

This overview report is a high level summary of the objectives of the work program and the main findings from Part 1 of Phase 1 of the Program (this project).

In total, the reports from this Part 1 of the work Program cover some 977 pages of text and include 838 cited references. A summary list of the reports from Part 1 is provided in the confidential annex to this report.

As part of the current work, a number of visits were arranged to local and international venues to inspect their research facilities and to determine equipment requirements for a pilot-scale test facility suitable for research on production of various chemicals from Victorian brown coal syngas. The visits also provided for the establishment of networks and linkages to international technical experts in the field. A summary list of the local and international research facilities that were visited as part of this work is given in Table 1 below.

Table 1. Summary List of Local and International Research Facilities

Research Facilities	
Facility	**Location**
VTT Technical Research Centre of Finland	Helsinki, Finland
Technical University of Munich	Munich, Germany
Technical Institute of Freiberg	Freiberg, Germany
Karlsruhe Institute of Technology	Karlsruhe, Germany
CANMET Energy	Ontario, Canada
Delft University	Delft, Netherlands
CSIRO – Queensland Centre for Advanced Technology	Queensland, Australia
Energy and Environmental Research Centre	North Dakota, USA
ECN	Netherlands

Background

The Challenge

Victoria has vast amounts of brown coal located in the Latrobe Valley to the east of Melbourne. Currently, the brown coal is almost exclusively used for power generation in large purposefully built pulverised-fuel fired power stations. The coal is close to the surface and easily mined by low cost open cut methods. The high moisture content of the Latrobe Valley brown coals (about two thirds water, one third organic matter) and the need for drying prior to transportation or any further processing has been a major challenge for many potential upgrading technologies. The cost of drying the coal often becomes a prohibitive hurdle to any potential future development, particularly if the products are of low value.

Because of these limitations, the Latrobe Valley brown coals are burnt in large pulverised-fuel fired boilers directly adjacent to the mine site. Only a small portion of the total annual tonnage of brown coal mined in the Latrobe Valley is dried and compressed into briquettes for domestic and international sales.

The brown coal burnt in the existing pulverised-fuel fired power stations produces greenhouse gas emissions. The challenge for the brown coal industry is the development of low emission, sustainable technologies which could expand the use of brown coal in a low emissions future. The conversion of Victorian brown coal into value-added products has been identified as a key part of expanding the utilisation of this vast resource.

The Opportunity

The development of high value chemical products from Victorian brown coal, via gasification to produce syngas and subsequent reaction of the syngas to form products, presents an opportunity for expansion of brown coal utilisation. However, demonstration of such systems will be required to encourage the development of commercial operations for conversion of Victoria's brown coal into value-added products via the syngas route.

Best Practice Power Generation Technology for Victoria's Brown Coal

Integrated Drying and Gasification (IDG) developed by HRL is a means of producing syngas from brown coal suitable for further processing into a range of products. Integration of the coal drying with gasification provides a number of potential environmental, technical, and economic benefits over existing technologies. The HRL IDG process was developed by HRL initially for lower emissions electricity generation in the HRL Integrated Drying and Gasification Combined Cycle (IDGCC) concept where the HRL IDG process is combined with a gas turbine combined-cycle power plant.

HRL has spent the last 20 years developing the IDGCC process from the initial concept studies, laboratory and pilot-scale test programs, 10 MW-scale demonstration plant research program and more recently the Front End Engineering Design and works approval for a 600 MW demonstration power plant.

HRL's proposed 600 MW Dual Gas (DG) Demonstration Power Station is the first large-scale application of HRL's IDG process. National and International experts who have reviewed the Dual Gas EPA Works Approval Application have concluded the following:

- "presently the DG process is the "best practice" technology for generating power from brown coal with the lowest environmental impact" (*Review of EPA Works Approval Application from Dual Gas Pty Ltd to build and operate the Dual Gas Demonstration Power Station, Maarten J. van der Burgt, May 2011*);
- "IDGCC is an innovative technology which, if successfully demonstrated, will have a performance that is competitive with, or better than the performance of currently available technologies" (*Review of EPA Works Approval Application from Dual Gas Pty Ltd to build and operate the Dual Gas Demonstration Power Station, Malcolm McIntosh, April 2011*).

Value Added Products

An additional potential application of the HRL IDG technology is for the production of syngas suitable for conversion into value-added products including transport fuels and chemicals and also for use in advanced power systems employing fuel cells. The technology for CO_2 capture from syngas is also commercially available, offering the potential for development of low CO_2 emission projects. One example of this is HRL's current work with a Japanese company, evaluating the prospect for hydrogen production via HRL IDG of Victorian brown coal.

HRL has conducted extensive R&D on the gasification of Victorian brown coal, although only limited data has been published as this Intellectual Property underpins the commercialisation of the HRL IDG process.

There are some publications on the application of gasification of brown coal for power generation, but fewer publications on the application of gasification for the production of value-added products. Such systems may have specific requirements depending on the product of interest, including particular syngas processing to tailor the syngas for downstream catalytic synthesis of value-added products. Further R&D involving technology providers for syngas processing is therefore required to determine the appropriate systems for utilising brown coal in value-added product manufacture.

Pilot-scale Test Facilities

The future development of value-added product manufacture from brown coal syngas would benefit from the availability of syngas from suitable pilot-scale test facilities. HRL's pilot-scale gasification facilities in Mulgrave were developed for air-blown gasification and are around 20-years old. A new facility specifically designed to underpin development activities focussed on the manufacture of value-added products including oxygen-blown gasification of brown coal, raw syngas conditioning, syngas conversion and fuel-cell performance is envisaged to be required in later phases of the work program.

Aims of Phase 1 of the Work

The purpose of the current work program was to establish the future markets for coal derived products and to provide the necessary information to design and build suitable pilot-scale gasification facilities to allow the research required to develop the next generation of gasification systems in later phases of the development program. It should be noted that, only a portion of the total funding required to achieve the Phase 1 goal was secured and so work on Part 1 of Phase 1 (as described above) of the work Program was completed. Further funding is currently being sought to allow completion of the later parts of Phase 1, Phase 2 and Phase 3 of the work Program.

In addition to market knowledge of the potential future demand for chemical products and the requirements for specially built pilot-scale research facilities described above, the viability of the future brown coal industry requires young engineers and scientists with the research skills to enable the realisation of the next generation gasification systems for Victoria. One of the key elements of the current work was the involvement and training of young researchers from HRL Technology, Monash University and the CO2CRC to gain the required knowledge to progress any future initiatives. The work program also enabled senior HRL Technology researchers to supervise five Chemical Engineering students from Melbourne University on Industry Projects related to brown coal utilisation. In total about 15 researchers worked on various aspects of the first Part of Phase 1 of the program at various times. It is expected that many of these researchers could potentially become future leaders in the Victorian brown coal industry.

High Level Summary of the Main Findings

Global Trends

The results of the work revealed that a vast array of chemical products, fertilisers and liquid fuels could potentially be made from brown coal syngas. It was also found that the majority of installed syngas capacity globally is used for production of chemicals and transport fuels.

The selection of the most viable products will be made based on the results of economic and engineering concept studies (next Part of the Work Program) and knowledge of the potential future market demand. It is essential that selection of the most viable products be done early in the next part of the work program so as to focus efforts on the design and costing of appropriate research facilities to progress later phases of the R&D work program.

Interestingly, about seventy per cent of planned syngas growth globally will be based on coal, highlighting that coal will be a major energy source into the future. There is significant interest in gasification globally, but the majority of activity (construction, commissioning and operation) is in developing countries, in particular China, where energy demand is growing rapidly.

Due to the push for lower CO_2 emissions in Europe, recent work in that region has focused on biomass gasification, which has some parallels to brown coal, although the results must be interpreted with caution. Although there is significant interest in biomass gasification worldwide, it is expected that the impact of biomass utilisation on world syngas capacity will be minimal, largely due to limited feedstock supply.

The development of large centralised power systems based on advanced solid oxide fuel cells has progressed significantly over the last decade, due mostly to large government R&D expenditure in Europe, Asia and the USA. Currently, commercially available fuel cell power systems of several MW capacity have been realised. The major focus of research for larger scale (e.g. 100 MW) stationary power is high-temperature fuel cells, which can directly utilise a range of fuels, including hydrogen, methane, carbon monoxide and syngas. The high temperature exhaust from the fuel cell can also potentially be used for additional power generation in an Integrated Gasification Fuel Cell (IGFC) / heat engine system, therefore increasing the overall system efficiency.

Currently, there are a number of factors including cost, durability, efficiency, scale, sensitivity to contaminants and the need to demonstrate the technology at large scale with coal-derived syngas, which limit the performance, operation and potential implementation of fuel cells for large scale power generation. Therefore, the technology can be considered as a next generation technology. Future development of fuel cell technology for IGFC systems to a commercially viable status is directed towards alleviating the current limitations.

Overseas Research Funding Models

Much of the gasification and syngas-to-chemicals and advanced power systems research occurring overseas is the result of substantial Government funding and often involves a number of large multi-national companies and research providers working co-operatively on various commercial and technical issues unique to the local regional resource feedstock and end use applications.

The Unique Characteristics of Latrobe Valley Brown Coals

The brown coals from the Latrobe Valley, Victoria, have unique chemical and physical properties that must be considered in any future commercial development. Unfortunately, most of the technical work published in the open literature relates to black coals and, in most cases, information and research results on black coal gasification are not relevant for high moisture Victorian brown coals. For this reason, it is imperative that the unique characteristics of the Latrobe Valley brown coals are considered in any future design and construction of pilot-scale research facilities.

The Path Forward

Due to the national importance and the nature and size of the effort required to develop a coal based chemical industry, most of the international work programs have considerable financial support from Government and large industry stakeholders. Investors and stakeholders (including Government(s)) must be engaged early to enable funding for remaining Phases of this work to be progressed further.

The next step in the technical work program is to undertake engineering and economic concept studies so as to select a number of potential products for pilot-scale development based on technical, commercial and market considerations. Once the short-list of products is selected, work can commence on the design, construction and commissioning of specialised pilot-scale test facilities specifically suited to study the syngas production from Victorian brown coal and manufacture of the chosen products.

A range of research activities would be required to determine the viability of fuel cells for large scale power production from brown coal syngas, either stand alone or as part of a complex producing "Products and Power". Fuel cells will be developed by large multinational companies, but their application and integration into brown coal gasification systems would need to be investigated in future phases of this project. The engineering and economic concept studies would need to consider the potential application of fuel cell technology for power production and how best they might be incorporated into the overall system design. Any future pilot-scale test facility should make allowance for the testing of downstream processes such as syngas cleaning and conditioning processes, syngas conversion processes and fuel cell systems.

In parallel with the technical development, further market research will be required to provide additional information for future product and process selection. This work will require specialist market expertise and intelligence.

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1 Introduction

1.1 Project Context

Brown coal has been used for power generation in Victoria for nearly 100 years and is currently used to produce about 85 per cent of the electricity requirements for Victoria. The brown coal resources in Victoria's Latrobe Valley are extensive and it is estimated that, based on current usage levels, Victoria's brown coal resource could support Victoria's electricity needs for the next 500 years.

A barrier to continued utilisation of brown coal in Victoria is the significant emissions of greenhouse gases associated with existing brown coal utilisation technologies. A challenge for the Victorian government, Brown Coal Innovation Australia (BCIA) and the brown coal industry is therefore to develop low emission, sustainable technologies which broaden the use of brown coal in a low emissions future. The conversion of brown coal into value-added products and electricity using advanced power systems has been identified as an opportunity to expand the utilisation of brown coal.

Integrated Drying and Gasification (IDG) developed by HRL is a means of producing syngas from brown coal suitable for further processing into a range of products. The HRL IDG process has been developed by HRL initially for lower emissions electricity generation in the HRL Integrated Drying and Gasification Combined Cycle (IDGCC) concept where the HRL IDG process is combined with a gas turbine combined-cycle power plant.

An additional application of the HRL IDG technology is for the production of syngas suitable for conversion into value-added products including transport fuels and chemicals and for use in advanced power systems. The technology for CO_2 capture from syngas is also commercially available, offering the potential for development of low CO_2 emission projects. One example of this is HRL's current work with a Japanese company, evaluating the prospect for hydrogen production via HRL IDG of Victorian brown coal.

HRL has conducted extensive R&D on the gasification of Victorian brown coal, although only limited data has been published as this Intellectual Property underpins the commercialisation of the HRL IDG process.

There are some publications on the application of gasification of brown coal for power generation, but fewer publications on the application of gasification for the production of value-added products. Such systems may have specific requirements depending on the product of interest, including particular syngas processing to tailor the syngas for downstream catalytic synthesis of value-added products. Further R&D involving technology providers for syngas processing is therefore required to determine the appropriate systems for utilising brown coal in value-added product manufacture.

1.2 Project Description

HRL Technology's Project "Next Generation Lower Emissions Gasification Systems R&D – Power and Products" involves research to expand on the existing knowledge on coal conversion processes and their application for production of value-added products. This project is a three phase program to identify products and to research, develop and demonstrate conversion systems for the most prospective products.

The three phases proposed for the project are:

- Phase 1 - Feasibility study to determine prospective value-added products
- Phase 2 - Detailed design, construction and commissioning of a pilot-scale test facility; and
- Phase 3 - Research program to investigate and develop prospective systems.

This report is a summary of work on Part 1 of Phase 1 of the project, which was part funded by BCIA. The first part of Phase 1 involved a comprehensive literature review to determine state-of-the-art in low emissions brown coal conversion systems to produce products and power.

1.3 Project Objectives

The first part of Phase 1 of the project involved review of brown coal gasification systems, with specific focus on syngas production, gas conditioning and identification of prospective value-added products (chemicals, liquid fuels, fertilizers, etc). The overall objectives of Phase 1 were to identify prospective gasification systems and products and to determine research, development and equipment needs for future stages of the project. The results of the first part of Phase 1 will form the basis for a continuation into future stages of the project when further funds become available.

The major project objectives included:

- Review state-of-the-art in brown coal gasification systems, including:
  - Review of syngas production fundamentals and technologies;
  - Review of gas conditioning including CO_2 removal;
  - Review of syngas utilisation technologies and products (chemicals, fuels and advanced power); and
  - Study tours to determine global state-of-the-art in coal gasification R&D;
- Identify prospective processes and products based on brown coal derived syngas;
- Identify gaps in current knowledge and advances in brown coal gasification systems required for production of value-added products;
- Determine research and equipment requirements for future stages of the project;
- Explore funding options for future stages of the project;
- Support and develop future scientists and engineers in the area of brown coal research and development for the future benefit of the brown coal industry; and
- Develop linkages and networks to foster international collaboration in innovation and low-emissions technologies.

1.4 Project Methodology

A detailed work program to achieve the project objectives was developed. The program incorporated activities, timing and milestones. Key components of the work program included technical reviews, focused research between research providers, communication with BCIA, and study tours to relevant national and international research institutions, seminars and conferences.

Gasification systems for production of value-added products represent large-scale complex systems with a number of processing steps. The approach taken for the state-of-the-art review was to undertake a number of independent reviews with respect to the key process steps of syngas production, gas conditioning (including CO_2 removal), product synthesis and advanced power production and then to combine the key findings to allow investigation of gasification systems for different products and to facilitate preparation of an overview report.

The aims of this overview report are to present project objectives, methodology, outcomes, achievements, conclusions and recommendations, and demonstrate that the project objectives have been achieved.

1.5 Research Providers and Personnel

Research providers for the project were HRL Technology, CO2CRC and Monash University, which are three leading research organisations with significant experience in various aspects of Victorian brown coal utilisation. A range of researchers from recent graduates through to experienced research leaders were involved in the project.

Although the three research providers had distinct project responsibilities, the project activities needed to be integrated to maximise the project outputs. Consequently, the project was undertaken in a collaborative manner, with regular project review meetings between project research providers to discuss project progress and other project matters.

1.6 Project Financials

Funding for the project was provided through contributions from BCIA and the three research providers. An independent audit of the financials was undertaken at the completion of the project. The audit report has been submitted separately to BCIA.

1.7 Skills Development and Linkages

Important objectives of the current project were to develop researchers and potential future leaders in the area of brown coal research and development and to develop national and international networks and linkages in the areas of brown coal R&D, gasification systems R&D and other low–emissions technologies.

1.7.1 Training and Development of Future Scientists and Engineers

The development of future scientists, engineers and potential leaders in the area of brown coal R&D was achieved through completion of the various project activities and involvement in other external activities related to the project. Highlights included:

- Involvement of about 15 staff from HRL Technology, CO2CRC and Monash University in the project;
- Development of young engineers and scientists in the fundamental understanding of various aspects relating to brown coal science and utilisation with specific focus on brown coal syngas conversion processes for production of chemicals, fuels and advanced power;
- Study tours to national and international research institutions, training courses and conferences to determine global gasification trends, develop networks, inspect test equipment and expand existing knowledge base in brown coal science and technology and a range of associated areas.

  One of the major benefits to HRL Technology is undertaking this work was the capability and capacity building of young engineers and scientists in the area of gasification research. The capability and capacity building will enable future phases of the program to be realised as funds become available and will provide a pool of experienced staff to progress future coal related technology development.

  The study tours enabled researchers to view first-hand the extent of research facilities required to undertake gasification at the pilot-plant scale. This knowledge was invaluable for determination of a pilot-plant specification for further research into the production of products via the gasification of brown coal. The study tours also enabled the researchers to build international linkages with some of the leading research establishments around the globe.

Attendance at international conferences allowed HRL's researchers to discuss current trends in gasification research with leading experts. It also allowed analysis of global market drivers and the research community response to those market trends.

- Involvement in Melbourne University's Chemical Engineering Masters program provided the opportunity for five undergraduate chemical engineering students to complete 12 week industry research projects on topics relevant to brown coal utilisation. HRL was involved in the program as a means of education and capacity building for the future development of the brown coal industry.
- Completion of presentations by various staff in different forums, including:
  - Presentations to BCIA and ANLEC;
  - Presentations to national and international researchers as part of the study tours;
  - Internal seminars at HRL attended by BCIA representatives;
  - Presentations by the students involved in the Melbourne University Masters program.

1.7.2 Development of Linkages and Networks

Development of linkages and networks is important from the perspective of individual staff development and for future development of the current project and the brown coal industry. It is envisaged that other phases of this project will need input from a range of participants and will require additional funding in order to proceed. Key activities which facilitated the development of linkages and networks included:

- Attendance at relevant national and international conferences and meetings; and
- Visits to Europe, US, China and Japan to explore international collaboration opportunities.

Examples of the major activities completed are presented in Table 2.

Table 2. Summary of Major Activities Completed in the Study Tours

Conferences			
Conference Name	**Location**	**Key Focus Areas of Facility / Event**	**Website link**
6th Annual CTL & Coal Gasification 2011	Brisbane, Australia	• Update on the status of the industry • Determine the global CTL demand and supply, its markets, its commercialisation • Examine the developing niche markets with gasification technologies • Case studies from overseas • The potential impact of the carbon pricing legislation • Networking with researchers in the field of coal upgrading and gasification.	http://www.globalccsinstitute.com/get-involved/events/2010/12/21/6th-annual-coal-liquids-coal-gasification-conference
The 6th Clean Coal Forum: Clean Coal 2010	Beijing, China	• Topics cover low carbon economy, CCS, coal processing, power generation, coal conversion, coal combustion and emission control • Networking with researchers in the field of coal upgrading and gasification.	http://www.holland-hebei.net/index.php/news/7-overall-news/84-the-6th-clean-energy-forum-clean-coal-2010-january-27-29-2010-tianjin-china-
The 36th International Technical Conference on Clean Coal & Fuel Systems – The Clearwater Clean Coal Conference	Clearwater, Florida, USA	• All aspects of carbonaceous fuel utilisation • The State-of-the Art in coal utilization was presented in up-to-date technical papers, tutorials, and panels, covering cutting-edge developments on a range of timely topics. • Networking with researchers in the field of coal upgrading and gasification.	http://www.coaltechnologies.com/
Future Fuels for Australia (FFA) 2011 Workshop	Brisbane, Australia	• Understand current Queensland and national policies on future fuels; • Identify current activities and trends in the liquid fuel industry in Australia; • Identify current research activities and research capabilities in the research community in Australia;	http://www.mechmining.uq.edu.au/ff-contact

		• Stimulate discussions on the best options of future fuels for Australia; • Enhance communication and create opportunities for cooperation in the area of future fuels.	
Research Facilities			
Facility	**Location**	**Key Focus Areas of Facility / Event**	**Website link**
VTT Technical Research Centre of Finland	Helsinki, Finland	VTT Technical Research Centre of Finland is the biggest multi-technological applied research organisation in Northern Europe. VTT provides high-end technology and innovation services. • Fluidised bed gasification of biomass and waste • Hot gas filtration/cleaning • Catalyst testing and development • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research.	http://www.vtt.fi/?lang=en
Technical University of Munich	Munich, Germany	Technical University of Munich (TUM) is one of Europe's top universities for research. One of Germany's first Universities of Excellence, it achieves impressive scores in all international rankings. Its mission is to add value to society. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research.	http://www.tum.de/en/homepage/
Technical Institute of Freiberg	Freiberg, Germany	The Technische Universität Bergakademie Freiberg is a modern resource and research university that consistently orientates its profile	http://tu-freiberg.de/index.en.html

		lines GEO, MATERIAL, ENERGY and ENVIRONMENT towards future requirements • Broad focus on coal and biomass technology including fluidised bed and entrained flow gasification research facilities. • Provider of gasification training. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research.	
Karlsruhe Institute of Technology	Karlsruhe, Germany	The research and development activities of Forschungszentrum Karlsruhe are embedded in the superordinate program structure of the Hermann von Helmholtz Association of National Research Centers. One of the research areas is Energy. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research. • Fast pyrolysis and hydrogasification of biomass • Syngas to liquids • Hot gas cleaning	http://www.kit.edu/english/
Delft University	Delft, Netherlands	The Delft Energy Initiative provides easy access to more than 700 energy researchers at Technical University of Delft and brings together researchers, students, companies and governments to tackle the energy challenge. • Fuidised bed gasification of biomass • Hot gas cleaning • Networking with researchers in the field of gasification. • Identify pilot-scale research facility	http://tudelft.nl/en/

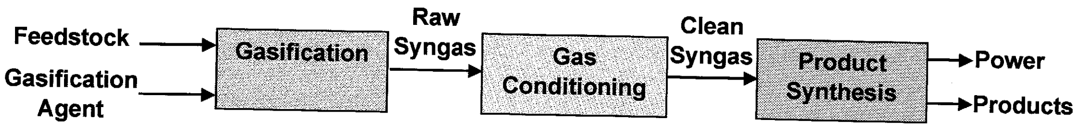
		requirements for brown coal gasification research.	
ECN	Netherlands	ECN plays a major international role in many fields. They develop, for example, solar energy, wind energy, biomass and energy efficiency. They evaluate energy and climate policies. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research. • Fluidised bed indirect gasification of biomass • Hot gas cleaning • Production of SNG	http://www.ecn.nl/home/
Energy and Environmental Research Centre	North Dakota, USA	EERC are the preeminent research facility focused on upgrading of the North Dakota Lignites, USA. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility for brown coal gasification research. • Entrained flow and fluidised bed gasification • Hot gas clean-up • Syngas conditioning • Syngas to liquid fuels	http://www.eerc.und.nodak.edu/
CANMET Energy	Ontario, Canada	CanmetENERGY is a global leader in clean energy research and technology development. With over 450 scientists, engineers and technicians and more than 100 years of experience, they are Canada's knowledge centre for scientific expertise on clean energy technologies. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility for brown coal gasification research.	http://canmetenergy.nrcan.gc.ca/home

		• Coal and biomass Gasification • Membrane reactors & hydrogen production	
CSIRO – Queensland Centre for Advanced Technology	Queensland, Australia	In partnership with industry and government CSIRO is developing new low emission coal technologies to dramatically reduce greenhouse gas emissions in combination with techniques to clean carbon from emissions and store it safely. • Networking with researchers in the field of gasification. • Identify pilot-scale research facility requirements for brown coal gasification research.	http://www.cat.csiro.au/
Monash University	Melbourne, Australia	Research within the Department of Chemical Engineering at Monash University is focused on many aspects of clean and sustainable energy production. A major aspect of this research work is on utilisation of Victorian Brown Coal. • Networking with researchers in the field of gasification.	http://www.monash.edu.au/campuses/clayton/
The University of Melbourne	Melbourne, Australia	Networking with researchers in the field of energy research and syngas conditioning.	http://www.unimelb.edu.au/
CO2CRC	Melbourne, Australia	Networking with researchers in the field of gas conditioning and CO_2 removal technologies.	http://www.co2crc.com.au/
		Commercial Facilities	
Facility	**Location**		
Coogee Energy Methanol Plant	Laverton, Victoria	The Coogee Methanol plant in Laverton Victoria is the only methanól production plant in Australia. • Site tour of methanol production facility	http://www.coogee.com.au/Our-Businesses/Chemicals-Manufacturing/Manufacturing-Facilities/Methanol-plant-in-North-Laverton,-Melbourne
Polk IGCC Power Station	Polk County, Florida, USA	The Polk Plant is one of the cleanest coal-based power generation facilities in the world. • Site tour of coal gasification-based power plant	www.tampaelectric.com

Training Course			
Course Name	**Location**		
Gasification Processes Compact Course	Technical Institute of Freiberg, Germany	The short course "Fundamentals of gasification processes" is designed to provide a general overview of gasification technologies and related issues.	http://www.gasification-freiberg.org/desktopdefault.aspx/tabid-17/12_read-161/

2 Introduction to Gasification Systems from Feedstock to Products

Gasification systems for production of value-added products represent large-scale complex systems with a number of processing steps. A basic schematic of a generic gasification system, highlighting key aspects of the process, is presented in Figure 1. The schematic highlights the three major areas of focus in the current project.



Gasification Inputs

Feedstock
- Coal
- Biomass
- Waste
- Other carbon source

Gasification Agent
- Oxygen
- Air
- Steam

Syngas Production

Feedstock Preparation
- Drying
- Particle size refinement
- Additives

Gasification Technology
- Fluidised Bed
- Moving Bed
- Entrained Flow

Gasification Mode
- Oxygen/air/steam blown
- Dry ash/slagging

Gas Conditioning

Gas Cooling

Gas Cleaning
- Particulates
- N-species
- S-species
- Alkalis
- CO_2
- Tars
- H_2O

Gas Properties
- CO/H_2 ratio
- Temperature
- Pressure

Products

Power
- IGCC

Advanced Power
- Fuel Cells
- IGFC

Chemicals and Fuels
- Transport Fuels
- DME
- Hydrogen
- Methanol
- Ammonia
- SNG
- Specialty Chemicals

Figure 1. Schematic of a Generic Gasification System, including the Key Processing Steps

A key point to note is that process system requirements for production of value-added products and advanced power systems are different to the process system requirements for current power production using IGCC systems or HRL IDGCC systems. Process systems for production of value-added products typically utilise oxygen blown gasification, rather than air blown gasification, in order to reduce the level of inert gases in the syngas, thus reducing the volume of gas to be processed in downstream processes. In addition, more rigorous gas conditioning is required to produce a syngas with suitable properties for the downstream catalytic synthesis of value-added products and advanced power production using fuel cell technology.

Reviews for existing process systems and for the key gasification system processes were completed to establish the state-of-the-art from laboratory through to commercial scale. This was done to facilitate identification of research areas requiring more detailed investigation during the project and to assist in determining the future R&D needs for "next generation" brown coal gasification systems. The major project objectives, outcomes and recommendations for the key system processes are presented in later sections of this report. In this section, a summary of the current status of gasification systems at large scale is presented. Both power generation and production of value-added products are considered.

2.1 Status of Commercial Gasification Systems

A range of local and global factors are impacting on the development of gasification systems for production of value-added products and power. Key factors include feedstock availability, process economics, environmental issues, markets for products, process alternatives and competition, investment security and government policy on issues such as coal utilisation, energy security, renewables, greenhouse emissions and financial support. As a result, global trends in the implementation of gasification systems vary by location. Trends in installed and planned syngas capacity on a global basis, by region, by feedstock and by product are illustrated in to . The major trends for different parameters are presented in .

Key findings of the literature review work include:

- The majority of installed syngas capacity globally is used for production of chemicals and transport fuels rather than power;
- Seventy per cent of planned syngas growth globally will be coal-based, highlighting that coal will be a major energy source into the future;
- Most facilities utilise higher rank coals, natural gas and petrochemical as feedstocks. For such feedstocks, high temperature gasification, including entrained flow gasification, is required to achieve acceptable conversion rates;
- There are limited reported examples of gasification systems operating on brown coals and lignites;
- Although there is significant interest in biomass gasification worldwide it is expected that the impact of biomass utilisation on world syngas capacity will be minimal, largely due to limited fuel supply; and
- There is significant interest in gasification globally but the majority of activity (construction, commissioning and operation) is in developing countries, in particular China, where energy demand is growing rapidly.

Table 3. Global Trends in Gasification Systems

Parameter	Trends
Global Capacity and Growth	• There are currently 144 plants with 412 gasifiers, producing a total syngas capacity output of $72GW_{th}$. • 11 plants are currently in the construction phase with an additional 37 in the planning stage to become operational from 2011 to 2016.
Feedstock	• The majority of new gasification plants (40 of 48) will utilise coal as the feedstock: o Based on plants in planning and construction phases, coal fed gasifiers will constitute 70% of capacity growth o Pet coke will account for almost all of the remaining capacity growth. o The impact of biomass utilisation on syngas capacity is expected to be minimal. • Higher rank coals are utilised in the majority of existing coal based gasification systems. There are limited reported examples of gasification systems operating on brown coals and lignites. • The feed material for the majority of the planned gasification facilities is simply defined as "coal", without further classification into classes such as brown or black coals. However, it is expected that the majority of facilities will use higher rank coals rather than brown coals or lignites.
Location	• The majority of syngas capacity (65%) currently under construction is in the Asia/Australia region, particularly China. • The majority of planned syngas capacity (63%) is in the US.
Product	• Currently, the majority of syngas capacity is used for chemicals production (45%) and transport fuels (38%). • 38% of planned capacity growth is for power production
Gasification Technology	• The majority of existing syngas capacity is based on entrained flow gasification. This is related to the major feedstocks in gasification systems being higher rank coals, natural gas and petrochemical based feedstocks. • Fluidised bed and fixed bed technologies have both been utilised for lignites. • Fluidised bed technology is the dominant technology for systems using biomass as feedstock

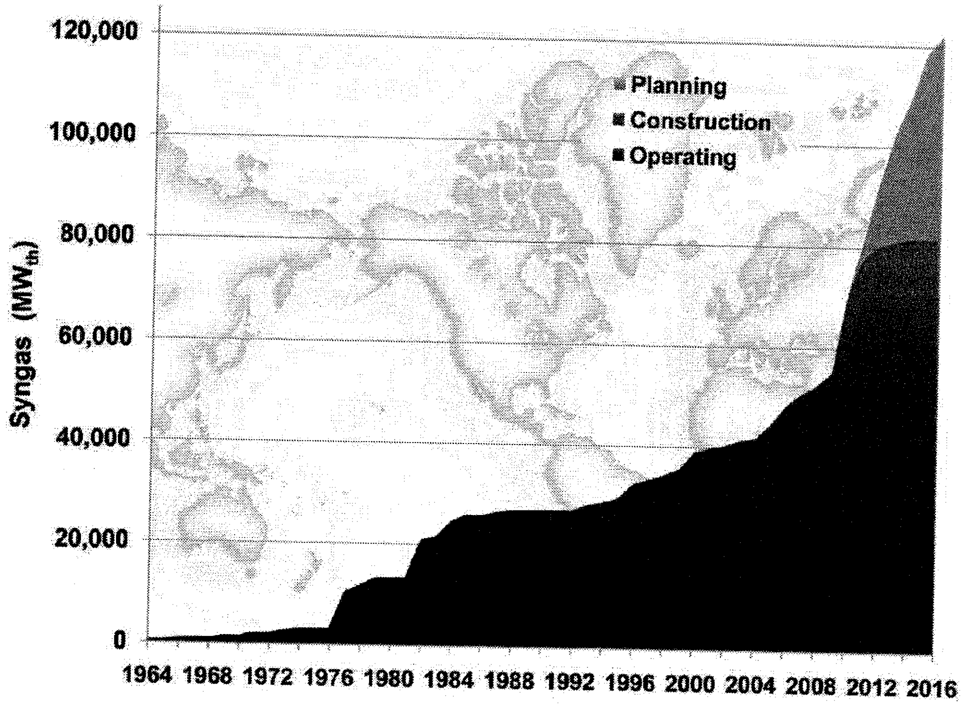


Figure 2. Global Gasification Capacity and Planned Growth [1]

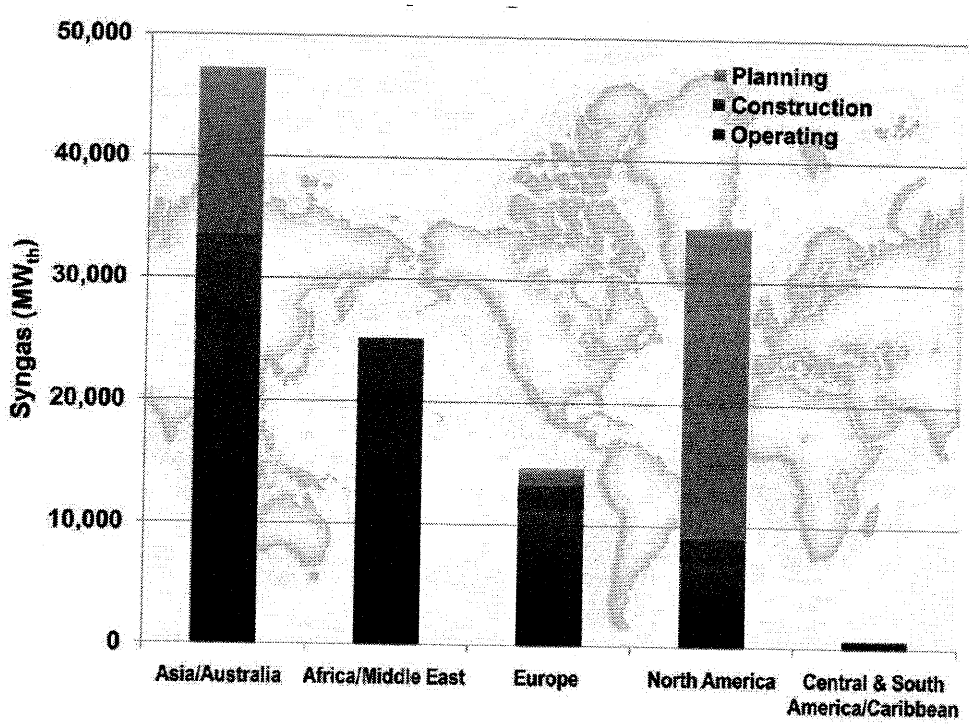


Figure 3. Global Gasification Capacity and Growth by Region [1]

[1] DOE (2010) Summary of world gasification database, http://www.netl.doe.gov/technologies/coalpower/gasification/worlddatabase/summary.html

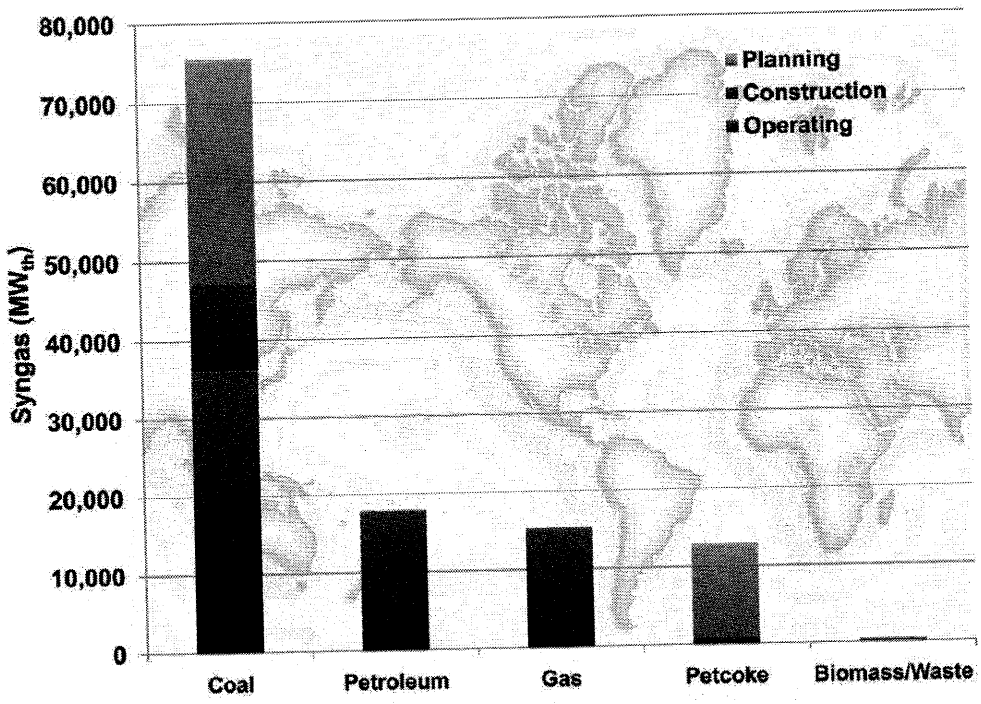


Figure 4. Global Gasification Capacity and Growth by Feedstock [1]

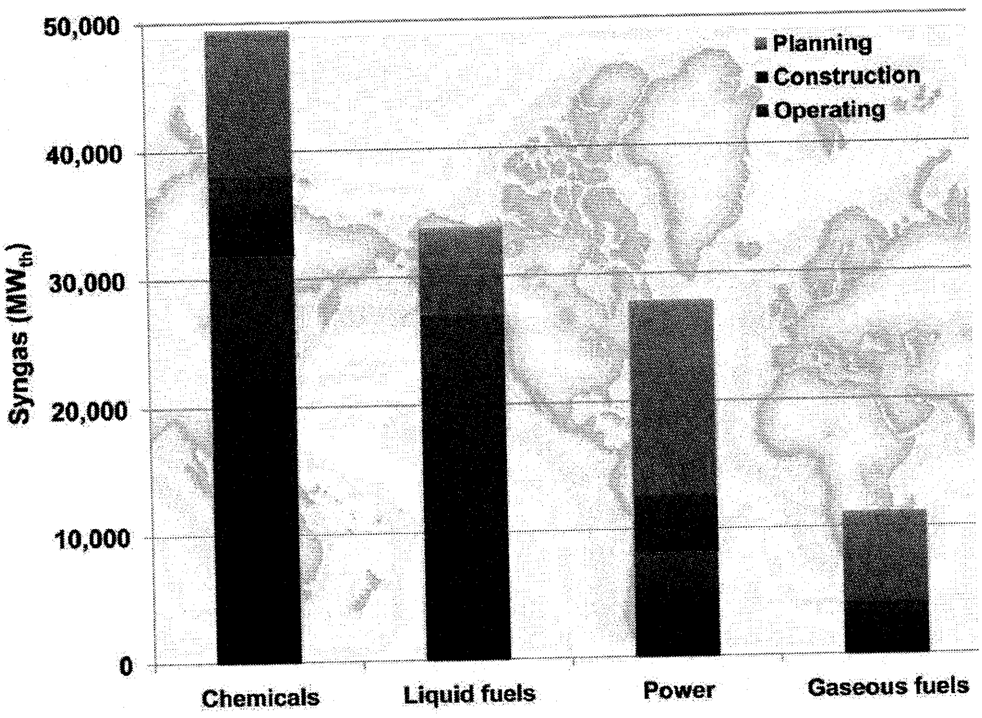


Figure 5. Global Gasification Capacity and Growth by Product [1]

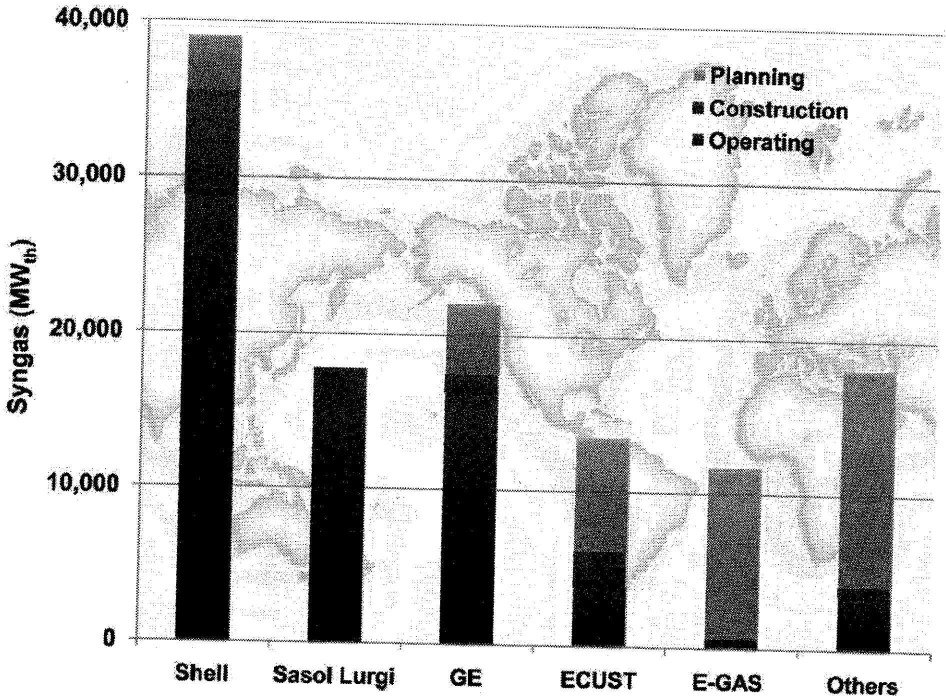


Figure 6. Global Gasification Capacity and Growth by Technology [1]

2.1.1 Status of Integration Gasification Combined Cycle (IGCC) for Power Generation

There are currently five large scale Integration Gasification Combined Cycle (IGCC) applications utilised for power generation. These IGCC plants are summarised in Table 4. Key points to note are:

- All plants utilise entrained flow gasification technology;
- All facilities utilise higher rank coals;
- The plants were constructed as demonstration plants, with government support; and
- Only one of the plants was constructed in the past decade, indicating that IGCC development for power generation has stagnated over the past decade;

Other IGCC projects currently under construction and commissioning, include:

- GreenGen (Tianjin, China); and
- Kemper County (Mississippi, USA). (lignite – scheduled for completion end 2014)

The major barriers to IGCC deployment are:

- Cost;
- Competition with other power generation technologies such as supercritical PCC, natural gas powered facilities and renewables;
- Public opposition to fossil fuel technology deployment, with concern for climate change; and
- Government support, policy and legislative uncertainty.

There is considerable research and development to improve gasifier reliability and efficiency, to reduce costs and to increase their range of suitable feedstocks. These efforts are in line with reducing the technical barriers to commercial IGCC deployment. R&D is focussed on:

- Gasification technology development, including improvements to existing technologies and development of novel technologies;
- Gas clean-up, with particular focus on elevated temperature and multi-component dry gas cleaning systems;
- Development of alternatives to cryogenic air separation units (ASUs) for oxygen production;
- Development of advanced, higher temperature syngas turbines; and
- Development of CO_2 capture and storage systems.

Table 4: Comparison of World Scale IGCC Facilities

Plant Name		Buggenum	Puertollano	Wabash River	Polk	Nakoso
Location		Buggenum, Netherlands	Puertollano, Spain	Indiana, USA	Florida, USA	Iwaki City, Japan
Start-up Year		1994	1998	1995	1996	2007
Gasification Technology		Entrained flow	Entrained flow	Entrained flow	Entrained flow	Entrained flow
Technology Provider		Shell	PRENFLO	CoP E-Gas	GE/Texaco	MHI
Oxidant		Oxygen	Oxygen	Oxygen	Oxygen	Enriched air
Feed		Bituminous coal	Subbituminous / petcoke	Subbituminous/ petcoke	Medium bituminous coal	Bituminous coal
Feed type		Dry	Dry	Slurry	Slurry	Dry
Capacity	MWe	253	300	262	250	250
Scale	t/day	2000	2600	2500	2200	1700
Operating Temperature	°C	1600	1600	1500	1500	1800
Operating Pressure	MPa	2.5	2.5	2.7	2.5	not reported
Efficiency HHV	%	41.4	41.5	39.7	37.5	40.5

3 Study Tours to Relevant Facilities and Existing Experience for Brown Coal Gasification Systems R&D

A significant amount of research related to gasification systems has been completed at various research facilities around the world. Important activities in the project work program were therefore study tours to relevant facilities and conferences in Australia, Asia, Europe, US and Canada. The major activities and sites visited are listed in Table 2. The key objectives of the study tours were to:

- Obtain information to assist in the review of state-of-the-art in gasification systems, with particular focus on review of current trends in gasification systems R&D;
- Determine requirements for a pilot-scale facility to investigate and demonstrate the viability of conversion of Victorian brown coal into value-added products and power via fuel cell systems;
- Determine future R&D needs for brown coal gasification systems; and
- Establish national and international networks and linkages.

3.1.1 Key Outcomes from Study Tours

Key outcomes from the study tours and the review of existing R&D experience included:

- There is a significant amount of research being completed globally on coal gasification systems for production of value-added products and for use in advanced power systems;
- Research focus is dependent on factors including feedstock availability, local market demand, and government policy and support;
- A wide range of end products, including power, advanced power using fuel cells, chemicals and transport fuels, are being investigated worldwide in different projects;
- All institutions visited which are undertaking gasification research at pilot-scale are also investigating gas conditioning at elevated temperature, suggesting that warm gas conditioning could be a key focus of future research;
- The undertaking of large scale gasification system demonstration projects requires significant funding, equipment and technical expertise. International projects typically have strong support from State and Federal Governments;
- R&D into gasification systems requires a combination of laboratory-scale, pilot-scale and desktop based research;
- Pilot-scale gasification research is essential to demonstrate prospective technologies, to identify areas requiring further research and to provide information to assist in development of the technology to larger scale;
- Selection of scale for a coal gasification and value-added product synthesis research facility is a balance between operational considerations, including cost, labour and maintenance requirements, and the ability to complete tests which are representative of a commercial facility;
- A large proportion of gasification R&D globally is related to higher rank black coals rather than low rank brown coals;
- The major focus of research into gasification of high moisture brown coals has centred mainly in Australia (by HRL) and in Germany where there are also significant reserves of brown coal; and

- Research and development into brown coal gasification has previously been directed towards power generation rather than production of value-added products. In order to encourage the development of commercial operations for conversion of Victoria's brown coal into value-added products via the syngas route, large–scale demonstration of such systems will be required.

4 State-of-the-Art Reviews for Major Gasification Process Operations

State-of-the art reviews for the major gasification process operations of syngas production, gas conditioning, CO_2 removal and product synthesis are presented in this section of the report.

4.1 Syngas Production

In the current work, the key aim was to review state-of-the-art in coal gasification fundamentals and systems with emphasis on the production of syngas from Victorian brown coal using fluidised bed gasification for downstream production of value-added products and power. The major development focus to this point has been electricity generation by feeding the syngas into a gas turbine combined-cycle power plant. An alternative application of the HRL IDG technology is for the production of syngas suitable for conversion into value-added products including transport fuels, chemicals and advanced power. One example of this is HRL's current work with a Japanese company, evaluating the prospect for hydrogen production via HRL IDG of Victorian brown coal.

Further R&D is desirable to expand on the existing knowledge base on brown coal conversion to syngas suitable for conversion into value-added products and next generation power systems. Areas covered in the review included:

- Review of state-of-the-art technology of coal gasification for power generation and for production of value-added products;
- Review of relevant physical and chemical fundamentals of brown coal for gasification processes;
- Identification of gaps in current knowledge; and
- Identification of future research needs for fluidised bed gasification of Victorian brown coal.

There is only limited publicly available information on gasification of Victorian brown coals, particularly relating to production of value-added products, and therefore it was necessary to consider gasification technologies utilising alternative feedstocks, including biomass and other low rank coals, in the review.

4.1.1 Gasification Technologies for Syngas Production

A range of gasification technologies are available commercially, each with unique characteristics. Major differences between technologies relate to type of oxidant (air, oxygen, and steam), feed properties (dry or slurry), gasifier geometry, mode of ash removal (dry ash or slag) and conditions for gasification (eg. pressure and temperature). Differences in gasifier parameters, combined with the inherent feedstock characteristics, determine the raw syngas composition from the gasifier.

The primary classification of gasification technologies is typically flow geometry, with technologies classified as moving bed (or fixed bed), fluidised bed or entrained flow gasifiers. Schematics of operation for these generic technologies are presented in Figure 7 and their important characteristics are summarised in Table 5. A brief description of the three main gasification types is presented in the following sections.

4.1.1.1 Moving Bed Gasification

The moving bed process is characterised by a bed in which large coal particles move slowly downwards under gravity and are gasified by an upward flow of oxidant gases. The counter-current flow results in low oxygen utilisation and product gas temperatures, and high carbon conversion. Ash is removed either as a dry ash or as a slag. The low syngas exit temperatures (350–600°C) are insufficient to break down tars, phenols and other aromatic compounds in the syngas which must subsequently be removed from the syngas. Moving bed gasifiers are suitable for solid fuels, including coal, biomass and waste. The main requirement is lump feedstock with good mechanical strength to ensure good bed permeability and maintain gas flow. The technology is thus not ideally suited to run of mine Victorian brown coal which is relatively fine and friable. Prior to the availability of natural gas in Victoria, Lurgi gasifiers were used to produce "town gas" from Latrobe Valley briquettes from 1956 to 1969.

4.1.1.2 Fluidised Bed Gasification

In a fluidised bed gasifier, an upward flowing gas (steam and air / oxygen) fluidises the bed of solid milled fuel particles. Good contact between the particles and gas is achieved, promoting heat and mass transfer and ensuring an even distribution of temperature and materials in the bed. Solids residence times are relatively short (minutes). Fluid bed gasifiers can be air blown or oxygen blown and typically operate at temperatures below the ash softening point (900 – 1050°C), since ash melting and hence clinker formation disturbs the fluidisation of the bed. Fluidised bed gasification is best suited to highly reactive coals, as the low temperature operation of fluidised bed gasifiers can limit the carbon conversion achieved in the process. Char particles entrained in the gas stream are recovered and recycled to the bed via a cyclone in order to increase carbon conversion within the gasifier. Carbon conversion is completed by burning the char to raise steam required by the process. Fluidised beds generally operate on solid milled fuels (1-6mm). Low rank feedstocks, such as lignites and brown coals, are thus considered most suitable for fluidised bed gasifiers. The majority of biomass gasifiers are also based on fluidised bed technology.

4.1.1.3 Entrained Flow Gasification

In entrained flow gasifiers, pulverised coal particles (generally <0.1 mm) react with steam and air or oxygen. The coal is fed into the gasifier in a dry form or as a coal/water slurry. The solids and gas residence time is short (seconds), giving entrained flow gasifiers a high load capacity. Gasification occurs at between 1200°C and 1600°C and pressures in the range 2-8 MPa. Hot syngas exiting the gasifier is cooled either in a high temperature syngas cooler or by quenching with water or recycled syngas. The proportion of energy that can be recovered from the syngas is dependent on the cooling method. The operating temperature is above the coal ash fusion temperature to melt the ash in the coal, producing a slag which runs down the wall of the gasifier. Reactor temperature is therefore dictated by the ash fusion temperature and viscosity. Fluxes such as limestone can be added to lower the ash melting point and reduce the required operating temperature of the reactor. The high temperature results in destruction of the tars and oils and also high carbon conversion. Relatively high oxidant requirements are required to achieve the high operating temperatures. Entrained flow technology can be used to gasify all coal types, though moderate ash and low moisture content is preferred for economic reasons. Low rank coals are not suited to slurry fed entrained flow reactors due to the high inherent moisture content, which results in low solids concentration slurries.

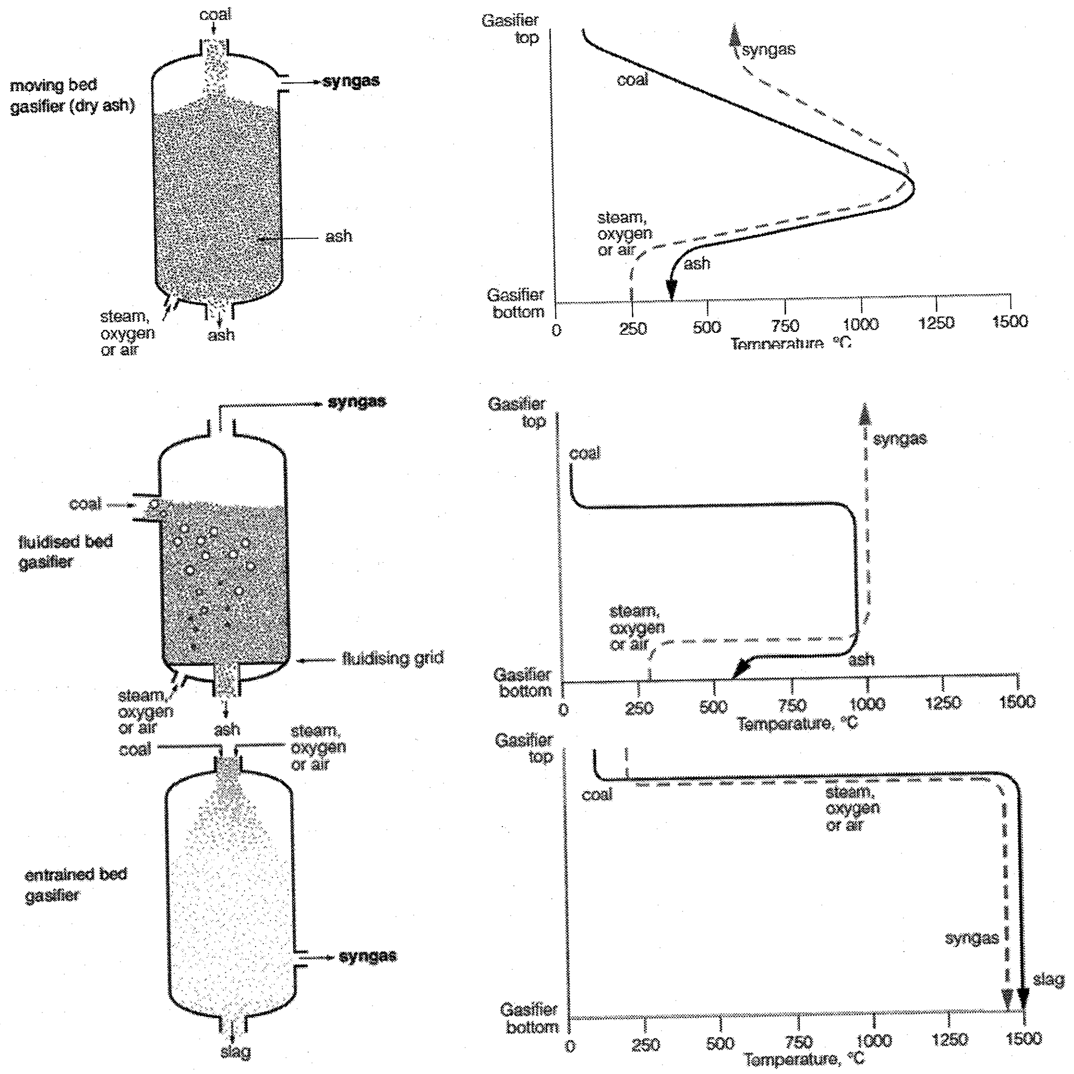


Figure 7: Generic Gasifier Technologies [2]

[2] Carpenter (2008) Polygeneration from Coal, IEA CCC Report CCC/139

Table 5: Gasifier Characteristics

Gasifier Type	Units	Moving Bed		Fluidised Bed		Entrained Flow
Feed Fuel Characteristics						
Ash Conditions		Dry	Slagging	Dry	Agglomerating	Slagging
Typical Technologies		Lurgi	BGL	HTW, KBR, HRL IDGCC	KRW, U-Gas	Shell, GEE, E-Gas, Siemens, MHI, OMB
Fuel Particle Size Limits	mm	5-80	5-80	<10	10	<0.1
Ash Content Limit	%	N/A	<25	N/A	N/A	<25
Preferred Ash Melting Temperature	°C	>1200	<1300	>1100	>1100	<1300
Operating Characteristics						
Exit Gas Temperature	°C	425-650	425-650	900-1100	900-1100	1250- 1600
Gasification Pressure	MPa	0.1 - 3	0.1 - 3	0.1- 3	0.1 - 3	2-8
Max. Bed Temperature	°C	1300	1500-1800	900-1050	900-1050	1200-1600
Oxidant Requirement		low	low	moderate	moderate	high
Steam Requirement		high	low	moderate	moderate	low
Typical Residence Time		15-60 mins	15-60 mins	10-100s	10-100s	1-4s
Unit Capacity	MW_{th}	10-350	10-350	100-700	20-150	up to 700

4.1.2 Fundamentals of Syngas Production

An extensive review of the open literature encompassing the physical and chemical fundamentals of brown coal gasification, with a focus on production of advanced products and power, was completed. The review covered areas including overview of Victorian brown coal, properties of Victorian brown coal in relation to gasification and syngas properties as a function of gasification parameters. The objectives were to:

- Establish the current status of understanding of the physics and chemistry of brown coal gasification;
- Determine gaps in the current knowledge; and
- Identify future research needs.

In this overview report, the key outcomes, knowledge gaps and future research needs are provided below.

HRL has conducted extensive R&D on the gasification of Victorian brown coal, although only limited data has been published as this Intellectual Property underpins the commercialisation of the HRL IDG process.

The major focus of research and development into the applications of brown coal gasification has related to air-blown gasification for power generation. Limited research has been completed with respect to the application of Victorian brown coal gasification for production of value-added products. The major differences relate to the preference for oxygen blown gasification in order to minimise syngas dilution, and the need for specific syngas compositions for downstream production of value-added products.

There is more information published for gasification of international brown coals. It was found that most of the general trends were universally similar, regardless of the feed coal utilised. The direct application of this knowledge to the gasification of Victorian brown coals, however, is not possible due to the specific properties of the fuels tested in the various studies, the wide range of operating conditions and the diverse goals and objectives of the studies. Many of the literature sources available present only a limited specific data set for publication. In addition, the emphasis of the available literature for Victorian brown coals is centred on power generation applications, with no specific research results published on the use of brown coal derived syngas for utilisation in chemical or petrochemical product applications.

There are similarities between the properties of Victorian brown coal and biomass materials. For instance, both materials can have high moisture content, low ash yield, low ash melting point, high gasification reactivity and aggressive molten slags. These similarities in turn lead to similarities in the gasification behaviour of brown coal and biomass materials. A brief review of biomass gasification was thus completed as part of the current project. Key outcomes from the review of biomass gasification, which are relevant to brown coal gasification include:

- There is considerable R&D in other countries into biomass gasification. A number of facilities have been constructed, predominantly for power production;
- The typical scale for a biomass gasification plant is small relative to the scale of coal gasification plants. A major reason for the smaller scale relates to limitations on local availability of biomass feedstocks and the high cost of transportation of biomass feedstocks;
- Most biomass gasification technologies are based on fluidised bed technologies, with major focus on bubbling fluidised beds and circulating fluidised beds. However, there has been considerable recent interest in entrained flow technology for biomass gasification. A number of novel gasification technologies have been developed for biomass materials;

- The key reasons for selecting fluidised bed technology are the fibrous nature of biomass, high reactivity and corrosive ash at high temperature.

4.1.3 Gasifier Selection in Brown Coal Systems

Selection of the most suitable gasification technology for a given application is a complex task which must consider a range of factors including feedstock parameters such as availability, cost and type, requirements for syngas properties, and operational characteristics such as gasifier reliability, availability and performance. Selection of the most suitable technology for a given application will be dependent on the weighting for different criteria.

Victorian brown coals have specific properties which impact on gasification technology selection. Important properties include high moisture content, high reactivity, low mechanical strength and low ash yield.

Factors which support development of HRL IDG technology for Victorian brown coal include:

- Fluidised bed technology has been demonstrated for reactive brown coals in both chemicals production and power systems;
- Integrated drying eliminates the need for expensive and potentially problematic standalone dryers;
- Integrated drying also humidifies the syngas, eliminating the requirement for the addition of steam to the syngas (and associated equipment) prior to Water Gas Shift;
- Low temperature operation;
- Simple low cost fuel preparation as a pulverised feed is not required; and
- High flexibility for different feedstocks.

The proposed next stage of this current project is the completion of technical and economic concept studies for HRL IDG systems utilising Victorian brown coal in order to allow more detailed evaluation of prospective gasification systems and products.

4.1.4 Syngas Production in Brown Coal Gasification Systems at Large-Scale

The major focus of the current project is fluidised bed gasification technology, which is utilised in the HRL IDG process. Fluidised bed gasification has been demonstrated in a number of demonstration plants up to 140MW_{th} scale. Details of plants which have utilised fluidised bed technology at large scale are presented in Table 6.

The most relevant example of a fluidised bed gasification system for chemicals production from brown coal is the Rheinbraun fluidised bed demonstration plant which was located at Berrenrath near Cologne, Germany. The plant was constructed in order to demonstrate the industrial-scale maturity of the process for methanol and electricity production. Operation of the Berrenrath demonstration plant over an extended period of 12 years demonstrated that the commercial scale conversion of brown coal, using fluidised bed gasification, into a value-added product (methanol) is technically feasible.

Another large scale fluidised bed plant was operated in Finland from 1989-1990 to demonstrate the production of ammonia from peat and wood. The 120MW_{th} scale plant was operated at elevated pressure using steam and oxygen as the gasification agents. Despite a number of operating issues, a key outcome of the work was that production of synthesis gas and ammonia from peat on a commercial scale is technically feasible.

A further example of large scale implementation of fluidised bed technology was the 140 t coal/d pressurised gasification plant which was operated in Wesseling (Germany) from 1989 to 1992. The key focus was to investigate the future application for power generation in an IGCC process.

The U-Gas technology is an alternative fluidised bed gasification technology which has been demonstrated at large scale for methanol production. A plant has been operated with high availability in China since 2008. There are plans to construct additional U-Gas gasification systems in China for conversion of coal into liquids, suggesting that fluidised bed gasification technology is commercially and technically competitive at large scale.

HRL's IDGCC process has been particularly developed to suit the high moisture content of Victorian brown coal and was demonstrated at $10MW_e$-scale in the mid 1990s for production of electricity. Operation of the demonstration plant indicated that HRL's IDGCC technology, including fluidised bed gasification, is technically feasible. There are plans to demonstrate the technology at commercial scale in the near future.

Fluidised bed technology has also been demonstrated at commercial scale utilising biomass as feedstock. The major interest has been in Europe with the focus on power generation through IGCC or cofiring of biomass in existing boilers. Circulating fluidised bed technology has been the gasification technology implemented in the majority of commercial applications for biomass. The scale of the biomass gasification plants has been relatively small, in the range of 5 to $100MW_{th}$.

Operation of fluidised bed gasification facilities at large scale has demonstrated the technical feasibility of:

- Fluidised bed gasification of brown coal (including Victorian brown coal) and other feedstocks;
- Gasification under both oxygen-blown and air-blown conditions; and
- Gasifier operation at elevated pressures (25 bar) which increases the specific gasifier throughput and is desirable for production of value-added products;

The previous focus of applications for gasification of Victorian brown coal has been directed towards power generation. More recent work has been directed towards the prospects for value-added products. Large-scale oxygen-blown gasification of Victorian brown coal for production of value-added products is desirable to demonstrate the prospects for commercial operations.

Table 6. Large Scale Examples of Fluidised Bed Gasification Systems.

Location	Berrenrath, Germany	Wesseling, Germany	Oulu, Finland	Shandong, China	Morwell, Australia
Operating time	1986-1997	1989-1992	1989-1990	2008-	1996-1997
Capacity (tpd)	600	168	1000	400	240
Thermal capacity (MW)	140	36	120	Not reported	10 MWe
Pressure (bar)	10	25	10	0.3-30	25
Temperature (°C)	900	-	750-950	900-1050	~900°C
Gasification agent	O2, steam	O2, steam, air	O2, steam	O2	Air, steam
Feedstock	Dry brown coal and blends	Brown and bituminous coals	Peat	Bituminous coal, lignite	Victorian brown coal
Product	Methanol	Power - IGCC	Ammonia	Methanol (sold over fence)	Power

4.1.5 Key Outcomes from Review of Syngas Production

Key outcomes of the literature review into syngas production include:

- Selection of the most suitable gasification technology for implementation in a gasification system application is a complex task. Often a range of factors including feedstock parameters such as availability, cost and type, and operational characteristics such as gasifier reliability, availability and performance, and requirements for syngas properties must be considered. Such factors vary by location and application and thus a range of gasification systems and technologies for syngas production have been developed for specific purposes;
- Key factors which support development of fluidised bed gasification for Victorian brown coal include:
    - Fluidised bed gasification is suited to gasification of highly reactive feedstocks including brown coals and biomass materials;
    - Fluidised bed technology has been proven at demonstration scale for reactive German brown coals in both chemicals production and power systems; and
    - Low temperature operation offers potential process benefits;
- Additional benefits of HRL's IDG technology include:
    - Avoidance of standalone dryers, with the additional benefit of syngas cooling; and
    - Syngas humidification without additional steam raising equipment;
- Research into brown coal gasification has mainly centred in Australia and Germany where there are large brown coal resources. The major focus of brown coal gasification R&D, including research into the HRL IDG process, has related to air blown gasification for power generation using gas turbine combined cycle systems;
- In large scale gasification systems for production of value-added products, oxygen blown gasification is preferred as it offers potential process and cost benefits;
- In Germany, oxygen-blown, fluidised bed gasification utilising brown coal has been investigated at demonstration scale in a gasification system for production of methanol;
- For Victorian brown coal, limited research has been published on oxygen-blown gasification for syngas production.

4.1.6 Recommendations for Future R&D in Syngas Production

Significant R&D has been undertaken into the gasification characteristics of Victorian brown coal, with demonstration of HRL IDG using air-blown gasification at $10MW_e$-scale.

The key recommendation for future R&D in syngas production is for the large-scale demonstration of HRL IDG of Victorian brown coal using oxygen-blown gasification. This should assist development of value-added product manufacture via syngas.

4.2 Gas Conditioning

Raw synthesis gas exiting a gasifier must be conditioned prior to use in downstream chemicals production processes. A review of syngas conditioning technologies and experience for brown coal derived syngas was undertaken to:

- Establish the state-of-the-art gas conditioning technologies which are most prevalent in industry;
- Determine the gas conditioning requirements for production of value-added products from brown coal syngas;
- Determine the status of prospective technologies which could be implemented in next generation gasification systems; and
- Establish requirements for future R&D in gas conditioning for brown coal syngas.

The extent of cleaning and conditioning required is dependent on the raw syngas properties and downstream product synthesis requirements. The syngas conditioning processes which may be required for a given gasification system and which were reviewed in this study include:

- Syngas cooling;
- Particulate removal;
- Halide species removal;
- Alkali species removal;
- Mercury removal;
- Removal of sulphur compounds;
- Removal of nitrogen compounds;
- Adjustment of syngas H_2:CO ratio through the water gas shift reaction;
- H_2, CO and CO_2 separation;
- Syngas reheating; and
- Syngas pressurisation.

4.2.1 Key Outcomes from Review of Syngas Conditioning

Selection of the necessary and most suitable gas conditioning steps for a given application must consider operational factors including feedstock properties, gasifier operating conditions, process integration and gas quality requirements. Commercial status of technologies, environmental emissions regulations and economics are further considerations. Specification of a gas conditioning train will be unique for a given application.

The syngas purity and composition requirements are particularly stringent for downstream utilisation in catalytic processes used in the synthesis of advanced products.

There is relatively limited information available in the open literature for the gas conditioning process steps for large scale and commercial scale gasification systems for production of advanced products. The largest number of coal to value-added plants using gasification technologies are located in China. However, there is limited technical information available on these plants. Three major coal to value-added products facilities outside China are the Sasol facility in South Africa, and the Eastman Chemicals and Great Plains facilities in the US. Extended operation of these plants, in addition to previous operation of the Berrenrath facility in Germany, for coal to value-added products has demonstrated the technical feasibility of gas cleaning and conditioning of coal-derived syngas, and demonstrated the synthesis of various value-added products from coal-derived syngas.

Some general trends in gas conditioning for gasification systems include:

- Gas conditioning below 250°C is currently the state-of-the-art in gas conditioning;

- Chemical solvent absorption systems operating at 35 to 50°C have been implemented in the majority of coal based IGCC systems for power generation;
- The Rectisol process for removal of sulphur, CO_2 and other contaminants has been implemented in the majority of large-scale applications for chemical and fuels production. The key advantages of Rectisol are that it is a multi-contaminant removal process, low contaminant levels can be achieved and it is widely proven at commercial scale. However, Rectisol is expensive and operates at very low temperature (-30 to -60°C) and thus there is significant interest in other acid gas removal technologies;
- Selexol, in conjunction with a guard bed for sulphur, has been selected for acid gas removal in a number of recent conceptual studies into gasification systems, suggesting that Selexol could be a viable option for future gasification systems. Selexol operates at higher temperature (0 to 40°C) than Rectisol, reducing energy consumption and increasing plant efficiency; and
- Sulphur recovery is often considered to produce valuable products including elemental sulphur and sulphuric acid.

There is currently limited published information with regard to gas conditioning in gasification systems for production of value-added products from syngas derived from Victorian brown coal. It is expected that the gas conditioning unit operations for gasification systems utilising Victorian brown coal will be similar to the gas conditioning unit operations which have been demonstrated at commercial scale for other coals and/or for other gasification technologies. However, the specific properties of syngas produced through fluidised bed gasification of Victorian brown coal may impact on the gas conditioning requirements.

4.2.2 R&D Directions for Syngas Conditioning

There is significant interest in the development of advanced gas conditioning processes, with the major focus on increasing the operating temperature of gas cleaning processes and the development of technologies which combine gas conditioning steps. The factors which are driving research and development of advanced gas conditioning technologies in the coal gasification area include:

- Potential for improved efficiency through implementation of higher temperature gas conditioning. The target operating temperature range for such technologies is between 250 and 500°C;
- Potential for simplified plant design and operation, and improved process economics through the development of unit operations that can remove multiple contaminants at elevated temperatures; and
- Potential to reduce the requirements for downstream gas conditioning processes and to maximise the yield achievable from downstream catalytic synthesis processes by adjusting the raw syngas composition from the gasifier.

Specific technologies and areas which are being investigated by various research institutes include:

- Development of catalytic reforming of a range of syngas compounds, including CH_4, tars and ammonia, prior to cooling of the raw syngas exiting the gasifier in order to adjust the syngas composition and reduce conditioning requirements for downstream processes;
- Development of water-gas shift (WGS) membrane reactors which improve the efficiency of the water gas shift reaction by removing the H_2 as it is produced. This can lead to reduced capital cost, or alternatively greater reactant conversion; and

- Scale-up and commercialisation of the Research Triangle Institute (RTI) warm syngas clean-up technology which is a warm, multi-contaminant syngas cleaning system for operation above 200°C and 40bar that will clean the syngas to the levels suitable for both power production and chemicals/fuels applications.

Some of the results of this work may have implications for brown coal derived syngas conditioning in the future.

A key barrier to commercial acceptance of warm gas technologies is the need for development of warm gas conditioning technologies for all gas conditioning steps. A large amount of research has been completed on warm gas sulphur removal but research into other warm gas conditioning steps is less advanced. RTI is planning to demonstrate a process for removal of multiple contaminants, including CO_2, sulphur, trace elements and ammonia, in an integrated system. The RTI project will be an important step in demonstrating warm gas removal of trace contaminants from raw synthesis gases.

Warm gas technologies which are currently in the development phase need to be further demonstrated at larger scale before they would be considered for implementation in a commercial system. Warm gas conditioning for use in gasification systems for production of advanced products is thus not an option in the immediate future but could be considered for next generation gasification systems once they have become proven technologies.

4.2.3 Recommendations for Future R&D in Gas Conditioning

Limited work has been published for oxygen-blown fluidised bed gasification of Victorian brown coal and consequently the specific requirements for gas conditioning need to be established and the viability of gas conditioning steps need to be investigated and demonstrated for brown-coal derived syngas at laboratory and larger scale. Areas for future research include:

- Demonstration of gas conditioning processes for brown-coal derived syngas at large scale;
- Development of process models to assist in investigation of process integration and completion of more detailed techno-economic studies; and
- Evaluation of next generation gas conditioning technologies for brown-coal derived syngas.

4.3 CO_2 Removal

The removal of CO_2 is a key consideration in the development of a "next generation" gasification system and thus a specific review for state-of-the-art CO_2 removal was included within the scope of the current project. The review, completed by the CO2CRC, was focussed both on existing technologies and emerging technologies that could provide significant cost reduction or efficiency improvement over current technology. Key activities included:

- Review of the state-of-the-art and emerging technologies for CO_2 removal from syngas;
- Evaluation of technologies for CO_2 removal in prospective gasification systems;
- Review of heat integration options for prospective processes;
- Identification of the most prospective technologies for CO_2 removal from syngas;
- Identification of gaps in current knowledge and barriers to commercialisation for prospective technologies; and
- Identification of future research needs for CO_2 removal from brown coal syngas.

The CO_2 removal technologies covered in the review included:

- Solvent absorption (physical and chemical);
- Membrane separation (CO_2 and H_2 selective membranes);
- Gas adsorption (physical and chemical); and
- Gas hydrates and cryogenics.

4.3.1 Status of Development of CO_2 Removal Technologies

- Based on literature reports, solvent absorption, membrane separation and gas adsorption are all able to remove CO_2 from the brown coal derived syngas to low levels and produce a high purity CO_2 product for sequestration. However, solvent absorption processes (predominantly physical) are the only processes in current commercial operation for CO_2 removal from coal derived syngas;
- Membranes have high H_2 selectivity at high operating temperatures and therefore show promise for CO_2 removal with minimal utility usage. In general, membranes for CO_2 removal are still in the development stage;
- There is significant research activity surrounding Palladium (Pd) based water gas shift membrane reactors (WGSMR) which combines the water gas shift and CO_2 removal in one stage. Potential benefits are improved conversion in the water gas shift reaction, improved process integration and equipment reduction. Barriers to the commercialisation of Pd membranes are the degradation by sulphur compounds and the high cost of materials;
- Gas adsorption technologies utilizing high temperature adsorbent, such as double salts and metal oxides, offer the promise of minimal utility requirements because of their high temperature operation. In addition, unlike the high temperature membranes, the syngas remains at high pressure resulting in a direct feed to the downstream processes. There is also the potential to combine the water gas shift and CO_2 removal steps in an enhanced water gas shift (SEWGS) reactor in order to decrease equipment requirements and thus reduce cost;
- The prospective technologies are still in the development phase and thus not commercially available;
- Based on the current rate of development it is expected that a next generation brown coal gasification system built in the next 10 to 15 years might employ a combined water gas shift CO_2 removal technology either using membranes or adsorbents. If realised, such a system could offer significant potential for reductions in cost and utility requirements.

4.3.2 R&D Directions for CO_2 Removal

There is significant interest and development of a range of alternative technologies for CO_2 removal. Future technologies for removing CO_2 from syngas that could offer significant advantages due to the reduction in the amount of equipment and utilities required are those which operate at high temperatures, remove sulphur compounds and are tolerant to water.

The CO_2 removal technologies that demonstrate promise as future technologies based on these criteria include:

- Potassium carbonate solvent processes;
- Carbon and thermally rearranged membrane separation processes; and
- Various gas adsorbent process employing materials including zeolites, double salts, metal oxides, metal organic frameworks and amine functionalised adsorbents.

Palladium (Pd) membranes also offer potential as a future CO_2 removal technology but are very sensitive to degradation caused by H_2S and produce a low pressure H_2 product which requires recompression for further use.

4.3.3 Recommendations for Future R&D in CO_2 Removal

It is recommended that future research into CO_2 removal should focus on the technology areas of solvent absorption, membrane separation and gas adsorption. The activities which are required for development of CO_2 technologies are in line with the activities required for development of gas conditioning processes, as listed in Section 4.2.3.

A key activity will be pilot scale testing of the CO_2 removal technologies using syngas at high temperature and pressure derived from brown coal gasification. This requires access to syngas from a pilot-scale gasifier. Further laboratory work and development of impurity resistant materials for membrane separation and gas adsorption should be completed in parallel with the pilot scale tests. In the area of heat integration and process development, desktop simulation studies based on the results of pilot plant trails would need to be completed to determine optimum configurations for larger scale processes.

4.4 Product Synthesis

Syngas derived from brown coal can potentially be used for production of a range of value-added products, including chemicals, fuels and power. The key objective of the current project was to identify low emissions advanced systems for more detailed investigation in future stages of the project. In the current phase of the project, the major activities included:

- Review of the state-of-the-art in syngas utilisation technologies and products;
- Review of the markets for prospective products;
- Identification of prospective processes and products which should be considered in further detail in future stages of the project;
- Determination of gaps in current knowledge and practice; and
- Determination of future research needs for production of value-added products from brown coal derived syngas.

Next generation gasification facilities utilising coal as feed stock could possibly be cogeneration or polygeneration plants, producing a combination of power and chemicals/fuels. Power will be required to meet on-site demands and could be exported to the grid. To facilitate discussion and comparison of the findings of the literature review, the two product areas of chemicals/fuels and power generation are presented separately.

4.4.1 Advanced Power Systems using Fuel Cells

Electricity will be required to meet on-site demands and could additionally be exported to the grid, either as the primary product from a facility or as a cogeneration product. Technology options for power generation include existing technologies and next generation advanced power systems, for example using fuel cells. Selection of the technology option(s) for power production will be influenced by a number of factors such as the energy source to be utilised for power generation, scale of production, status of technology development and economics.

Technology options for power generation include heat recovery steam generator (HRSG) systems to utilise waste heat, established combined cycle heat engine systems utilising syngas or advanced power fuel cell systems utilising syngas. The current project is directed towards next generation gasification systems and therefore advanced power systems using fuel cells have been a major focus of the review.

The key outcomes of the review of fuel cells for large scale power generation include:

- Electricity generation in advanced power systems using fuel cells represents a future utilisation option for brown coal derived syngas. The major drivers for development of fuel cell technology are the potential for:
  - Increased efficiency due to the direct conversion of the energy in a fuel into electricity, without the need for an intermediate step (for example raising steam to drive a turbine); and
  - Low emissions power, for example through the concept of a hydrogen economy.
- Considerable research into fuel cells for power generation has been undertaken over the last decade as a result of Government incentives, particularly in the USA, Europe and Asia;
- Fuel cell development is focused on a range of applications, including mobile applications (eg. vehicles) and stationary power generation. A significant number of small (up to about 3 to 5 MW size) stationary fuel cell systems have been developed and are available commercially;
- The major focus of research for large scale stationary power is high-temperature fuel cells (solid oxide fuel cells and molten carbonate fuel cells), which can directly utilise a range of fuels, including hydrogen, methane, carbon monoxide and syngas. The high temperature exhaust from the fuel cell can be used for additional power generation in an integrated gasification fuel cell (IGFC) / heat engine system, therefore increasing the overall system efficiency;
- Market entry fuel cell products in the large scale stationary generation market will most likely be fuelled by reformed natural gas. Fuel cells fuelled by coal derived gas are likely to be second generation fuel cell systems due to additional technical challenges around gasification, gas conditioning requirements and process integration, as outlined in previous sections of this report;
- The HRL IDG process using Victorian brown coal presents potential advantages for an IGFC system due to low temperature operation and the specific syngas composition;
- Currently there are a number of factors, including cost, durability, efficiency, scale, sensitivity to contaminants and the need to demonstrate the technology at large scale for coal-derived gas, which limit the performance, operation and potential implementation of fuel cells for large scale power generation. Therefore, the technology can be considered as a next generation technology. Development of fuel cell technology for IGFC systems to a commercially viable status is directed towards alleviating current limitations;
- A range of research activities would be required to determine the viability of fuel cells for large scale power production from brown coal syngas, either stand alone or as part of a complex producing "Products and Power". Fuel cells will be developed by large multinational companies, but their application and integration into brown coal gasification systems would need to be investigated in future phases of this project.

4.4.1.1 Research Directions for Fuel Cells and IGFC Systems

Major factors limiting the commercial development of fuel cells are cost, durability, sensitivity to contaminants and the need to demonstrate the technology at large scale for coal-derived gas. Key areas of development of fuel cell technology and IGFC systems are directed towards alleviating these limitations and include:

- Cost reduction to make IGFC competitive with other coal fuelled systems;
- Improvement of fuel cell cost, durability, reliability and efficiency;
- Scale-up of small scale fuel cell stacks to large scale power generation systems;
- Operation of high temperature fuel cells directly on coal gas; and
- Continued development of high temperature gas conditioning.

SOFCs offer advantages of high temperature operation (700 to 1000°C), high efficiency and utilisation of a solid electrolyte and thus the majority of R&D for large scale power systems is being directed towards development of SOFC technology. In particular, the US Department of Energy, through the SECA program, has made significant advances in research and development of Solid Oxide Fuel Cells (SOFC) for potential large scale stationary power production.

4.4.1.2 Recommended R&D for Fuel Cells Utilising Brown Coal Syngas

A range of research activities would be required to determine whether fuel cells are a viable future option for large scale centralised power production from brown coal, either stand alone or as part of a complex producing "Products and Power". Fuel cells will be developed by large multinational companies, but their application to brown coal syngas (raw or conditioned) and how they might be integrated into a HRL IDG system would need to be investigated in future phases of this project. Recommended activities include:

- Develop a process model for a SOFC to determine likely performance when utilising HRL IDG brown coal syngas and identify:
    - Fuel cell performance as a function of operating conditions; and
    - Further syngas processing requirements to improve fuel cell performance;
- Develop alternative system models, including costs, for production of:
    - Power using HRL IDG - hybrid fuel cell / heat engine systems;
    - Combined power and products using HRL IDG – hybrid fuel cell systems
- Select most appropriate system(s) for utilisation of brown coal via HRL IDG/FC based on cost, markets, technology risk, etc.;
- Undertake bench and pilot scale tests to demonstrate feasibility of use of HRL IDG syngas with fuel cells and address high risk technical issues or novel processing steps; and
- Undertake preliminary process design and costing for a large scale plant.

4.4.2 Chemicals and Fuels

Coal gasification is a process in which coal is partially oxidised to produce a syngas comprised mainly of carbon monoxide and hydrogen. Syngas can therefore be considered a source of CO and/or H_2. CO and H_2 are the building blocks for a large number of chemicals widely used in industry. A list of some of the chemicals commonly produced from CO and/or H_2 is shown in Figure 8 and highlights that a range of primary, secondary and tertiary chemicals and fuels can potentially be produced from brown coal derived syngas.

The focus of the current work is products that could potentially be produced on a reasonably large scale, in line with the scale of HRL IDG systems. There are many other products that could be produced from syngas or from primary products but most would be at a relatively small scale. The major products covered in the review were:

- Ammonia and ammonia derivatives;
- Synthetic natural gas (SNG) and liquefied natural gas (LNG);
- Methanol and chemical derivatives including DME;
- Petrol and LPG;
- Olefins and polymers;
- Synthetic crude oil;
- Fischer-Tropsch products including diesel, naphtha, lubricating oils and waxes; and
- Hydrogen.

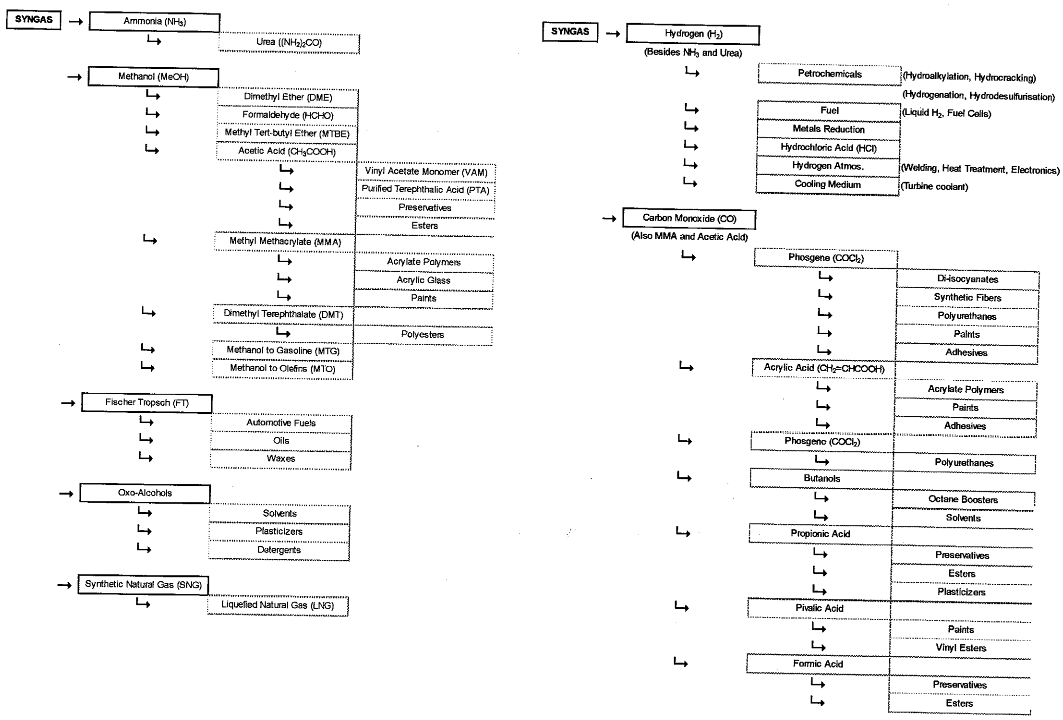


Figure 8 - List of Major Syngas Derived Products

4.4.2.1 Technologies for Product Synthesis

Processes for synthesis of many of the potential products are well established. However, the processes have typically been developed utilising different feedstocks, including reformed natural gas or other petrochemical feedstocks. There is limited experience in the generation of products using brown coal derived syngas as the feedstock.

A key point to note is that almost all of the processes under investigation employ a catalyst. These catalysts are susceptible to poisoning by a number of compounds. Most of the literature has been focused on catalyst poisons found in syngas from conventional feedstocks such as natural gas. Limited research has been completed on the catalyst poisons present in brown coal derived syngas.

4.4.2.2 *Key Outcomes from the Review of Prospective Chemicals and Fuels*

The key outcomes from the review into prospective chemicals and fuels include:

- Integration of a gasification technology, using brown coal as feedstock, with gas conditioning can produce a syngas with suitable specifications for production of a range of products.
- Products that could potentially be produced on a reasonably large scale were the focus of the current work. Potential products include primary products such as ammonia, synthetic natural gas (SNG), methanol, Fischer-Tropsch products (eg. gasoline, diesel, oils, waxes) and hydrogen, and secondary derivatives including urea, DME and olefins;
- Natural gas and crude oil are the major feedstocks used in conventional processes for the production of chemicals and fuels. The costs and availability of these feedstocks are thus critical to the competitiveness of utilisation of brown coal derived syngas;
- Systems using coal-derived syngas are more complicated than conventional systems utilising syngas from natural gas due to the need for a gasification step and different requirements for gas conditioning;
- There are a number of chemicals and fuels for which there could be market opportunities. However, identification of the most prospective product is a complex task requiring detailed consideration of many factors including market demand, technical viability, cost competitiveness and government policy. Further work is required in later phases of the project to identify the most prospective products;
- The required next steps to evaluate the potential for different products are:
  - Completion of technical and economic concept studies to define the gasification systems more accurately and to allow screening of different product options, and
  - Identify key industry stakeholders and technology providers for potential investment in the development of products from syngas.

5 Key Project Conclusions

The first part of Phase 1 of the project involved a literature review of brown coal gasification systems for conversion of brown coal into value-added products and advanced power, with specific focus on syngas production, gas conditioning and identification of prospective products and advanced power systems. The overall objectives were to identify prospective gasification system alternatives and to identify research, development and equipment needs for the production of value added products from brown coal to be investigated in future stages of the project.

The major project outcomes and conclusions included:

- It is expected that increases in gas and oil prices will present potential future opportunities for conversion of brown coal into value-added products;
- Integration of a gasification technology, using brown coal as feedstock, with gas conditioning can produce a syngas with suitable specifications for production of a vast range of chemical products and fuels;
- Electricity generation in advanced power systems using fuel cells represents a potential "next generation' utilisation option for brown coal derived syngas;
- Selection of the most attractive options will require further work in the next part of the work program to develop alternative flow sheets of various process concepts, mass balances and costs;

- Most of the coal gasification work published in the open literature has been on black coals. For black coals, high temperature gasification, including entrained flow gasification, is required to achieve acceptable conversion rates and thus information available in the literature in many cases is not relevant for brown coal gasification;
- Due to the European push for lower CO_2 emissions, work has been done recently on biomass gasification, which has some parallels to brown coal gasification, although again the results must be interpreted with caution;
- Little information is published in the open literature on gasification of Victorian brown coal, particularly for the case of oxygen blown gasification;
- Victorian brown coals have unique properties that must be considered in any future research and development work;
- Pilot-scale testing will be required to develop the chosen concepts and provide the necessary engineering data for process scale-up. This will require a purpose built facility that has the ability to investigate the various gasification, gas conditioning (including CO_2 capture) and syngas reaction concepts.
- International work on R&D into gasification processes for production of value-added products has considerable Government and industry support;
- Due to the high costs involved, stakeholders and investors will need to be engaged to develop this project further;

Other important outcomes of the current project included development of researchers and leaders in the area of brown coal R&D and the development of national and international networks and linkages in the areas of brown coal R&D, gasification systems R&D and other low–emissions technologies.

The outcomes of the first part of Phase 1 will form the basis for a continuation into future stages of the project when further funds become available.

5.1 Path Forward

A number of steps will be required to progress the project from the completion of Part 1 of Phase 1 through to later phases and to development of a commercial facility producing value-added products from brown coal. The path forward involves the following:

- Identifying and engaging investors and stakeholders (including Government(s)) to enable this work to be progressed further;
- Undertaking the second part of Phase 1 of the technical work program to select a number of potential products for development based on technical, commercial and market drivers;
- Carry out further market development work in parallel with the second part of Phase 1 to provide additional information for future product and process selection.
- After completion of Phase 1, commencement of Phase 2 to establish appropriate pilot-scale test facilities to research the concepts and develop the processes to commercial reality; and
- Utilise the pilot-scale facilities to undertake the Phase 3 R&D program to demonstrate the production of value-added products from brown coal.

6 Future R&D Direction

6.1 Status

The detailed literature review showed that gasification of coals of different rank and grades was of high interest in the early twentieth century in order to provide a syngas as input for processes to produce gases and/or liquids as alternative fuels and basic chemicals. Coal to value-added products technology was developed and subsequently utilised. However, utilisation of the technology ceased due to the introduction of oil and natural gas as alternative, more economic feedstock in the chemical and petrochemical industry.

More recently the gasification of solid fuels has gained renewed interest due to the significant and rapid growth in demand for products which can be produced from coal and due to increasing costs for alternative feedstocks. In particular, significant growth has occurred in developing countries over the last decade. The use of brown and low-rank coals for the production of value-added products is of specific interest due to the low cost, long-term availability and advantageous properties of brown coals.

A large proportion of gasification R&D has related to higher rank black coals rather than low rank brown coals. The major focus of research into gasification of high moisture brown coals has centred mainly in Australia (by HRL) and in Germany where there are also significant reserves of brown coal. The major focus of brown coal gasification research and development has related to air blown gasification for power generation.

HRL has conducted extensive R&D on the gasification of Victorian brown coal, although only limited data has been published as this Intellectual Property underpins the commercialisation of the HRL IDG process.

There are some publications on the application of gasification of brown coal for power generation, but fewer publications on the application of gasification for the production of value-added products. Such systems may have specific requirements depending on the product of interest, including particular syngas processing to tailor the syngas for downstream catalytic synthesis of value-added products and for use in advanced power systems.

6.2 Requirements for Fundamental R&D

Fundamental areas of R&D requirements were presented for the major processes of syngas production (Section 4.1), gas conditioning (Section 4.2), CO_2 removal (Section 4.3) and product synthesis (Section 4.4).

6.3 Requirements for R&D at Pilot-Scale

HRL's IDGCC process was developed through the following stages:[3]

1. Laboratory scale testing;
2. Atmospheric pressure testing at 50kg/hr dry coal feed rate;
3. Pressurised gasifier at 1.0 MPa, 300 kg/hr dry coal feed rate;
4. Pressurised gas combustion test rig at 0.6 MPa, 500 kg/hr gas flowrate; and
5. Pressurised coal drying test rig at 1.0 MPa, 1500 kg/hr wet coal feed rate.

[3] Johnson, T. "Prospects for Brown Coal IDGCC", Coal 21, 1st Annual Conference Sydney, Australia, 5th – 6th April 2005.

The results gained in this research program lead to the design, commissioning and testing of a demonstration facility for power production using HRL's air-blown IDGCC process.

To demonstrate the conversion of Victorian brown coal into value-added products liquid fuels, and power (e.g. via fuel cells) utilising HRL's IDG gasification technology an integrated process train on a semi-technical scale is required. Such a train has to include all modules from fuel preparation through gasification, gas treatment and cleaning to the final purification required as input conditions for the production of one or several selected potential products.

The main purpose of such an installation with a capacity of at least 500 kW_{th} is to allow for the optimisation of thermal interaction and flow configuration for certain selected product trains in order to provide data for process modelling as well as to gain process dependent experience both required for considerations regarding a potential larger plant as the next step towards commercialisation.

In order to enable these goals the installation should be designed with the following considerations:

- Integration of all necessary process modules;
- Fuel flexibility in the range of fuel compositions intended for large scale use;
- Operation flexibility regarding temperature and pressure; and
- Arrangements for incorporation and testing of alternative and innovative gas treatment processes (main stream or slip stream).

The requirements for the pilot scale research facility will be dependent on a range of factors such as cost, research requirements, funding and collaboration. At this stage of the project it is proposed that the facility should include the following:

- Scale: Selection of the most suitable scale for a pilot-scale research facility must consider a range of aspects including costs, labour requirements, maintenance requirements and size required to be representative of an industrial plant;
  - A scale of ~500kWth presents a balance between these factors;
- Adiabatic Operation: Design the gasifier to run adiabatically by using external heating on the gasifier, cyclone and recirculation leg or alternatively by housing these items within an electrically heated pressure vessel to allow compensation for heat losses;
- Feeding: Flexible feed system to allow for feeding of alternate feedstocks or bed additives;
- Gasification/Fluidising Agent: Flexibility in operation with different gasification/fluidisation agents (air, steam, N2, O2, etc.);
- Downstream flexibility: Design split stream for product gas (0-100% of flow) to provide flexibility and allow testing of different process option in the same run;
- Fixed bed reactors: Consider inclusion of fixed bed reactors in the syngas train to allow investigation of catalytic reforming, shift reactors, etc;
- Slip stream to other reactors for smaller scale investigation of:
  - Particulate removal;
  - Catalytic reforming;
  - Contaminant removal;
  - Chemicals/fuels production; and
  - Catalyst testing;
- Gas Analysis: A high level of on-line gas analysis (gas analysers, GC, GC-MS, FTIR, etc), in addition to off-line gas analysis will be required;
- Measurement and sampling capability – A range of techniques will be required. The specific requirements will be dependent on the research areas to be investigated as part of future stages of the project;

- Supporting Gasification Equipment: Smaller scale gasification units should be constructed to complement the larger scale research; and
- Plant Location: Locate plant in a suitable location - based on scale requirements, infrastructure requirements, environmental considerations, local community considerations, etc.

6.4 Overall R&D Plan

The recommended future R&D activities to investigate and demonstrate conversion of Victorian brown coal into value-added products using the HRL IDG concept and to provide a pathway to commercial implementation of brown coal gasification systems include:

- Develop alternative system models, including economic models, for production of:
    - Products using HRL IDG systems;
    - Power using HRL IDG - hybrid fuel cell / heat engine systems; and
    - Combined power and products using HRL IDG – hybrid fuel cell systems;
- Complete technical and economic concept studies to:
    - Facilitate more detailed evaluation of the viability of coal to value-added product processes;
    - Determine the key factors which impact on process performance and economics;
    - Determine the driver for implementation of coal gasification systems; and
    - Facilitate selection of the most appropriate system(s) and product(s) for utilisation of brown coal based on factors including cost, markets and technology risk.
- Design, construct and commission pilot-scale test facilities;
- Undertake bench and pilot scale research to:
    - Advance the understanding of the fundamentals of brown coal gasification systems;
    - Demonstrate feasibility of use of HRL IDG syngas in downstream processes for production of prospective value-added products and in advanced power systems;
    - Provide information to assist in design and development of larger gasification systems; and
    - Address any high risk technical issues or novel processing steps;
- Undertake preliminary process design and costing for large scale plants for production of value-added products and power.

The next steps in the development of brown coal gasification systems are to secure funding and then to develop and undertake a targeted research program. The scope and timeframe of the research program will be determined based on the availability of funds.

7 References

A significant amount of information was reviewed in this project. Sources of information included journal articles, targeted research papers, internet information, other publicly available information and confidential HRL documents.

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