Positioning brown coal for a low-emissions future 2009–2015

BROWN COAL INNOVATION AUSTRALIA

Chairman's Foreword

As governments and communities across the world come to grips with the challenges of climate change the question arises about whether or not coal has a role in our future. There can be no doubt that emissions of greenhouse gases, principally carbon dioxide, from the burning of coal and other fossil fuels is causing changes in the earth's atmosphere and these are leading to a range of unintended and unwanted impacts including climatic change, sea level rise and ocean acidification. This form of pollution can and must stop quickly.

Yet the very basis of coal is the element carbon which we are increasingly using in the technologies and products we require to deliver the sustainable future we are demanding. Carbon is essential for the chemical processes we use to make steel, cement and glass which form the very fabric of the sustainable cities of the future. Carbon is essential for the production of the silicon we use for solar panels, computers and smart phones. Carbon is essential for the carbon fibre and carbon polymers we now use for modern transport in our cars, planes, trains and trams and even the bicycles which many are turning to in order to reduce their carbon footprint. Carbon is the basis of life on our planet and it therefore underpins the agricultural and food industries.

So how do we resolve this paradox of reducing our carbon footprint by using more and more carbon in our sustainable future?

Brown Coal Innovation Australia (BCIA) has taken up this challenge with a particular focus on Latrobe Valley brown coal, which, contrary to some perceptions, is a relatively clean world class resource with low sulfur and ash, making it highly suitable as a feedstock for a range of chemical and industrial uses. Even the high moisture content of brown coal, which when used with old technology for electricity generation leads to high GHG emissions, can in fact be turned to advantage in other chemical processes.

This report sets out the progress we have made in the first five years of our journey of innovation following establishment as a private company by the Victorian Government and also identifies a number of pathways for future investment.

With a continuing strategic focus on products, innovation and commercialisation pathways together with a supportive policy framework, the Latrobe Valley could be a world centre for low emissions uses of coal, and a centre for manufacture of coal-derived products such as carbon polymers, carbon fibre, fertilisers and hydrogen. Society is demanding the carbon products for our sustainable future, so we should secure the innovation, investment and employment opportunities in the Latrobe Valley where there is a world class source of carbon.

Gerry Morvell
BCIA Chairman

CEO's Foreword

It is a pleasure to share with you this report on the outcomes of the first five years of activity of BCIA. This report covers the work undertaken by BCIA and our partner organisations and details how we have delivered on our mission to develop research, technologies and people to reduce the environmental impact – and deliver social and economic benefits – from sustainable use of brown coal.

Over the period covered by this report, BCIA has received support and funding from the Victorian Government, from the Commonwealth Government through the auspices of Australian National Low Emissions Coal Research & Development, and from our member organisations. We have invested funds into a variety of Research & Development (R&D), pilot-scale and demonstration projects, as well as programs to build the skills necessary for new brown coal utilisation technologies, and links to similar global R&D efforts.

To deliver on our mission requires working with world-class research teams. Over the period covered by this report, nearly 50 local and international, industry, government and research organisations have been actively involved in BCIA's research agenda.

In addition, we have been able to support nearly 40 PhD students at local universities, many of whom have now gone on to productive careers in academia and in industry, and who are continuing to build the legacy of brown coal R&D. The research funded by BCIA has generated in excess of 650 publications and presentations, and six patents, clearly demonstrating the importance of the work done.

BCIA's focus is unashamedly on applied technologies, and we provide support to assist R&D to move out of the laboratory and into real-world application. Through BCIA and industry support, projects such as Direct Injection Carbon Engine (DICE) have moved from lab scale through to pilot scale testing, with emerging commercial interest. With partners such as IHI Corporation, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), BCIA has been able to support three pilot-scale carbon-capture facilities operating at power stations in the Latrobe Valley. Moreover, BCIA's work on generating hydrogen from brown coal, and on the agricultural uses of coal, has demonstrated the potential economic viability of whole new industries based around the Latrobe Valley's coal resources.

While this report looks back on the work undertaken in recent years, BCIA is now looking to the next five years and beyond. The current use of Victoria's brown coal is exclusively for electricity generation, while the future outlook is for a far broader range of uses. The R&D programs supported by BCIA are therefore vital for the creation of new uses for brown coal in Australia. We look forward to continuing the work of BCIA, together with our members, stakeholders and partner organisations, and supporting the development of new, commercially viable and environmentally responsible uses of brown coal.

Dr Phil Gurney
BCIA Chief Executive Officer

Table of Contents

Brown Coal Innovation Australia Ltd (BCIA) was established in 2009 with the goal of advancing the environmentally responsible uses of brown coal. The company achieves this through the following.

1. Investing in a comprehensive research and development (R&D) program for future environmentally responsible use of brown coal.
2. Rebuilding Victoria's relevant scientific expertise and the skills needed for the future workforce.
3. Establishing strong linkages with industry, governments and the research community throughout Australia and internationally that lead to new research collaborations and opportunities to accelerate technology development.

Key Achievements of BCIA

- Enabled over A$50 million of investment program of research and skills development focused on environmentally responsible uses of coal.
- Secured support and investment from nearly 50 local and international companies and research institutes.
- Accelerated the development of low-emission coal technologies, taking key projects from bench and pilot scale through to demonstration and commercial licensing.
- Sustained academic excellence, with support for 40 higher degree students, and research leading to over 600 academic papers and presentations.
- Firmly established presence as an industry-focused organisation and leader in the research and development (R&D) and skills landscapes.
- Built an international network spanning nearly 1,200 individuals and over 500 partner organisations.

Abbreviations

ACALET	ACA Low Emissions Technologies Ltd
ALDP	Advanced Lignite Demonstration Program (Victorian and Commonwealth Governments)
ANLEC R&D	Australian National Low Emissions Coal Research and Development
ASU	Air Separation Unit
BCIA	Brown Coal Innovation Australia
C	Carbon
Ca	Calcium
CCS	Carbon Capture and Storage
CFD	Computational Fluid Dynamics
CLC	Chemical Looping Combustion
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCFC	Direct Carbon Fuel Cell
DICE	Direct Injection Carbon Engine
DME	Dimethyl Ether
ESA	Electrical Swing Adsorption
ETIS	Energy Technology Innovation Strategy (Victorian Government)
Fe	Iron
GCCSI	Global Carbon Capture and Storage Institute
GHG	Greenhouse gas
GJ	Gigajoule
H_2	Hydrogen
H2O	Water
H2S	Hydrogen Sulfide
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JCOAL	Japan Coal Energy Center
K	Potassium
kg	Kilogram
kWh	Kilowatt hour
LNG	Liquefied Natural Gas
LSCF	Lanthanum Strontium Cobalt Ferrite
LVPCC	Latrobe Valley Post-Combustion Capture
m^2	Meter squared
MEA	Monoethanolamine
Mg	Magnesium
MILD	Moderate or Intense Low-oxygen Dilution combustion
MJ	Megajoule
MRC	Micronised Refined Carbon
Mt	Megatonne
MW	Megawatt
MWh	Megawatt hours
N	Nitrogen
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxide
OHD	Oxidative Hydrothermal Dissolution
O_2	Oxygen
P	Phosphorous
PCC	Post-Combustion Capture
PDMS	Poly Dimethyl Siloxane
PF	Pulverised Fuel
pH	Potential of Hydrogen
R&D	Research and Development
SECV	State Electricity Commission of Victoria
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxide
T_{crit}	Critical Temperature
TLDS	Tuneable Laser Diode Spectroscopy
WES	Westec Environmental Solutions

Executive Summary

Greenhouse gas (GHG) induced global warming is one of the most challenging problems of our times. Since the first electricity began to flow in 1924, brown coal mining and electricity generation has provided low cost power that has assisted the economic development of the State of Victoria, and supported thousands of jobs in the Latrobe Valley. However, Australia's use of brown coal is highly emissions intensive, and the way in which we use this resource in the future must change.

For the last five years, BCIA has been the driver of environmentally responsible Australian brown coal technology development. The company works at the research level from bench through to pilot scale, and has supported skills development through project funding and student support. BCIA's focus has been to develop new pathways for brown coal in a carbon-constrained future, and address both the challenges and opportunities that this presents for Victoria, and Australia more broadly. This report provides a summary of the company's activities and achievements, and our plans for future work.

High-efficiency, low emissions power

The major use of brown coal around the world is for electricity generation. The excellent quality of Victorian brown coals – combined with the low cost of mining – has meant that coal supplies over 85% of the State's electricity needs, and also provides power to export to other states.

Victoria's power stations are old, and inefficient. Replacing them with state-of-the-art power plants would reduce emissions, but BCIA's ambition is higher, seeking to demonstrate cost-effective pathways to 50%–100% emissions cuts.

Any future brown coal power plants will also need to support an increasing intermittent load generated from renewable sources – issues such as power plant flexibility, and ramp up / down rates will be key to new designs. BCIA supports several projects in this area, with the Direct Injection Carbon Engine (DICE) project progressing to large-scale trials in Japan.

Carbon capture technologies

The Intergovernmental Panel on Climate Change (IPCC) has stated that the use of carbon capture is a key technology that will significantly reduce the cost of mitigating the effects of climate change.

Australia cannot simply be a 'technology taker' for carbon capture technologies – we must develop solutions to meet our local regulatory, economic and policy requirements. This requires an ongoing R&D program.

BCIA funding has supported the operation of three pilot scale capture plants at power stations in the Latrobe Valley, as well as a wide range of other research projects that are reducing the cost, and accelerating the time-frame, for local implementation of carbon capture and storage (CCS).

Alternate uses of coal

Brown coal has application as a feedstock for a range of processes, such as production of hydrogen, plastics and fine chemicals, as well as a variety of agricultural and metallurgical uses. Coal is also a valuable source of the carbon that is essential for production of silicon, steel, cement, carbon fibre, carbon polymers and graphite.

Technologies for transforming coal to chemicals and coal upgrading have been proven internationally at commercial scale, particularly with recent developments in China. However, each coal deposit is chemically different, and R&D is required to optimise technologies developed overseas for use with Australian coals.

BCIA has funded projects addressing these non-power applications of coal, for example demonstrating the viability of coal-to-hydrogen in Victoria, and showing that coal-urea blends not only make better fertilisers, but can significantly reduce agricultural GHG emissions.

Skills programs

Any major new coal project will require a different skills mix from that of the current power generation industry. Some jobs will stay the same – the mining and engineering support functions will not change significantly, and existing skills will be required for the new construction and transport jobs.

However, the majority of new uses of coal require chemical transformation. This means that the knowledge-based jobs for new projects will be closer to those found in an oil refinery than those currently found in the workforce of a brown coal power station.

BCIA provides support to develop the knowledge and research skills necessary for new projects, as well as supporting workforce-planning initiatives. To date the company has supported nearly 40 higher degree students through its on-going program of R&D activity, and has funded 16 direct scholarships to assist students.

The case for coal in a decarbonising economy





Over the last few decades, the Australian economy has benefited significantly from the mining, use and export of coal. However, making the changes needed to mitigate global warming will have a significant impact on all future uses of fossil fuels.

In order to prevent global temperatures rising by more than 2°C, the International Energy Agency (IEA) estimates that the GHG intensity of electricity production must fall by 90% globally between 2015 and 2050. The same IEA data also shows that any short-term economic gains from delaying investment in clean energy technologies will be overcome by longer-term costs, and that continued investment in innovation is required now if we are to achieve the GHG emission targets for the future.

The way we use coal must change, and this change represents both an opportunity and a challenge for Australia. Against this background, BCIA's mission has never been more relevant – to deliver economically viable, low emissions coal technologies requires ongoing investment in R&D.

Victoria has one of the world's largest reserves of brown coal, estimated at 430 billion tonnes. This coal has very low levels of mineral impurities (ash), and the 33 billion tonnes of coal that is economically recoverable at today's prices would supply Victoria's power plants for 500 years.

Electricity generation from brown coal is the backbone of the local economy, accounting for about 21% of the gross regional product of Latrobe City, supporting approximately 5,600 jobs and directly contributing A$181 million in wages each year.

Brown coal not only supplies around 85% of Victoria's electricity needs, but also provides additional energy exports to other states. But today, Victoria's power stations rank among the highest per megawatt GHG emitters in the world.

For coal to have a future in a low emissions world, new uses of coal must address the challenge of CO_2 emissions. The good news is the introduction of the first generation of low emissions coal plants in the US and Canada – with the first two operating on brown coal. New coal technologies, such as DICE, also offer the potential for low emissions, dispatchable power to back up intermittent renewable sources of energy.

To meet future emission targets, any new fossil-fuel power station (coal or gas) will need to use CCS. Almost all of Victoria's electricity generation capacity is concentrated in the Latrobe Valley, close to the Gippsland Basin, which is Australia's most prospective carbon storage site. This creates a significant opportunity for near zero emissions power for Victoria.

But coal's applications are not limited to power generation. There is also growing interest and investment in non-power uses of coal, either as stand-alone applications, or in combination with CCS. There continues to be significant interest in such projects in Victoria.

As detailed in this report, in its first five years BCIA has made some impressive achievements. However, there is still a long way to go. A number of our current projects are well along the pathway to deliver on the promise of the emissions and cost reductions necessary for widespread adoption of new coal uses.

Continued investment and support will be vital to ensure that the promise of these new coal technologies is brought to fruition.

Source: © CSIRO.

New opportunities for brown coal

Future development of brown coal technologies in Victoria will need to meet three main objectives.

Developing options for future uses of Victoria's carbon resources

The Victorian economy would benefit enormously if cost-effective low emissions processes can be developed to transform its massive carbon reserve into high value products. There is a range of new technologies that show promise for use with brown coal, including oxygen-blown entrained flow gasification, torrefaction, micronisation and advanced cleaning techniques, oxidative hydrothermal dissolution and densification. These technologies could be used to transform brown coal into a wide range of valuable products, including industrial chemicals (e.g. hydrogen, ammonia, methanol, dimethyl ether, ethylene glycol) which can be transformed into higher-value products such as fertilisers, clean fuels, plastics, carbon fibres and graphene. Such products are in high international demand, and have the potential to transform Victoria's huge carbon reserves into a thriving export economy.

For these and other prospective processes, emphasis should be given to those that can deliver both a competitive advantage and low GHG emissions. BCIA has made a promising start in this area, but a significantly larger investment will be required to bring new technologies to fruition. Much of this work builds on international developments that require adaptation to optimise them to the unique chemistry of Victorian coals. It is important to support new processes in the transition from the laboratory to pilot scale, so that proof-of-concept work can be undertaken at sufficiently large scale to attract funding for commercial deployment. Support is also needed for the development of green technologies that can convert waste CO_2 into value-added products such as plastics.

Supporting the lowest-cost transition to a low emissions economy

The new paradigm for power generation in Australia is for an increasing penetration of intermittent renewable energy from wind and solar photovoltaics. To ensure that the power generated matches the demand as it varies across the day, intermittent generation must be partnered with some form of flexible, dispatchable power delivery system. This variable demand is currently mostly met by gas, but gas prices are increasing to international parity. Coal is far cheaper than gas and other dispatchable energy sources such as battery storage, but current coal technologies are inflexible, suitable mainly for baseload power, and have high emissions.

New coal technologies, such as DICE and solid-carbon fuel cells, offer the promise of lowest-cost, low emissions, reliable and dispatchable power, and can support a significant penetration of intermittent energy sources. In particular, brown coal DICE is likely to be able to deliver load following power and be cost-competitive with gas. DICE technology could be installed progressively in modular units as renewable power sources are introduced and existing generation is closed. This would enable a balance of both baseload and load following generation capacity, and would help facilitate the transition from existing high CO_2 emitting power generation technology, while making use of the existing power distribution and mining infrastructure.

Together with CCS (which can offer pathways to negative emissions), these technologies could allow Victoria to continue to use its natural resources to deliver the lowest-cost, low emissions energy. However, continued development of these technologies requires further R&D support to ensure their transition to commercial adoption.

Supporting economic growth and job creation via new manufacturing opportunities

In the Latrobe Valley, electricity generation from brown coal is the backbone of the local economy. Viable options exist for the production of electricity and other higher value products from coal in ways that overcome today's problems of CO_2 emissions to the atmosphere. The Latrobe Valley has the potential to become a powerhouse of new low emissions economic growth and commercial activity, securing the jobs of the current coal workforce and building new knowledge-based employment.

While it is still possible to take action to create this future, there is no reason why Victoria should have to abandon its massive carbon reserve as a stranded asset, or suffer the effects of reduced employment opportunities in the Latrobe Valley. Ongoing investment in low emissions coal technology development and innovation, and support for the most promising technologies on their pathway through to commercial deployment will be required if the State is to secure this future.

The size of the resource available means that the scale of developments will be significant– job creation in the construction and commissioning of plant and equipment will be supported by new jobs in resource extraction and manufacturing industries. Each new project will create hundreds of long-term local jobs, supplemented by thousands of additional jobs during the construction phase.

Introduction to BCIA

During the 20th century, the successful extraction of brown coal through open cut mining methods and its subsequent use for electricity generation and briquette production, have been instrumental in Victoria's economic and social expansion. The State Electricity Commission of Victoria (SECV) designed the existing power stations to produce electricity from raw coal (which contains 60%–70% moisture) at the lowest possible cost. Efficiency was not a concern because the coal was inexpensive to mine. Cheap electricity has successfully underpinned Victoria's economy for 90 years, but at the cost of high GHG emissions to the atmosphere.

GHG induced global warming is one of the most challenging problems of the 21st century. In order to prevent global temperatures rising by more than 2°C, the IEA estimates that the carbon intensity of electricity production must fall by 90% globally between now and 2050 [(1)]. Technologies that have the potential to deliver significant efficiency improvements for brown coal power generation are well advanced, but still require further R&D to take them from pilot and demonstration activities to commercial scale.

Efficiency improvements alone will not be sufficient to achieve zero greenhouse emissions. Continued use of Victoria's brown coal will rely on the ability to cost-effectively capture the carbon dioxide emissions at source and prevent them entering the atmosphere, using affordable CCS technologies. However, CCS is not cost-effective today, and further R&D is required to drive cost reductions that will underpin the commercial viability of future CCS projects.

Technologies already exist to upgrade coal to higher value products, and in recent years these have been deployed in China and elsewhere. The brown coal in the Latrobe Valley is of high quality and can be used to develop new industries and attract multi-billion dollar investments to Victoria. But such technologies require adaption if they are to work with the unique chemistry of Australian brown coals.

In order to advance research into low emissions brown coal technologies, in late 2009 the Victorian Government established Brown Coal Innovation Australia (BCIA) as an independent, not-for-profit company. BCIA's mission is to *invest proactively in the development of technologies and people to broaden the use of brown coal for a sustainable future*.

Strategic objectives of BCIA

- Build and enhance Victoria's research capability to ensure the State is ready and able to accelerate the deployment of technologies appropriate to the unique characteristics of Victoria's brown coal and suitable for deployment in an emissions constrained future.
- Work closely with industry and researchers on technologies that industry sees as critical in the medium to long term.
- Facilitate development of the next generation skills base to support industry and the continued development of major coal projects in Victoria.
- Coordinate and invest in fundamental and applied public and private sector R&D projects that contribute to successful exploitation of Victoria's brown coal into the future.
- Foster linkages and collaboration between all stakeholders – locally, nationally and internationally.

Over its first five years, BCIA has built a portfolio of contracted research activity involving nearly 50 companies and research institutes, with a total leveraged value of A$51.1 million. Funding for BCIA's portfolio has come from the Victorian Government, from the Commonwealth and from industry, as shown in Figure 1.

(1) International Energy Agency (2015). Energy Technology Perspectives 2015.

Figure 1: BCIA's sources of funding

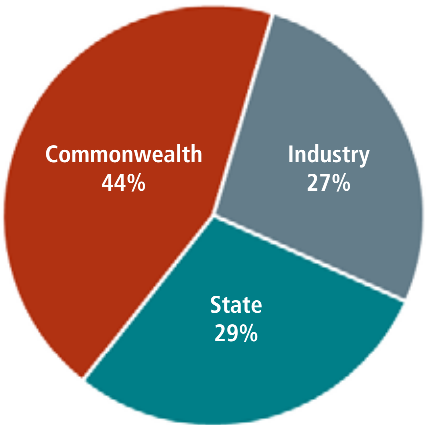
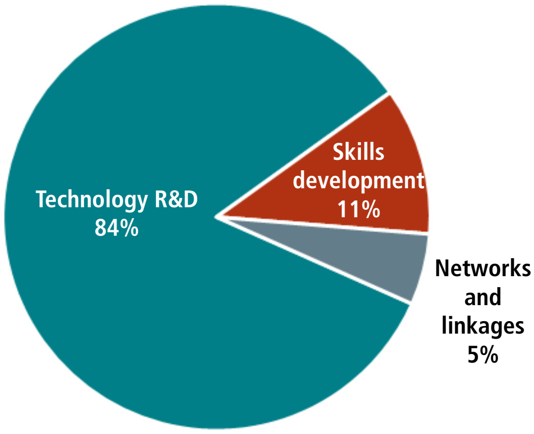


Figure 2: BCIA's overall research portfolio



BCIA allocated resources across three core areas

Technology Research & Development

BCIA has co-ordinated and directed a joint investment from industry, government and the research community in a diversified R&D portfolio that is aimed at adapting leading clean coal technologies to increase the use and value of brown coal in Australia, both for power generation and the creation of new export opportunities.

Skills Development

BCIA has established Research Leader Fellowships and PhD scholarship programs to enhance the future knowledge base and technical skills capability in the brown coal sector.

Networks and Linkages

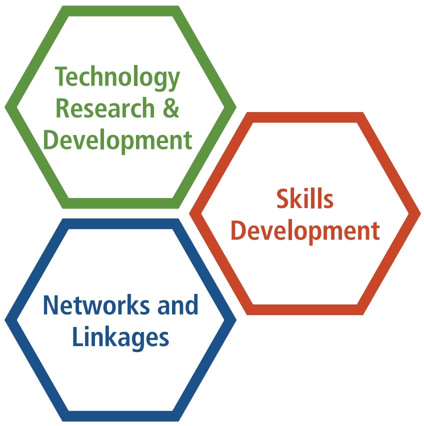
BCIA has built a membership base and leveraged the technology R&D portfolio to secure links between the Victorian, Australian and international energy sector, and facilitated the exchange of knowledge between industry, government and research communities.

The proportion of funding allocated to each of these activities is shown in Figure 2.

The research funded by BCIA has generated in excess of 650 publications and presentations. BCIA has contributed to nearly 40 PhD student projects, two senior research leader fellows, and maintains regular contact with its stakeholder database of over 1,200 individuals representing more than 500 organisations worldwide.

BCIA has conducted three competitive R&D funding grants and commissioned research to inform future decision-making in R&D investment. BCIA has co-funded three carbon capture plants in the Latrobe Valley to accelerate the deployment of CCS in Victoria, fast-tracked the development of technologies that will more than halve GHG emissions from coal use, and built strong international collaborations with Japan, US, China and Europe.

The following sections provide more information about each of BCIA's three core areas of activity.



Technology Research & Development

BCIA's technology Research & Development portfolio has been constructed to achieve a strategic balance over three areas of activity.

BCIA's technology R&D portfolio has been constructed to achieve a strategic balance over three areas of activity.

1. Low emissions power from brown coal

Research into technologies that will allow brown coal power production to be cost-effectively integrated with carbon capture and storage (CCS). This has included processes to improve the efficiency of brown coal combustion, with the aim of reducing the size and cost of subsequent CO_2 capture equipment.

It has also included research into emerging technologies that allow brown coal to be combusted in pure oxygen, producing a pure CO_2 stream that is much cheaper to capture.

2. CO_2 capture technologies

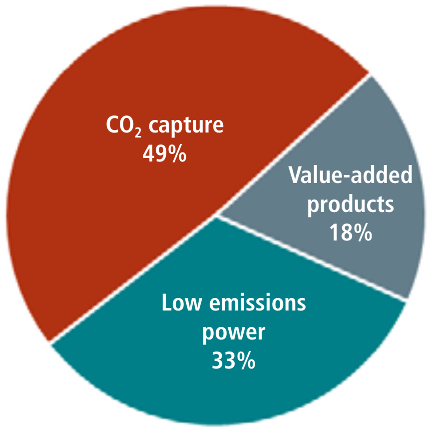
Research into the integration of a range of CO_2 capture technologies into brown coal processes. The aim has been to develop low-cost CCS technologies that can operate effectively on the gas streams produced during brown coal combustion and gasification.

3. Low emissions value-added products from brown coal

Research into a range of processes that can produce export-quality products from Victorian brown coal, either as stabilised dry coal, as chemicals derived from coal gasification, or as new products created by the physical / chemical treatment of brown coal.

Figure 3 shows the proportion of resources allocated to each of these research areas.

Figure 3: BCIA's technology R&D portfolio



1. Low emissions power from brown coal

Continued use of brown coal in a carbon-constrained future will rely on the ability to cost-effectively capture the carbon dioxide emissions at source and prevent them entering the atmosphere, using affordable CCS technologies. BCIA has supported research, development and demonstration projects in reducing the cost of CCS and accelerating its commercial deployment.

BCIA has funded research to develop processes that can generate power from Victorian brown coal in a manner compatible with CCS technologies. One of the biggest barriers to the deployment of CCS is the capital cost of the equipment involved. BCIA's research portfolio includes technologies that can improve the efficiency of brown coal combustion, thereby reducing the size of the CO_2 capture equipment needed.

BCIA has supported research into emerging technologies that allow brown coal to be combusted in pure oxygen, removing the need for the large equipment necessary to capture CO_2 from flue gas, which comprises 79% inert nitrogen. The resulting CO_2 stream from oxy-fuel combustion is highly concentrated, making it easier and cheaper to capture for storage.

1.1. Improved efficiency of brown coal combustion

1.1.1. Pulverised Fuel (PF) steam boilers

All coal-fired power stations in Australia employ PF combustion technology, which involves burning finely-ground coal. The heat produced converts water into high-pressure steam to drive an electrical generator.

The four power stations in the Latrobe Valley use subcritical PF boiler technology, in which steam pressure is below 22MPa and temperature is below 540°C. These power stations were designed to produce inexpensive electricity by burning raw brown coal, at the expense of high GHG emissions.

Supercritical PF boilers, which are used elsewhere in Australia, operate at higher pressures and temperatures, resulting in higher efficiencies and lower GHG emissions. BCIA has supported research to improve the efficiency of both subcritical and supercritical PF boilers through evaluation of a new laser-based monitoring and control system that allows tighter control of operating conditions.

BCIA has also supported research to improve knowledge of the advanced materials used in supercritical power plants and to develop improved techniques for their assessment and repair..

For more details see page 36.

1.1.2. Direct Injection Carbon Engine (DICE)

DICE has the potential to be a 'game-changing' power generation technology that could reduce CO_2 emissions by up to 45%, with the potential for further reductions when combined with CCS technologies. DICE involves using a finely dispersed slurry of coal in water as a fuel in large two-stroke, slow-speed diesel engines, with the potential to achieve thermal efficiencies of 48%–50%.

BCIA has supported research aimed at producing a high quality liquid fuel from Victorian brown coal, and establishing the technical feasibility of the DICE concept from laboratory through to small demonstration scale.

For more details see page 40.

1.1.3. Direct Carbon Fuel Cells (DCFCs)

DCFCs are an emerging ultra-low emission technology that can convert solid fuels to electricity via electrochemical oxidation rather than combustion, with efficiencies of 65%–70%. An attractive feature of the technology is that DCFCs produce two separate exhaust streams, one that is essentially oxygen-depleted air and the other a concentrated stream of CO_2. This eliminates the need for a separate CO_2 capture step.

BCIA has supported investigations into the feasibility of DCFC operation using Victorian brown coal, to help understand the further research requirements for this promising technology.

For more details see page 44.

1.1.4. Moderate or Intense Low-oxygen Dilution (MILD) combustion

MILD combustion, also known as flameless combustion, is a promising new technology with the potential to significantly improve thermal efficiencies. The technology involves recirculation of combustion products within the furnace to preheat the reactants to above their ignition point, resulting in uniform temperature distribution and the absence of a visible flame. MILD combustion has been commercialised for natural gas burners, but little has yet been done with solid fuels such as coal.

BCIA has supported a preliminary investigation into the feasibility of MILD combustion with Australian brown coals to better understand the opportunities presented by this technology.

For more details see page 46.

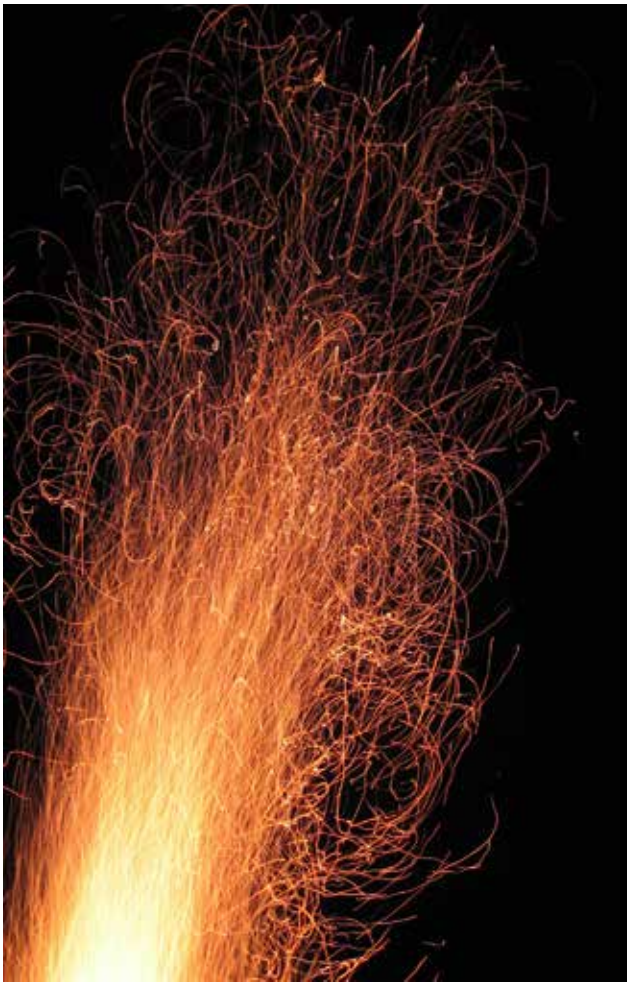
1.2. Combustion in oxygen instead of air

1.2.1. Oxy-fuel combustion of brown coal

Oxy-fuel combustion involves burning coal in the presence of oxygen and recycled flue gas instead of air, offering the potential for a 'step change' in CO_2 capture costs by producing a CO_2-enriched stream that is suitable for direct storage / sequestration with minimal further purification. Oxy-fuel combustion is a new but strongly developing technology, in which Australia has played a leading role through the Callide oxy-fuel demonstration project in Queensland.

BCIA has supported pilot-scale research into oxy-fuel combustion of Victorian brown coal in order to understand the practical implications of combustion in recycled flue gas and the subsequent formation and deposition of ash-forming components.

For more details see page 48.



1.2.2. Chemical looping combustion of brown coal

Chemical looping combustion is an emerging alternative technology that can facilitate capture of CO_2 at a lower energy and cost penalty. It has been developed to overcome the main limitation of oxy-fuel combustion: the high cost of producing large quantities of pure oxygen.

In chemical looping combustion, an oxygen carrier such as metal oxides provides an inexpensive oxygen source that can be continuously recycled and regenerated in hot air. The process results in two separate exhaust streams, one that is essentially oxygen-depleted air and the other a concentrated stream of CO_2.

BCIA has supported the development of this technology for use with Victorian brown coal, from bench-scale studies on alternative oxygen carrier materials through to pilot-scale process development trials and techno-economic assessment.

For more details see page 52.

2. CO_2 Capture Technologies

More than half of BCIA's technology R&D portfolio has been dedicated to investigation of appropriate CO_2 capture technologies. The high cost of CO_2 capture processes is the greatest barrier to their deployment, so intensive effort is needed to improve process efficiencies and identify new technologies that can achieve a dramatic reduction in costs.

BCIA has supported research into a range of different CO_2 capture technologies, including chemical absorption systems, physical adsorption systems and membrane separation processes.

BCIA has also provided funding for ancillary research activities to support the deployment of CCS, including the identification of design tools that can be used for new CO_2 pipelines in Australia, and an independent assessment of the feasibility of novel bio-sequestration and mineral CO_2 sequestration techniques.

2.1. Amine solvent absorption systems

Amine solvent scrubbing relies on the chemical absorption of CO_2 using aqueous alkanolamine solutions. It is a robust technology that has been used to separate CO_2 from natural gas and hydrogen since the 1930s and has recently been installed on the SaskPower lignite-fired power station in Canada. The current commercial solvents require large, expensive capital equipment and impose a high energy penalty for recovery of the CO_2.

In addition, the commercial solvents are quickly inactivated by the sulfur compounds present in coal, usually requiring additional expensive scrubbing equipment. Sulfur scrubbing is not used in Australian power stations, since Australian coals contain low levels of the element, but the residual levels are enough to deactivate amine solvents.

BCIA has supported research on strategies to reduce the cost of amine solvent systems through the evaluation of new, efficient solvents with lower energy penalty, and on novel processes that avoid solvent deactivation without the need for expensive sulfur scrubbing equipment.

For more details see page 55.

2.2. Precipitating carbonate absorption system

UNO MK 3 is a novel solvent absorption process that has been developed by the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) over the last decade. It is based on capturing CO_2 using a precipitating potassium carbonate process that is environmentally benign, has a low energy penalty and can operate in the presence of sulfur impurities.

BCIA has supported research underpinning the development of the UNO MK 3 process, as well as pilot-scale trials at a power station. The UNO MK3 solvent process is now being commercialised through UNO Technology, an Australian based company.

For more details see page 61.

2.3. WES froth generator absorber system

The absorber columns used for CO_2 capture consist of structured packings which provide a large surface area for mass transfer. Limitations in the performance of packings result in columns that are large and expensive. The Westec Environmental Solutions (WES) froth generator absorber shows potential as a more efficient mass transfer device, offering the possibility to substantially reduce the size and cost of equipment needed for CO_2 capture.

BCIA has supported the transfer of this novel absorber concept from laboratory scale to pilot plant scale for CO_2 capture from power station flue gas.

For more details see page 64.

2.4. Physical adsorption systems

Capture of CO_2 using solid-phase adsorbents can potentially avoid some of the disadvantages of solvent absorption systems, such as low mass transfer area and low CO_2 loading. The objective is to develop high-capacity, low-cost adsorbents that can capture CO_2 efficiently in the presence of water vapour and sulfur impurities.

BCIA has supported the development of some novel adsorbent materials and pilot-scale demonstration of efficient operating strategies.

For more details see page 65.

2.5. Membrane systems

Polymeric membranes have been commercially proven in removing CO_2 and H_2S from natural gas and are commonly used for H_2 recovery in refineries. Membranes have the potential to cost-effectively separate CO_2 from brown coal power station emissions in a selective manner, although to be commercially viable must be highly selective, fast and energy efficient.

BCIA has supported research into this emerging technology, with a focus on the performance of commercial membranes in the presence of typical brown coal impurities.

For more details see page 69.

2.6. Dispersion modelling for CO_2 pipelines

Effective deployment of carbon capture and storage infrastructure in Australia will require pipelines to transport compressed CO_2 from the point of capture to the point of storage. All aspects from design through to operation of a new CO_2 pipeline in Australia will be expected to conform to Australian Standard 2885 'Pipelines – Gas and liquid petroleum'. However, the design tools provided in the Standard are applicable to pipelines carrying flammable natural gas and not directly applicable to CO_2.

BCIA has supported a project to investigate CO_2 pipeline design and to identify suitable design tools that can be applied to new CO_2 pipeline infrastructure in Australia.

For more details see page 73.

2.7. Novel CO_2 capture technologies

The effective deployment of carbon capture and storage technologies relies on the availability of suitable storage options for the large quantities of CO_2 that must ultimately be sequestered. The main focus in Victoria is on geological sequestration, but other options have been proposed, broadly falling into the areas of bio-sequestration and mineral sequestration.

BCIA has provided support for a study by a carbon capture task force, with the objective of providing an independent assessment of the feasibility and cost of novel bio-sequestration and mineral sequestration techniques in Australia, and to make recommendations about appropriate R&D needs and priorities.

For more details see page 74.

3. Low emissions value-added products from brown coal

Victorian brown coal is geologically young, comprising compressed plant material with very little mineral ash. On a dry, ash-free basis, the coal contains about 68% carbon and thus represents a valuable resource of carbon that can be transformed into a range of new products. This potential has been recognised for many decades but has not yet been developed.

BCIA has identified new opportunities to produce value-added products from brown coal. In a carbon-constrained future, any such opportunities can only be realised if the associated greenhouse emissions are low. Drying of the coal is an essential first step, upon which all new product opportunities are based, so BCIA has supported research that will assist in the development of practical coal upgrading techniques. Once dried, the coal can be transformed into new products by gasification or through physical and/or chemical treatments.

BCIA has supported research that demonstrates the wide range of product opportunities that could lead to new industries and jobs creation in Victoria.

3.1. Brown coal upgrading

Use of Victorian brown coal in applications at any great distance from the mine site is a challenge. The freshly-mined coal comprises about two-thirds water, making it expensive to transport. The dried coal is highly reactive and has a tendency to combust spontaneously, making it dangerous to transport and stockpile in this form.

To date, these issues have prevented the commercial exploitation of brown coal for anything other than local power generation. The development of economical new uses for Victorian brown coal depends upon being able to upgrade and stabilise the coal efficiently and cheaply.

BCIA has supported research to underpin the development of practical coal upgrading techniques.

For more details see page 77.

3.2. Products from gasification of brown coal

Gasification is the process of heating coal with insufficient oxygen to support combustion. The result is a gaseous mixture known as synthesis gas, or syngas. Through control of the gasification and subsequent refining processes, the syngas can be converted into a range of industrial chemicals and clean fuels. Air-blown gasification of Victorian brown coals has been extensively studied for advanced power generation systems. However, oxygen-blown gasification, which is needed to make value-added products, has received little attention.

BCIA has supported preliminary studies to evaluate the gasification technologies that would be suitable for use in Victoria, and to identify the knowledge gaps that should be the focus of future research.

BCIA has also supported investigations into the feasibility of producing three potential value-added products from Victorian brown coal: hydrogen, urea and dimethyl ether.

For more details see page 80.

3.3. Value-added products from brown coal

Victorian brown coal can serve as the basis for a range of value-added products. BCIA has supported preliminary evaluation of a variety of such products, including agricultural soil amendments and fertilisers, blast furnace coke and advanced activated carbons for renewable hydrogen storage.

BCIA has also supported research into the use of brown coal ash, a substantial by-product of the power industry, for production of geopolymer concrete for use in building and construction.

For more details see page 89.

Source: © CO2CRC.

Skills Development

The environmentally responsible use of Victoria's coal resources promises much – new projects, economic development and job creation and the establishment of a new manufacturing industry, to name a few.

To deliver on these prospects will require the development of improved technologies and better technical understanding, and this requires a skilled workforce.

Some skills will be transferable – for example the skills used today in the construction, mining and transport industries will be applicable to the construction of new plants, transport of new products, and continued mining of coal. Skills from the oil and gas sector will be transferable to the transport and storage of CO_2. However, other skills will be needed for the success of the new industries – a coal-to-products plant will be more like an oil and gas refinery or a plastics manufacturing facility than a power station.

BCIA has a major focus on the knowledge jobs required for the new industries, and supports building the research skills base needed to support coal projects through academic training and helping to align the Latrobe Valley skills base with future needs. These activities represent a strategic investment by BCIA in the development of skills to secure the scientific, engineering and trade expertise required for new low emissions brown coal technologies.

The major elements of BCIA's skills program have been as follows.

- Support for maintaining the research base. Nearly 40 higher degree students have worked on BCIA funded activities to date, either through participation in research projects or through full or top-up PhD scholarships.
- Support for academic excellence. BCIA has funded two high profile research leader fellowships, with recipients undertaking research activities aimed at enhancing the uses of Victorian brown coals.
- Support for workforce planning initiatives, including two employment focused workshops held in the Latrobe Valley.
- Support for training and professional development, including research seminars and a gasification short course.

The BCIA research leader fellowship program recognises outstanding researchers of international repute who can provide a significant leadership and mentoring role in building Australia's internationally-competitive research capacity within the brown coal innovation sector.

In 2010, BCIA awarded two research leader fellowships. One was to Dr Klaus Hein, in joint roles as Professor of Low Emissions Technology at the Department of Chemical Engineering, Monash University, and as Research and Development Manager at HRL Technology Pty Ltd. The second fellowship was to Dr Alan Chaffee, as Professor and BCIA Research Leader at the School of Chemistry, Monash University.

BCIA's support for Professors Hein and Chaffee has strengthened Victoria's capacity and international reputation in brown coal research. The research leader fellowship program has provided world-class training and mentoring for 27 higher degree students and 21 undergraduate students at Monash University. It has facilitated a team of engineers from HRL Technology to gain unprecedented access to the top international coal gasification research facilities, as well as collaborations with leading research institutes around the world and has ensured that Victorian research has been regularly showcased at international conferences and in peer-reviewed publications. By any measure, the research leader fellowship program has been an outstanding success for BCIA and for the sustainable development of Victorian brown coal.

BCIA has also coordinated a postgraduate research scholarship program to help attract top students to the brown coal area. This program provided PhD scholarships to 16 promising young researchers through a competitive selection process. In 2010–2011 there were six full scholarships awarded, and in 2014–2015 there were 10 scholarships awarded to supplement Australian Postgraduate Awards. Scholarships provided a higher level of support for living, travel and research costs than a standard PhD scholarship, giving incentive to undertake brown coal research in Victoria.

Projects funded through BCIA's research portfolio have contributed to the training of higher degree students. Research on many projects relied on PhD students taking a leading role, usually supported by experienced supervisors and early-career post-doctoral fellows. Between them, BCIA's research scholarship program and research project portfolio have provided support for nearly 40 higher degree students and six post-doctoral fellows.

Source: © CO2CRC.

BCIA has been active in working to align the Latrobe Valley skills base with future needs. This has been achieved by organising awareness raising, knowledge exchange and networking opportunities. It has included facilitating regional industry and employment focused workshops, and subsidising access to technical training seminars.

BCIA instituted a future-skills working party for Victoria's brown coal industry. The working party identified the need for a skills audit in the Latrobe Valley, and for efforts to improve the public perception of the brown coal industry as a whole. It developed an action plan to assist in Victoria's transition to a low emissions future.

BCIA's skills development program has been successful in attracting recognised brown coal leaders to Australia, in setting a purposeful research agenda and in helping to champion the next generation of brown coal leaders.

For more details see page 99.

Networks and Linkages

Australia is one of the most creative and innovative nations in the world, however, we represent just 0.33% of the world's population.

With Australian government spending on science and innovation at its lowest levels in 30 years, it is more important than ever that Australia links to and builds upon international technology advances.

The US, Japan, Europe and China are showing the way forward for low emissions coal-to-power, coal upgrading and carbon capture technologies. By linking with these activities, Australian researchers are able to share our developments and advances, and can access know-how and facilities that may not exist locally. This helps to accelerate the local development and deployment of new, environmentally responsible uses of brown coal.

One of BCIA's prime objectives is to foster these linkages between Australian R&D projects and local and international stakeholders. The company has had great success in this regard. Nearly 50 local and international government, industry and research organisations are involved in BCIA's research activities. In addition, BCIA has built a database of nearly 1,200 brown coal stakeholders across over 500 local and international organisations. We share information on R&D progress with our stakeholders through newsletters, media releases, research seminars and conferences, and produce commissioned reports on topics of relevance to the industry.

BCIA has established formal and informal networks and linkages across the brown coal sector, connecting stakeholders, providing expert technical advice, providing market intelligence for policy setting, and helping to leverage investment opportunities across Victoria, Australia and globally.

BCIA functions as a trusted intermediary on behalf of all stakeholders in the brown coal innovation cycle.

- **Collecting vital business intelligence** and acting as a 'trusted advisor' to industry and government to assist in policy and project development.
- **Engaging directly with industry and researchers** and co-ordinating an outcome-based R&D investment program that is aligned with identified needs.
- **Shaping a 'futures' perspective for the use of Victorian brown coal**, building on global experience to direct a local R&D agenda that focuses on medium- to long-term technological advances and skills development.
- **Fostering efficient and effective collaboration** across government, industry and the research community, whilst maintaining an appropriate level of transparency and accountability to key stakeholders.
- **Leveraging international capability and advancements** in environmentally responsible uses of coal, attracting international technology vendors to trial technologies in Australia, and gaining access to international pilot- and demonstration scale facilities to accelerate the development of local technologies.

BCIA has successfully established a reciprocal membership option to attract international organisations. The flexibility of this arrangement suits both parties, providing a two-way knowledge exchange platform. Flagship international members include Japan Coal Energy Center (JCOAL), the Japanese coal industry body, and the US based Lignite Energy Council, the major body fostering new developments in brown coal in the US.

As a participant in the Australian Coal Industry Consortium, BCIA is also a member of the IEA Clean Coal Centre, based in the UK.

A major component of BCIA's Networks and Linkages program has been our involvement in global CCS activities, as members of the CO2CRC from 2010–2015, and of the Global Carbon Capture and Storage Institute (GCCSI).

BCIA's membership of the CO2CRC has allowed the company to provide input into, and access to the findings of, the storage and capture research programs. In addition, BCIA has supported the development and operation of pre- and post-combustion capture facilities operated by the Cooperative Research Centre (CRC).

Through our membership of the GCCSI, BCIA gains access to international information on CCS development, as well as access to the policy development and advocacy of the Institute.

Examples of international projects sponsored by BCIA include the testing of Australian coals in pilot scale facilities in the US (gasification) and China (oxy-fuel), and the relocation of a Japanese built carbon capture pilot plant to the Latrobe Valley to support long-term trials on local flue gas composition.

BCIA has supported local research teams with funding to coordinate their developments with EU-funded projects, and provided support to facilitate large-scale testing of coal-water fuels in a demonstration engine in Japan.

BCIA has helped form international groups to support technology development, and was a founding member of DICE-net, aimed at accelerating the development of the DICE technology.

In additional to formal activities outlined above, BCIA encourages sharing of ideas and knowledge through sponsorship of events, and running conferences, research seminars and community forums.

We have sponsored workshops to build collaboration between local researchers and industry, as well as workshops building research partnerships with groups in Europe, Asia and the US (Figure 4). BCIA has presented its work at international conferences and continues to support local researchers to share their results.

For more details see page 105.

Figure 4: BCIA has sponsored workshops with groups in Europe, Asia and the US

BCIA MEMBER

History of BCIA's members

State Government Victoria
Since 2009

anlecr&d
Since 2011

JCOAL Japan Coal Energy Center
Since 2011

MONASH University
Since 2011

CSIRO
Since 2011

Ignite Energy Resources
Since 2012

Lignite Energy Council
2013

exergen
Since 2016

Federation University Australia
Since 2014

Greenpower Energy
Since 2014

CoalEnergy Australia Limited
Since 2016

Environmental Clean Technologies Limited
2011–2016

HRL Technology | HRL
2011–2015

Mantle Mining Corporation Ltd
2012–2014

Steele Australia
2012–2016

EnergyAustralia
2011–2015

New Opportunities for Victorian Brown Coal

"Expectations get raised when people first read about a technological breakthrough. They speculate about its potential. Then nothing seems to happen because the growth curve for technologies in their early stages is more or less flat. Disappointment sets in and the blame game begins. Then, like popcorn in a microwave, the kernels start to pop faster. New products come out of nowhere. The technology curve slopes steeply upwards and disappointment turns into amazement."(1)

While the above quote was written about 3D printers, it applies equally to coal technologies. Many in the community will think that "coal is dead", but this is far from being true. Coal has experienced the largest growth of any power-generation technology over the past decade. This has been driven by the economic development of Asia and India, and is projected to continue for several decades to come. At the same time, China has led the way in developing a modern coal-to-chemicals industrial base. Following on from these developments, the prospects for a coal-to-chemicals industry in Australia has never been greater.

World-changing innovations can be a hard sell when they are new. For example, the first laptop computer had only 340 kilobytes of memory and sold for an eye-watering A$27,000. Today, CCS is an expensive option, but as stated by the UN's Intergovernmental Panel on Climate Change, the world's climate goals may be unobtainable without it. Already great strides have also been taken towards reducing costs and delivering commercially affordable carbon capture technologies. However, further R&D is needed to deliver even greater cost reductions.

The cost of new build low emissions coal plants today is higher than for existing power generation technologies, and the future of coal for power generation in Australia is under question.

Australia is focused on achieving an increase of intermittent renewable energy sources such as solar and wind. For a considerable time to come, however, the increased use of these intermittent power sources will need to be supported by the availability of reliable, dispatchable low emissions power.

New brown coal technologies plus CCS can meet this need, delivering flexible, low-cost low emissions power, and insulating the country from the volatility of gas prices.

Brown coal can have a bright future in an emissions constrained future – not just for power generation, but as a feedstock for a range of products such as hydrogen and fertilisers. Such uses of coal will not only support existing power-sector jobs, but deliver increased economic prosperity, especially in regional Victoria.

However, to secure this future requires a strong focus on innovation to adapt technologies to Australian conditions, reduce the cost of CCS, optimise manufacturing processes and deliver greater flexibility from low emissions coal-to-power options. Investment into a continuing program of R&D will deliver great rewards, and deliver new options to reduce the cost of a transition to a lower emissions future.

In looking to the future of brown coal, BCIA sees the need to focus on three main areas.

1. Developing options for future uses of Victoria's carbon resources.
2. Providing low cost technology pathways for transition from current brown coal based electricity generation.
3. Supporting economic growth and job creation via new manufacturing opportunities.

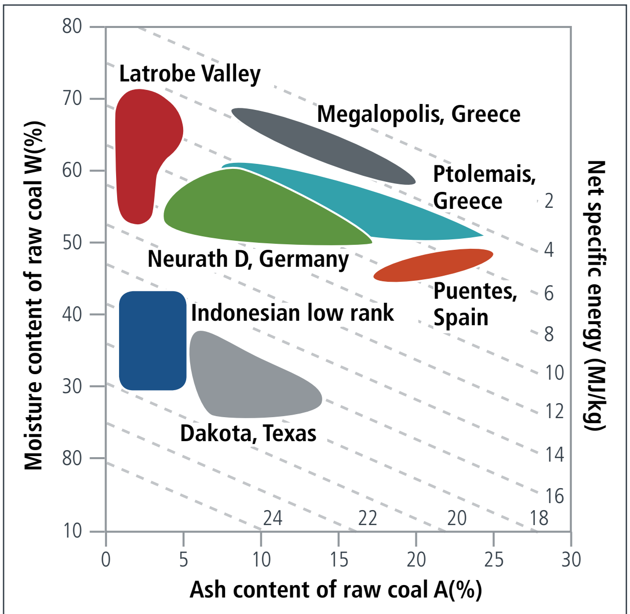
The opportunities associated with each of these areas are discussed below.

(1) Vivek Wadhwa, Washington Post, 2 August 2013.

Options for future uses of Victoria's carbon resources

Victoria's Latrobe Valley contains a vast resource of brown coal, approximately one quarter of the known reserves in the world, of which 33 billion tonnes are potentially economic. The chart below shows that Latrobe Valley brown coal contains very low impurities by world standards, but a high moisture content. To date, the high water content and reactivity of Victoria's brown coal have been a barrier for export, so the main economic use has been for local power generation.

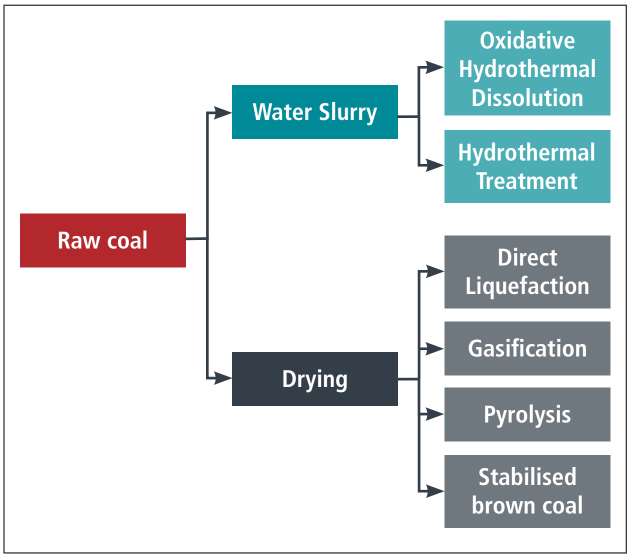
Figure 5: Moisture content vs. ash content of raw coal



The economic reserve of Latrobe Valley brown coal contains about 14 billion tonnes of carbon. This is equivalent to about half the carbon content of Saudi Arabia's crude oil reserve, so it is a very significant resource by world standards. The Victorian economy would benefit enormously if cost-effective low emissions processes can be developed to utilise this plentiful and relatively clean resource.

There are a range of processing techniques that could be used to add value to Victorian brown coal, as shown in Figure 6. Brown coal has the potential to be transformed into a wide range of valuable products, ranging from relatively low value (e.g. agricultural inputs), through a variety of industrial chemicals and fuels, through to high value specialty materials (e.g. polymers, carbon fibres). Many of these materials are either directly or indirectly required for the manufacture of low emissions power technologies such as solar, wind and storage batteries.

Figure 6: Coal processing options



To date, there have been only a few products from brown coal that have been successfully commercialised for the export market, e.g. briquettes, char, humates. There is clearly potential for Victoria's clean carbon resource to underpin a new generation of export-oriented manufacturing industries.

Currently, heavy manufacturing industries, such as cement, iron and steel, chemicals and refining, account for one fifth of global greenhouse gas (GHG) emissions. Economic growth in China and India will see demand for these products continue to grow. Fortunately, CCS is beginning to be applied to these industries. In fact, up until mid-2014, all large-scale CCS and CO_2 capture projects in operation were in industrial sectors.

Plants that capture up to 1 megaton of CO_2 per year operate today in the gas processing, refining, chemicals and biofuels sectors. These sectors have developed technologies to take advantage of commercial demand for cheap CO_2 and their relatively low specific costs of CO_2 capture [(2)].

The Victorian economy can potentially be transformed by industrial processing of brown coal, but only if the resulting CO_2 emissions are captured. Victoria has some of Australia's best geology for CO_2 sequestration in the Gippsland Basin, so it is feasible to achieve low-emission brown coal processing. In addition, recent years have seen increasing development of industrial applications of waste CO_2, especially in the fields of solar fuels (power-to-fuel, power-to-gas) – but also in CO_2-based chemicals and polymers. This presents a further opportunity for green manufacturing industries in Victoria.

The technologies that could be used to create new products from brown coal are at various stages of development. The most mature are pyrolysis and entrained flow gasification, which are commercial elsewhere in the world. Direct liquefaction has been operated at demonstration scale in Victoria, and hydrothermal treatment has been demonstrated at pilot scale. New processes, such as torrefaction for coal drying, oxidative hydrothermal dissolution and production of Micronised Refined Carbon (MRC) fuel for DICE, require further development at pilot and demonstration scale.

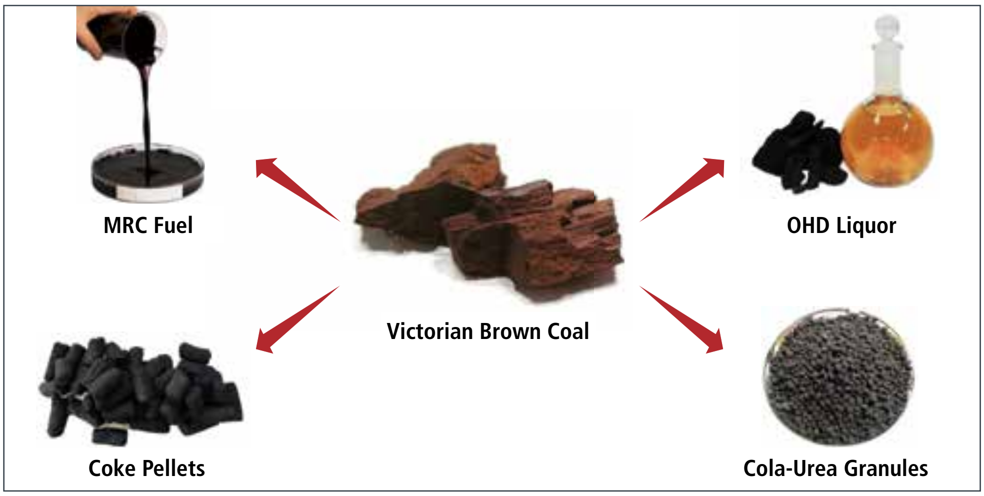
Through its first five years of operations, BCIA has committed 15% of its total portfolio to research on new products from brown coal. This has included research on the production of stable granules from brown coal, and transformation of coal into blast furnace coke and activated carbons for hydrogen storage and CO_2 capture. BCIA has also supported research into the agricultural applications for brown coal and coal-derived humates, which has identified the potential for coal-fertiliser blends to reduce agricultural GHG emissions.

Oxidative Hydrothermal Dissolution (OHD) is a novel process that is being developed by Thermaquatica with the support of Greenpower Energy, a BCIA member company. In the OHD process, brown coal can be dissolved in oxygenated hydrothermal water. Essentially complete conversion of the coal is readily achievable, converting brown coal to a solution of monoaromatic acids and phenols. The composition is completely different than that produced by liquefaction of coal by hydrogenation, and offers a host of new product possibilities, including conversion to plastics, carbon fibres, liquid fuels and agricultural inputs. Researchers at the Carbon Nexus research facility in Geelong have shown that a similar material (organosolv lignin) can be used as a precursor for carbon fibres [3].

Some of the new products that have been produced from brown coal over the past five years are illustrated below. Each of these represents a very early stage of development, but each has great potential to create new product opportunities.

(2) International Energy Agency. Industrial applications of CCS. www.iea.org/topics/ccs/subtopics/industrialapplicationsofccs
(3) Oroumei A, Fox B, Naebe M. Thermal and rheological characteristics of biobased carbon fiber precursor derived from low molecular weight organosolv lignin. ACS Sustainable Chem. Eng. 3: 758–769.

Figure 7: Value-added products from brown coal



BCIA has also supported research on the fundamentals of entrained flow gasification, products from gasification (e.g. hydrogen, dimethyl ether, ethylene glycol), and opportunities for solar-assisted gasification. Oxygen-blown entrained flow gasification is regarded as a key enabling technology to unlock the true industrial potential of Victorian brown coal, as it allows production of a range of important industrial chemicals (e.g. hydrogen, ammonia, methanol) which can be transformed into higher-value products such as fertilisers, plastics and fuels. Such products are in high international demand, and have the potential to transform Victoria's huge carbon reserves into a thriving export economy.

One product of particular interest is hydrogen, which can be used as a fuel for electric vehicles. The Japanese Government is strongly supporting the development of a hydrogen supply chain in anticipation of a sharp increase in the use of hydrogen as an energy source from 2025. Japan has plans to turn the athletes' village for the 2020 Olympics in Tokyo into a "hydrogen town", where electricity and hot water are generated from hydrogen (4).

Both Toyota (5) and Honda (6) will launch inexpensive fuel cell vehicles ahead of the Olympics, and 35 hydrogen filling stations will be installed around Tokyo (7). Victoria's brown coal is regarded as a prime candidate to provide hydrogen to Japan (8). There is thus a real opportunity to create a significant new export industry for Victoria and, at the same time, support an emerging market for hydrogen-fuelled vehicles in Australia.

Figure 8: Illustration of a hydrogen ship

Similarly, the People's Republic of China is seeking to import clean fuels to help solve its air pollution problems. China regards diesel engines as its longer-term transport option, and is developing coal-derived dimethyl ether (DME) as an environmentally benign diesel alternative (9). An ammonia-fuelled car is being developed in South Korea (10) and ammonia-fed fuel cells are being developed in Europe for stationary power generation (11).

Value-added products such as hydrogen, DME and ammonia, produced from brown coal and decarbonised using CCS, represent potential new export markets for Victoria. The Latrobe Valley is thus ideally positioned to become a powerhouse of new economic growth and commercial activity, supported by world-leading innovation, R&D in low emissions coal technologies.

It is important that efforts continue to be made to develop new product opportunities for Victorian brown coal. It is especially important to focus on product opportunities that will be commercially competitive in an emissions-constrained economy.

Examples from more mature industrial sectors indicate that CO_2 capture can provide a competitive advantage if the CO_2 can be effectively utilised. Little emphasis has been given to this in Australia, where the main focus has been on geosequestration, but green manufacturing processes involving CO_2 upgrading may provide a crucial competitive advantage.

As an example of this, Bayer is currently operating a polyol pilot plant using carbon dioxide captured from a lignite power plant in Niederaußem, Germany.

(4) www.ibtimes.co.uk/japan-plans-develop-2020-olympics-village-into-hydrogen-town-1482091.
(5) www.inhabitat.com/test-drive-10-things-you-need-to-know-about-toyotas-2015-hydrogen-fuel-cell-vehicle.
(6) www.automobiles.honda.com/fcx-clarity.
(7) www.bdlive.co.za/business/innovation/2015/02/17/japan-to-use-olympics-to-enter-hydrogen-era.
(8) Yoshino Y, Harada E, Inoue K, Yoshimura K, Yamashita S, Hakamada K (2012). Feasibility study of "CO_2 free hydrogen chain" utilizing Australian brown coal linked with CCS. Energy Procedia 29: 701–709.
(9) Fleisch TH, Basu A, Sills RA (2012). Introduction and advancement of a new clean global fuel: The status of DME developments in China and beyond. J. Natural Gas Sci. Eng. 9: 94–107.
(10) www.nh3fuelassociation.org/2013/06/20/the-amveh-an-ammonia-fueled-car-from-south-korea.
(11) www.nh3fuelassociation.org/2013/04/25/project-alkammonia-ammonia-fed-alkaline-fuel-cells.

Polyols are the major component of polyurethanes, which make up foams or thermoplastic urethanes in a wide range of applications, and are usually made from fossil fuel-based feedstocks. The Bayer process emits 11%–19% less GHG and saves 13%–16% of fossil resources in comparison to traditional polyether polyols. In addition, each 1kg of carbon dioxide used to produce polyols can save more than 2kg of carbon dioxide-equivalent emissions, due to the substitution of emission-intensive epoxides [(12)]. Clean, green processes such as this have the potential to help transform Victoria's manufacturing sector.

The Victorian and Commonwealth Governments are supporting the development of brown coal upgrading technologies through its Advanced Lignite Demonstration Program (ALDP). This program will allow the pre-commercial evaluation of hydrothermal and pyrolysis processes, producing stabilised coal solids and oils for market evaluation. It may be expected that further research is needed to optimise the operating conditions and downstream processing methods to tailor the products to meet market requirements.

Beyond this, further research funding is essential if the full industrial potential of Victorian brown coal is to be realised. BCIA has made a promising start in this area using only 15% of its portfolio budget, but a significantly larger investment will be required to bring new technologies to fruition. It is important to support new processes in the transition from the laboratory to pilot scale, so that proof-of-concept work can be undertaken at sufficiently large scale to attract investor funding. The potentially bright future for Victorian brown coal simply will not eventuate unless the government continues to support early pilot-scale research.

BCIA has proven its ability to successfully cultivate promising new technologies. There is a range of new technologies that justify further support and development.

- Granulation and blending of coal with organic or chemical fertilisers, to improve fertiliser efficiency and reduce agricultural GHG emissions. Scale up and field trials are required.
- Pilot-scale torrefaction of coal produce a dry, stable semi-char from brown coal, wood or agricultural waste, suitable for granulation.
- Development of MRC fuel production process, to convert any grade of brown coal (potentially blended with biomass) into a standardised fuel suitable for use with DICE.
- Pilot-scale entrained flow gasification of brown coal for production of hydrogen.
- Pilot-scale OHD processing of brown coal and evaluation of production of polymers, carbon fibres, agricultural inputs and fuels.
- Development of blast furnace reductants from pyrolysed or hydrothermally treated brown coal.
- Production of hydrogen using solar-assisted electrolysis of MRC fuel.

For these and other prospective technologies, emphasis should be given to those that can deliver both a competitive advantage and low GHG emissions. Support should also be given to the development of green technologies that can convert waste CO_2 into value-added products such as plastics.

The Latrobe Valley has the potential to become a powerhouse of new economic growth and commercial activity, with new manufacturing industries transforming Victoria's massive carbon reserves into a variety of low emissions products for international export. Such industries could be the source of many new, highly-skilled jobs in the region, reducing the reliance of the Latrobe Valley economy on the power generation sector.

Providing low cost technology pathways for transition from current brown coal based electricity generation.

(12) www.rsc.org/chemistryworld/2014/05/polyol-polymers-greenhouse-gas-emissions-polyurethanes-fossil-fuel-depletion.

Market failures lead to under-investment in innovation. This concept has been the driving principle for publically funded R&D for the last half century, and is central to the need for support for innovation in the area of low emissions technologies.

The entrenched difficulty of tackling climate change through market mechanisms is clear for all to see. Across the world, governments are addressing the market failure through policy initiatives including putting a price on environmental negatives, and financing incentives for delivering environmental positives. Such policies generally include government support for technology research and development, particularly in light of the public good outcomes from R&D in this arena.

For new energy technology development in Australia, there are additional barriers for innovation including the following.

- The high up-front cost of development.
- Long timescales for infrastructure replacement.
- Market uncertainties caused by past policy variability.

These barriers to innovation introduce a high degree of uncertainty and risk when evaluating potential new low emissions technologies. Numerous past examples show that there is a very real risk that changing circumstances can render new technologies obsolete before they reach maturity.

For this reason, prudent innovation policy should involve support for a portfolio of potential new low emissions technologies to reduce the overall exposure to risk. Moreover, the technology portfolio should be actively managed over time, to provide continued support for successful technologies and to divert resources away from those that prove unsuccessful.

In the energy sector, where a variety of new renewable and non-renewable technologies is emerging, a portfolio approach is an especially important investment strategy. There is no one technology that is likely to replace the current fleet of brown coal power stations in Victoria. Instead, there will need to be a suite of technologies that can support increased penetration of intermittent renewable energy sources while still delivering dispatchable, low emissions electricity.

Supporting one approach (e.g. renewables) in the absence of support for others will not deliver the suite of technologies required. Similarly, support for basic research alone, without policies to foster the commercialisation of green innovations, may lead to projects that are “stuck in the laboratory”.

BCIA was established primarily to manage innovation funding to support the development of Victoria’s brown coal reserves. It has supported the development of new, low emissions power generation technologies using a portfolio approach, with a strategic, industry-led and policy informed focus.

BCIA’s main emphasis in its first five years has been predominantly on technologies to produce low emissions dispatchable power from brown coal. It has supported research on a number of prospective new technologies, including oxy-fuel combustion, Chemical Looping Combustion (CLC), Moderate or Intense Low-oxygen Dilution (MILD) combustion, Direct Injection Carbon Engine (DICE) and Direct Carbon Fuel Cells (DCFCs).

Each of these offers significant advantages in terms of efficiency and reduced cost of CO_2 capture, but they are all at different levels of technological readiness. Each of these technologies has the potential to be successful over the longer term, depending on the interplay of a variety of external factors.

While the current fleet of inefficient brown coal power stations will definitely need to be phased out, the need for inexpensive dispatchable power will remain, especially for industrial use. The increased penetration of intermittent renewable energy sources will create a number of problems that must be creatively managed.

Wind is the leading form of distributed renewable power being installed in Victoria. Since wind power is intermittent and varies throughout the day, it must be partnered with some form of flexible power delivery system to ensure that the power generated matches the hour-by-hour demand.

The brown coal power stations currently in operation have been designed to operate continuously at full capacity. Operating at partial loads reduces their efficiency, leading to increased CO_2 emissions per megawatt of power produced. The effect can get worse the more intermittent energy is added to the system. Real data has been used to show that in Ireland, at just 17% penetration of wind, the effectiveness of wind as a CO_2 abatement measure was almost halved [13].

A solution to this problem is to use a mix of baseload and load following power plants to balance the intermittent power from renewables. Load following power plants are brought on and off line in response to changing output from renewables, and so must be flexible enough to start up and shut down without losing efficiency. Load following power plants are typically hydroelectric, diesel or gas engine, or combined cycle gas turbine power plants.

The demand for load following power will rise with increasing penetration of renewables. Currently, the need for load following power in Australia is met using gas and hydroelectricity. However, there is limited ability to build new dams for hydroelectric power, and volatility in gas prices has already led to significant price spikes in the wholesale electricity market in South Australia, so a lower-cost alternative will be needed.

Another issue of concern is that the sources of renewable energy are not necessarily close to the main population centres, requiring extension of the existing electricity grid. In Victoria, for example, the main sources of wind and solar thermal are in the north and west of the state, and there is insufficient grid infrastructure to power Melbourne and Geelong from these locations.

A similar situation exists in Germany, where the main population is in the south, close to dispatchable nuclear power, while the main source of wind is in the north. Over the past 15 years, as the proportion of renewable energy has grown to 28%, the total investment cost for new transmission systems, etc., has reached nearly €20 billion and electricity prices have doubled [14].

Germany is also similar to Victoria in that it has a strong reliance on lignite for inexpensive power generation. Germany plans to increase the proportion of renewables from the current 28% to 75% by 2020, but is grappling with the problem of ensuring a stable power supply. There is currently a policy to pay some lignite power stations to idle in reserve to ensure that there is sufficient spinning capacity to meet peak demands. However, this is a very expensive and short-term solution, and it is unclear what the solution will be for the long-term.

The goal of Victoria's energy investment policy should be to transform the power sector to a low emissions target at the lowest possible cost, while maintaining reliability of supply. Balancing the three pillars of low emissions, high reliability and low cost will necessarily involve striking an appropriate and cost-effective balance between intermittent renewables and alternate sources of power such as dispatchable fossil fuel plus CCS.

Of all the prospective new technologies that have been supported by BCIA, only two have the capacity to be used as load following power plants for integration with renewables, these being DICE and DCFC. DICE is much closer to commercial reality than DCFC, which is still at an early stage of development. The current national DICE Development program, which will demonstrate combustion of black and brown coal MRC fuels in a test engine in Japan, follows several decades of successful DICE development work in the US. The engine manufacturer involved in the current program, MAN Diesel & Turbo, has the expertise to overcome any technical challenges involved, so the main risks to the success of DICE in Australia are commercial ones, just as they were in the US.

If the research outcomes are as anticipated, brown coal MRC-DICE will be able to provide efficient, flexible power, cost competitive with gas, while operating at double the efficiency of the current Latrobe Valley power stations.

(13) Wheatley, Energy Policy Volume 63, December 2013, p 89–96. Great care must be taken in extrapolating the magnitude of such effects to other grids that use a different power generation mix.
(14) Professor Andreas Löschel. Germany's energy transition and implications for Australia. University of Melbourne, 2-Sep-2015.

DICE would be an ideal load following power plant to complement wind farms, such as the Macarthur wind farm in western Victoria. The 140 turbines have the ability to produce a peak power of 420MW, with a long-term average generating capacity of around 147MW. Assuming that 420MW of DICE capacity would need to be installed to cover for times when wind is too strong or too slow, calculations using Bureau of Resources and Energy Economics (BREE) cost data indicate that using DICE as a backup for Macarthur would reduce overall power prices, and enable 420MW dispatchable power. Even without CCS, net emissions for this hybrid wind-coal plant would be roughly one third of the emissions from today's brown coal plants.

Both the heat and CO_2 produced from large diesel engines can be used for agricultural purposes (below: a diesel generator being installed at a greenhouse operation in Europe). Alternatively, the heat generated can cost-effectively power a CO_2 capture system, with the CO_2 then geologically sequestered or converted into new products. Using a proportion of fuel sourced from renewable resources such as biomass can reduce the emissions profile further, and the combination of DICE and CCS could ultimately provide zero, or negative emissions.

Figure 9: A diesel generator being installed at a greenhouse operation in Europe

The DICE technology therefore has the potential to assist in reducing Victoria's GHG emissions, while also generating significant revenue for Victoria. Flexible power from DICE generation using Victorian manufactured fuel could support increased renewables penetration across Australia, Japan and Korea, with markets opening up across the world as the technology gains wider acceptance.

Recognising the international potential of DICE technology, BCIA has been instrumental in establishing a consortium of local and international industries with an interest in promoting its development, known as DICEnet (visit www.dice-net.org for more details).

Members of DICEnet include MAN Diesel & Turbo (Denmark), AGL Loy Yang, EnergyAustralia, Ignite Energy Resources, Exergen, GHD, Worley Parsons, Glencore, Newcrest, Yancoal, RWE Power (Germany), JGC Coal Fuel (Japan), Sinarmas Group (Indonesia), CSIRO, ACALET and BCIA.

The mission of DICEnet is to support the development of DICE for integration with renewable energy sources, through the following.

- Development of DICE fuels utilising abundant and low-cost coal reserves and biomass.
- Demonstrating low market entry cost through modularisation and using standard engine technology.
- Demonstrating the CO_2 emissions and other environmental credentials of DICE.
- Demonstration of DICE as a complementary generation partner with load variable and distributed renewable energy sources.

DICEnet meets on a quarterly basis, with international participants attending by teleconference. The strong support shown by industry has been very important to MAN Diesel & Turbo, which is eager to pursue the commercial development of DICE and has set out a pathway to achieve this.

The successful completion of the current DICE development program will set the stage for the next phase of technology development, which will involve thousands of hours of operation in a demonstration scale engine. This work is necessary to validate the working life of the hardened engine components, so that the manufacturer can provide the necessary commercial performance guarantee.

DICEnet will take the lead in progressing DICE through to the demonstration stage, and is keen for this to occur in Victoria. Hosting the demonstration engine in the Latrobe Valley would be a major coup for Victoria. While the intellectual property for the engine itself will belong to the engine manufacturer, commercialisation of the technology will require know-how relating to fuel preparation, fuel storage, exhaust gas filtration, integration with CCS, etc. There will be an opportunity for local companies to develop valuable expertise that could be commercialised internationally along with DICE. This opportunity will be unique to those companies involved in the demonstration phase.

Commercialisation of DICE will create new prospects for brown coal power generation in the Latrobe Valley. It would no longer be necessary to close down the existing power stations completely, causing a massive blow to the local economy and a loss of highly skilled expertise. Instead, it would be possible to encourage the phased introduction of DICE power generation, to adjust the balance of baseload and load following power to match the progressive introduction of renewable power. Using brown coal as the source of load following power will be cheaper than gas, ensuring that Victorian electricity prices remain competitive with other states.

Even without CCS, the introduction of DICE technology along with renewable energy sources will substantially lower Victoria's GHG emissions. If DICE is coupled with CO_2 capture, and CO_2 storage in the Gippsland Basin, emissions would fall further. If the brown coal fuel is supplemented with plantation biomass then emissions would fall further still.

Therefore, DICE technology could allow the Latrobe Valley power industry to transform in a way that complements the progressive introduction of renewables, preserving jobs, reducing GHG emissions, avoiding the cost of new grid infrastructure, and keeping the cost of electricity as low as possible. As such, it is important to support the development and deployment of DICE in the Latrobe Valley as quickly as possible.

Supporting economic growth and job creation via new manufacturing opportunities.

The mining and power industries are key generators of employment, wealth and general demand for goods and services in regional areas. Jobs in mining and energy in regional areas have a high multiplier effect in terms of flow-on benefits to job creation in the local community. This is because these industries are capital intensive, pay above-average wages, and sell their product beyond the region (thereby bringing income into the region). Each job in the mining and energy sector creates four to five other jobs. When dependent family members are included, each mining or power station job directly or indirectly supports about ten people [15].

In the Latrobe Valley, electricity generation from brown coal is the backbone of the local economy. This industry accounts for about 21% of the Gross Regional Product of Latrobe City, supporting approximately 5,600 jobs [16] and contributing A$181 million in wages to the economy each year [17].

Transformation of the Latrobe Valley into a low emissions power and manufacturing hub will necessarily require implementation of CCS technologies. This will bring additional benefits to the local community.

(15) www.energyandresources.vic.gov.au/energy/about/legislation-and-regulation/near-zero-emissions/strategic-policy-framework-for-near-zero-emissions-from-latrobe-valley-brown-coal/submissions/latrobe-valley-brown-coal-submissions-cfmeu?SQ_DESIGN_NAME=mobile&SQ_ACTION=set_design_name
(16) Latrobe City Council (2011). Submission on Clean Energy Finance Council, 11-Dec-2011.
(17) IBIS World Industry Report B0602 (2013). Brown Coal Mining in Australia.

Research in the UK has suggested that between 1,000 and 2,500 jobs are created during construction in each new CCS installation, with a further 20 to 300 jobs created in operation and maintenance and the associated supply chain (40 to 100 jobs at the plant itself) [18]. This is consistent with the CCS installation at the Boundary Dam lignite power station in Canada, which employed more than 1,500 people during construction and maintains 41 operational employees at the plant itself.

The Latrobe Valley is already home to a strong oil and gas industry. The skills and expertise in this industry are directly applicable to new CCS installations, which will involve engineering design, project management, procurement and commissioning activities. The installation of a pipeline to transport CO_2 for storage would create additional opportunities for such skills, and operation of the pipeline would create more highly paid jobs.

The expertise gained in construction and operation of CCS infrastructure in the Latrobe Valley would be applicable elsewhere in Australia and internationally. It is expected that global deployment of CCS will proceed rapidly during the 2020 to 2030 period, creating new opportunities for Latrobe Valley engineering companies and generating revenue for the local economy.

The Latrobe Valley has the potential to become a powerhouse of new low emissions economic growth and commercial activity, while securing the jobs of the current coal workforce. Achieving this will require investment in low emissions coal technology development and innovation, and support for the most promising technologies on their pathway through to commercial deployment.

R&D is known to be an important driver of economic growth. It is a key factor in developing and applying the new technologies that underpin many of the industries that are crucial to economic competitiveness. In the long run R&D investment benefits competitiveness, growth of companies and overall economic growth, delivering a return of nearly A$2 for every dollar invested.

Successful R&D cannot be supported by the private sector alone. The long-term nature of innovative research means that it cannot deliver the short-term return on investment that industry demands. This creates a market failure with respect to successful R&D, which is further reinforced by the following [19].

- **Significant knowledge externality and spill over.** Knowledge is a public good therefore industry will not be able to capture the full knowledge benefit of investment in innovation.
- **Second mover advantage.** Due to the conceptual risks associated with innovation, investors prefer to contribute rather than initiate R&D.
- **High short-term opportunity costs.** The cost of investing in the development of new technology is comparatively higher than adapting existing technology – acting as a short-term disincentive to invest.

Long-term government commitment (and funding) to overcome this market failure is critically important for achieving sustained economic growth. However, simply investing more in research (especially in academic research) is not sufficient for successful innovation. Applied R&D, education, market development, the quality of organisation and management, etc. are all just as important.

The transition from laboratory to pilot scale to demonstration scale must be properly supported, with industry becoming more responsible for funding as the technology matures.

This process must be professionally coordinated to avoid unnecessary waste of scarce resources. And, importantly, there must be realism about the timeframe involved in validation of new technologies to the degree necessary for commercial investment.

Over the past five years, BCIA has played an important role in fostering new technologies that can help to transform Victoria's economy. It has adopted a strategic portfolio investment approach, working to get technologies out of the laboratory and setting signposts for success.

BCIA has focused on building the research and job skills that will be needed for new projects, and has created a network of industry links and international contacts to support investment in new technologies.

Victoria is home to world-class research facilities, with the specialist equipment and experience to support the development of low emission brown coal technologies. These include CSIRO, HRL Technology, the Australian Synchrotron, Monash University, Federation University, the University of Melbourne, Deakin University and RMIT University. Other facilities with brown coal research expertise are located throughout Australia, i.e. CSIRO in Newcastle and Brisbane, the University of Adelaide, and Curtin University in Perth. Each of these facilities offers specialised resources, and no one facility has the ability to undertake all aspects of brown coal R&D.

To make the most efficient use of the resources available for brown coal R&D, it is necessary to undertake research in a collaborative and coordinated manner. BCIA is the only Australian organisation focused solely on the environmentally beneficial development of Victoria's brown coal by investing proactively in the development of technologies and people to broaden the use of brown coal for a sustainable future. Over the past five years, BCIA has actively worked to shape a 'futures' perspective for the use of Victorian brown coal, by fostering efficient and effective collaboration across government, industry and the research community.

BCIA has effectively managed brown coal R&D funding in an open and transparent manner, using an evaluation framework focused on milestones and deliverables. It has leveraged Victorian government funding by 250% to create a balanced investment portfolio worth A$51.1 million, with short and long-term commercialisation pathways aligned with industry outcomes. BCIA has achieved a reputation amongst its members as a 'trusted advisor', promulgating the uniqueness of Victoria's brown coal and how and why the success of commercialisation in the State requires investors to fund local R&D programs to adapt technologies.

Victoria's carbon resource can be transformed into low emissions power and new value-added products, and will rejuvenate the Latrobe Valley economy in the process, but courage, vision and sustained support for research, development and demonstration activities are needed.

(18) Carbon Capture and Storage Association (CCSA) and the Trades Union Congress (TUC) joint report "The Economic Benefits of CCS in the UK", February 2014.
(19) Garnaut Climate Change Review Update (2011), Low Emissions Technology and the Innovation Challenge.

Technology Research & Development

This section provides brief summaries of each of the projects in BCIA's technology R&D portfolio. In order to show how BCIA has supported the development of individual technologies, the projects are grouped according to technology area and are presented in chronological order. Since PhD projects form an integral part of the technology investigations, summaries of PhD projects supported by BCIA are also included in this section.

1. Low emissions power from brown coal

1.1. Improved efficiency of brown coal combustion

1.1.1. Pulverised Fuel (PF) steam boilers

All coal-fired power stations in Australia employ PF combustion technology, which involves burning finely-ground coal, with the heat used to convert water into high-pressure steam to drive an electrical generator. The four power stations in the Latrobe Valley use subcritical PF boiler technology, in which steam pressure is below 22MPa and temperature is below 540°C. Supercritical PF boilers, which are used in other Australian states, operate at pressures greater than 22MPa and temperatures of 600°C and above, resulting in higher efficiencies and lower greenhouse gas (GHG) emissions.

The Latrobe Valley power stations were designed to produce inexpensive electricity by burning brown coal fresh from the adjacent mines, but this benefit came at the expense of high GHG emissions. The average GHG intensity of Victorian coal-fired power stations is around 1.35 tonnes CO_2-equivalent per megawatt hours, which is 50% higher than the Australian average [(1)].

The power stations are all old – the youngest is 20 years old while the oldest is approaching 40 years of service – but that does not mean that efforts to reduce GHG emissions intensity should not be made.

Victorian sub-critical PF boilers operate at a maximum efficiency of around 28%, which is too low for viable post-combustion CO_2 capture. Eventually, the existing power plant will have to be closed, possibly to be replaced by new efficient, low emissions technology. In the shorter term, the most likely option would be to upgrade to supercritical PF combustion technology, or even to the emerging ultra-supercritical PF boilers.

Regardless, the next generation of boilers will operate at higher temperatures, and will be constructed from different grades of steel with markedly different properties.

The local industry will have to develop in-house knowledge to be able to effectively work with, and maintain, these new materials.

BCIA has supported two industry-led projects that address the issues faced by current power station operators. One involved a live trial of laser oxygen (O_2) and carbon monoxide (CO) monitoring instrumentation, with the potential to allow tighter control of the operating conditions for PF boilers (both sub-critical and supercritical).

The second was essentially a skills development exercise, providing local engineers an opportunity to develop their knowledge of the advanced materials that can lead to increased power plant efficiency, and to evaluate new plant life assessment methods that can potentially improve safety.

Laser based O_2 and CO monitoring

Improvements in on-line monitoring of power station outputs, such as monitoring the composition of the flue gas, can enable better control of boiler operation. This in turn can deliver reductions in CO_2 emissions and lower cost of operations.

A challenge for Australian brown coal power stations has been the accurate monitoring of oxygen and carbon monoxide – currently used gas probes monitor only at a single point, and so give only part of the picture.

The gas composition at a boiler outlet is not uniformly distributed, and changes with unit load and mill configuration. Current practice is to control the boiler using measurements of O_2 and CO from probes installed in the duct wall. These probes can measure only the concentration at a single point, which can be significantly different from the average in the duct. This problem is common to both black- and brown-coal-fired power stations.

This project involved long-term trials of two Siemens SITRANS-SL Tuneable Laser Diode Spectroscopy (TLDS) gas analysers, one measuring O_2 and other CO.

(1) "The Greenhouse Challenge for Energy", Position paper published by the Department of Infrastructure and Department of Sustainability and Environment, Victorian Government, December 2004.

Each instrument included a laser transmitter and receiver, located on opposite sides of the gas duct, allowing measurement of the average gas concentration along the path of the laser beam.

Laser instrumentation is not currently used in Australian coal-fired power stations. It is too expensive to purchase, install and calibrate a laser analyser for an equipment trial at an individual power station, particularly when the effectiveness of the instrument is unknown.

Accordingly, the BCIA-funded project was undertaken as a collaboration between both brown- and black-coal-fired power stations, so that the project outcomes could be available to power stations across Australia.

This project was led by HRL Technology in conjunction with EnergyAustralia Yallourn, with the support of Siemens and nine local and interstate coal-fired power stations. The aim was to test the two Siemens instruments and to determine if the use of laser based monitoring can improve power station performance and reduce GHG emissions.

The project involved the installation of O_2 and CO laser instruments at Air Heater #1 Inlet on Unit 3 of Yallourn W Power Station. The performance of both instruments was monitored under a range of different operating conditions (low load operation, different mill configurations and different O_2 set points) to check their accuracy and response.

The accuracy of the readings was determined by comparison with results obtained by duct traverses using HRL Technology's Multi Point Horiba Gas Analysis System (MPHGAS), a state-of-the-art extractive flue gas analysis system that is used to optimise boiler combustion.

Figure 10 shows an example of the measured CO distribution in the flue gas within the duct (*x* and *y* represent duct dimensions in mm), as well as the position of the laser beamline path.

Figure 11 shows the corresponding estimation of CO concentrations along the laser path, which was used to calculate the average concentration.

Figure 10: Measured CO distribution in the duct

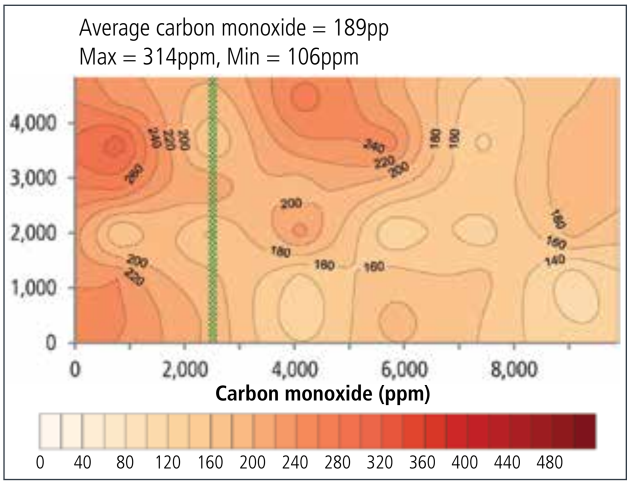
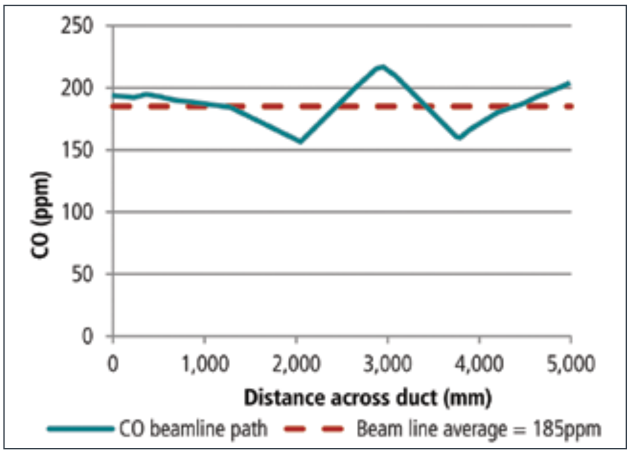


Figure 11: Estimated CO concentration profile



A major technical challenge during the project was that the laser instruments were designed to be operated with a continuous stream of nitrogen purge gas to prevent ash accumulating on the optics. Only bottled nitrogen was available at the power station site, which is not a cost-effective long-term operating option. However, compressed air was readily available and inexpensive. Accordingly, HRL Technology investigated the use of both nitrogen and compressed air as potential purge gases.

Using a nitrogen purge, the O_2 laser produced readings that were more representative of actual O_2 concentrations than the existing sensors used in the power station. When air was used as the purge gas, however, the O_2 readings fluctuated widely. The project concluded that the O_2 monitor could not operate with sufficient stability using a compressed air purge gas, and so an on-site nitrogen generator would be needed to produce the purge gas for the O_2 laser instrument. Conversely, the performance of the CO monitor was completely unaffected by the compressed air purge.

HRL Technology demonstrated that a 0.1% improvement in boiler thermal efficiency at Yallourn Power Station was possible by trimming the excess air until the CO measurements approach 300ppm. This would save 2,365MWh of auxiliary power over a year, equating to increased annual revenue of around A$57,000. The improved plant efficiency would lead to an abatement of 6,700 tonnes CO_2-equivalent per annum for Unit 3 alone.

HRL Technology concluded that the Siemens SITRANS-SL laser gas analyser is robust enough to withstand the heat and vibration in a power station, and has the potential to provide more accurate and reliable concentration measurements than the O_2 and CO instruments currently in use.

The CO laser can be purged using compressed air, which is readily available, and can be used to trim the excess air and make substantial reductions in power requirements and GHG emissions. The project concluded that the revenue raised from increased power sales would justify the purchase price of the CO monitor.

Use of the laser O_2 monitor for boiler control would deliver more accurate results than current O_2 probes, but requires installation of an on-site nitrogen generator to produce the necessary purge gas for accurate results.

Advanced materials assessment

Modern ultrasupercritical power stations use higher temperature boilers to deliver greater efficiency, and reduced GHG emissions. The higher temperatures require the use of different metal alloys than those used in Victoria today. Local knowledge is lacking on how these alloys operate under the conditions in a new ultrasupercritical brown coal power stations, and this research program aimed to fill some of the gaps.

The research program was conducted by HRL Technology Pty Ltd in association with Monash University, with significant contributions from the main Latrobe Valley power generators, GDF SUEZ – Loy Yang B, GDF SUEZ – Hazelwood, AGL Loy Yang and EnergyAustralia Yallourn with the following aims.

- Improve our knowledge of conventional and advanced materials for power plant applications.
- Accelerate the introduction of new materials without increasing risk to the plant or personnel.
- Improve plant life, safety and asset utilisation through improvements in life assessment methods.
- Increase the knowledge and experience of young engineers working in power generation and related businesses.

The project was undertaken in four strands, each addressing different aspects in the evaluation of advanced steel alloys.

Strand 1
Understanding oxide growth kinetics in a steam environment and developing improved algorithms relating oxide thickness to operating temperature for alloy steels, including 9% and 12% chromium steels.

Strand 2
Characterisation of microstructure changes of ferritic and austenitic steels as a function of ageing, to assess the fitness of materials and components.

Strand 3
Developing improved creep testing techniques to provide more rapid and accurate prediction of life of plant, with particular focus on the measurement of creep strain rate as an indicator of remaining life.

Strand 4
Evaluating improved welding techniques to reduce outage times, specifically by comparing the creep properties of flux-core versus conventional weld repairs and evaluating the risks of using the more rapid flux core techniques.

One of the most significant outcomes of this project was the establishment of high-temperature steam oxidation test facilities at both Monash University and at Loy Yang B power station. These facilities allowed samples of advanced steel alloys to be exposed to ultra-supercritical steam temperatures (~790°C) for up to 12,000 hours.

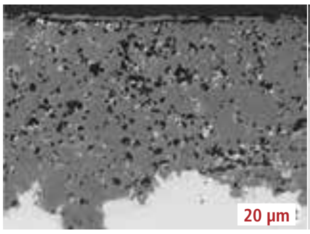
Figure 12: Steam oxidation facility at Loy Yang B power station

In Strand 1, the steam oxidation facilities were used to create a library of steel samples that had been exposed to steam at various temperatures and times. The resulting build-up of oxide scale was carefully measured, and a predictive model for oxide growth was developed. This model can be used to predict the build-up of oxide scale in an operating ultra-supercritical power station.

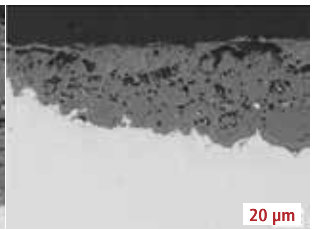
In Strand 2, samples treated in the steam oxidation facilities were used to create an atlas of photographs, documenting the changes in the steel microstructure as a function of both temperature and time. This atlas can be used to help diagnose the likely time-temperature history of a steel component from within a boiler.

In Strand 3, a suite of advanced creep assessment equipment was commissioned by HRL Technology Pty Ltd, to allow measurement of structural extension (i.e. 'creep') of steel components under load at high temperature. This type of testing is used to estimate the likely remaining working life of boiler components.

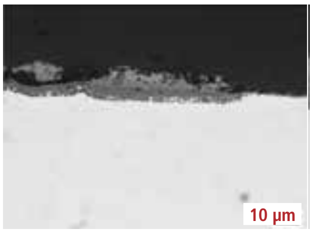
Figure 13: Oxide layers on different stainless steels



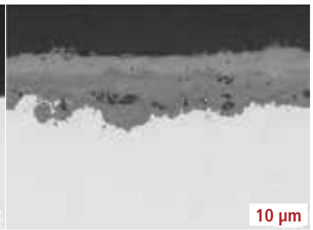
Monash: 347HFG – 4,000h, 760°C (375x)



Monash: Super 304F – 4,000h, 760°C (375x)



Monash: AFA – 4,000h, 760°C (750x)



Monash: HR3C – 4,000h, 760°C (750x)

New predictive methods were assessed, offering the potential to reduce the time for such analysis from months to weeks, a very significant improvement.

In Strand 4, methods for welding and repairing the high-performance steel alloys were evaluated. The knowledge gained will be very useful in reducing the downtime for boiler maintenance without increasing the risk to personnel.

Overall, this project delivered a number of significant benefits to the participants.

- New oxide thickness equipment and an improved protocol for interpreting apparent maximum metal temperature from measurements of oxide thickness.
- A technique to accelerate testing to determine the remaining creep life of high temperature components, with assessments available from ~1,000 hours of testing rather than over a year.
- Data to suggest that flux-core welding could be a suitable alternative to conventional manual metal arc welding in some instances, although further evaluation is required.
- Improved assessment techniques to determine fitness for service of aged materials.

- More information on the risks of weld cracking in high performance alloys (which are widely used in the Latrobe Valley) as components exceed 200,000 hours of service, and of appropriate methods to manage risk.
- An opportunity for Latrobe Valley power generators to discuss problems and share technical information.

This project contributed significantly to the professional development of young engineers associated with the Latrobe Valley power industry. Three graduate engineers were directly involved for a large proportion of their time, and one transferred from a Master of Engineering Science to a Doctor of Philosophy for aspects of work on oxidation.

1.1.2. Direct Injection Carbon Engine (DICE)

DICE uses a mixture of refined and micronised coal suspended in water as a fuel for stationary diesel engines, such as those used to power ocean liners. These stationary engines, which can range in size from 1MW to 100MW, can be used to generate electricity. Victorian brown coal has the potential to make an excellent fuel for DICE engines, as it has low mineral content, high moisture and high reactivity.

Figure 14: CSIRO research laboratory for DICE

Counterintuitively, a diesel engine operated on a coal water fuel is inherently more energy efficient and has far lower capital cost than a conventional coal fired boiler. This is because the conversion of water to steam increases the thrust on diesel engine pistons, whereas in a PF boiler the conversion reduces the flame temperature and boiler efficiency. Current slow-speed diesel engines can achieve thermal efficiencies of 50%–55%, and can run on poor quality fuels.

Previous studies by CSIRO have shown that micronised and refined coal water fuel (Micronised Refined Carbon (MRC)) produced from processed Victorian coals should be capable of fuel cycle efficiencies of 48%–50%, producing GHG emissions of less than 700kg CO_2 per megawatt hours.

DICE has the potential to provide a distributed electricity generation option at a 45% reduction in CO_2 compared to the best existing plants in the Latrobe Valley, and would provide over 25% improvement compared to the new technologies being developed incorporating various forms of integrated drying.

As well as having the potential to produce electricity from brown coal at high efficiency, DICE is capable of providing low cost peaking and intermediate power that could provide back-up for an increasing penetration of intermittent renewable energy such as solar and wind as it provides the following.

- Flexible and only runs when needed.
- Responsive and can rapidly load follow.
- Adaptable as DICE has the ability to utilise waste materials (coal fines, bio-char and woody biomass) for beneficial utilisation; this assists with lowering the carbon footprint.
- Capable of providing peaking, intermediate or even base load capacity within a grid.

The concept of using coal as a fuel for diesel engines has a long history. It was originally explored by the inventor of the diesel engine, Rudolf Diesel, in support of his basic engine patent. Two German companies commercialised the technology prior to and during World War II, but the production facilities were destroyed in 1944.

The US Department of Energy funded a series of programs to develop commercial DICE engines and fuels from 1978 through to 2006. During this time, a modified Cooper-Bessemer six-cylinder 1.8MW diesel engine operated for over 1,000 hours, conclusively demonstrating the technical feasibility of DICE. The program was sidelined by the emergence of shale gas in the US as an abundant, inexpensive fuel source.

In 2008, CSIRO Energy Technology produced a report on the potential of coal-water fuels for the Cooperative Research Centre (CRC) for 'Coal in Sustainable Development'. CSIRO Energy Technology subsequently began the development of DICE technology for Australian black and brown coals in separate projects with Yancoal, Exergen, Ignite Energy Resources, Newcrest, JCG and Xstrata. The outcomes from these projects remain confidential.

Since 2011, BCIA has supported three projects to further advance the development of DICE technology and move the technology along its commercialisation pathway.

High efficiency power from Victorian brown coals

The DICE technology is prospective as a high-efficiency, low emission method of producing electricity from coal, and use of DICE engines could provide a low-cost option to provide back-up for an increasing penetration of intermittent solar and wind energy in the grid.

BCIA's first DICE project involved fundamental studies to establish methodology for producing high quality MRC fuel from Victorian brown coal and evaluate its likely performance in a diesel engine. This project was led by CSIRO Energy Technology in collaboration with Exergen and Ignite Energy Resources. The project involved a series of theoretical and laboratory-scale investigation which achieved the following.

- Established the procedures required to manufacture a stable, high quality MRC fuel from Victorian coal.
- Evaluated the atomisation and combustion performance of the MRC fuel.
- Investigated the likely effects of coal ash on engine components.
- Developed a business case to attract the interest of a major diesel engine manufacturer.

This project demonstrated that high quality MRC fuels can successfully be produced from Victorian brown coals and upgraded coal products, and that these fuels can successfully be atomised and combusted at bench scale in CSIRO's high efficiency coal test apparatus.

Wear studies were conducted with the resulting ash, indicating that brown coal ash appears to be generally less abrasive than ash from bituminous coal, so the engine modifications recommended during the earlier DOE-funded research programs should also be appropriate for brown coal fuels.

A detailed thermodynamic model was developed for one cylinder of a two-stroke K98MC-C7 engine, which is the largest bore engine in commercial production and is capable of around 6MW per cylinder. Subsequent modelling work suggested that the efficiency of a diesel engine correctly configured to operate on brown coal MRC is likely to be close to that for operating on diesel fuel.

A key achievement of the project was a techno-economic model for the DICE technology, which included mass and energy flow models for the entire fuel cycle, as well as likely capital and operating costs. The modelling suggested that it should be possible to achieve a fuel cycle efficiency of 48%, including the process energy penalty associated with hydrothermal treatment of the coal. The capital cost for DICE is likely to be A$1,200 to A$2,000 per kilowatt, which is about half the anticipated cost of supercritical PF plants. Added advantages of DICE are that it can be installed progressively as discrete power modules, spreading the load of the capital investment, and that it is a complementary generation partner for load variable and distributed renewable energy sources.

Assuming that MRC can be produced at a cost of A$3 per gigajoule, the preliminary economic analysis concluded that, for natural gas prices of more than A$8 per gigajoule, the cost of electricity is lower from DICE than natural gas combined cycle, irrespective of CO_2 price. With the wholesale price of natural gas in eastern Australia expected to rise in the near future, DICE appears to be a prospective technology for the next generation of efficient coal-fired power stations in Victoria.

A further objective of the project was to engage with large diesel engine manufacturers to assist in the further development of DICE technology. The project leader, Dr Louis Wibberley, was successful in establishing a good working relationship with MAN Diesel & Turbo, the world's largest stationary diesel engine developer, based in Denmark.

In addition, BCIA assisted in the establishment of a consortium of local and international industries, known as DICEnet, with an interest in promoting the development of DICE (see www.dice-net.org). Members of DICEnet include MAN Diesel & Turbo (Denmark), AGL Loy Yang, EnergyAustralia, Ignite Energy Resources, Exergen, GHD, Worley Parsons, Glencore, Newcrest, Yancoal, RWE Power (Germany), JGC Coal Fuel (Japan), Sinarmas Group (Indonesia), CSIRO, ACALET and BCIA. The mission of DICEnet is to support the international development of DICE.

MRC-DICE risk review

Having demonstrated the potential for use of Victorian brown coals in low emissions DICE engines, BCIA's second project in this area involved an independent assessment of the technical and commercial risks involved in the development of DICE technology. For any project, moving from the laboratory to commercial stage involves management of risk, and the aim of this review was to identify and categorise the key risks for the development programme of the MRC-DICE technology, and identify strategies for mitigating these risks. The outcomes of this project were intended to inform decisions on the future requirements for the R&D that could enable the DICE technology to be taken on the next step towards commercialisation.

The review was funded by BCIA member organisations and conducted by Worley Parsons. The risk review involved participation from 16 stakeholders, including those representing potential fuel suppliers, energy purchasers, an engine manufacturer and organisations who may be involved in the supply chain. The scope covered the two different value chains for MRC-DICE, namely the following.

1. MRC-DICE for power generation (grid connected in Australia).
2. MRC-DICE for power generation (off grid including export).

Each of these value chains is made up of the following blocks.

- Feedstock materials for slurry preparation.
- Slurry preparation, including grinding and de-ashing of feedstock.
- Slurry transport.
- Slurry storage.
- Power generation in DICE generators.

The review examined possible technical, commercial and project execution risks for each of the blocks in the MRC-DICE value chains. From this process, 65 risks were identified, with ratings that ranged from 'extreme' to 'low'. The existence of 'extreme' risks would be expected at this stage of development of the DICE technology, and the purpose of future developments would be to mitigate these risks through further R&D and development of a commercialisation pathway.

An important outcome of the risk review was that none of the risks were considered by stakeholders as 'showstoppers', and none would justify halting the MRC-DICE development programme. However, even after applying appropriate treatments, there were a number of residual risks that were rated as having the potential – without further action – to prevent the commercial development of MRC-DICE technology. These risks will need to be monitored and addressed during the commercialisation pathway.

Victorian DICE development – derisking and small scale demonstration

BCIA's third DICE project involves a national collaboration of both black and brown coal industry groups with a major international diesel engine manufacturer, with the aim of undertaking demonstration scale proof-of-concept trials using a test engine in Japan. It is hoped that successful completion of these BCIA-funded trials will lead to future activity, including a long-run demonstration test to confirm fuel and engine performance and provide the cost data necessary for commercial adoption. The broad objectives of the national program were as follows.

- Undertake proof-of-concept trials of both brown and black MRC fuels in a test engine in Japan.
- Create sufficient data to allow an engine manufacturer to implement an engine development program.
- Define the specification parameters and initial acceptable ranges for both brown and black coal derived MRC fuels.
- Undertake sufficient tests to confirm (or otherwise) that risks associated with the supply and combustion of MRC fuel (derived from brown and black coal) in a contemporary low- or medium-speed diesel engine are acceptably low.

CSIRO Energy Technology leads and coordinates the joint DICE Development program. The program is funded through two separate but coordinated research agreements, one with BCIA and the other with Australian National Low Emissions Coal Research & Development (ANLEC R&D). Each project contains brown- or black-coal specific aspects, as well as shared aspects relating to the fuel system and engine development work undertaken by MAN Diesel & Turbo. The main focus of the joint project is the development of modified fuel handling and injection equipment to allow successful handling of MRC fuel slurry, and then to undertake 20 hour combustion trials of black and brown coal MRC fuels in a test engine in Japan. MAN Diesel & Turbo will undertake this work with support from CSIRO Energy Technology.

The project involves a close collaboration between CSIRO Energy Technology and MAN Diesel & Turbo, with support from local electricity generators (AGL Loy Yang, EnergyAustralia) and developers of brown coal upgrading technologies (Ignite Energy Resources, Exergen).

The three-year project, which began in 2014, will include preparation and characterisation of a brown coal MRC fuel that will remain stable during transport to Japan, small-scale engine testing to investigate possible fouling issues, investigation of the effects of coal ash components on atomiser wear and cylinder abrasive wear, and development of standardised specifications and testing protocols for MRC fuels.

Successful completion of this project will confirm the technical feasibility and inform our understanding of the commercial viability of DICE, which has great promise as a low-cost, low-emission power generation technology.

Key Publications

Wibberley LJ (2011). Coal base-load power using Micronised Refined Coal (MRC). Energy Generation 35–39 (January–March 2011).

Wibberley LJ (2011). Future low CO_2 power from Victorian brown coal. Energy Generation 35–39 (July–September 2011).

Wibberley LJ (2011). High efficiency power using micronized refined coal in low speed diesel engines. International Technical Conference on Clean Coal & Fuel Systems, Clearwater, Florida.

Wibberley LJ (2013). DICE – Emerging technology for ultra-efficient carbon power. Energy Generation 1–5 (January–March 2103).

1.1.3. Direct Carbon Fuel Cells (DCFCs)

DCFC is an emerging technology that has the potential to increase the efficiency of power generation from brown coal to 65%–70%. This is higher than any other carbon fuel technology, and would lead to a significant reduction in the production of CO_2 per megawatt of electricity generated. DCFCs achieve such high efficiency by directly converting solid high-carbon fuels (such as coal and biomass) into electricity through electrochemical oxidation.

The principle of DCFC operation is illustrated in Figure 15. The fuel cell comprises two electrodes separated by a solid oxide ceramic membrane that conducts oxygen ions.

At the cathode, oxygen in the air is ionized:

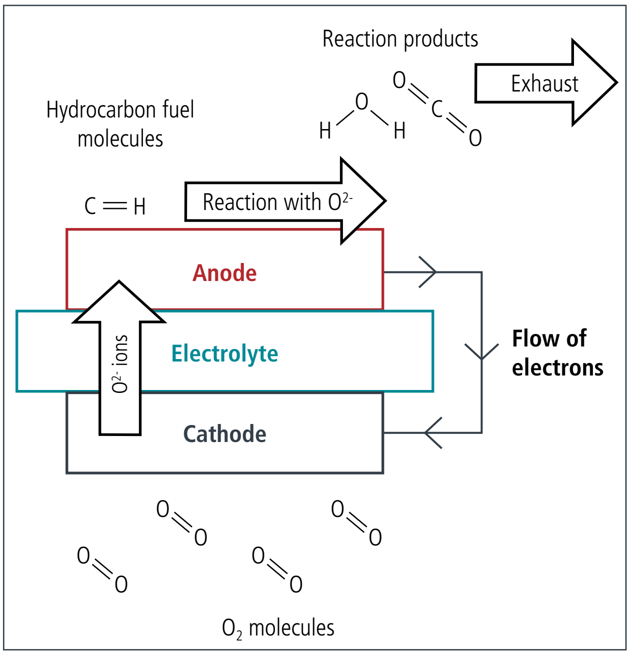
$$O_2 + 4e^- \rightarrow 2O^{2-}$$

The oxygen ions flow across the membrane and react with the solid carbon fuel to produce CO_2 at the anode:

$$C + 2O^{2-} \rightarrow CO_2 + 4e^-$$

The electrons released by this process move through an external load, producing a current, that will continue to flow as long as the supply of air and carbon to the electrodes is maintained.

Figure 15: Operation of a DCFCs



DCFC technology is at an early stage of development, with many organisations seeking to optimise the balance between cost, performance and lifetime. A variety of DCFC designs are possible; there is no concensus yet as to which would be most applicable for use with coal.

In Australia, CSIRO Energy Technology in Clayton has been at the forefront of research into electrochemical energy devices for the past 25 years. CSIRO developed a solid oxide fuel cell technology that was commercialised in 2008 as BlueGen® by Ceramic Fuel Cells Ltd, with sales in the UK, Netherlands and Germany.

Demonstrating the real-world efficiency of fuel cells, BlueGen® is capable of electrochemically converting natural gas into electricity at up to 60% efficiency and can also be used to produce hot water, which improves the total efficiency to approximately 85%. The device, about the size of a washing machine (Figure 16), is sufficient to power a house or small office.

Figure 16: BlueGen® converts natural gas in to electricity

Since 2009, CSIRO has invested in significant new infrastructure for the construction, testing and characterisation of DCFCs. These are the largest such R&D organisation facilities in the world. CSIRO has examined a number of different fuels for DCFCs, concluding that Victorian brown coal is a particularly attractive option.

BCIA has supported two research projects to investigate the potential of DCFC technology for use with Victorian brown coal.

Evaluation of Victorian brown coals as fuel for DCFCs

Although DCFCs offer the potential for extremely high efficiency power generation, they are still in the early stages of development with many technical challenges to overcome. The suitability of Victorian coals for use in DCFCs had not been proven.

BCIA's first project in this area was a scholarship for a PhD student at Monash University, Mr Adam Rady, in collaboration with CSIRO Energy Technology. The scholarship was part of BCIA's skills development program, and was supported as a preliminary exploration of DCFC technology that allowed Mr Rady to gain valuable hands-on experience in the construction of fuel cells.

Mr Rady found that char produced from Morwell coal performed better (produced higher current densities) than a commercial carbon black reference standard. The superior performance was attributed to the catalytic activity of inorganic elements present in the coal, particularly iron, calcium and magnesium.

Performance of the DCFC deteriorated over time. This was due to a buildup of ash on the anode and an increase in electrical resistance as the fuel was consumed.

The anode material used in the experimental DCFC was Lanthanum Strontium Cobalt Ferrite (LSCF). Mr Rady used the Australian Synchrotron to analyse the changes in the anode structure after exposure to brown coal char and ash at 850°C. He discovered that mineral impurities in the coal led to the formation of new phases within the LSCF structure, which may also have contributed to the deterioration in performance over time.

Further research will be needed to investigate the interactions between brown coal mineral matter and alternative anode materials.

Feasibility study for DCFC operation on Victorian brown coal

Following the initial demonstration that Victorian coals, in particlar Morwell coal, showed promise as a fuel for a low emissions fuel cell, BCIA funded a second study to look at the technical risks.

The main objective was to determine the best way to use brown coal in DCFC, taking into account the presence of ash-forming impurities, and to explore critical steps such as continuous feeding of the fuel. This was intended to assist in prioritising future research needs.

The project, led by Dr Sarb Giddey of CSIRO Energy Technology, was predominantly a desk-top study, supplemented by limited experimental work using CSIRO's lab-scale electrolyte-supported tubular DCFC.

This project examined the effect of impurities in brown coal on the materials of construction of the high temperature fuel cells and how these impurities interact with materials at these high temperatures. It has also looked at ways to modify the fuel cell design to increase performance and mitigate some of the issues posed by feeding fuel to the cell.

The project found that anode materials were degraded through reaction with coal minerals. The cell design was changed to avoid this problem, resulting in an increase in performance of over 40%.

Coals from the Morwell and Yallourn regions present the most attractive options for DCFCs, due to the presence of a number of beneficial elements, such as iron and calcium.

Overall this study found that Victorian brown coal is an attractive feedstock for fuel cells. The results are being used to guide the further development of direct carbon fuel cell technology at CSIRO.

The results are also applicable to another process being developed by CSIRO, known as 'carbon assisted electrolysis', in which solar energy is used to produce hydrogen from a carbon slurry. This process is more efficient than solar electrolysis, and can convert a coal slurry into pure streams of hydrogen and CO_2. CSIRO has recently demonstrated this process using carbon black, so further research to explore the potential with brown coal is warranted.

Key Publications

Rady AC, Giddey S, Badwal SP, Ladewig BP, Bhattacharya S (2012). Review of fuels for direct carbon fuel cells. Energy & Fuels 26: 1,471–1,488.

Rady AC, Giddey S, Kulkarni A, Badwal SP, Bhattacharya S, Ladewig B P (2014). Direct carbon fuel cell operation on brown coal. Applied Energy 120: 56–64.

Rady AC, Giddey S, Kulkarni A, Badwal SP, Bhattacharya S (2014). Degradation mechanism in a direct carbon fuel cell operated with demineralised brown coal. Electrochimica Acta: 143, 278–290..

1.1.4. Moderate and Intensive Low-oxygen Dilution (MILD) combustion

The push for higher efficiency and lower CO_2 emissions from applications of coal has typically focused on increasing the temperature of combustion. Although this increases efficiency, it also requires the use of more exotic metal alloys in power station design. In addition, the higher furnace temperatures lead to greater formation of nitrogen oxides (NO_x), which are pollutants if emitted into the atmosphere.

MILD combustion is possibly the most important recent achievement of combustion technology because it achieves higher thermal efficiency while reducing NO_x emissions by more than 70%. Fuel is oxidised in an environment that contains a substantial proportion of inert flue gases. The combustion air is delivered with high momentum, inducing a strong recirculation that reduces the peak temperature in the combustion chamber and prevents thermal NO_x formation. MILD combustion is also known as ‘flameless combustion’ because the chemical reactions take place in almost the entire volume of the combustion chamber, leading to a uniform temperature distribution and no visible flame.

MILD combustion technology has been studied extensively for gaseous and liquid fuels, and has been implemented mainly in the steelmaking and metallurgical industries. The use of solid pulverised coal under MILD combustion conditions has received much less attention than that of gaseous fuels, so its burning characteristics are poorly understood.

Experimental and computational study of solid fuels under MILD combustion

A team at the University of Adelaide, led by Professor Bassam Dally, is at the forefront of international research on the application of MILD combustion for solid fuels. BCIA supported a PhD student, Mr Manabendra Saha, under the supervision of Professor Dally to investigate the MILD combustion characteristics of both South Australian and Victorian brown coals.

Mr Saha's project involved an investigation of the operating conditions required to achieve stable MILD combustion with brown coal, including the influence of jet inlet velocities of a stream of CO_2 and brown coal (at room temperature) on both the flame stability and the formation and destruction of pollutants. Moreover, the project investigated the impact of turbulence on the devolatilisation of brown coal and the reaction of volatile species under MILD combustion conditions.

The project involved the design, construction and operation of a new vertical co-flow furnace, shown in Figure 17. Flameless combustion was successfully achieved with brown coal (Figure 18 and Figure 19). Increased turbulence resulted in better mixing and formation of a broad devolatilisation zone.

The experimental work was complemented by the development of a comprehensive Computational Fluid Dynamics (CFD) model, to provide a better understanding of the flow field, turbulence intensity, volatiles release rate, combustion of volatile matters, and overall carbon consumption inside the furnace.

The model indicated that increasing the turbulence of the jet increases the volatiles release rate, and that stable MILD combustion was associated with a large recirculation vortex around the centre of the furnace.

This study has established that MILD combustion of Victorian brown coal is feasible, and has resulted in a CFD modelling tool that can help design the next phase of research. This represents a significant step toward the development of a cleaner, more efficient way to use Victorian brown coal for power generation.

Figure 18: Schematic of the Adelaide MILD combustion furnace

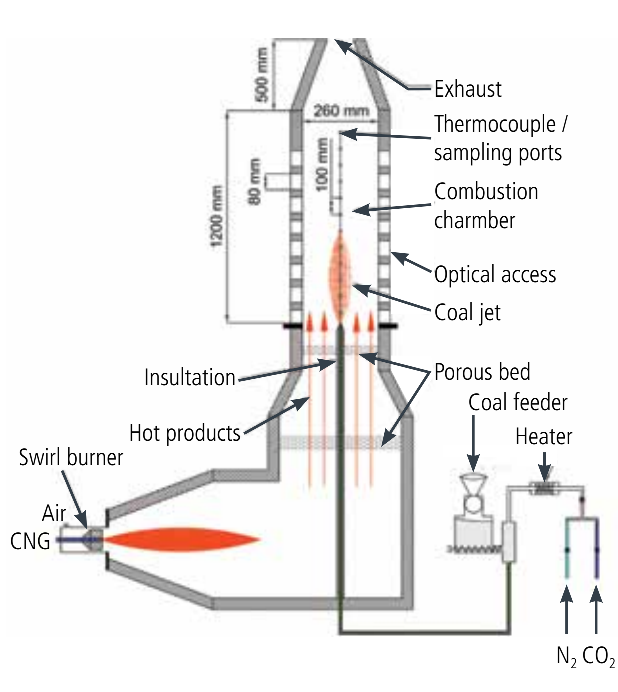
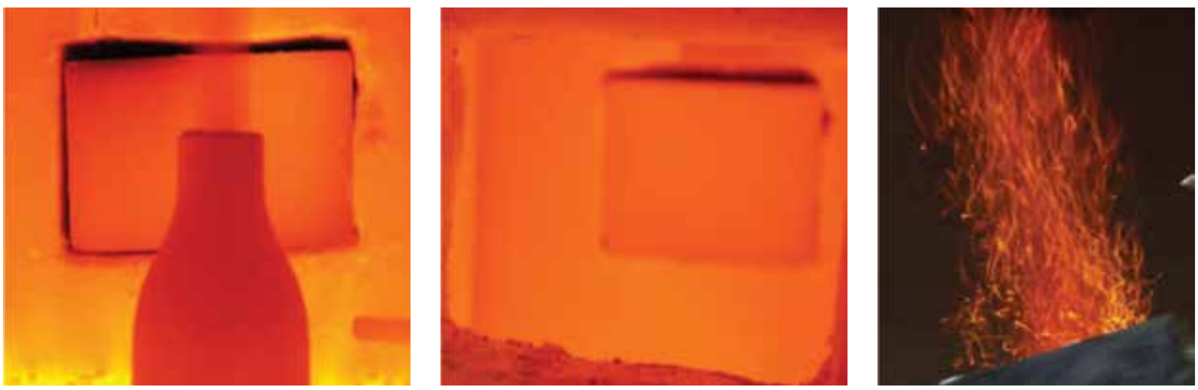


Figure 17: Photograph of the bottom, middle, and exit of the furnace when operating under MILD combustion condition with Loy Yang brown coal carried by CO_2



Bottom **Middle** **Exit**

Figure 19: Photograph of the Adelaide MILD combustion furnace

Key Publications

Saha M, Dally BB, Medwell PR, Cleary EM (2014). Moderate or Intense Low Oxygen Dilution (MILD) combustion characteristics of pulverized coal in a self-recuperative furnace. Energy & Fuels, 28: 6,046–6,057.

Saha M, Chinnici A, Dally BB, & Medwell PR (2015). Numerical study of pulverized coal MILD combustion in a self-recuperative furnace. Energy & Fuels, 29: 7,650–7,669.

Saha M, Dally BB, Medwell PR, & Chinnici A (2016). Burning characteristics of Victorian brown coal under MILD combustion conditions. Combustion and Flame, 172: 252–270.

Saha M, Dally BB, Medwell PR, & Chinnici A (2016). Effect of particle size on the MILD combustion characteristics of pulverised brown coal. Fuel Processing Technology. Available at www.dx.doi.org/10.1016/j.fuproc.2016.04.003.

1.2. Combustion in oxygen instead of air

1.2.1. Oxy-fuel combustion of brown coal

A major aim of BCIA's low emissions power activity is to identify low-cost, low emissions options for base load power generation. Oxy-fuel combustion is a promising new technology that could enable efficient production of power from Victorian brown coal with little to no GHG emissions. Indeed, the research and modelling to date shows that oxy-fuel combustion, in combination with CO_2 storage, could deliver power with near-zero emissions at almost zero net efficiency penalty compared to today's Victorian brown coal plants.

Essentially, the process involves burning coal in oxygen instead of air, with recirculation of flue gas to maintain efficient heat transfer velocities in the boiler. Since nitrogen (as the major component of air) is not added, the volume of flue gas is considerably smaller than for a conventional plant, and is comprised mainly of steam and CO_2. Recovery of CO_2 for transport and storage requires only a relatively simple process of dehydration and compression. Thus, oxy-fuel combustion has the potential to produce injection-ready CO_2 from brown coal combustion, without the need for an expensive, intermediate CO_2-capture step.

Australia has been at the forefront of the development of oxy-fuel combustion technology. The successful completion of the Callide Oxyfuel Project in December 2014 was a major international milestone. This demonstration project involved an oxy-fuel retrofit to Unit No. 4 at the Callide A coal-fired power station in central Queensland, with facilities to capture 75 tonnes per day of liquid CO_2. During the three-year project, the oxy-fuel boiler was operated for 5,500 hours, demonstrating (i) increased boiler combustion efficiency; (ii) greater than 50% reduction in stack nitrogen oxides (NO_x) mass emission rates; and (iii) almost complete removal of all toxic gaseous emissions including sulfur oxide (SO_x), NO_x, particulates and trace elements from the flue gas stream in the CO_2 capture plant [(1)].

(1) www.globalccsinstitute.com/publications/callide-oxyfuel-project-lessons-learned.

In 2007, Monash University undertook studies into the feasibility of applying oxy-fuel combustion technology to Victorian brown coal, as part of the (then) Victorian Department of Primary Industry's Energy Technology Innovation Strategy (ETIS).

The objectives of this project were to investigate the issues associated with combustion of Victorian brown coal under oxy-fuel conditions and to determine the likely feasibility of deploying oxy-fuel technology.

To date, BCIA has supported four projects in the area of oxy-fuel combustion. These projects have advanced our understanding of this low emission technology, and have progressed the development from bench-scale experiments, through techno-economic evaluations to pilot-scale tests aimed at delivering results that can contribute to designs for future plants.

Oxy-fuel combustion of Victorian brown coal

Based on the initial positive results achieved under the Victorian state government's ETIS project, BCIA supported a study led by Professor Sankar Bhattacharya at Monash University to investigate the techno-economic feasibility of retrofitting oxy-fuel combustion technology to existing brown-coal-fired power stations.

Monash University and HRL Technology conducted two separate but similar studies in collaboration with local power generators. One study examined the feasibility of retrofitting oxy-fuel combustion and CO_2 capture to Unit 7 at International Power Hazelwood, while the other focused on Unit B at Loy Yang International Power.

Both studies suggested that oxy-fuel combustion could be cost-competitive with post-combustion CO_2 capture for producing low emissions power, especially when waste heat is efficiently used.

The single largest barrier to cost-effective implementation of oxy-fuel combustion is the large energy penalty associated with producing the huge volumes of pure oxygen required. The conclusion was that further work to develop oxy-fuel combustion technology for deployment in Victoria is justified.

Pilot-scale oxy-fuel combustion of Victorian brown coal

Following the positive outcomes from the techno-economic evaluations, BCIA supported a second oxy-fuel combustion project, completed in March 2014, with funding from ANLEC R&D.

The objective of this project, led by Dr Lian Zhang at Monash University, was to investigate oxy-fuel combustion at pilot-scale and develop a Computational Fluid Dynamics (CFD) model for the process. These CFD models are vital to understanding the challenges and opportunities in scale-up of such technologies.

As suitable pilot-scale facilities do not exist in Australia, the trials were conducted using a $3MW_{th}$ oxy-fired boiler at Shanghai Boiler Works Ltd (SBWL) in Shanghai, China. SBWL is the second-largest boiler manufacturer in China, and has already commercialised oxy-fuel boilers for black coal. The project also involved two local power companies (EnergyAustralia and GDF SUEZ Australian Energy) and universities in China and Japan.

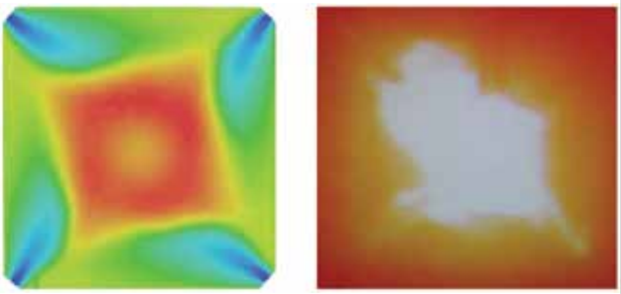
A series of trials at the $3MW_{th}$ oxy-fired boiler established the feasibility of oxy-fuel combustion of Victorian brown coals that had been dried to moisture contents ranging from 12% to 40% (Figure 20).

The research established a range of outcomes including the stable and faster combustion of Victorian brown coal under oxy-fuel conditions, production of high purity CO_2 (up to 80%) in flue gases, and led to a greater understanding of the distinct slagging/fouling propensities of Victorian brown coal in oxy-fuel mode.

The knowledge gained at both laboratory and pilot scales was used to develop and validate new CFD modelling codes to account for: the radiation properties of CO_2 and steam; the higher char-CO_2 and char-steam reactivity of Victorian brown coal; and the reaction rates for volatiles under oxy-firing conditions.

Monash University has licensed these codes to Shanghai Boiler Works Co Ltd for application in commercial design of oxy-fuel boilers.

Figure 20: Comparison of CFD model and 3MW$_{th}$ boiler flame for Yallourn coal in oxy-firing mode



30% O_2 / CO_2 ~30% O_2 / CO_2

Additional techno-economic modelling was undertaken for both retrofit and new oxy-fuel combustion systems. For a retrofit scenario, where it is important to maintain similar heat transfer characteristics, the moisture content of the coal must be no greater than 40%. Otherwise, the radiant heat transfer from the oxygen-enriched flame is too high. This fact highlights the critical need for pre-drying of the coal that was also observed in the earlier techno-economic studies.

For new-build oxy-fuel combustion systems, a combination of pre-drying and supercritical operating temperatures can compensate for the energy penalty of the oxygen separation and CO_2 compression processes. An energy efficiency of 25%–28% can be achieved, equivalent to current brown-coal-fired power stations, but with no CO_2 emissions.

Developing an advanced computer modelling program for the prediction of brown coal ash slagging / fouling propensity under oxy-fuel combustion mode

The pilot-scale oxy-fuel experimental work has been complemented by efforts to develop advanced CFD simulation tools to assist in further scale-up. This work has been supported by a BCIA top-up scholarship to Mr David De Girolamo, a PhD student at Monash University. The objectives of Mr De Girolamo's research are as follows.

- Develop and validate a sub-model for the vaporisation of alkali metals (Na, K) and their capture by refractory particles.
- Develop and validate sub-models describing ash particle collision and deposit growth on the water tube surface.
- Incorporate the developed sub-models into commercial CFD software.

The outcomes of this research will contribute to a mature ash slagging / fouling prediction tool that can be used in the design of pulverised lignite-fired boilers under both air-firing and oxy-fuel modes.

Accelerating the deployment of oxy-fuel combustion technology

Since 2014, BCIA has supported collaboration between Monash University and SBWL to accelerate the deployment of oxy-fuel technology in Victoria. This new project is investigating the ash fouling and water tube corrosion that occur under optimised oxy-firing conditions. Understanding the coal-specific factors that control fouling and corrosion is essential for commercial boiler design.

The focus of the project is on oxy-fuel combustion of dried Victorian brown coal under supercritical and ultra-supercritical conditions. The project will involve long-term ash exposure experiments in the 3 MWth SBWL boiler, and the development of advanced modelling tools for the prediction of lignite ash slagging/fouling and water tube corrosion propensities in an industrial oxy-fired boiler.

The project has already established that water tube corrosion is always enhanced under oxy-fuel conditions, irrespective of the tube material and fly ash type. The extent of corrosion can be reduced by adding clay to the coal during combustion. A CFD model has been developed for predicting the composition of flue gas, ash and slag within a boiler under these oxy-firing conditions.

Experiments in a lab-scale horizontal tube furnace at Chubu University in Japan have allowed the interactions between brown coal ash and water tubes to be studied under simulated oxy-firing conditions. Figure 21 and Figure 22 shows the elemental composition of the corroded metal samples measured using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS).

EXECUTIVE SUMMARY
OVERVIEW OF BCIA PORTFOLIO
NEW OPPORTUNITIES FOR BROWN COAL
SHARING OUR FINDINGS
FIGURE SOURCES AND COPYRIGHTS

Figure 21: SEM-EDS analysis of Hazelwood ash deposit, collected at 700°C

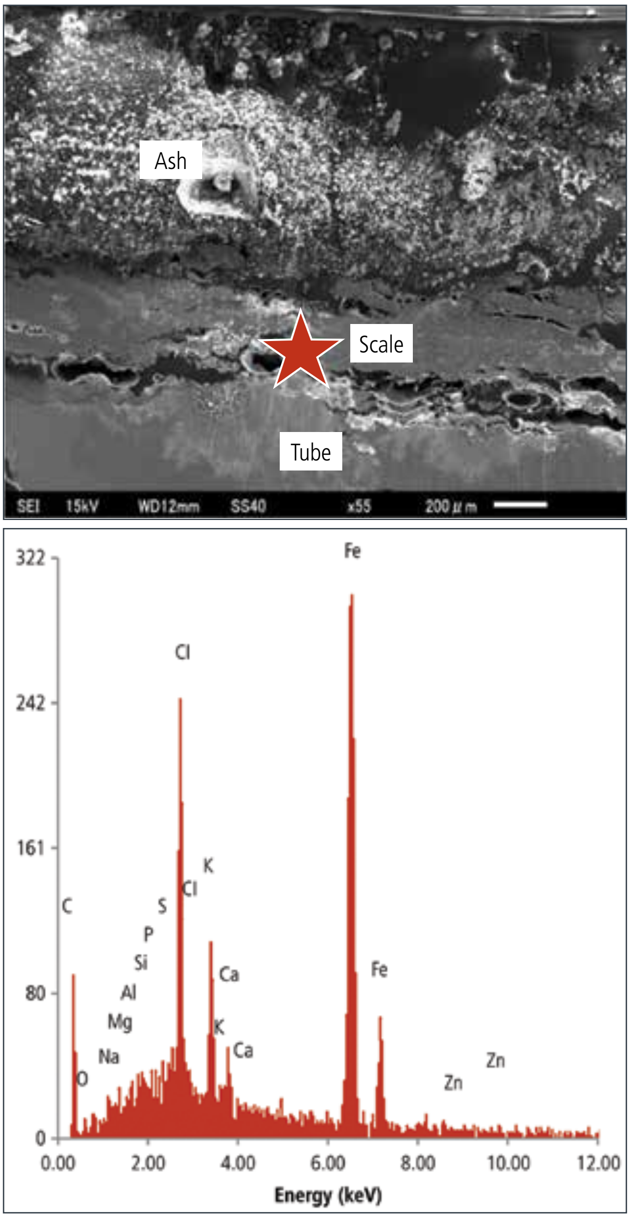
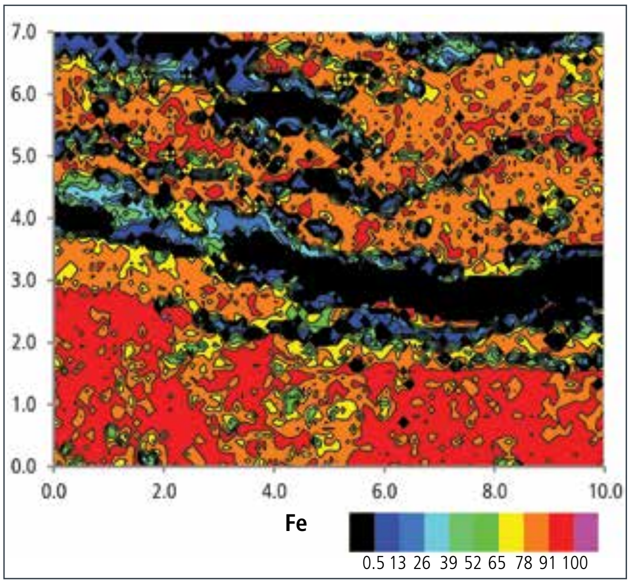


Figure 22: Iron distribution in ash deposit at 700°C



Detailed mapping of the elemental composition over a 2D grid allowed the production of detailed distribution profiles for each element. Figure 22 shows a representation of the distribution of Fe in the above sample, indicating the loss of iron metal into the scale layer.

Such detailed analytical work has led to the identification of advanced steel alloys that are suitable for construction of water tubes for oxy-fired boilers using Victorian brown coal.

Key Publications

Binner E, Zhang L, Li CZ, Bhattacharya S (2011). In-situ observation of the combustion of air-dried and wet Victorian brown coal. Proceedings of the Combustion Institute 33: 1,739–1,746.

Binner E, Facun J, Chen L, Ninomiya Y, Li CZ, Bhattacharya S (2011). Effect of coal drying on the behavior of inorganic species during Victorian brown coal pyrolysis and combustion. Energy & Fuels 25: 2,764–2,771.

Chen J, Jiao F, Zhang L, Yao H, Ninomiya Y (2012). Use of synchrotron XANES and Cr-doped coal to further confirm the vaporization of organically bound Cr and the formation of chromium (VI) during coal oxy-fuel combustion. Environmental Science & Technology 46: 3,567–3,573.

Chen J, Dai B, Low F, Zhang L (2012). XANES investigation on sulfur evolution during Victorian brown coal char gasification in oxy-fuel combustion mode. Energy & Fuels 26: 4,775–4,782.

Jiao F, Chen J, Zhang L, Wei Y, Ninomiya Y, Bhattacharya S, Yao H (2011). Ash partitioning during the oxy–fuel combustion of lignite and its dependence on the recirculation of flue gas impurities (H2O, HCl and SO_2). Fuel 90: 2,207–2,216.

Jiao F, Wijaya N, Zhang L, Ninomiya Y, Hocking R (2011). Synchrotron-based XANES speciation of chromium in the oxy-fuel fly ash collected from lab-scale drop-tube furnace. Environmental Science & Technology 45: 6,640–6,646.

Low F, Zhang L (2013). Arsenic emissions and speciation in the oxy-fuel fly ash collected from lab-scale drop-tube furnace. Proceedings of the Combustion Institute 34: 2,877–2,884.

Roy B, Choo WL, Bhattacharya S (2013). Prediction of distribution of trace elements under oxy-fuel combustion condition using Victorian brown coals. Fuel 114: 135–142.

Yan K, Wu X, Hoadley A, Xu X, Zhang J, Zhang L (2015). Sensitivity analysis of oxy-fuel power plant system. Energy Conversion and Management 98: 138–150.

Zhang J, Dai B, Meng Y, Wu X, Zhang J, Zhang X, Ninomiya Y, Zhang Z, Zhang L (2015). Pilot-scale experimental and CFD modeling investigations of oxy-fuel combustion of Victorian brown coal. Fuel 144: 111–120.

Zhang J, Prationo W, Zhang L, Zhang Z (2013). Computational fluid dynamics modeling on the air-firing and oxy-fuel combustion of dried Victorian brown coal. Energy & Fuels 27: 4,258–4,269.

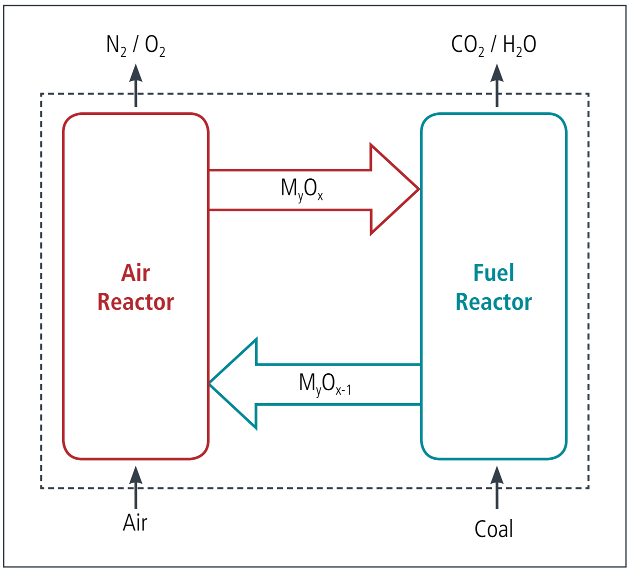
1.2.2. Chemical Looping Combustion (CLC) of brown coal

Combustion of coal in a pure oxygen atmosphere allows the generation of power with almost no CO_2 emissions. The flue gas in such a system consists primarily of CO_2 and steam, and it is possible to easily dehydrate and compress the CO_2 for transport and storage. However, generating a pure stream of oxygen at the scale required for a power station can be a costly and energy intensive process, usually achieved through an Air Separation Unit (ASU) that refrigerates air to separate nitrogen.

CLC is an emerging technology to facilitate capture of CO_2 at a lower energy and cost penalty. In CLC, the oxygen for combustion of the fuel is provided by a recyclable metal oxide as oxygen carrier instead of using gaseous oxygen.

CLC is a modification of the fluidised bed coal combustion method that is already in commercial use. CLC comprises two interconnected reaction chambers: a fuel reactor and an air reactor as shown in Figure 23. In the fuel reactor the metal oxides serve as an oxygen source for the coal. The reduced metal particles then pass into the air reactor where they are oxidised back into the oxide form.

Figure 23: Schematic of chemical looping combustion



Direct contact between air and the coal is avoided, creating a flue gas that is rich in CO_2. By condensing the associated water vapour, the CO_2 can be recovered in pure form ready for compression and transport for geological sequestration.

CLC is therefore similar in concept to oxy-fuel combustion, but by removing the need for expensive oxygen separation, CLC offers the potential for a cost-effective route to near zero-emissions power from brown coal.

Chemical looping has been widely studied for the combustion of natural gas but research into its application for solid fuels commenced only in recent years. Victorian brown coal is low in slag-forming ash and thus should be suitable for use in a fluidised bed combustion system. However, the performance characteristics of Victorian brown coals in a chemical looping system are unknown.

BCIA has supported two consecutive projects on CLC at Monash University, led by Professor Sankar Bhattacharya.

1. This project generated baseline information and established the feasibility of CLC with Victorian brown coal.
2. This project is intended to advance the commercial prospects of this emerging technology through an evaluation of brown coal CLC performance under more continuous operating conditions and to improve understanding of the longer term coal and oxygen carrier interaction effects.

Development of CLC process for fuel production and CO_2 capture from Victorian brown coal

While the general concept of CLC is well understood, the applicability of the CLC process to Victorian brown coals had not been studied. BCIA's first project on CLC was led by Monash University, in collaboration with EnergyAustralia, CSIRO Energy Technology, Chalmers University of Technology (Sweden) and Technical University of Darmstadt (Germany).

The objective of the project was to generate new and critical technical information relating to the effect of the unique properties of Victorian brown coal (low ash, high reactivity, inherent minerals) on the CLC process, including the following.

- Reaction kinetics
- Stability of the oxygen carrier
- Ash mineral and oxygen carrier interactions
- Kinetic modelling for process optimisation

The CLC process was investigated through fundamental studies using thermogravimetric analysis and a custom-built $500W_{th}$ bench scale chemical looping rig. This work was supported by the technical expertise in CLC technology of the international project participants, Chalmers University of Technology and Technical University of Darmstadt.

The project systematically assessed various oxygen carriers for use with Victorian and international lignite samples and found that the high reactivity and high oxygen content of Victorian brown coal is particularly suited to chemical looping. The low ash content minimises the potential for deactivation of the oxygen carrier.

Iron ore (haematite) has great potential as an effective but inexpensive oxygen carrier. Best carbon conversion was achieved at an operating temperature of 900°C. The combustion efficiency can be significantly improved by doping the haematite with low levels of nickel.

A new laboratory-scale $10kW_{th}$ fluidised bed reactor was designed and constructed in the Department of Chemical Engineering at Monash University (Figure 24).

Carbon conversion efficiencies of greater than 92% were achieved in this reactor, producing flue gas containing more than 82% CO_2. Efficiencies improved with increasing scale, so better results may be expected at pilot scale.

Figure 24: $10kW_{th}$ CLC reactor at Monash University

Advancing CLC technology for Victorian brown coals

The promising results achieved in the initial CLC project led to BCIA support for a second project with a more applied focus. This project will extend the preliminary research through bench-scale research and experiments using a Victorian purpose-built, compact fully looped and continuously fed reactor system.

The research objectives are to examine the feasibility of the CLC process in the continuously looping reactor, establish the techno-economics of a commercial scale brown coal CLC and develop a detailed process model for a commercial scale CLC plant.

This project was again led by Monash University, working in collaboration with CSIRO Energy Technology, two local companies (EnergyAustralia and Lycopodium), a Belgian research institute (VITO) and the major international champion of CLC technology, Alstom Boiler France.

The techno-economic evaluation will build on Alstom's expertise in this area, and will be used to identify a pathway to achieving more that 90% CO_2 capture efficiency while limiting the increase in power generation costs to no more than 35%.

The project will entail both bench-scale research and targeted experiments to be conducted in a Victorian purpose-built, compact fully looped and continuously fed reactor system at CSIRO in Clayton (Figure 25).

Three metal oxides were selected for evaluation as oxygen carriers – iron ore (Fe_2O_3), ilmenite ($FeTiO_3$), and a synthetic Mn-Fe oxygen carrier. Each oxygen carrier will be evaluated at bench scale over 50 oxidation-reduction cycles, to determine its effective working life and deactivation mechanisms.

Figure 25: Continuous looping CLC rig

The current BCIA-funded project will involve a techno-economic study with input from Alstom, which will produce the first publicly-available costing of a CLC process, and will be specifically targeted at Victorian brown coal. This will be a major development in the progression of CLC technology in Australia.

Key Publications

Ma J, Zhao H, Tian X, Wei Y, Rajendran S, Zhang Y, Bhattacharya S, Zheng C (2015). Chemical looping combustion of coal in a 5kW$_{th}$ interconnected fluidized bed reactor using hematite as oxygen carrier. Applied Energy, in press.

Rajendran S, Zhang S, Xiao R, Bhattacharya S (2015). Use of synthetic oxygen carriers for Chemical Looping Combustion of Victorian brown coal. Proceedings of the Combustion Institute 35: 3,619–3,627.

Saha C, Bhattacharya S (2011). Comparison of CuO and NiO as oxygen carrier in chemical looping combustion of a Victorian brown coal. International Journal of Hydrogen Energy 36: 12,048–12,057.

Saha C, Bhattacharya S (2012). Chemical looping combustion of low-ash and high-ash low rank coals using different metal oxides – A thermogravimetric analyser study. Fuel 97: 137–150.

Saha C, Bhattacharya S (2014). Experimental investigation of fluidized bed chemical looping combustion of Victorian brown coal using hematite. Journal of Environmental Chemical Engineering 2: 1,642–1,654.

Saha C, Bhattacharya S (2014). Determination and Comparison of CuO Reduction/Oxidation Kinetics in CLC Experiments with CO/Air by the Shrinking Core Model and Its Characterization. Energy & Fuels 28: 3,495–3,510.

Saha C, Roy B, Bhattacharya S (2011). Chemical looping combustion of Victorian brown coal using NiO oxygen carrier. International Journal of Hydrogen Energy 36: 3,253–3,259.

Saha C, Zhang S, Hein K, Xiao R, Bhattacharya S (2013). Chemical looping combustion (CLC) of two Victorian brown coals – Part 1: Assessment of interaction between CuO and minerals inherent in coals during single cycle experiment. Fuel 104: 262–274.

Saha C, Zhang S, Xiao R, Bhattacharya S (2012). Chemical Looping Combustion (CLC) of two Victorian brown coals – Part 2: Assessment of interaction between CuO and minerals inherent in coals during multi cycle experiments. Fuel 96: 335–347.

Xiao R, Chen L, Saha C, Zhang S, Bhattacharya S (2012). Pressurized chemical-looping combustion of coal using an iron ore as oxygen carrier in a pilot-scale unit. International Journal of GHG Control 10: 363–373.

Zhang S, Saha C, Yang Y, Bhattacharya S, Xiao R (2011). Use of Fe_2O_3-containing industrial wastes as the oxygen carrier for chemical-looping combustion of coal: effects of pressure and cycles. Energy & Fuels 25: 4,357–4,366.

2. CO_2 Capture Technologies

2.1. Amine solvent absorption systems

Amine solvent scrubbing is based on the chemical absorption of CO_2 using aqueous alkanolamine solutions. It is a robust technology that has been used to separate CO_2 from natural gas and hydrogen since the 1930s and has recently been installed on the SaskPower lignite-fired power station in Canada.

The current commercial solvents require large, expensive capital equipment and impose a high energy penalty for recovery of the CO_2. In addition, the commercial solvents are quickly 'poisoned' by the sulfur compounds present in coal, usually requiring additional expensive scrubbing equipment.

Desulfurisation equipment is not used in Australian power stations since Australian coals contain low levels of sulfur. Even so, sulfur compounds can accumulate in CO_2 absorption systems over time and will eventually reduce the capacity and efficiency of CO_2 capture.

BCIA has supported research on strategies to reduce the cost of amine solvent systems through the evaluation of new, efficient solvents with lower energy penalty, and on novel processes that avoid solvent deactivation without the need for expensive sulfur scrubbing equipment.

In Australia, CSIRO is leading research to make post-combustion capture cheaper and more efficient. CSIRO laboratory research has identified improved efficiencies from testing more than 100 novel solvents, ionic liquids, solid absorbents and enzyme technologies [(1)]. CSIRO also conducts 'learning by doing' research at post-combustion capture pilot plants in Victoria, New South Wales, Queensland and China [(2)].

In Victoria, AGL Loy Yang has played a prominent role in supporting the development of post-combustion capture technologies suitable for use in brown coal power stations, through its collaboration with CSIRO.

Loy Yang power station, owned by AGL Loy Yang, has been the site of a CSIRO pilot plant (Figure 26) that has been used for two BCIA-supported projects. Loy Yang power station is also hosting a new pilot plant built and owned by the Japanese technology provider, IHI Corporation. BCIA is also supporting trials in this plant.

BCIA has also supported four PhD projects that complement the pilot scale research. Each of these projects has been integrated with the CSIRO research activities, in collaboration with the Churchill campus of Federation University Australia (formerly Monash University).

Latrobe Valley Post-combustion Capture (LVPCC) Project – CSIRO stream

The Victorian Government initially supported the LVPCC project through its Energy Technology Innovation Strategy (ETIS) program. The overall aim of the LVPCC project was to conduct research and pilot scale evaluation of prospective technologies for post-combustion capture from the flue gases of brown-coal-fired power stations.

The CSIRO stream of the LVPCC project involved an investigation of CO_2 capture from power station flue gas using monoethanolamine (MEA) solvent and some new amine solvent blends. The CSIRO pilot plant was installed and commissioned at AGL Loy Yang power station during the original ETIS project, representing the first capture of CO_2 from a coal-fired power plant in the southern hemisphere.

BCIA subsequently supported further work on the CSIRO pilot plant. This project was led by AGL Loy Yang, as owners of the site, although the research was conducted by CSIRO. The project involved the following objectives.

- To evaluate four new solvents.
- To investigate the use of two separate absorber columns.

(1) www.csiro.au/en/Research/EF/Areas/Coal-mining/Carbon-capture-and-storage.
(2) Cottrell A. CSIRO PCC pilot plant research in Australia. PCC Science & Technology seminar, 26-Mar-2013.

- To validate a simulation model for the absorber.
- To understand the degradation kinetics of MEA solvent.

Each of the four solvents was able to capture 80%–90% of the CO_2 from the flue gas. One of the amine blends required significantly less heat duty in the stripper reboiler, while maintaining good CO_2 sorption / desorption kinetics, translating to an overall lower energy penalty for CO_2 capture.

This result demonstrates the value of fine-tuning the solvent composition to achieve optimal performance with minimum energy penalty.

Figure 26: CSIRO Post-Combustion Capture (PCC) pilot plant at AGL Loy Yang power station

Another key finding was that it is more energy efficient to operate two small absorber columns in series than a single tall column. Although the initial capital cost of such a system might be somewhat higher, over the longer term the cost would be significantly lower.

It is known that MEA solvent can degrade over time, but the safety implications of the degradation products are unknown. As a first step, a comprehensive review was undertaken, and subsequently published as a reference point for further studies. Efforts were made to detect MEA degradation products in the pilot plant solvent, but the results were inconclusive. Development of more sensitive analytical methods became a focus for on-going work.

Evaluation of advanced PPC process and equipment with two advanced liquid absorbents for application in Victorian brown coal fired power stations

This project was led by Dr Erik Meuleman of CSIRO, in collaboration with AGL Loy Yang and IHI Corporation, of Japan. The project involves the installation and operation of a A$1 million Japanese-built post-combustion capture pilot plant at Loy Yang power station, which will be the first such pilot plant in Victoria to operate around the clock.

This project entails a two-year evaluation of two advanced liquid absorbents, two advanced process designs and an advanced gas / liquid contactor. The combination of these three aspects represents a significant step forward in post-combustion capture technology application for Victorian brown-coal-fired power stations.

In the first year, IHI Corporation designed and manufactured a 0.5 tonnes per day CO_2 capture pilot plant – incorporating an advanced, low-pressure packing material. The plant was transported to Australia for re-commissioning at AGL Loy Yang Power station in the Latrobe Valley (Figure 27).

The combination of three new technology innovations – simultaneous improvements in capture agents, equipment and process design – is expected to deliver almost a 40% reduction in the absorbent energy requirement of the pilot plant compared to a standard amine process.

Figure 27: IHI Corporation's 0.5tpd pilot plant (left) and 20tpd PCC pilot plant (right) in Japan

IHI Corporation's amine-based technology will be evaluated through a parametric study to determine the minimum thermal energy requirement for liquid absorbent regeneration for the two selected be followed by a similar study of an advanced liquid absorbent developed by CSIRO. Each of these studies will involve continuous operation for 5,000 hours to assess the performance and robustness of the two liquid absorbents under brown coal flue gas conditions.

Combined low-cost pre-treatment of flue gas and capture of CO_2 from brown coal-fired power stations using a novel integrated process concept – coCAPco

Sulfur dioxide (SO_2) is an acidic gas that is formed as a combustion product from sulfur compounds present in coal. Environmental emissions of SO_2 contribute to 'acid rain', which has led to mandated requirements for SO_2 scrubbers on coal-fired power stations in the US, Europe and Japan. Australian coals, including Victorian brown coal, are low in sulfur by world standards so flue gas desulfurisation is not necessary. However, this creates a local problem when it comes to post-combustion capture using amine solvents. SO_2 is a stronger acid than CO_2 and is absorbed preferentially by amines, reducing the pH.

Figure 28: TNO CASPER process

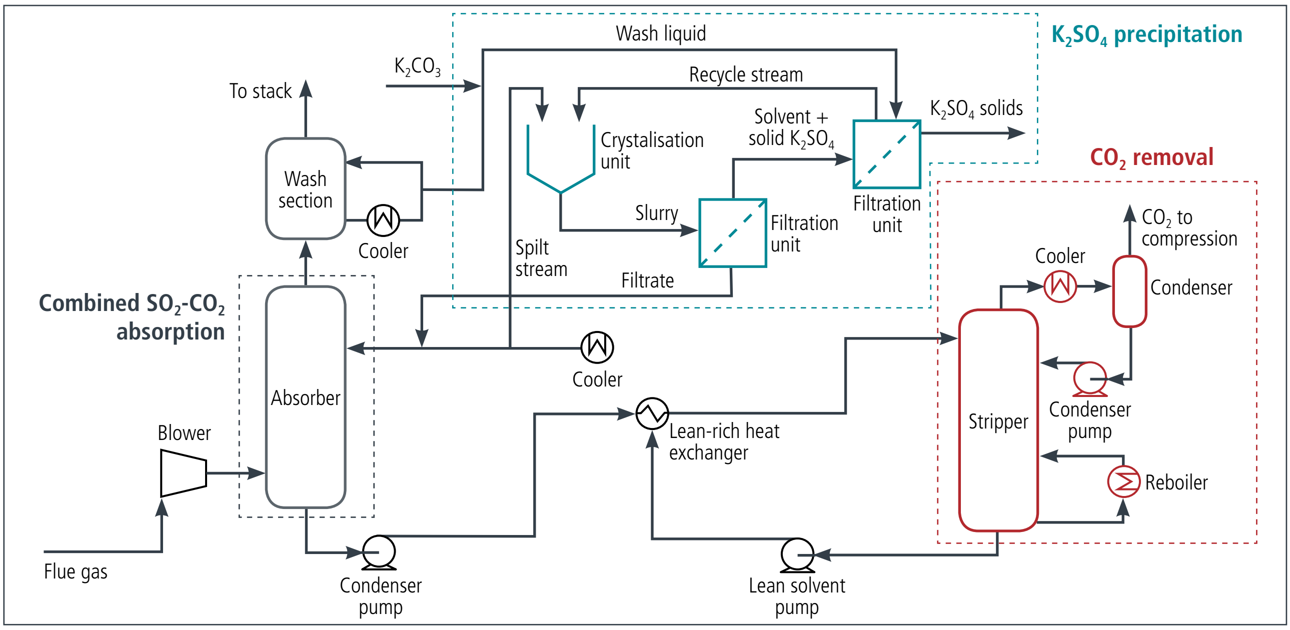
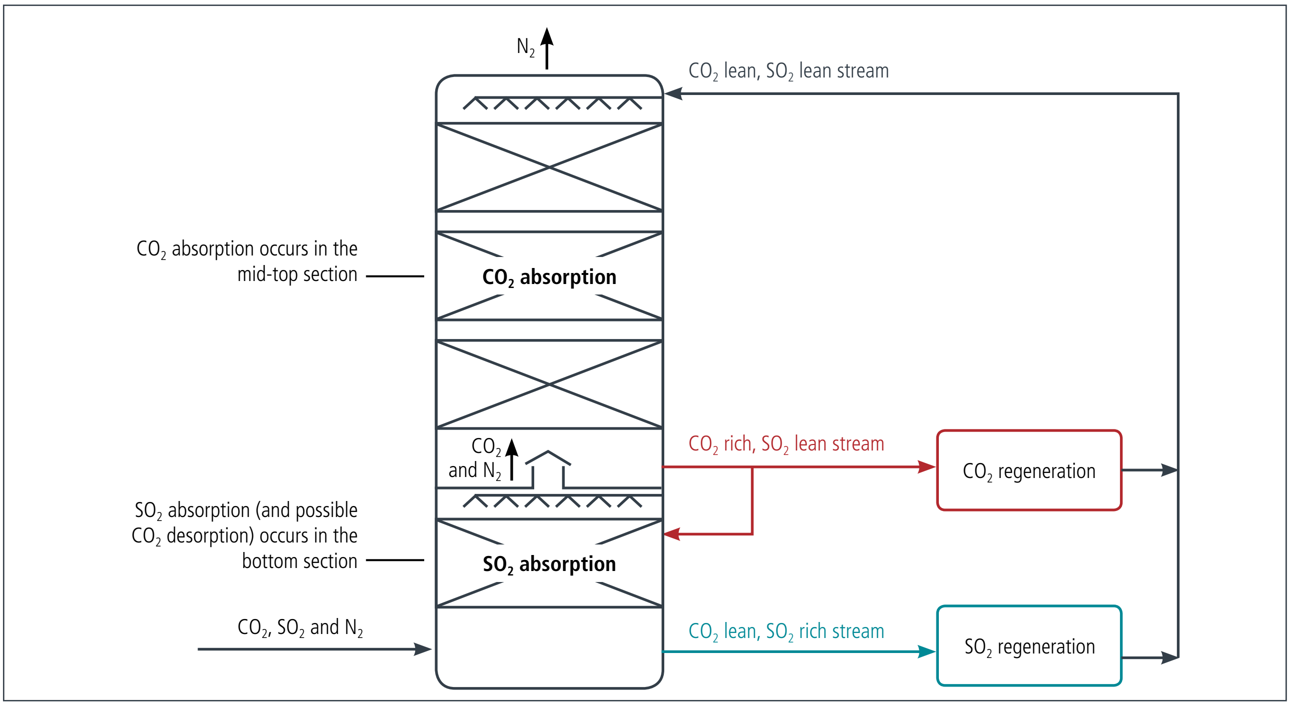


Figure 29: CSIRO CS-CAP process



As a result, both the rate of CO_2 absorption and the overall CO_2 capacity of the solvent are decreased. The objective of this project was to develop a new absorber system to allow effective simultaneous capture of SO_2 and CO_2. This was intended to allow post-combustion capture to be implemented effectively in Australia without the need for an expensive preliminary desulfurisation step. The project was led by AGL Loy Yang, with the research being conducted by CSIRO.

The research was undertaken in two parallel streams. The first involved a collaboration between CSIRO and the European Union iCap project consortium (3), to test a process developed by TNO, dubbed 'CASPER', at the CSIRO post-combustion capture pilot plant at the AGL Loy Yang power station. The CASPER process (Figure 28) involves continuous precipitation of SO_2 in the form of K_2SO_4 from a bleed stream off the main amine solvent loop.

The second stream involved pilot scale testing of a novel amine-based solvent developed by CSIRO (building on experience gained in the previous process) and a novel post-combustion capture process configuration, dubbed 'CS-CAP' (Figure 29). In this patented process, both CO_2 and SO_2 are removed using a single column and a single solvent. CO_2 is absorbed using the bulk of the solvent in the upper section of the column while SO_2 is absorbed in a fraction of the solvent in the lower section of the column. The concentrated SO_2 stream can be recycled, while the bulk of the solvent remains SO_2 free.

Both the TNO CASPER process and the CSIRO CS-CAP process were able to capture over 90% of the CO_2 in the flue gas and all of the SO_2, irrespective of the concentration in the flue gas. A model for the sulfur chemistry as a function of SO_2, CO_2 and absorbent composition was validated. Both technologies were shown to have the potential to capture SO_2 and CO_2 simultaneously, eliminating the need for a separate flue gas desulfurisation step.

A techno-economic assessment suggested that the CASPER process should represent a cost saving of about A$200 million for a 500MW plant fitted with amine-based post-combustion capture. The cost of CO_2 avoidance using the CASPER process, assuming retrofit to a fully amortised 500MW brown coal boiler, was estimated at A$78 per tonne of CO_2.

(3) www.sintef.com/home/projects/sintef-materials-and-chemistry/2010/ICAP---Innovative-CO2-capture.

Equivalent costings for the CS-CAP process were not possible, as the solvent regeneration process was not optimised. BCIA provided additional support for solvent regeneration in the coCAPco² project.

Combined low-cost pre-treatment of flue gas and capture of CO_2 from brown coal-fired power stations using a novel integrated process concept; closing the sulphur loop (coCAPco²)

This project was led by Dr Erik Meuleman of CSIRO, builds upon the previous BCIA-funded coCAPco project. The project examines the feasibility and cost-effectiveness of a range of methods for regeneration of SO_2-loaded amine solvent, including crystallisation and alternatives such as nanofiltration, electro-dialysis, ion-exchange and distillation. The goal is to determine the best option for scale-up in CSIRO's CS-CAP process.

CSIRO will produce the SO_2-loaded solvent at the pilot plant at Loy Yang power station. A PhD student at Federation University Australia at Churchill will conduct research on alternative regeneration methods.

Identification and monitoring of by-products generated from amine-based solvents and adsorbents during PCC from brown coal flue gases

This project was undertaken by Ms Alicia Reynolds, a BCIA-funded PhD scholarship recipient at Monash University Gippsland (now Federation University). The objectives of this study were as follows.

- Detect and identify trace compounds formed in amine solvents during the PCC process and determine the reaction pathways involved.
- Identify suitable chemical markers indicative of solvent degradation and are amenable to on-line analysis.

The project involved the development of appropriate methods for analysis of the organic structural changes that occurred as 30% aqueous MEA was progressively aged in the CSIRO post-combustion capture pilot plant (Figure 30). The aqueous MEA absorbent had previously been used for more than 700 hours of post-combustion capture. Samples were then collected over a further 834 hours of PCC operation. No defoamer, anticorrosion or antioxidants were added to the absorbent at any time, despite difficulties maintaining stable operation of the pilot plant.

Figure 30: Twelve samples of increasingly degraded 30% MEA

It was found that amine degradation was correlated with increasing iron concentrations due to corrosion. The project also demonstrated that N-(2-hydroxyethyl) imidazole (HEI) is a suitable molecular marker for oxidative degradation of MEA [(4)].

Solvent degradation during post-combustion capture of CO_2

BCIA is providing scholarship support for this project by Mr Rahul Chowdhury, a PhD student at Federation University. The objectives of this project are as follows.

- Review current knowledge of reactions and interactions of aqueous amines with metal and mineral surfaces.
- Determine which classes of heterogeneous reactions and interactions are most likely to impact on solvent degradation, PCC plant integrity and environmental effects.
- Investigate the impact of PCC operating conditions on important heterogeneous reactions and interactions.

(4) Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Evaluation of methods for monitoring MEA degradation during pilot scale post-combustion capture of CO_2. International Journal of GHG Control 39: 407–419..

- Develop operation and design guidelines to minimise and manage the impact of heterogeneous interactions on PCC solvent management and plant integrity.

Management of new process streams from post-combustion capture of CO_2 in the Latrobe Valley

BCIA is providing scholarship support for this project by Mr Adeel Ghayur, a PhD student at Federation University. The objectives of this project area are as follows.

- Establish the characteristics and amounts of waste likely to be generated by a PCC industry in the Latrobe Valley.
- Ensure the extensive research already completed by CSIRO into PCC waste mitigation is taken into account in assessing the magnitude of the waste management challenge that would result from a PCC industry in the Latrobe Valley.
- Determine the ability of Latrobe Valley's current resource management industry to absorb the waste streams likely to be generated by a PCC industry in the Latrobe Valley.

And either,

- identify opportunities to optimise industrial ecology within the power station and PCC plant complex; or
- investigate and develop recommendations for treatment of degraded solvents.

This project will assess the industrial waste management challenge presented by a PCC industry in the Latrobe Valley and assess the initial strategies for managing the risks posed to the local community and environment.

Key Publications

Artanto Y, Jansen J, Pearson P, Do T, Cottrell A., Meuleman E and Feron P (2012). Performance of MEA and amine-blends in the CSIRO PCC pilot plant at Loy Yang Power in Australia. Fuel, 101, 264–275.

Artanto Y, Jansen J, Pearson P, Puxty G, Cottrell A, Meuleman E and Feron P (2014). Pilot-scale evaluation of AMP/PZ to capture CO_2 from flue gas of an Australian brown coal–fired power station. International journal of GHG control, 20, 189–195.

Beyad Y, Puxty G, Wei S, Yang N, Xu D, Maeder M, Burns R, Meuleman E and Feron P (2014). An SO_2 tolerant process for CO_2 capture. International Journal of GHG Control, 31, 205–213.

Bui M, Gunawan I, Verheyen V, Artanto Y, Meuleman E and Feron P (2013). Dynamic modeling and validation of post-combustion CO_2 capture plants in Australian coal-fired power stations. Energy Procedia, 37, 2,694–2,702.

Meuleman E, Puxty G and Feron P. "Process for capturing acid gases" U.S. Patent Application 13/980,161, filed 18-Jan-2012.

Meuleman E, Puxty G and Feron P. "Process for capturing acid gases" International Publication Number WO 2012/097406 A1, published 26-Jul-2012

Pearson P, Hollenkamp AF and Meuleman, E. (2013). Electrochemical investigation of corrosion in CO_2 capture plants – Influence of amines. Electrochimica Acta, 110, 511–516.

Reynolds AJ, Verheyen TV, Adeloju SB, Meuleman E and Feron P (2012). Towards commercial scale postcombustion capture of CO_2 with monoethanolamine solvent: key considerations for solvent management and environmental impacts. Environmental Science & Technology, 46(7), 3,643–3,654.

Reynolds AJ, Verheyen TV, Adeloju SB, Meuleman E, Chaffee A, Cottrell AJ and Feron P (2013). Chemical characterization of MEA degradation in PCC pilot plants operating in Australia. Energy Procedia, 37, 877–882.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee A and Meuleman E (2014). Quantification of aqueous monoethanolamine concentration by gas chromatography for postcombustion capture of CO_2. Industrial & Engineering Chemistry Research, 53(12), 4,805–4,811.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Evaluation of methods for monitoring MEA degradation during pilot scale post-combustion capture of CO_2. International Journal of GHG Control 39: 407–419.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Primary sources and accumulation rates of inorganic anions and dissolved metals in a MEA absorbent during PCC at a brown coal-fired power station. International Journal of GHG Control 41: 239–248.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). MEA degradation during pilot scale post-combustion capture of CO_2 from a brown coal-fired power station. Energy & Fuels.

2.2. Precipitating carbonate absorption system

Current amine absorbents are the most commercially mature CO_2 capture technology, as they are extensively used for CO_2 removal during natural gas processing. In this application, economical performance is possible because the CO_2 is present at high concentrations in the raw natural gas stream. The application of amine absorption systems to brown coal emissions reduction, however, presents a number of challenges.

Firstly, the concentration of CO_2 in air-blown brown coal processes, whether gasification or combustion, is relatively low due to dilution with atmospheric nitrogen. This will increase the size and cost of the equipment involved.

Secondly, the gas streams will include sulfur compounds that can reduce the efficiency of amine solvents. As described earlier, BCIA has supported research to develop strategies to allow amine solvents to operate on brown coal flue gases without the need for a separate desulfurisation step.

In addition, BCIA has supported innovative research by the CO2CRC, which led to a patented process for a precipitating potassium carbonate absorption system, dubbed 'UNO MK 3'. This process evolved through three consecutive pilot-scale projects led by the CO2CRC. There are two main ways that absorbents can be used for CO_2 capture associated with power production from brown coal – pre-combustion capture and post-combustion capture.

The term 'pre-combustion capture' relates specifically to coal gasification processes, in which CO_2 is removed from the syngas before the gas is combusted to drive a power generating turbine. The same approach could be used to capture CO_2 from syngas before it is transformed into value-added products. Pre-combustion capture involves recovery of CO_2 from the flue gas exiting a furnace or boiler.

Pre-combustion carbon dioxide capture technologies for brown coal power generation

Pre-combustion CO_2 capture can be used in coal gasification processes to clean the syngas (a mixture of CO, CO_2 and H_2) before combustion or further processing. Dr Abdul Qader of the CO2CRC led a project to evaluate the performance of a pilot-scale potassium carbonate absorption process (UNO MK 1) using syngas from an air-blown pilot-scale gasifier (Figure 31). The project involved collaboration with HRL Developments Pty Ltd, Process Group, the University of Melbourne, Monash University and UNSW. The overall objectives of this project were as follows.

- To evaluate solvent, adsorbent and membrane pre-combustion capture techniques.
- To reduce the technical risk and cost of capturing CO_2 from pre-combustion sources.
- To identify the most cost-effective technologies for deployment in Victoria.

The potassium carbonate solvent work involved three campaigns of pilot plant operation. The process was refined further in each campaign, resulting in a final CO_2 capture efficiency of 56%. Even so, the process was not optimised due to difficulties in maintaining the water balance in the pilot plant and operational difficulties caused by syngas impurities in the solvent.

Figure 31: CO2CRC pre-combustion CO_2 capture rig at HRL Developments

Perhaps one of the most important findings from this work was that sulphur and nitrogen impurities in the syngas interact with the potassium carbonate solvent, altering the CO_2 capture properties. These interactions were incorporated into a simulation model for use in process design and optimisation.

An economic evaluation found that the CO2CRC potassium carbonate solvent incurred a lower CO_2 capture cost than either physical adsorption or membrane separation. It was concluded that the CO2CRC's potassium carbonate solvent technology is worthy of further technical development.

Latrobe Valley Post-combustion Capture (LVPCC) project – CO2CRC stream

The Victorian Government initially supported the LVPCC project through its Energy Technology Innovation Strategy (ETIS) program. The aim of the project was to conduct research and pilot scale evaluation of prospective technologies for post-combustion capture from the flue gases of brown-coal-fired power stations.

The CO2CRC stream of the LVPCC project involved parallel pilot-scale investigations of three CO_2 capture technologies (solvents, membranes and solid-phase adsorption) using flue gas from the GDF SUEZ Hazelwood power station.

BCIA subsequently supported further work on the three CO2CRC pilot plants at Hazelwood power station (Figure 32). As part of this project, the performance of CO2CRC's potassium carbonate solvent was compared with PuraTreat-F™ solvent at pilot scale.

PuraTreat-F™ is a commercial monoethanolamine (MEA) solvent, which served as a reference for comparison. As expected, this solvent performed well, capturing 20–25 tonnes of CO_2 per day at a recovery efficiency of 80%–90%. Sulfur compounds accumulated continuously, eventually reducing the absorption and regeneration efficiency of the solvent. This confirmed the need for a pre-treatment step to remove sulfur impurities from the flue gas when using MEA solvent.

The pilot plant was then modified to accommodate the use of potassium carbonate as a solvent. Under the operating conditions used, the CO_2 capture efficiency was only about 20%, significantly lower than with PuraTreat-F™. In this system, the sulfur compounds precipitated out as potassium sulfate crystals, offering the potential for continuous removal of impurities without the added cost of a separate sulfur removal step.

Figure 32: CO2CRC pilot plant trials at Hazelwood power station

The experimental data from the potassium carbonate trials was used to design an optimised system that should be able to achieve a similar CO_2 capture efficiency as PuraTreat-F™.

This process included a novel strategy for continuous precipitation of the potassium carbonate, which increases the driving force for CO_2 removal and reduces the parasitic energy load. An economic evaluation of this process, known as UNO MK 3, suggested that it was likely to be about half the cost of using conventional MEA solvent.

CO2CRC's Carbon Capture Technologies in Brown Coal Fired Power Plants (CCT-BCFPP) – capture demonstration for cost reduction

This project was led by Dr Abdul Qader of the CO2CRC, in collaboration with GDF SUEZ Hazelwood and Process Group. The objective of the project was to demonstrate the UNO MK 3 concept at pilot scale and develop a comprehensive process model to facilitate further scale-up. The project involved operation of the pilot plant in a series of campaigns, in which a number of different process modifications were evaluated. These included performance evaluation of alternative absorber configurations (i.e. Sulzer structured packing, WES frother absorber column and the TurboScrubber® system), as well as different solvent formulations.

Figure 33: UNO MK 3 pilot plant at Hazelwood power station

Operational data from the pilot plant operating on flue gas from the Hazelwood power station (Figure 33) was analysed using a comprehensive simulation model for the precipitating potassium carbonate system. Limitations of the pilot plant equipment meant that the full potential of the technology could not be demonstrated. Maximum CO_2 capture efficiency was 50% at best, and persistent foaming problems prevented long-term stable operation. However, the process simulation model was successfully verified, and will be used to inform the design for the next stage of scale-up.

Outcomes of this project included a comprehensive model to facilitate scale-up, along with designs for full-scale equipment items including contactors, exchangers and solids removal devices, ready for commercial development. Updated modelling of the UNO MK 3 process retrofitted to a 500MW brown-coal-fired power station showed that it should be more cost-effective than amine solvents. A life cycle assessment showed that UNO MK 3 is more environmentally benign than amines.

Following this project, the CO2CRC licensed UNO MK 3 for commercialisation to a spin-off company, UNO Technology [1].

(1) www.unotech.com.au

Key Publications

Anderson C, Hooper B, Qader A, Harkin T, Smith K, Mumford K, Pandit J, Ho M, Lee A, Nicholas N, Indrawan I, Gouw J, Xiao J, Thanumurthy N, temple N, Stevens G, Wiley D (2014). Recent developments in the UNO MK 3 process–A low cost, environmentally benign precipitating process for CO_2 capture. Energy Procedia 63: 1,773–1,780.

Anderson C, Scholes C, Lee A, Smith K, Kentish S, Stevens G, Webley PA, Qader A, Hooper B (2011). Novel pre-combustion capture technologies in action– results of the CO2CRC / HRL Mulgrave capture project. Energy Procedia 4: 1,192–1,198.

Endo K, Stevens G, Hooper B and Kentish SE. "A process and plant for removing acid gases", WO2011130796, 27-Oct-2011.

Grant T, Anderson C, Hooper B (2014). Comparative life cycle assessment of potassium carbonate and monoethanolamine solvents for CO_2 capture from post-combustion flue gases. International Journal of GHG Control 28: 35–44.

Hooper B, Stevens G and Kentish S. "Plant and process for removing carbon dioxide from gas streams", WO2007/019632, 16-Aug-2006.

Mumford KA, Smith KH, Anderson CJ, Shen S, Tao W, Suryaputradinata, YA, Qader A, Hooper B, Innocenzi RA, Kentish SE, Stevens GW (2011). Post-combustion capture of CO_2: Results from the solvent absorption capture plant at Hazelwood power station using potassium carbonate solvent. Energy & Fuels 26: 138–146.

Qader A, Hooper B, Innocenzi T, Stevens G, Kentish S, Scholes C, Mumford K, Smith K, Webley PA, Zhang J (2011). Novel post-combustion capture technologies on a lignite fired power plant-results of the CO2CRC/H3 capture project. Energy Procedia 4: 1,668–1,675.

Smith KH, Anderson CJ, Tao W, Endo K, Mumford KA, Kentish SE, Qader A, Hooper B, Stevens GW (2012). Pre-combustion capture of CO_2 – Results from solvent absorption pilot plant trials using 30wt% potassium carbonate and boric acid promoted potassium carbonate solvent. International Journal of GHG Control 10: 64–73.

Smith K, Xiao G, Mumford K, Gouw J, Indrawan I, Thanumurthy N, Quyn D, Cuthbertson R, Rayner A, Nicholas N, Lee A, da Silva G, Kentish S, Harkin T, Qader A, Anderson C, Hooper B, Stevens G (2013). Demonstration of a concentrated potassium carbonate process for CO_2 capture. Energy & Fuels 28: 299–306.

Stevens G, Hooper B, Dugan C and Webley PA. "Reactor, plant and process", WO2008138054, 20-Nov-2008.

2.3. Westec Environmental Solutions (WES) froth generator absorber system

Development of process internals for application of the WES froth generator gas / liquid absorption technology

The capital cost of absorber columns is a significant proportion of the cost of post-combustion capture. The height of the columns is dictated by both the volumetric flowrate and the mass transfer efficiency of the column internals. Westec Environmental Solutions (WES), a US company, has developed a novel froth generator absorber which is a more efficient mass transfer device than conventional column packings. The WES froth generator absorber could substantially reduce the size and cost of equipment needed for CO_2 capture.

This project was led by Process Group in collaboration with WES and the CO2CRC. The objective was to translate the WES froth generator absorber concept from laboratory scale to pilot plant scale for CO_2 capture from power station flue gas. Experiments in similar sized columns were run in parallel at the WES facility at Maui, Hawaii, using a model air / CO_2 gas mixture, and in the CO2CRC pilot plant at the GDF Suez Hazelwood power station (Figure 34). The aim was to validate the results obtained at Maui with real flue gas, and to develop a CFD model that could be used for subsequent scale-up.

Figure 34: Internals of laboratory-scale WES froth absorber

The intention was to use the CFD model to build a larger pilot column, for validation at the CO2CRC pilot plant, as a next step toward commercialisation. However, it was found that the complexity of the co-current gas / liquid flow created by the WES internals was such that a workable CFD model was beyond the capability of current state-of-the-art programs and hardware. It was concluded that the system is too complex to allow accurate modelling of the fundamental processes occurring in the WES absorber, forcing the abandonment of this line of research.

The small pilot-scale WES absorber was operated successfully as part of the CO2CRC trial program at the GDF Suez Hazelwood power station, with trials on both the CO2CRC potassium carbonate solvent and sodium glycinate.

The results achieved were consistent with those obtained in the Maui laboratory. This confirmed that the WES absorber is more efficient than conventional structured packing, and can effectively halve the length of absorber column required.

In the absence of a suitable modelling tool, it was not possible to progress the project further. The project was abandoned by mutual consent. WES will continue to develop a suitable process design methodology at the Maui facility.

Key Publications

Dugan C, Pellegrin RJ, Hargrove WL and Liu ZB. "Absorber", WO2012112224, 23-Aug-2012.

Pellegrin R. "Method and means for simultaneously generating an aqueous froth and numerous micro-droplets for use in filtering a contaminated stream", WO2008005080, 10-Jan-2008.

Pellegrin R. "Method and means for simultaneously generating an aqueous froth and numerous micro-droplets for use in filtering a contaminated stream", US Patent US7854791, 21-Dec-2010.

Westec Environmental Solutions, LLC. "Regenerative froth technology for unprecedented mass transfer in gas/liquid absorption".

2.4. Physical adsorption systems

The most widely adopted approach for CO_2 capture is to use chemical solvents, which can absorb CO_2 by chemical reaction during the capture stage and then release the CO_2 when heated during the desorption stage. The problem with such solvents is that they tend to be corrosive and may be unstable at high temperatures. They also have the potential to produce a range of hazardous reaction products after long-term operation. The safety implications for disposal of spent solvent are not yet well understood.

As an alternative approach, solid phase physical adsorption systems are being developed which have the same surface functionality as solvent absorbents, while avoiding the corrosion and instability problems. The main challenge for physical adsorbent systems is to maintain long-term operational stability at high temperatures in the presence of moisture.

BCIA has supported four research projects on new physical adsorption systems, involving investigations of new materials of construction and high-efficiency operating strategies.

Pre-combustion CO_2 capture technologies for brown coal power generation

The project was led by Dr Abdul Qader of the CO2CRC in collaboration with HRL Developments Pty Ltd, Process Group, the University of Melbourne, Monash University and UNSW. The project involved an evaluation of alternative techniques for pre-combustion CO_2 capture, using syngas from HRL Technology's pilot-scale air-blown gasifier. The key objectives were as follows.

- To evaluate solvent, adsorbent and membrane pre-combustion capture techniques.
- To reduce the technical risk and cost of capturing CO_2 from pre-combustion sources.
- To identify the most cost-effective technologies for deployment in Victoria.

The aim of the absorption work was to demonstrate the potential of pressure swing vacuum adsorption, using solid adsorbents for CO_2 capture. This technology has the potential to recover CO_2 with relatively low energy consumption, while CO_2 purity can be enhanced through optimisation of operating cycle design.

A pilot adsorption system was constructed for trial on the HRL Mulgrave gasifier, capable of operating at pressures up to 30 bar and temperatures up to 400°C, at a maximum gas flow rate of 5 litres per minute and maximum vacuum of 1kPa (Figure 35). The pilot rig was operated in conjunction with an in-house process simulator, MINSA (Monash Integrated Numerical Simulation of Adsorption), a powerful tool for evaluating cycle design and investigating the effects of a large number of variables on CO_2 capture performance. Simulation results were used to do the following.

- Design novel pressure vacuum swing adsorption (PVSA) cycles.
- Optimise operation of the pilot plant under the given daily syngas conditions.
- Anticipate the process results at a larger scale by extrapolating experimental results.

Figure 35: Operation of the pilot adsorption system on the HRL Mulgrave gasifier

Preliminary process modeling work with MINSA indicated that PVSA cycles could be developed to achieve carbon dioxide purity of greater than 95% at an overall recovery of more than 90%.

Lab-scale experiments showed that zeolite 13X and calcium chabazite have high adsorption capacity and fast kinetics at temperatures of less than 200°C. Preliminary results with novel adsorbents such as polyethylenimine and double salt materials showed promise for CO_2 capture at high temperatures.

Pilot-scale results of pressure swing vacuum adsorption with zeolite 13X showed that sophisticated operating cycles could produce CO_2 concentration greater than 95%, the target for effective transportation and sequestration of CO_2. Further work is needed to understand the effects of syngas contaminants on the long-term operational stability of such adsorbents at large scale.

Latrobe Valley post-combustion CO_2 capture – CO2CRC stream

The CO2CRC led a PCC project at the GDF-SUEZ Hazelwood power station, representing a world first in demonstrating PCC using three different separation technologies (solvents, membranes and adsorption) in parallel in a real power plant setting. The objective of the project was to reduce the technical risk and cost of post-combustion capture for Victorian coal-fired power stations by the following.

- Testing solvent, adsorbent and membrane PCC techniques with real power plant flue gas.
- Reducing the technical risk and cost of capturing CO_2 from post-combustion sources.
- Identifying the most cost-effective capture technologies for use in Victoria.
- Providing large scale designs for all capture technologies and comparing their technical and economic performance.

The adsorption part of the project involved a three-column, vacuum swing adsorption pilot plant. Multiple layered adsorbents were used as well as CO_2-selective adsorbent materials (Figure 36). Water-selective adsorbents removed the water in the gas stream, and acid resistant adsorbents removed SO_x and NO_x. The pilot rig (Figure 37) was operated in a six-step cycle continuously and automatically, achieving a recovery of approximately 60% at a purity of around 71%. Better results should be achievable through process optimisation.

Figure 36: Multi-layer adsorption

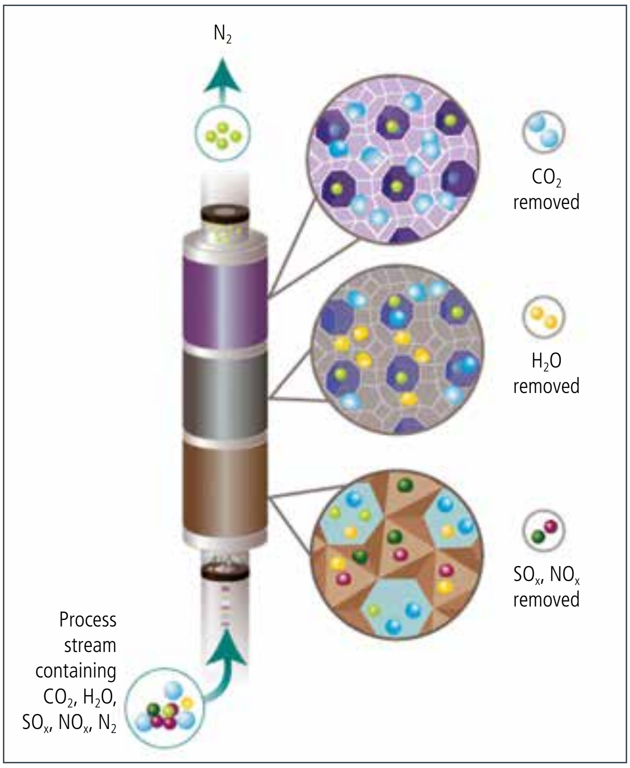


Figure 37: Pilot-scale adsorption rig at Hazelwood power station

The pilot plant operations served to validate a process model that had been developed for selection and evaluation of operating conditions for CO_2 capture using vacuum swing adsorption. Simulations indicated that high CO_2 purity and recovery should be possible through careful management of the CO_2 profile within the bed, by control of the cycle design and operating conditions.

The vacuum swing adsorption model was used in association with an economic study to quantify the effects of adsorption cycle design on CO_2 capture costs. The operating capture cost varies by a factor of two as process conditions of the vacuum swing adsorption are altered, suggesting significant scope for optimisation.

Carbon materials from Victorian brown coal for CO_2 capture

A large part of the cost of adsorption systems is due to the need to regularly replace the adsorbent bed and dispose of the waste materials. Costs could be reduced significantly if the adsorbent bed could be fabricated from low-cost Victorian brown coal. Waste disposal costs could then be minimised by burning the spent adsorbent as fuel.

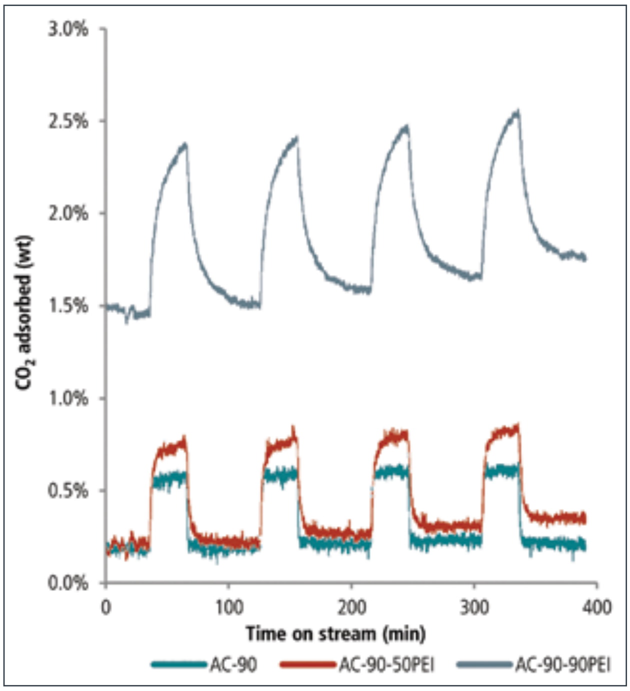
Monash University undertook an investigation of the potential to produce activated carbons from Victorian brown coal for use in CO_2 capture . This was one of three projects established through a collaborative agreement between the Victorian Government and Japan's Kyushu Electric Power Company (KEPCO) in 2009. BCIA assumed management of these projects at the end of 2010.

This project involved a PhD student, Mr Lachlan Ciddor, supervised by Professor Alan Chaffee, in collaboration with Australian Char and the University of Melbourne.

Mesoporous carbons were prepared using steam activation catalysed by cerium, lanthanum and yttrium. A novel acid washing procedure removed post-synthetic catalyst. All of the resulting mesoporous carbons showed a higher CO_2 adsorption capacity than the commercial activated carbon standard.

Surface impregnation with polyethyleneimine (PEI) further modified some of the mesoporous carbons, which further increased the CO_2 adsorption capacity as shown in Figure 38.

Figure 38: Multi-cycle CO_2 adsorption on modified activated carbons



This project produced promising results, although further work is needed to improve the CO_2 adsorption capacity and physical stability of mesoporous adsorbents derived from brown coal. A subsequent project undertook follow-up work.

Evaluation of carbon monoliths for capture of CO_2 by Electrical Swing Adsorption (ESA)

This project involves a collaboration between Monash University and the University of Melbourne (Professor Paul Webley), and is part of the international MATESA consortium (www.sintef.no/projectweb/matesa/consortium).

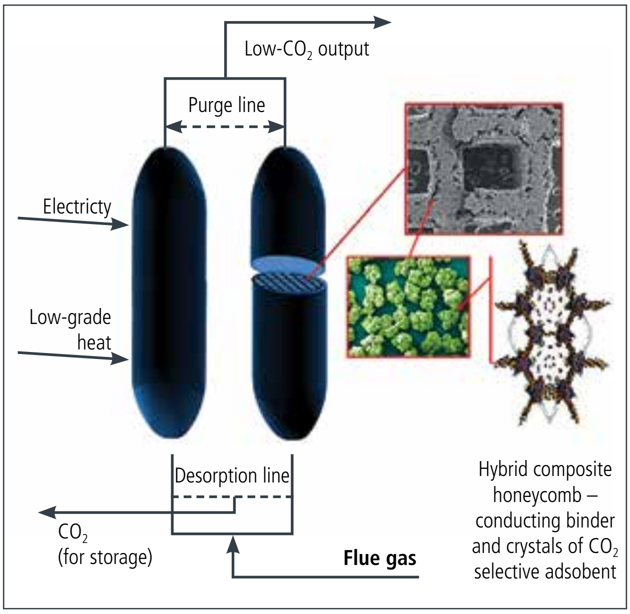
The project focuses on the development of carbonaceous adsorbent monolithic solids that can be used to capture CO_2 in a process known as electrical swing adsorption (Figure 39). The monoliths must be electrically conductive so that the CO_2 can be recovered (desorbed) in a concentrated form by applying electrical current.

Research will involve the fabrication of improved adsorbents, their evaluation at bench scale and process integration modelling. All this will be considered in a life cycle analysis context to determine optimum configurations to reduce the environmental impact. This information will provide proof-of-concept at a respectable scale and quantify the energy and cost efficiency that can be realistically and sustainably achieved.

One part of this project, at Monash University, will pursue the development of carbon monoliths from Victorian brown coal. These will be fabricated and tested at laboratory scale for their physical strength and electrical conductivity. Their capacity and selectivity in separating CO_2 from other components of flue gas will be evaluated both in their own right and after incorporation of metal organic framework that form part of the MATESA project.

The University of Melbourne will pursue process evaluation of electrical swing adsorption through testing monoliths in an experimental rig, supplemented by CFD modelling.

Figure 39: Conceptual diagram of ESA



Key Publications

Ciddor LA, Knowles GP, Chaffee AL (2013). Improving the CO_2 Capacity and Selectivity of Carbon Adsorbents by Post-Synthetic Amine Modification. Proceedings of the International Conference on Coal Science & Technology (ICCS&T) 2013, State College PA, 29-Sep-2013 to 3-Oct-2013, 8pp.

Dong X, Zhang J, Gang L, Xiao P, Webley P, Zhai YC (2011). Effect of water vapor from power station flue gas on CO_2 capture by vacuum swing adsorption with activated carbon. Journal of Fuel Chemistry and Technology 39: 169–174.

Xiao G, Xiao P, Lee S, Webley PA (2012). CO_2 capture at elevated temperatures by cyclic adsorption processes. RSC Advances 2: 5,291–5,297.

Zhang J, Xiao P, Li G, Webley PA (2009). Effect of flue gas impurities on CO_2 capture performance from flue gas at coal-fired power stations by vacuum swing adsorption. Energy Procedia 1: 1,115–1,122.

2.5. Membrane systems

Compared with absorption or adsorption technologies, membrane technology is relatively new but has the potential to provide significant capture cost reductions. Membranes can be used to separate CO_2 from other gases (gas separation membranes) or to allow CO_2 to be absorbed from a gas stream into a solvent (membrane gas absorption).

In the context of power production from brown coal, there are two main ways that membranes can be used for CO_2 capture: either for pre-combustion capture or post-combustion capture. The term 'pre-combustion capture' relates specifically to coal gasification processes, in which CO_2 is removed from the syngas before the gas is combusted to drive a power generating turbine. However, the same approach could be used to capture CO_2 from syngas before it is transformed into value-added products. Post-combustion capture involves recovery of CO_2 from the flue gas exiting a furnace or boiler.

The main difference between these two CO_2 capture scenarios is that pre-combustion syngas is produced under reducing conditions, while post-combustion flue gas is in an oxidised state. This affects the chemical state of gas components (e.g. sulfur is present as H_2S in syngas and SO_2 in flue gas), which has implications for the materials of construction in the membrane system. It is not likely that there will be a 'one size fits all' solution, so suitable processes have to be developed independently for each scenario.

BCIA has supported two research projects and two PhD scholarships to evaluate the potential of membranes in cleaning emissions from brown coal processes.

Pre-combustion CO_2 capture technologies for brown coal power generation

The Pre-Combustion CO_2 Capture project was led by Dr Abdul Qader of the CO2CRC in collaboration with HRL Developments Pty Ltd, Process Group, the University of Melbourne, Monash University and UNSW. The project involved an evaluation of alternative techniques for pre-combustion CO_2 capture, using syngas from HRL's pilot-scale air-blown gasifier (Figure 40). The key objectives were as follows.

- To evaluate solvent, adsorbent and membrane pre-combustion capture techniques.
- To reduce the technical risk and cost of capturing CO_2 from pre-combustion sources.
- To identify the most cost-effective technologies for deployment in Victoria.

The objective of the membrane work was to evaluate the potential of various commercially-available membranes for CO_2 capture. The membrane pilot plant was designed to separate out around 5.6kg CO_2 per day, and could operate three different membrane processes in parallel.

- Two-stage membrane module separation in series.
- High-temperature membrane separation (i.e. close to the water-gas shift temperature).
- Membrane gas-solvent absorption contactor, with the membrane forming a permeable interface between the syngas and a solvent.

Figure 40: CO2CRC membrane pilot plant at HRL Mulgrave gasifier

The work trialled nine gas separation membranes and four different combinations of membrane gas-solvent contactors.

Membranes composed of Poly DiMethyl Siloxane (PDMS), a rubbery polymer, performed best under syngas conditions, exhibiting high CO_2 permeability as well as good CO_2 / H_2 and CO_2 / N_2 selectivity.

The CO_2 permeability of the PDMS membrane deceased over a 6–8 hour period to a long-term steady state value, apparently due to fouling from hydrocarbon and ash components of the syngas.

The permeability of PDMS membranes reduced upon exposure to CO, H_2S and water in a clean gas mixture, due to the competitive sorption of these gases into the polymeric matrix.

Two PDMS membranes in series were almost able to achieve the purity of CO_2 required for storage. Further modelling of the two-stage process using Aspen HYSYS and a custom membrane simulation module indicated that it should be possible to achieve a CO_2 purity of 96%.

The best performing H_2-selective membrane was a nanoporous carbon membrane, which achieved adequate H_2 / CO_2 and H_2 / N_2 selectivity at high temperature. Matrimid membranes also showed potential for H_2 separation, although at a lower temperature.

For the membrane gas-solvent contactor, a porous polytetrafluoroethylene (PTFE) contactor, with 30 wt% monoethanolamine (MEA) as the solvent, achieved the highest overall mass transfer coefficients. However, the corrosive nature of MEA caused polymer degradation, suggesting that a more benign solvent, such as potassium carbonate, would be a better option for high temperature operation.

Latrobe Valley post-combustion CO_2 capture: CO2CRC stream

The CO2CRC led a post-combustion capture project at the GDF-SUEZ Hazelwood power station, representing a world first in demonstrating post-combustion capture using three different separation technologies (solvents, membranes and adsorption) in parallel in a real power plant setting (Figure 41).

The objective of the project was to reduce the technical risk and cost of PCC for Victorian coal-fired power stations by the following.

- Testing solvent, adsorbent and membrane PCC techniques with real power plant flue gas.
- Reducing the technical risk and cost of capturing CO_2 from post-combustion sources.
- Identifying the most cost-effective capture technologies for use in Victoria.
- Providing large scale designs for all capture technologies and comparing their technical and economic performances.

The objective of the membrane work was to trial gas separation membranes and membrane gas-solvent absorption contactors to separate CO_2 from flue gas, to determine which membrane technology has the greatest potential for successful PCC.

The membrane pilot plant was designed to separate out around 15 tonnes CO_2 per annum, and could operate two membrane separation processes in parallel.

- A gas separation membrane (Air Products PRISM polysulfone membrane), where the membrane is a nonporous polymer selective for CO_2 and the permeate stream is under vacuum.
- A membrane gas-solvent absorption contactor, where CO_2 separation was achieved by absorption into a solvent (from the solvent pilot plant), with the interaction area between the flue gas and solvent rigidly controlled by a porous polysulfone membrane (Membrana Liqui-cell X50).

With the gas separation membrane, only about 25% of the CO_2 in the feed passed into the permeate stream. Minor components, including NO_x and CO, did not pass through the membrane, although the data for SO_x was inconclusive.

Figure 41: Membrane pilot plant at Hazelwood power station

With the membrane gas-solvent absorption contactor, 85% of the CO_2 in the flue gas was absorbed into BASF PuraTreat™ F solvent. The potassium carbonate solvent was much less efficient at absorbing CO_2, since the potassium carbonate system has much slower kinetics at the operating temperature and pressure.

There was an extensive laboratory research program conducted in support of the pilot plant work. This allowed for more detailed evaluation of polysulfone membranes (as used in the pilot trials) and two polyimides (Matrimid 5218 and 6FDA-TMPDA). The polyimides are more prospective membranes for large scale carbon capture, but were unavailable as modules for testing in the pilot plant.

For all membranes, there was a clear trend of increasing gas permeability in the following order: N_2, CO, NO, CO_2. The polyimide membranes exhibited higher permeability for each gas than the polysulfone membranes.

With the Matrimid 5218, CO_2 was adsorbed faster than CH4 and N_2, while water was strongly absorbed into the polymer matrix.

The membranes used commercially are of a composite nature, where the active polymeric layer is ultra-thin (<2μm thick). With use, interaction with CO_2 can cause plasticisation, permanently altering membrane performance and increasing the possibility of a failure. Trials on ultra-thin polysulfone membranes showed that they plasticised at pressures lower than those reported for dense membranes.

The results of the pilot plant trials were incorporated into an Aspen HYSYS simulation to allow design of large scale membrane-based capture plants. The Air Products PRISM polysulfone gas separation membrane was incapable of delivering a design that could achieve 90% CO_2 recovery. Potentially, polyimide membranes are more suited to the task, but it was not possible to obtain useful data for such membranes at pilot scale.

Conversely, the combination of the Membrana Liqui-cell X50 polysulfone membrane and the BASF PuraTreat™ F solvent in an absorption contactor arrangement could potentially be scaled up to achieve 90% CO_2 removal from flue gas.

An economic analysis of both membrane processes indicated that they are substantially more expensive to implement than either solvent absorption or vacuum swing adsorption. However, the skills and knowledge developed through this project have made the CO2CRC Membrane group one of the leaders in polymeric membranes and membrane gas-solvent contactors for post-combustion carbon capture. A major outcome was the training of researchers and students (five in total) in carbon capture technologies and the communication of information and skills learned.

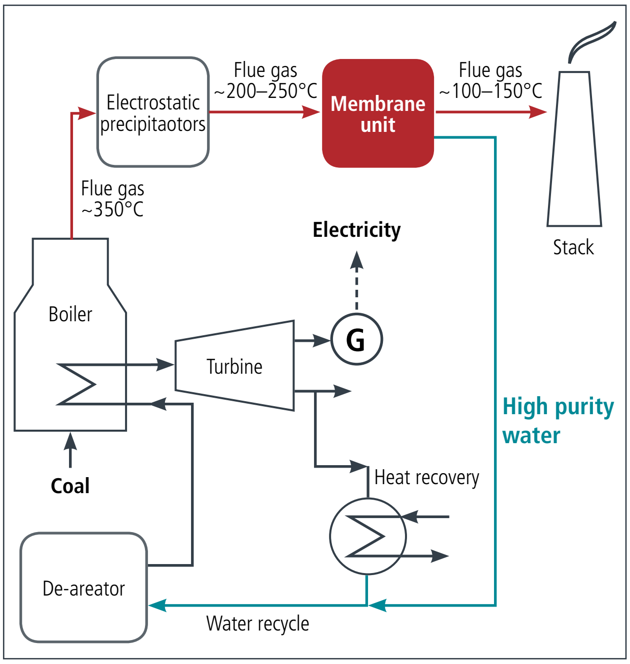
Membrane processes for water recovery from brown coal flue gases

Approximately 60 million tonnes of brown coal is burned for power generation in the Latrobe Valley each year. Since brown coal contains about two thirds moisture, about 40 million tonnes of water is discharged annually to the atmosphere as moisture in the flue gas.

This represents a valuable resource that could potentially be recycled for use as boiler feed water, but the water recovered needs to be of a high purity. The present of CO_2, SO_x and NO_x in the recovered water would make it acidic and cause corrosion issues in the boiler.

Membrane technology can potentially allow recovery of high purity water from boiler flue gas. Membrane materials such as Nafion™ are almost 100% selective for water, allowing production of near-drinking quality water supplies. Previously, studies have focused on the water flux through Nafion membranes at temperatures below 100°C. In order to recover water from power station flue gases, the membrane needs to operate effectively at temperatures of 100°C to 150°C.

Figure 42: Schematic diagram of a coal-fired power plant with a membrane unit to recover and recycle water vapour



BCIA provided a PhD scholarship to Ms Hirra Azher at the University of Melbourne to investigate the performance of Nafion membranes over the temperature range of 70°C–150°C. Ms Azher investigated the permeation of water, CO_2 and N_2 through Nafion 115 as a function of both water activity and temperature. All permeances increased with increasing water activity but reduced with increasing temperature. The permeance of water and CO_2 at 150°C were also studied for four other candidate polymers. Nafion 112 exhibited the highest H_2O / CO_2 selectivity.

The performance data was modelled with Aspen HYSYS. A permeate stream with pH 5.67 is achievable with Nafion 115 at 150°C, but the membrane area required is impractically large. Water recovered from flue gas using Nafion 115 membranes would be acidic and would require pH adjustment prior to use.

The impact of impurities on the performance of cellulose acetate membranes for CO_2 separation

Cellulose acetate membranes are widely used in industrial gas separation processes, and represent over 90% of the capacity of membranes used for H_2S removal from natural gas. Their commercial availability makes them ideal candidates for use in CO_2 capture applications. However, the effect of gaseous components such as water, H_2S, SO_x and NO_x on the performance of cellulose acetate membranes at flue gas temperatures is unknown.

BCIA is providing scholarship support for this project by Mr Hiep Lu, a PhD student at the University of Melbourne. The objectives of this project are to produce experimental data to quantify the effects of flue gas impurities on cellulose acetate membranes and develop a process design modelling tool. It is expected that the outcomes from this project will establish the practical feasibility of using cellulose acetate membranes for CO_2 recovery in brown coal power stations.

Key Publications

Azher H, Scholes CA, Stevens GW, Kentish SE (2014). Water permeation and sorption properties of Nafion 115 at elevated temperatures. Journal of Membrane Science 459: 104–113.

Kanehashi S, Chen GQ, Ciddor L, Chaffee A, Kentish SE (2015). The impact of water vapor on CO2 separation performance of mixed matrix membranes. Journal of Membrane Science 492: 471–477.

Scholes CA, Bacus J, Chen GQ, Tao WX, Li G, Qader A, Stevens GW, Kentish SE (2012). Pilot plant performance of rubbery polymeric membranes for carbon dioxide separation from syngas. Journal of Membrane Science 389: 470–477.

2.6. Dispersion modelling for CO_2 pipelines

Effective deployment of CCS infrastructure in Australia will require pipelines to transport compressed CO_2 from the point of capture to the point of storage. While Australians are generally familiar and comfortable with the presence of natural gas pipelines, pipelines for CO_2 are not known and present uncertain risks. Figure 43 shows installation in the US of a pipeline for transporting CO_2.

Natural gas pipelines in Australia must conform to the design and risk management approach set out in Australian Standard 2885 'Pipelines - Gas and liquid petroleum'. Any new CO_2 pipeline will also be designed using this Standard, but the methods for assessing the consequences of a gas release are not clearly specified.

One of the most important differences between natural gas and CO_2 is that natural gas is lighter than air, while CO_2 is heavier. In any event where gas is released from a pipeline, the dispersion of CO_2 into the atmosphere will be markedly different from the behaviour of natural gas.

Another important difference is that natural gas is highly flammable and explosive, while CO_2 is not. However, CO_2 is an acidic gas that can cause a pH imbalance in the bloodstream, with the physiological consequences depending on the dose and duration of the exposure.

These two key differences mean that the consequence analysis tools used for natural gas pipeline design are not applicable to CO_2 pipelines. In order for a CO_2 pipeline to be designed in accordance with Australian Standard 2885, appropriate modelling tools need to be identified, especially for reliable simulation of release and dispersion of CO_2 into the atmosphere.

BCIA has supported a project that investigated the application of CO_2 dispersion modelling in the context of new CO_2 pipeline infrastructure in Australia. The project was conducted in two stages, with the first led by Ramboll Environ Australia and the second by Sherpa Consulting. Valuable international input was gained through technical contributions from Dr Stephen Hanna, an eminent expert in dense gas dispersion modelling, and through a critical review by Dr Simon Gant of the UK Health and Safety Laboratory, who was involved in recent European CO_2 release projects. The Victorian Department of Economic Development, Jobs, Transport and Resources and Australian National Low Emissions Coal Research & Development provided project funds.

The investigation considered a series of modelling tools that may be regarded as fit for purpose for simulating the dispersion characteristics of CO_2 gas. The assessment was based on a number of criteria.

- Availability, ease of use, access to technical support.
- Ability to calculate appropriate source terms for different CO_2 release scenarios.
- Validation history, particularly with CO_2.
- Ability to account for complex terrain and variable atmospheric conditions.
- Applicability to different stages of the design process.
- Acceptability to Australian regulators.

Modelling of a release of dense phase CO_2 from a pipeline requires consideration of a number of aspects, including transient pipeline depressurisation, multi-phase jet release, and dispersion of both dense and neutral gas. Appropriate models that can be used for each of these aspects were identified.

A range of dense gas dispersion models were investigated, including empirical correlations, integral models, Lagrangian particle and plume dispersion models and computational fluid dynamics (CFD) models. Selected models were reviewed and evaluated against the various criteria to determine if they could be considered 'fit for purpose'.

One of the main conclusions from this project was that sufficient information and modelling tools are available to allow a new CO_2 pipeline to be designed in accordance with Australian Standard 2885. The project deliverable was a comprehensive report that provides guidance on the current international best practice in modelling CO_2 dispersion, and identifies appropriate, fit-for-purpose modelling tools that can be used at different stages in the pipeline design process.

The final report is available to the public and will be useful to both pipeline designers and regulatory authorities. The guidance provided in this report will allow the risks associated with new CO_2 pipelines to be reduced to as low as reasonably practicable, equivalent to the community expectations for natural gas pipelines.

Figure 43: A CO_2 pipeline being laid in the US

Key Publications

Sherpa Consulting (2015). Dispersion modelling techniques for carbon dioxide pipelines in Australia. Available through the Global CCS Institute website: www.globalccsinstitute.com/publications/dispersion-modelling-techniques-carbon-dioxide-pipelines-australia

2.7. Novel CO_2 capture technologies

The effective deployment of carbon capture and storage (CCS) technologies relies on the availability of suitable storage options for the large quantities of CO_2 that must ultimately be sequestered. The main focus in Victoria is on geological sequestration, but other options have been proposed, broadly falling into the areas of bio-sequestration and mineral sequestration.

The Australian Government under the National Low Emissions Coal Initiative established the Carbon Capture Task Force to develop a National Carbon Mapping and Infrastructure Plan for geological storage of CO_2. BCIA provided support for the study, along with ANLEC R&D and the Global CCS Institute.

The role of the Carbon Capture Task Force was to provide an independent assessment of the feasibility and cost of novel bio-sequestration and mineral sequestration techniques in Australia, and to make recommendations about appropriate R&D needs and priorities. In this project, bio-sequestration and mineral sequestration were defined as follows [(1)]:

- **Bio-sequestration** is the capture and storage of atmospheric CO_2 by biological processes. This may be by increased photosynthesis (through re-forestation, or decreased de-forestation); by enhanced soil carbon trapping in agriculture; or by the use of algal bio-sequestration to absorb CO_2 from industrial processes.
- **Mineral sequestration**, or mineral carbonation, involves reaction of CO_2 with metal oxides that are present in common, naturally occurring rocks. This process mimics natural weathering phenomena, and results in natural carbonate products that are stable on a geological time scale.

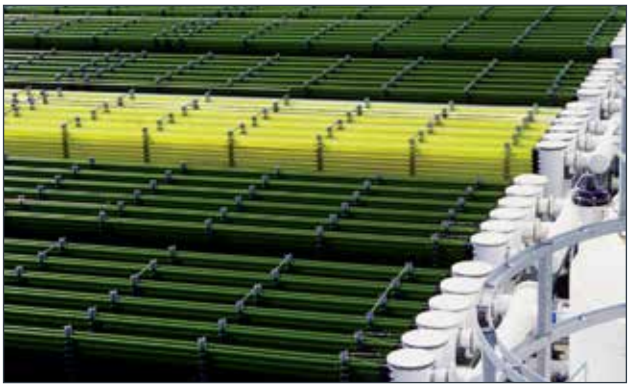
The Carbon Capture Task Force has made recommendations in relation to the following novel technologies [(2)].

(1) www.hub.globalccsinstitute.com/publications/novel-co2-capture-taskforce-report/executive-summary
(2) www.hub.globalccsinstitute.com/publications/novel-co2-capture-taskforce-report/recommendations

1. The growth of algae by consumption of CO_2 from coal-fired power stations using photosynthesis can provide a relatively small contribution to the stations' overall CO_2 emissions (Figure 44). The R&D on algae for CO_2 mitigation should be focused on the following.

- Increasing algal productivity, including new algal species research.
- Reduction of capital costs and raw material requirements.
- Mass transfer efficiency for CO_2 absorption in bio-reactors at low CO_2 concentrations.

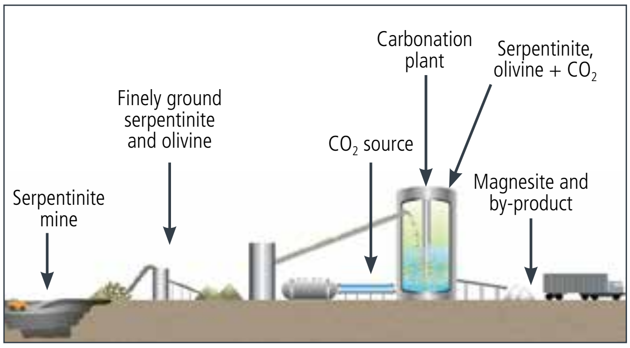
Figure 44: Large-scale cultivation of microalgae



2. Mineral carbonation technology in Australia has been found by the Task Force to be apparently following two streams: (i) development of the work undertaken previously in the US on serpentine rock heat activation followed by reaction with CO_2, and (ii) technologies based on novel chemistry and flowsheets (Figure 45). Since the technology offers the scale and permanency required for the capture of CO_2 from coal-fired power stations close to the rock resources, the Task Force recommends that research, development and demonstration continue so that the nation can have multiple options in the area, including the following.

- Further fundamental research at the bench scale to move the novel chemistry technology approaches beyond the concept stage.
- Scale-up to beyond bench or laboratory scales to demonstrate that small-scale performance can be achieved at larger scale.
- Focused research on the reduction of capital costs and increase in the efficiency of use of raw materials and energy. This should include rock activation, comminution (action of reducing a material to minute particles), carbonation, particle separation technology, tailings dewatering, and tailings disposal.
- Independent review of the costs of mineral carbonation for the different processes listed above, taking into account expected efficiency improvements due to research and innovative process developments.

Figure 45: Conceptual scheme for mineral carbonation



3. The regulatory environment for forestry sequestration of CO_2 from the atmosphere in terms of credits for CO_2 capture should be resolved to provide investment certainty. Research in the forestry area should be focused on life cycle carbon accounting, including soil carbon effects. Risk management needs to be undertaken on the impact of natural events.

4. Sequestration through soil carbon enhancement has potential to make a contribution to CO_2 mitigation and to improvements in agriculture. There are, however, questions about carbon permanence in soils at the time scales required.Research should be carried out in the following areas.

- Effective and efficient methods of soil carbon measurement, including remote technologies to monitor CO_2 and other GHG fluxes into and out of soils.

- Bench and field trials at scale to monitor the soil carbon balance over time and space, including a range of soil carbon amendment types and simultaneous scientific measurement of the beneficial effects on agriculture (Figure 46).

Figure 46: Sampling agricultural soil carbon content

5. Biochar is a potential soil amendment that could provide permanence while improving agricultural outcomes (Figure 47). Permanence of biochar is variable, but could be available for centuries under some conditions. Research on biochar should be undertaken in the following areas.

- Field trials on different biochars to investigate the carbon flux to and from soils into which biochar has been added. This is particularly important in the case of fossil-derived biochars and humic materials.
- The pyrolysis and chemical treatment processes to produce biochar should be scaled up and the resulting produced biochars used to scientifically establish permanence criteria as a function of char properties.
- The balance between exogenous and endogenously developed soil carbon for biochar additions as a function of biochar type, soil type, space and time.
- Scale-up of existing pyrolysis processes to determine whether the costs of large-scale pyrolysis can be reduced.

Figure 47: Biochar for soil amendment

6. Life cycle analysis should be routinely employed in any analysis of CO_2 sequestration by the above technologies.

Key Publications

Burgess J, Jeffery L, Lowe A, Schuck S, Flentje W (2011). Novel CO_2 Capture Task Force Report. Available at www.hub.globalccsinstitute.com/publications/novel-co2-capture-taskforce-report.

3. Low emissions value-added products from brown coal

3.1. Brown coal upgrading

Utilisation of Victorian brown coal in applications at any great distance from the mine site is a challenge. The freshly-mined coal contains about two-thirds water, making it expensive to transport. The dried coal is highly reactive and has a tendency to combust spontaneously, making it dangerous to transport and stockpile. These problems have prevented the commercial exploitation of brown coal for anything other than local power generation.

The development of economical new uses for Victorian brown coal depends upon being able to upgrade and stabilise the coal efficiently and cost-effectively. BCIA has supported fundamental research to underpin the development of practical coal upgrading techniques.

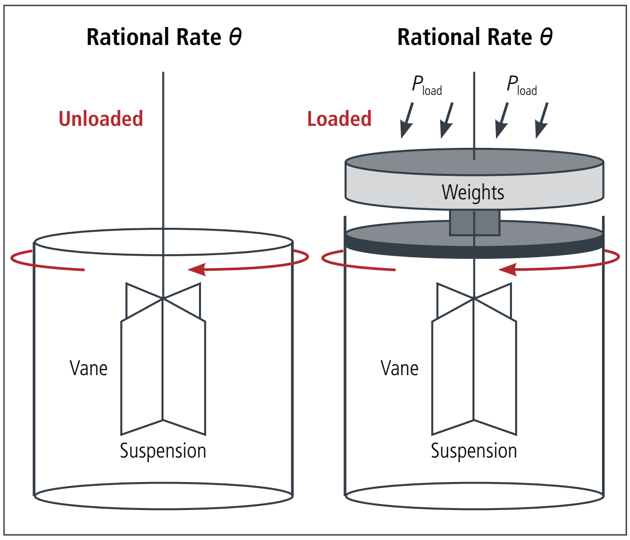
Novel coal dewatering techniques

The high energy associated with drying brown coal is a major impediment to its broader use. Researchers at the University of Melbourne have developed a new method for economical dewatering of brown coal, which involves compression of the coal between rollers rotating at different speeds. It has been found that the addition of shear during compressional dewatering processes significantly reduces the pressure required.

A balance between shear and compression is required to achieve optimum moisture reduction for a given throughput. While it is possible in practice to find the right balance through a trial and error approach, there is no suitable theoretical basis for design and scale up of this type of equipment.

BCIA has supported the development of this novel dewatering approach through a scholarship for Ms Hui-En Teo, a PhD student at the University of Melbourne. In approaching this problem, Ms Teo had to develop new rheological tools to allow characterisation of viscoelastic fluid behaviour under controlled application of both shear and compression (Figure 48). While the rheological theory for one-dimensional shear and compression fields are well established, there is no theoretical basis for characterising the effects of combined shear and compression in two or three dimensional systems.

Figure 48: Measurement of combined shear and compression



Ms Teo chose to work initially with a well characterised experimental system before moving on to brown coal. The majority of her experimental work was conducted using a homogeneous suspension of finely-dispersed calcite (calcium carbonate), which is used as a thickener in paints. However, even this simple system exhibited complex non-monotonic flow, in which the flow response to shear was not uniform, with adjoining regions in the fluid showing significantly different behaviour. Flow response was variable, depending on how the calcite suspension was tested and, specifically, at the rate at which it was sheared.

This work has led to a new rheological model that can be used to characterise such systems. Its validity when extended to brown coal has not yet been demonstrated.

Spontaneous combustion propensity of upgraded brown coal

The vast majority of brown coal in Victoria is burned for power generation in its wet, as-mined form. In the past, dry coal briquettes were produced for gasification and as a supplementary fuel source, with small quantities exported overseas. Interest in the export potential of Victorian brown coal has increased in recent years, with demonstration of new coal upgrading technologies currently being supported by the Victorian Government's 'Advanced Lignite Demonstration Program' (ALDP) [(1)].

Handling and transport of briquettes always results in the formation of dust and small particles, known collectively as 'grus'. The grus is highly reactive, presents a large surface area and can initiate spontaneous combustion in storage bunkers or stockpiles of briquettes.

The scientific understanding of the physical and chemical factors involved in the spontaneous combustion of Victorian brown coal briquettes and char was reviewed in 1988 [(2)] and 1991 [(3)].

Oxygen consumption was measured, apparent changes were observed spectroscopically, the involvement of free radicals was considered, reaction kinetics were investigated – but a satisfactory description of the fundamental causes eluded researchers.

While the industry was successful in developing pragmatic operating practices for safe storage and shipping of briquettes, these practices will not necessarily be applicable to new types of upgraded coal, such as the products created through the ALDP.

In order to improve the understanding of the processes involved in spontaneous combustion, BCIA has supported a study at Monash University led by Professor Allen Chaffee as part of the 'Improved properties of lignite-based products' project.

The objective was to observe the effects of systematic changes in the chemical composition and physical structure of brown coal on its spontaneous combustion behaviour.

(1) www.energyandresources.vic.gov.au/energy/innovation-and-research/energy-technology-innovation/advanced-lignite-demonstration-program.
(2) Mackay GH (1988). Spontaneous combustion behaviour of brown coal briquettes and solar dried coal slurry. State Electricity Commission of Victoria, Report No. SO/88/147.
(3) Mulcahy MFR, Morley WJ, & Smith IW (1991). Combustion, gasification and oxidation. In: The Science of Victorian Brown Coal: Structure, Properties and Consequences for Utilization, Durie RA (ed), Butterworth-Heinemann Ltd, Chapter 8, pp 359–463.

Researchers induced changes in the physical structure by kneading and extrusion, mechanical thermal expression or by hydrothermal dewatering. Changes in the chemical composition were accomplished by washing with water or acid, addition of alkali or salts, or by oxidation treatment. The full range of treatments used is shown in Figure 49 below.

Figure 49: Full range of treatments used

Treatment	Effect of treatment	Effect of treatment
None	None	Control
Water wash / acid wash	Chemical	Removal of some cations
Addition of cations (different valency)*	Chemical	Add more cations
Addition of phosphate	Chemical	Reaction with cations
Mechanical thermal expression (MTE)* varying pressure and temperature	Chemical	Some loss of cations, but mostly physical change to pore structure
Hydrothermal dewatering (HTD)* varying temperature /additives	Physical / Chemical	Greater loss of cations than with MTE, but less physical changes
Kneaded and extrusion (kneading time)*	Physical	Change of pore sizes
Addition of alkali for Kneading then extrusion (kneading time and alkali chemistry / concentration)*	Physical / Chemical	Digestion of coal structure, neutralise acid groups
Oxidation treatment (gaseous or wet oxidation methods)*	Physical / Chemical	Oxygen reaction with coal surface, change in surface chemistry / structure

* Subsets for different conditions may give a range of systematic changes to properties.

Samples of treated coal were heated slowly in an oven, with the particle temperature closely monitored. At a certain critical temperature (T_{crit}), the particle temperature rose higher than the oven temperature, indicating the onset of spontaneous combustion. In this method, a lower value of T_{crit} corresponded to a higher tendency for spontaneous combustion.

The project confirmed that spontaneous combustion is strongly influenced by the porosity of the coal. A higher internal surface area allows faster reaction with atmospheric oxygen. The project also found that the type and quantity of cation present are also important. For example, when added as phosphate salts, increasing sodium cations had no effect on spontaneous combustion, whereas potassium promoted, and both calcium and magnesium suppressed, spontaneous combustion.

The effect of different dewatering techniques on the value of T_{crit} could generally be explained by the associated changes in surface area or cation concentration.

Densification of coal by kneading and extruding could be improved by the addition of alkali, which reduces the surface area. Higher concentrations of alkali resulted in lower surface area and reduced spontaneous combustion tendency.

Dewatering by mechanical thermal expression increased the surface area and decreased T_{crit}, thus increasing the tendency to spontaneous combustion. The changes in surface area and T_{crit} became greater as the severity of the mechanical thermal expression conditions increased.

Hydrothermal dewatering increased the porosity of the coal and decreased T_{crit}, increasing the tendency to spontaneous combustion. While the porosity increased, the internal surface area was reduced. The changes to coal properties during hydrothermal dewatering increase with increasing temperature. This finding was unexpected, as previous researchers have assumed that the loss of carboxylic acid groups during hydrothermal dewatering would result in a reduction in spontaneous combustion. Volatile hydrocarbons produced during hydrothermal dewatering may have been trapped within the coal structure, increasing the reactivity of the particles.

Spontaneous combustion of coal can be prevented by allowing the coal to oxidise slowly at low temperatures. With briquettes, this was accomplished by storing in stockpiles below a critical height, allowing them to 'age'. This project found that upgraded coal can be chemically aged by treatment with UV / hydrogen peroxide, thereby rapidly reducing the risk of spontaneous combustion.

The work has provided important insights into the effects of different upgrading strategies on the spontaneous combustion tendency of Victorian brown coal. Perhaps more importantly, the project has established analytical tools that will be useful for optimisation of any new coal upgrading processes that may be developed.

Work on this topic is ongoing through a PhD project by Mr Mohammad (Mehrdad) Reza Parsa, so additional technical insights may be anticipated.

Key Publications

Buscall R, Kusuma TE, Stickland AD, Rubasingha S, Scales PJ, Teo HE, Worrall GL (2014). The non-monotonic shear-thinning flow of two strongly cohesive concentrated suspensions. Journal of Non-Newtonian Fluid Mechanics. In press.

Buscall R, Scales PJ, Stickland AD, Teo HE, Kusuma TE, Rubasingha S, Lester, D. R (2014). The yielding of concentrated cohesive suspensions can be deformation rate-dependent. BSR Bulletin 55: 79–88.

Buscall R, Scales PJ, Stickland AD, Teo HE, Lester DR (2015). Dynamic and rate-dependent yielding in model cohesive suspensions. Journal of Non-Newtonian Fluid Mechanics 221: 40–54.

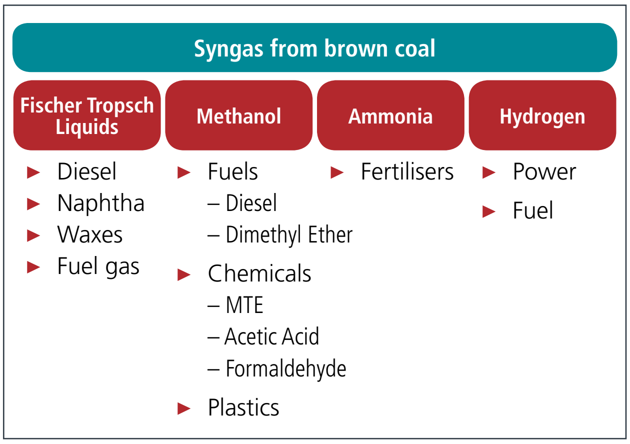
Stickland AD, Teo HE, Franks GV, Scales PJ (2014). Compressive strength and capillary pressure: Competing properties of particulate suspensions that determine the onset of desaturation. Drying Technology 32: 1,614–1,620.

3.2. Products from gasification of brown coal

Gasification is a technology that can convert brown coal into a gaseous product (syngas) that can be burned for electricity production or converted into a wide range of value-added products, including fuels and industrial chemicals.

Gasification involves partial combustion of coal in a mixture of steam and either oxygen or air to convert the coal into a mixture of CO, CO_2 and H_2 (and N_2 if air is used). The syngas has a high energy content and can be burned to produce electricity in a gas turbine. Alternatively, the CO and H_2 can be processed to create a wide range of products, as illustrated in Figure 50.

Figure 50: The diversity of products from syngas, which can be formed from gasification of brown coal



Gasification has had a long history in Victoria, beginning with the commissioning of the Morwell Gas Plant in 1956 to produce town gas from Yallourn brown coal briquettes. An oxygen-blown fixed bed Lurgi gasifier produced the town gas, based on pilot scale research undertaken at the University of Melbourne.

During the 1950s and 1960s, CSIRO investigated fluidised bed gasification of Victorian brown coal at pilot scale, with an emphasis on hydrogasification to produce a methane-rich synthetic natural gas. In the early 1990s, the State Electricity Commission of Victoria developed the integrated drying gasification combined cycle process to produce low emissions electricity from brown coal. The process involved gasification of coal using a high temperature Winkler fluidised bed gasifier. The integrated drying gasification combined cycle was subsequently licensed to HRL Technology for commercialisation.

Further research on gasification for low emissions power was continued in two consecutive Cooperative Research Centres, the CRC for New Technologies for Power Generation from Low-Rank Coal and the CRC for Clean Power from Lignite. The Victorian Government's Energy Technology Innovation Strategy supported subsequent research on syngas cleaning strategies.

BCIA has continued the support for gasification research in Victoria, but has shifted the emphasis away from low emissions power generation to the production of value-added products. In all, BCIA has supported 12 gasification-related projects, to help underpin the development of new value-adding processing industries in the Latrobe Valley:

- 'Advanced brown coal gasification', with Monash University, to investigate the use of inexpensive catalysts for syngas cleaning and to develop a computer model for ash formation and agglomeration.
- 'Next generation lower emissions gasification', with HRL Technology, to investigate the unique processing steps and issues relating to different routes to power and products from gasification (funded by ANLEC R&D).
- 'Near CO_2-free hydrogen energy supply chain', with HRL Developments, to investigate the potential of some new technologies that could be used in the production of export-quality hydrogen from brown coal.
- 'Oxygen-blown gasification of Victorian brown coal', a report for BCIA members.
- 'Catalytic steam gasification and assessment of DME', with Monash University and Kenco / Kyushu University, to investigate production of dimethyl ether (DME) fuel from Victorian brown coal.

- 'Brown coal derived syngas generation for utilisation in higher value product processes', a BCIA-funded PhD scholarship with Monash University, to investigate the fundamental reaction kinetics of brown coal under high-temperature entrained flow gasifier conditions.
- 'Development of oxy-blown entrained flow gasification for use with a range of Victorian brown coals' (Mr Tao Xu).
- 'Development of entrained flow gasification technology', with Monash University, to investigate the viscosity of slags likely to be produced from Victorian brown coals.
- 'Coal blending combustion and gasification' (Mr Baiqian Dai)
- 'Solar conversion of brown coal', a study funded by BCIA members.
- 'Demonstration of pilot-scale hydrogen and CO_2 separation membrane technology on lignite-derived syngas', a study funded by BCIA members.
- 'Victorian based coal to chemicals: Economics and technology status', a study funded by BCIA members.

Advanced brown coal gasification

The Advanced Gasification project was led by Professor Sankar Bhattacharya at Monash University, in collaboration with AGL Loy Yang, GDF SUEZ Australian Energy and EnergyAustralia. This brief project involved preliminary investigations of two strategies for managing the removal of ash and impurities from the syngas produced from Victorian brown coal.

- The use of inexpensive catalysts, based on brown coal char or flyash, for syngas cleaning and conversion of CO to CO_2.
- Development of a computer model for characterising the composition and phase state of ash.

The project found that it was not possible to produce effective catalysts from inexpensive local raw materials. The surface area of flyash catalysts was too low, while the brown coal char catalysts tended to disintegrate during use. There are already commercial catalysts available for syngas processing, but they tend to be expensive. It was hoped that using a local resource would help to reduce the cost of gasification. The conclusion is that this is probably not worth further pursuing.

The second part of the project involved developing a simulation model for ash production and agglomeration, using FactSage 6.1 software. Under certain conditions, depending on coal composition and operating conditions, the ash can melt and begin to form slag. The aim of this project was to develop a tool that could be used to predict when this might occur, to assist with the selection of appropriate operating conditions.

The FactSage model showed that three different Latrobe Valley coals would each behave differently, producing different ash components with unique properties. This was a positive outcome, but further work was recommended to validate the predictions experimentally.

Next generation lower emissions gasification systems R&D – power and products

This project was led by Professor Klaus Hein at HRL Technology, in collaboration with Monash University and the CO2CRC. The project involved desktop research and literature reviews, with Monash University (with input from HRL) concentrating on products and HRL on power. HRL also undertook study tours to establish the international state of coal gasification research.

The objective of the project was to develop a short-list of feasible products that could be produced by gasification of Victorian brown coal, along with a conceptual design for a pilot plant facility suitable for undertaking further product development research.

The work included reviews of: syngas technologies and products; alternative concepts for Victorian brown coal gasification, gas treatment and use; pre-combustion CO_2 capture technologies; identification of research gaps and priorities; and pilot plant design.

Some of the conclusions from the project were as follows.

- Raw synthesis gas exiting a gasifier must be conditioned prior to use in downstream processes, with stringent requirements for chemicals and fuels. Specification of a single gas conditioning train for all value-added products is not possible.
- Cool gas conditioning (below 250°C) is currently state-of-the-art. There is a research focus on developing warm gas cleaning (250°C–500°C), but this has not been proven at large scale.
- Identification of a range of technically feasible product options. Further work is needed to assess their likely commercial feasibility.
- There is great promise in combining high-temperature fuel cells with integrated drying and gasification technology for more efficient power production. Research in a range of areas is required to develop fuel cell systems for use with brown coal-derived syngas.
- An outline of the requirements for technical-scale evaluation of gasification and gas conditioning.

Oxygen-blown gasification of Victorian brown coal – research and technology review

Air-blown gasification of Victorian brown coals has been extensively studied from the late 1980s, when integrated gasification combined cycle was identified as the most efficient strategy for the next generation of coal-fired power stations. However, oxygen-blown gasification is the preferred strategy for producing value-added products via gasification. However, its applicability with brown coal is not well understood.

This project constituted a report commissioned by BCIA on behalf of its members, and was intended to build understanding and confidence in the potential application of oxygen-blown gasification technologies to Victorian brown coal. The project was undertaken by CSIRO and Monash University and was informed through consultation with key technology developers, vendors and operators of oxygen-blown gasification facilities.

The objective was to identify the state-of-the-art in commercially available plant, identify issues that must be considered in choice of technologies, and pinpoint areas where there needs to be further research. The review focused on the key issues anticipated when moving from air-blown to oxygen-blown brown coal gasification and produced recommendations for research to address knowledge gaps. The final report for this project is available only to BCIA members.

Hydrogen energy supply chain development

The disaster at the Fukushima Power Station caused by the tsunami that hit Japan in 2011 led to the shutdown of the nuclear industry and a search for an alternative, with an emphasis on low-emission sources of power.

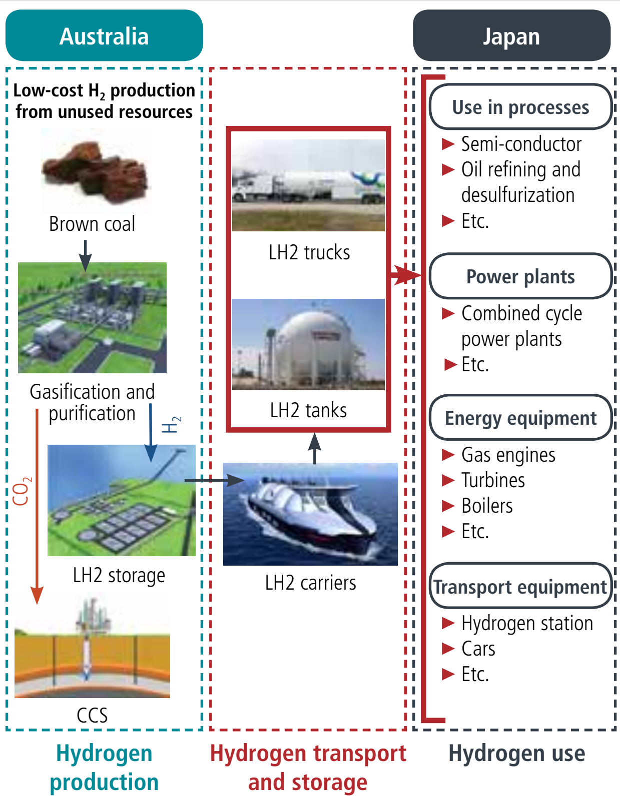
Oxygen-blown gasification of brown coal produces a mixture of CO, CO_2 and H_2. Further reaction with steam (the water gas shift reaction) can convert these to just CO_2 and H_2. The CO_2 can then be captured and geologically sequestered leaving H_2 as a zero-emission energy source.

The Japanese Institute of Applied Energy has studied the energy mix that is likely to result from the Japanese Government's GHG emission reduction targets of 15% by 2020 and 80% by 2050 (compared with 1990). Hydrogen is likely to become the dominant energy source for Japan after 2035 [(1)].

Kawasaki Heavy Industries Ltd (KHI) has proposed the concept of a CO_2-free hydrogen energy supply chain based on producing hydrogen from brown coal in Australia and transporting it for consumption in Japan (Figure 51). The concept involves gasification of brown coal in the Latrobe Valley, separation and sequestration of the CO_2, and transport of the hydrogen gas to a port facility by pipeline. The port facility will include a hydrogen liquefaction plant and a hydrogen loading base, where liquid hydrogen is loaded onto specially designed carrier ships for transport to Japan [(2)].

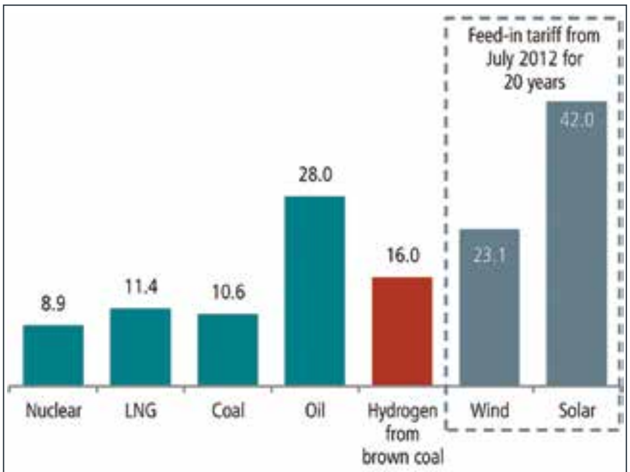
(1) Yoshino Y, Harada E, Inoue K, Yoshimura K, Yamashita S, & Hakamada K (2012). Feasibility study of 'CO_2 free hydrogen chain' utilizing Australian brown coal linked with CCS. Energy Procedia, 29, 701–709.
(2) Kamiya S, Nishimura M, & Harada E (2015). Study on introduction of CO_2 free energy to Japan with liquid hydrogen. Physics Procedia, 67, 11–19.

Figure 51: The steps involved in producing hydrogen from Victorian brown coal and transporting it to Japan as an energy source



Economic modelling suggests that in 2030 the cost of brown coal hydrogen generation will be ¥16 per kilowatt hour, which is higher than that of fossil fuel power generation using coal or LNG, but is lower than the cost of wind or solar power [3] (Figure 52).

Figure 52: Comparing the costs of power generation from a range of sources



BCIA has supported development of the 'CO_2-free hydrogen energy supply chain' through a project involving KHI and HRL Developments Pty Ltd. The objective was to develop a conceptual design for production of hydrogen from Victorian brown coal using HRL's integrated drying and gasification technology and other commercially-available technologies. The assumption was that the CO_2 produced would be captured and sequestered through the Victorian Government's CarbonNet Project [4].

The project involved confirmation of process modelling, identification of key infrastructure, resources, and preliminary cost estimation. There was also evaluation of alternative syngas processing technologies, with selection for optimal results.

The outcomes of this project have largely remained confidential. The project obtained information on the costs and performance of specific syngas processing steps. It also developed an overall model for the process, incorporating heat and mass balances, and utility requirements, as well as a financial model. Researchers evaluated and modelled a number of prospective alternative technologies to establish the most feasible. Designs were developed for pilot-scale and demonstration scale hydrogen production plants, including considerations of hydrogen liquefaction and transport.

Catalytic steam gasification and assessment of dimethyl ether

In 2009, the Victorian Government and Japan's Kyushu Electric Power Company (KEPCO) each committed up to A$250,000 per annum over three years for complementary collaborative lignite research projects in their respective regions. In Victoria, there were three projects led by Monash University. BCIA assumed management of these projects at the end of the first year.

One of the KEPCO projects involved an investigation of the potential to produce dimethyl ether (DME) by gasification of Victorian brown coal. DME is a non-

(3) Ibid.
(4) www.energyandresources.vic.gov.au/energy/carbon-capture-and-storage/the-carbonnet-project.

toxic, environmentally benign fuel which is being developed overseas as a diesel substitute for motor vehicles. It is produced by catalytic conversion of methanol, which is an inefficient two-stage process. The KEPCO DME project evaluated the feasibility of one-pot synthesis using bi-functional catalysts (hydrogenation plus methanol dehydration). Professor Sankar Bhattacharya at Monash University led the project, with support from CSIRO Energy Technology and HRL Technology.

Gasification at 900°C can produce syngas with a ratio of H to CO appropriate for DME synthesis. The project developed a detailed process design model. However, the bi-functional catalyst deactivated rapidly at temperatures above 300°C due to phase mobility and thermal sintering of the methanol dehydration catalyst.

Three new bi-functional catalysts were developed that performed as well as or better than the commercial catalyst mixture, giving DME yields of 35%–40%. The catalysts should be reasonably tolerant to the levels of H_2S produced from Victorian brown coal, but more research is needed.

This project successfully established the feasibility of efficient production of DME from Victorian brown coal. Monash University is continuing work to develop improved catalysts for this application.

Brown coal derived syngas generation for utilisation in higher value product processes

Most gasification research with Victorian brown coal has focused on fluidised bed gasifiers. However, all current commercial syngas generation processes are based on entrained flow gasification technologies, which can achieve high carbon conversion efficiencies and produce a cleaner syngas product. Entrained flow gasifiers operate at higher temperatures and pressures than fluidised bed gasifiers, so the previous gasification research is not directly relevant to commercial gasification processes.

To begin to rectify this knowledge gap, BCIA sponsored a PhD project at Monash University to study the fundamentals of entrained flow gasification of Victorian brown coal. The PhD student involved, Ms Joanne Tanner, has worked under the supervision of Professor Sankar Bhattacharya to generate kinetic data, gas composition and yield data over the full temperature range of commercial interest.

Ms Tanner designed and commissioned a new entrained flow reactor at Monash University. The new reactor, dubbed 'HELENA' (High temperature ELectrically heated ENtrained flow Apparatus), can handle coal particles up to 500µm diameter at temperatures to 1,600°C. The rig can be used to prepare char samples and measure char conversion and the yield and composition of syngas.

Experimental work on HELENA has been completed with two Victorian brown coals and four Rhenish lignites. Publications on this work are being prepared, and Ms Tanner's project is nearing completion.

Development of oxy-blown entrained flow gasification for use with a range of Victorian brown coals

BCIA is providing scholarship support for a second entrained flow gasification project at Monash University to gain a deeper insight into the effect of the mineral components of Victorian brown coal on gasification behaviour. The PhD student, Mr Tao Xu, is studying under the supervision of Professor Sankar Bhattacharya.

This project will extend the analysis of brown coal gasification through detailed characterisation of chars and an investigation of the speciation of mineral elements into the gas and slag phases.

The objective is to integrate the outcomes of the laboratory work with existing gasification models to develop new process models applicable to Victorian brown coal.

Development of entrained flow gasification technology with brown coal

A key issue in the operation of entrained flow gasifiers is the removal of slag. Excessive build-up of slag melt on the refractory wall reduces heat transfer and can cause the gasifier to be shut down. It is important that the liquid slag viscosity is low enough so that slags flow down the gasifier walls and can be drained away as 'molten slag'. Thus, information on composition, viscosity and the change of viscosity with temperature for coal ash slags is essential for efficient operation of an entrained flow gasifier.

Prior research at Monash University has shown that slag viscosity models developed for high rank coals do not give consistent results with the slag composition expected from gasification of Victorian brown coal [5]. Current slag viscosity modelling may not be suitable for the design of an entrained flow gasifier for deployment in Victoria. BCIA has supported a research project led by Professor Sankar Bhattacharya at Monash University in collaboration with Mitsubishi Heavy Industries in Japan and the Institute for Energy and Climate Research in Jülich, Germany. The objective was to develop viscosity and slag composition models for design of entrained flow gasifiers operating with Victorian brown coal.

The project involved the design and construction of a sophisticated rheometer for high-temperature slag viscosity measurements at Monash University. This facility allowed the measurement of slag viscosity under different gas atmospheres, representative of both gasification and oxidation environments.

A model was developed for the slag viscosity of various Victorian brown coals as a function of temperature, composition and gas-phase composition. The trace element composition of the slags was measured using existing equipment at Monash University and used to develop a model for simulation of trace element emissions. The measurements and models were calibrated against data obtained by Mitsubishi Heavy Industries from a commercial gasifier.

For satisfactory operation, the Mitsubishi Heavy Industries entrained flow gasifier requires the slag viscosity to be in the range of 100–250 Poise. This investigation showed that Loy Yang, Yallourn and Morwell coals require different temperatures to achieve a suitable slag viscosity.

Yallourn coal requires a temperature of 1,450°C, where Loy Yang and Morwell coals require temperatures in excess of 1,500°C and need to blended with Yallourn coal to achieve acceptable performance.

The project also showed that existing models do not accurately predict the slag viscosity of Victorian brown coals. Further work is needed to understand the effect of ash chemistry on slag viscosity so that a useful predictive tool can be developed. This project has facilitated the training of two PhD students, one Research Fellow, and four undergraduate students. Apart from learning about the fundamentals of gasification, these researchers gained knowledge of the design, construction, commissioning and operation of a high temperature entrained flow reactor and a viscometer assembly, and in advanced chemical analysis of fuel samples, and in thermodynamic modelling.

Coal blending combustion and gasification

The Victorian Government is supporting the commercialisation of coal upgrading technologies through its Advanced Lignite Demonstration Program (ALDP) [6], with the aim of creating export opportunities for dried brown coal products. China has the world's highest installed capacity of coal gasifiers, but a diminishing supply of high-rank coal as feedstock, so there is interest in using blends of brown and black coal in the existing gasifiers. BCIA is providing scholarship support for a PhD project at Monash University that is intended as a preliminary investigation into the potential benefits of using blends of upgraded brown coal and black coal in both gasification and combustion. The PhD student, Mr Baiqian Dai, is studying under the supervision of Dr Lian Zhang.

The objectives of this project are to elucidate the optimum mixing ratios between low-rank coal and high-quality bituminous coal for coal blend combustion and gasification, through process flow sheeting and techno-economic analysis; clarify the ignition, oxidation and gasification reactivity of coal blend, and the interaction between different coal particles, if any; and reveal the ash interaction and ash slagging / fouling propensity during coal blend combustion and gasification.

(5) How HHH, Roy B, & Bhattacharya S (2010). Prediction of slag composition and viscosity during high temperature gasification of Australian lignites. In: Chemeca 2010: Engineering at the Edge; 26–29 September 2010, Hilton Adelaide, South Australia. Engineers Australia, 2,535–2,544.
(6) www.energyandresources.vic.gov.au/energy/innovation-and-research/energy-technology-innovation/advanced-lignite-demonstration-program.

This project seeks to clarify the benefits that may be gained through the use of blends on brown and black coals in gasification and combustion processes, and thereby to improve the market potential for upgraded Victorian brown coal products.

Background paper on solar conversion of brown coal

Gasification is a key enabling process for developing high efficiency power production via combined cycle systems, and for production of a range of value-added products from brown coal. In conventional approaches to gasification, a fraction of the coal is oxidised to provide the energy needed to drive the endothermic gasification reaction, which reduces the energy efficiency of the process.

Concentrating solar thermal technologies can drive a range of high temperature endothermic reactions. Accordingly, there is growing interest in various coal-solar hybrid systems, such as solar thermal gasification of coal and solar dissociation of CO_2 for sustainable fuels production. Solar thermal electricity is the most expensive form of power available. Demonstrations at large scale are needed to help bring the cost down. One way to accomplish this is to use solar thermal technologies to improve the efficiency of conventional power / product processes, in a hybrid system.

Combining input from brown coal gasification and concentrating solar technologies may offer an overall system that improves the environmental sustainability of brown coal while accelerating the stand-alone feasibility of solar thermal. BCIA commissioned a background paper to brief BCIA members on the background to solar gasification. The questions addressed in this study are as follows.

- What is the current status of solar technologies that could be applied to coal-based power generation or gasification processes?
- What solar energy input would be required for these processes?
- What would be an approximate energy balance for these solar hybrid approaches?
- Could transport of brown coal to a high solar resource be justified?
- To what extent could solar technology reduce production costs and CO_2 emissions?

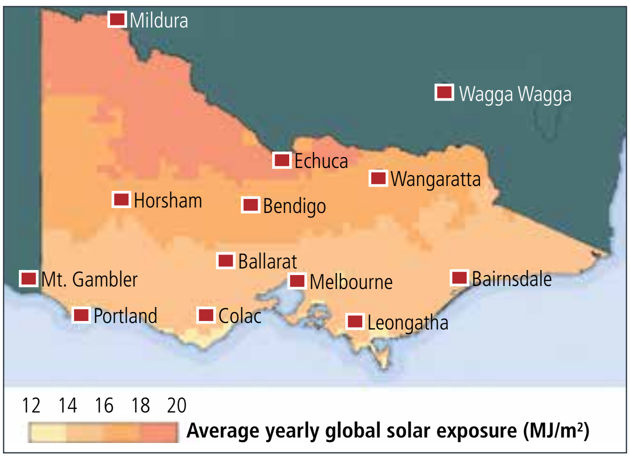
The project was undertaken by IT Power (Australia) Pty Ltd, part of the IT Power Group. Globally, ITP has extensive experience in renewable energy feasibility studies, with expertise in all aspects of renewable energy, including photovoltaics, solar thermal, wind, hydro, hybridisation and biofuels.

The report found that gasification of brown coal using solar heat appears to be technically feasible via a number of possible routes. Based on the uncertain cost data available, it appears that solar driven conversion of coal to liquids is just viable with current costs of solar. It would be marginally competitive with natural gas priced at A$6 per gigajoule, but will become more attractive as gas prices increase. Solar cost is projected to fall strongly over time so the return on investment should improve.

Unfortunately, the Gippsland basin, which is the source of most of Victoria's brown coal, has one of the lowest levels of solar radiation in mainland Australia. Figure 53 shows the average annual solar irradiation in Victoria [(7)]. The minimum average solar irradiation required for realistic operation of a concentrating solar thermal system is 18MJ–20MJ per meter squared. The Latrobe Valley in Victoria's south-east receives 13MJ–15MJ per meter squared annually, while Mildura in the north receives about 21MJ per meter squared. It is not feasible to operate a hybrid solar gasification plant in the Latrobe Valley.

Figure 53: Solar exposure across Victoria

The feasibility of transporting brown coal in slurry form via pipeline to Mildura was also considered.



(7) www.energyandresources.vic.gov.au/energy/sustainable-energy/solar-energy/what/victorias-solar-resource-details.

Transport costs are likely to be sufficiently low, making this a cost-effective option.The report recommended undertaking a more detailed feasibility study of technical options and costs.

Demonstration of pilot-scale hydrogen and CO_2 separation membrane technology on lignite-derived syngas

BCIA member funds partially sponsored a pilot-scale evaluation of Praxair's hydrogen separation membrane, in which hydrogen is purified from lignite-derived syngas. The project was undertaken by the Energy & Environmental Research Center (EERC) in North Dakota. Praxair provided a pilot-scale hydrogen separation membrane that was tested on syngas produced in the EERC's pilot-scale transport reactor development unit.

The goal of the project was to conduct a pilot-scale demonstration of coal-to-hydrogen production technology using warm-gas clean-up techniques and Praxair's hydrogen separation membrane. The baseline coal was a Powder River Basin lignite; also tested was a high-sodium Freedom lignite from North Dakota.

Hydrogen concentrations leaving the gasifier were as high as 15% and were further increased to 20% on a dry basis after the water-gas shift reactor. Operation of the sour shift catalyst near 400°C provided the highest level of shift, and CO was reduced below 1%. Generable RVS-1 sulfur sorbent reduced sulfur concentrations from nearly 4,000ppm to below 5ppm in a single reactor. A hot-side syngas compressor was successfully demonstrated to raise the syngas pressure from 120psi to above 450psi while maintaining the temperature above 450°C.

The Praxair membrane operated on syngas over two separate test campaigns. The membrane flux was maximised when the highest partial pressure of hydrogen was delivered to the system at high-flow conditions and 425°C. Membrane performance did not appear to significantly change with time during the campaigns. Process modelling showed that hydrogen membranes have the potential to improve the efficiency of a 550MW power plant with CO_2 capture from 31.7% to 35.7% (with Selexol as the base case for CO_2 capture). Additional optimisation of the membrane technology is required to achieve this goal.

Aspen Plus modelling evaluated the likely performance of Loy Yang and Lochiel brown coals in the transport reactor gasifier. It may be possible to achieve more than 30% hydrogen concentration in the post-shift syngas for both of the brown coal fuels. Experimental testing of the brown coals should be undertaken to determine the optimum conditions to achieve high carbon conversion while minimising bed agglomeration issues.

This project has provided insight into the likely performance of Victorian brown coal in an advanced gasification and hydrogen separation facility. These preliminary results are promising, suggesting that hydrogen production from Victorian brown coal is likely to be technically feasible.

Victorian based coal to chemicals – economics and technology status

Victoria has substantial brown coal resources supported by significant infrastructure, from extraction to electricity generation and distribution. Brown coal is used exclusively for electricity generation, however it is a suitable resource for other applications.

The Latrobe Valley is an ideal site for a coal to chemicals facility. Victoria offers investors the opportunity to develop projects using one of the world's largest, high-quality coal resources, located close to potential geological CO_2 sequestration sites.

An understanding of the cost of potential coal to chemical technologies will play an important role in determining the future opportunities for Victorian brown coal.

This report was commissioned by BCIA on behalf of its members as a screening analysis of potential coal to chemicals projects based on gasification of brown coal. The report was prepared by Dr Nikolai Kinaev, Strategic Energy Consulting P/L, and Dr Geoff Bongers, Gamma Energy Technology P/L.

The screening analysis was based on a single gasifier design, the transport integrated gasification (TRIG) reactor, which is a high velocity, circulating fluidised bed design for which good costing data is available.

The analysis was based on applying mature chemical technologies that have been applied recently in coal to chemicals plants, primarily in China. However, the analysis assumed a first-of-a-kind build in Australia, using current data for capital and construction costs in Victoria. The focus of this work was to present the following.

- Succinct description of various coal to chemicals options.
- Brief description of global trends of coal to chemicals.
- High level estimates of coal to chemicals options in Victoria.
- Capital cost of the plant (first-of-a-kind).
- Levelised cost of product.
- High level estimates of the regional economic impact of a coal to chemicals project.
- Options that may be required to make a coal to chemicals project feasible.

The screening analysis showed that the feasibility of a coal to chemicals facility is dependent on the particular chemical produced the following.

- The levelised cost of hydrogen production is within the upper bound of current market prices, but is sensitive CO_2 cost of transportation and storage.
  - Capital subsidies are not likely to be a useful incentive for hydrogen production.
- Urea may also be feasible, however the levelised cost of urea mid-point is above current market prices (which are at an historical low).
  - Capital subsidies or other financial instruments (e.g. loan guarantees) would lower the levelised cost of product, reducing the risk and making the process more economic.
  - Urea production is relatively insensitive to the cost of CO_2 transportation and storage.
- Synthetic petroleum products (from a Fischer-Tropsch facility) are not likely to be feasible unless the crude oil price is above A$130 billion for the life of the facility.
- Both methanol and ammonia require significant subsidies or assistance to become competitive at current market prices.

The Latrobe Valley has traditional strengths in heavy industry associated with the power generation sector and hosts a workforce with the necessary specialised skills and knowledge for construction of coal to chemicals projects.

This report found that a large workforce would be required to construct a coal to chemicals facility, peaking at some 6,000 workers ranging from labourer through to skilled craftsmen and supervisors, over an eight-year construction period. In addition, 400 to 500 long-term operational roles will be created, depending upon the specific coal to chemicals process, and three times that many local jobs to support these operational roles. More than 300 local businesses are also likely to be engaged with the facility.

Key Publications

Bhattacharya S, Kabir KB, & Hein K (2013). Dimethyl ether synthesis from Victorian brown coal through gasification–Current status, and research and development needs. Progress in Energy and Combustion Science, 39, 577–605.

Kabir KB, Hein K, & Bhattacharya S (2013). Process modelling of dimethyl ether production from Victorian brown coal – Integrating coal drying, gasification and synthesis processes. Computers & Chemical Engineering, 48, 96–104.

Kabir KB, Maynard-Casely HE, & Bhattacharya S (2014). In situ studies of structural changes in DME synthesis catalyst with synchrotron powder diffraction. Applied Catalysis A: General, 486, 49–54.

Kirtania K, Tanner J, Kabir KB, Rajendran S, & Bhattacharya S (2014). In situ synchrotron IR study relating temperature and heating rate to surface functional group changes in biomass. Bioresource Technology, 151, 36–42.

Tanner J, Bläsing M, Müller M, & Bhattacharya S (2014). Influence of temperature on the release of inorganic species from Victorian brown coals and German lignites under CO_2 gasification conditions. Energy & Fuels, 28, 6,289–6,298.

Tanner J, Bläsing M, Müller M, & Bhattacharya S (2015). The temperature-dependent release of volatile inorganic species from Victorian brown coals and German lignites under CO_2 and H_2O gasification conditions. Fuel, 158, 72–80.

Tanner J, Kabir KB, Müller M, & Bhattacharya S (2015). Low temperature entrained flow pyrolysis and gasification of a Victorian brown coal. Fuel, 154, 107–113.

3.3. Value-added products from brown coal

3.3.1. Improved handling properties of lignite-based products

In order for the export potential of Victorian brown coal to be realised, a method must be found to economically dry the coal and convert it into a stable form for transport. Drying of brown coal in hot air is problematic because the coal breaks down to fine dust and creates an explosion risk. Even when dried at low temperatures, brown coal typically crumbles to dust and becomes prone to spontaneous combustion, which makes handling difficult and dangerous.

Wet granulation of coal into coarse particles with desirable size and strength is one way to improve the handling properties. Wet granulation is a common method for producing granules and is used as a solution to many industrial power-flow problems. There are many applications where a granulated product offers significant benefits.

For example, it can be pneumatically conveyed (allowing easy loading and unloading during transport), fluidised (which may facilitate both combustion and gasification processes), or handled by mechanical equipment, granule by granule, due to the controlled size and mechanical strength of each granule.

Granulated lignite products have been developed for a range of applications, including boiler fuels, as a feedstock for briquette manufacture and in blended fertiliser products. Although a number of coal granulation processes have been patented (mostly overseas), there is a scarcity of knowledge on the principles that would allow control of particle size and optimisation.

Researchers at the University of Queensland have developed a new approach called 'regime separated granulation', in which the steps of powder wetting, granule growth and granule drying are physically separated to allow better control of the granule properties [(1)]. The regime separated approach has not previously been applied to lignite granulation.

To avoid the hazards associated with drying in hot air, brown coal can be dried using superheated steam. In a previous project funded by the Victorian Government's ETIS program, researchers at Monash University demonstrated simultaneous granulation and drying of mixture of sewage sludge and brown coal in a commercial rotated drum superheated drying system [(2)].

The brown coal improved the quality of the dried granules, resulting in a product that had potential as a new type of fertiliser. This system could be used as a general approach to make a range of granulated coal-based products, such as upgraded dry coal or a variety of blended organic or inorganic fertilisers.

BCIA supported a research project at Monash University, led by Associate Professor Andrew Hoadley, to further investigate the potential of this granulation and drying technology. Pinches Consolidated Industries supported the project and provided access to a pilot-scale rotary superheated dryer. It was anticipated that a second industrial participant would provide access to a large-scale pan granulation facility, but this did not eventuate. The objectives of this project were to establish the following.

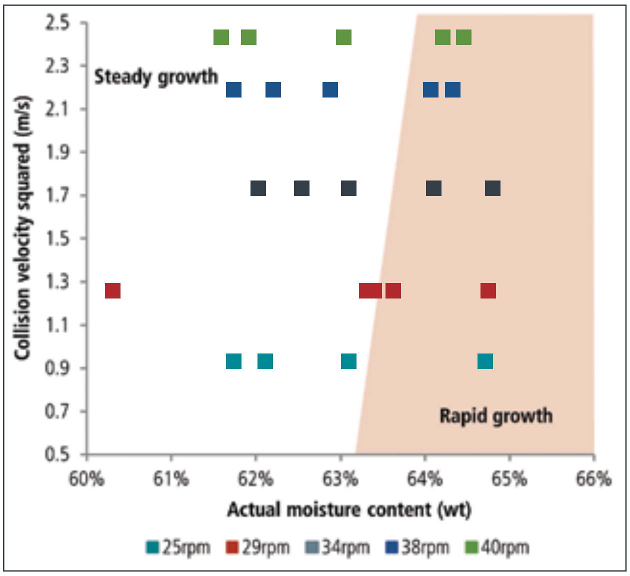
Effective processes for granulation of brown coal at both laboratory and pilot scales. A method for drying the granules using superheated steam.

The aim of the laboratory work was to develop a 'regime map' for brown coal granulation, to help distinguish granule growth behaviour as a function of operating conditions. The regime map concept, as developed by Iveson and co-workers [(3)], distinguishes three main types of granule growth behaviour exhibited in batch granulation systems.

The first type is induction growth, where there is little or no growth for a long period followed by very rapid growth. The second type is steady growth behaviour, where the average granule size increases steadily. The third type, rapid growth, occurs when the moisture content of the granules approaches saturation. A regime map can be used to predict granule growth based on properties and system operating conditions, to assist in process design and control.

The project developed a regime map for as-mined Loy Yang brown coal, which had a typical initial moisture content of 60%–61%. Granules were produced in a laboratory drum granulator, with water spray used as a binder. Due to its inherent moisture content, Victorian brown coal can be granulated with minimal additional water as binder. The granules exhibited steady growth behaviour up to a moisture content of about 64%, above which rapid growth was encountered, as shown in Figure 54.

Figure 54: Granular growth behaviour as a function of moisture content



The granulation behaviour for brown coal was found to fit well with established granulation theory, indicating that granulation of brown coal may be controlled by manipulating the amount and type of binder and the drum speed to ensure the granule growth follows a steady growth curve.

Granule strength increased with increasing binder content and drum speed, but decreased with increasing granule size. The use of water as a binder did not produce granules with sufficient strength for industrial use. Further research is needed to identify efficient and cost-effective binder materials.

The final moisture content of the granules also affected the granule strength. Drier granules were stronger than those with higher moisture content.

The project showed that the granule strength was dependent on both the drying rate and the drying method used. Laboratory scale drying experiments showed that air drying produces stronger, less porous granules than steam drying. Steam dried granules had larger average pore size, greater pore volume and had more visible surface cracks than granules air-dried at the same temperature.

The project included evaluation of fertiliser granule formulations, using brown coal blended with organic and inorganic fertilisers. The addition of small amounts of brown coal to a hydrophobic fertiliser formulation improved the wetting characteristics of the fertiliser. The granulation behaviour of the fertiliser also improved to be that of controllable steady growth, producing a more uniform final granule size distribution.

Brown coal may be enriched with inorganic fertilisers during the granulation process. Suitably sized granules of brown coal mixed with urea were produced, although the granules were not strong enough for agricultural use. Further research is needed to develop a suitable binder for this application.

Simultaneous granulation and superheated steam drying was successfully achieved at pilot scale for both brown coal and urea-enriched brown coal. The process produced granules of a suitable size for agricultural use, although further work is required to increase the granule strength.

This project has demonstrated the feasibility of producing new products from brown coal using a combination of granulation and superheated steam drying. The regime map approach was verified, providing an engineering tool for process design and optimisation.

(1) Ramachandran R, Poon JMH, Sanders CF, Glaser T, Immanuel CD, Doyle FJ, Litster JD, Stepanek F, Wang FY, & Cameron IT (2008). Experimental studies on distributions of granule size, binder content and porosity in batch drum granulation: Inferences on process modelling requirements and process sensitivities. Powder Technology, 188, 89-101.
(2) Hauw S, Hapgood KP, Hoadley AF, & Desai DK (2010). Investigating the role of lignite as a drying aid in rotary superheated steam drying of dewatered sludge. Chemeca 2010: Engineering at the Edge, 26-29 September 2010, Hilton Adelaide, South Australia. Engineers Australia, 2716-2726.
(3) Iveson SM, Wauters PA, Forrest S, Litster JD, Meesters GM, Scarlett B (2001). Growth regime map for liquid-bound granules: further development and experimental validation. Powder Technology, 117: 83–97.

Preliminary products were produced, including granulated brown coal and granulated brown coal plus organic/inorganic fertiliser. Further work is needed to optimise these products through selection of efficient and cost-effective binder materials.

3.3.2. Blast furnace coke from lignite

This is one of three projects established through a collaborative agreement between the Victorian Government and Japan's Kyushu Electric Power Company in 2009. BCIA assumed management of these projects at the end of 2010.

This project involved a PhD student at Monash University, Mr Mamum Mollah, supervised by Professor Alan Chaffee, in collaboration with CSIRO, HRL Technology, and Australian Char.

The objective was to investigate whether Victorian lignite (brown coal) can be heated and chemically treated to become similar to coking coal, which is used in the production of steel. This research was motivated because coking coal has become rarer and more expensive as global steel demand grows.

Blast furnace coke must be able to maintain its mechanical strength while it reacts with CO_2 to maintain the permeability of the reaction bed. The hard char produced by pyrolysis of Victorian brown coal is too reactive, quickly breaking down to fines. Research efforts in this project were directed to production of hard, low reactivity cokes from brown coal.

Combinations of thermal coal treatments, binding agents and processing conditions were investigated. Briquettes were produced and tested for compressive strength and reactivity. The research involved evaluation of a range of processing conditions, involving the following.

- Separation of tarry (guest) material from the brown coal.
- Briquetting of the mixture including the residue, a binder and a cementing agent under a carefully regulated heating regime.

The project was successful in producing a briquetted product with acceptably low reactivity by using a combination of optimised processing conditions and a binder material derived from brown coal.

Opportunities to commercialise this valuable intellectual property are being explored with proponents of the Advanced Lignite Demonstration Program (ALDP).

3.3.3. Brown coal and humate products as agricultural inputs

Humic substances are highly complex organic mixtures that are created through the decay of plants. They make up a large component of soil organic matter and can improve soil properties such as aggregation and water-holding capacity. They also form complexes with plant nutrients, creating a slow-release reservoir of nutrients within the soil. Lignites and brown coal can be used to produce a range of commercial humic substance products, which are claimed to increase the growth and yields of a variety of agricultural crops. The advantages of brown coal as a soil amendment have been recognised for many years and it is commonly added to potting mixes [(4)].

More than 200 humic substance products are being manufactured and sold as soil amendments by Australian companies, which are marketed with a myriad of claims for improved physical, chemical and biological soil properties and enhanced plant growth [(5)].

However, little research has been conducted in Australia to provide a scientific basis for such claims. This has created an attitude of scepticism toward unsubstantiated humic substance products that erodes their commercial potential.

BCIA has supported four interrelated projects at Monash University, conducted by a team led by Associate Professor Antonio Patti.

- Coal derived soil additives: A green option for improving soil carbon, soil fertility and agricultural productivity?
- Sustainable soil carbon and soil health through brown coal-derived products.

- Evaluation of granular humate-phosphate fertilisers on soil phosphorus availability and plant growth.
- Optimising fertiliser composition utilising brown coal, biomass wastes and conventional fertilisers .

To complement this research, BCIA's Research Investment Manager, Dr David McManus, prepared a report on behalf of BCIA members. The report is entitled 'Applications for brown coal in Australian agriculture'.

Coal derived soil additives – green option for improving soil carbon, soil fertility and agricultural productivity?

Humic substances, specifically humic acids and fulvic acids derived from low-rank coals, have been widely reported to have beneficial effects on soil health and plant growth. Increased plant growth, improved soil properties and enhanced microbial activity are thought to create conditions in which a higher equilibrium level of carbon is maintained in the soil. The addition of humic substances to crops has the potential to enhance CO_2 capture from the atmosphere through the increased photosynthesis resulting from better plant growth conditions. The objectives of this project were as follows.

- Characterise the humic substance content of a range of commercial products.
- Assess the effects of humic substance products on agricultural plants in glasshouses.
- Evaluate the impact of humic substance products on degraded soils.
- Undertake field assessments of humic substance products on agricultural productivity and soil carbon.

A number of laboratory and field studies were conducted on commercial humic substance products and as-mined Victorian brown coal, based on standardised levels of humic substance content. Despite a range of plant growth investigations covering pasture (ryegrass and mixed pasture) cereals (wheat) and vegetables (leeks), responses to humic substance were spasmodic and no clear trend emerged. A number of these plant growth studies were conducted in the field on operating farms and results communicated to local farmers through public information sessions.

Where brown coal itself was applied, soil properties were improved and carbon level increases were observed. Suppliers of commercial humic substance products generally recommend application rates that are significantly below the levels of the organic matter (and hence humic materials) already present in the soil, yet beneficial effects, even at these low levels, have been reported. These applications rates were also used in this project, as well as some higher levels.

The variability in responses encouraged the researchers to undertake an extensive survey of the literature reporting on humic substance effects on plant growth. The project undertook a meta-analysis of 81 peer-reviewed research papers and analysed data from 181 different experiments.

The findings revealed that positive, negative or neutral responses have all been reported. It is likely that where negative and even neutral responses were found, such studies may not be reported in the scientific literature. The plant growth responses were found to be linked to complex interactions between humic substances and their source, application rates, soil types, environmental conditions and plant species. Hence, a 'one-size fits all' product or solution is unlikely. Given the low application rates used, changes in soil characteristics are only likely over longer time periods through cumulative effects. The literature survey and analysis also revealed that humic substances from compost sources (25%–29% increases in plant growth) significantly outperformed those from brown coal (12% increase) and peat (4% increase).

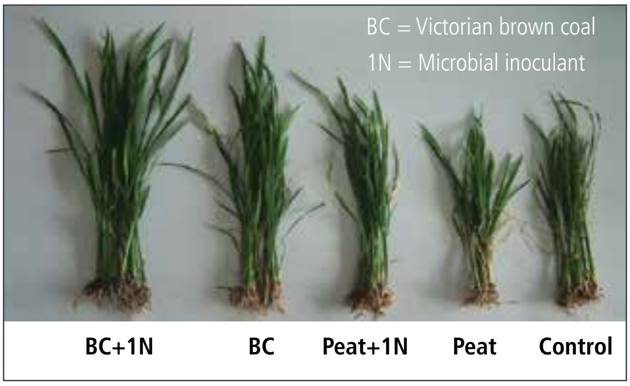
Microbes are likely to play a significant role in explaining the variable plant growth responses that are observed with humic substance amendments.

(4) Perry GJ, Royston D, & Allardice DJ (1987). The development of new uses for Victorian brown coal. Symposium Proceedings: Fourteenth Biennial Lignite Symposium on the Technology and Utilization of Low-Rank Coals, Dallas TX, 19 May 1987, University of North Dakota.
(5) Billingham KL (2012). Humic products–potential or presumption for agriculture? Can humic products improve my soil? www.grasslandnsw.com.au/FreeContent/2012/05-2012-Billingham.pdf.

A glasshouse pot trial with rice showed significant differences between treatments, with Victorian brown coal having the most positive effect on plant growth, particularly when inoculated with nitrogen fixing bacteria (Figure 55).

The combination of brown coal and nitrogen fixing bacteria had a greater effect than either treatment alone, indicating that multiple factors are at work. As well as providing a plant growth promoting effect, the brown coal also seemed to support increased viability of the microbial inoculant.

Figure 55: Rice in glasshouse trial after 30 days



The interactions between humic substances, soil, plants and microbial populations are still not well understood. However, the results obtained in this project provide strong evidence for the beneficial effects of humic substance in agriculture.

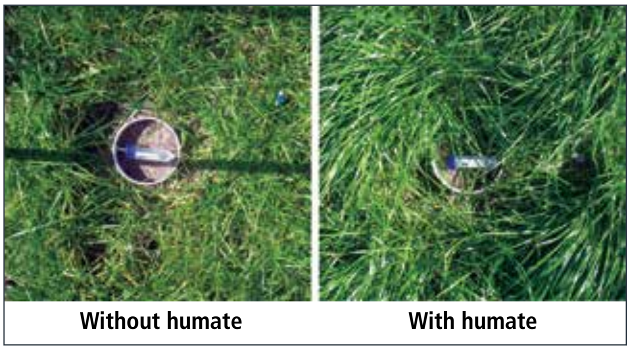
The research tools developed through this project can help support the development and validation of new commercial agricultural products based on Victorian brown coal.

Sustainable soil carbon and soil health through brown coal-derived products

In association with the previous project, BCIA provided a scholarship to support PhD student Ms Karen Little, who undertook an extensive study on the effects of a commercial potassium humate on plant growth and soil properties.

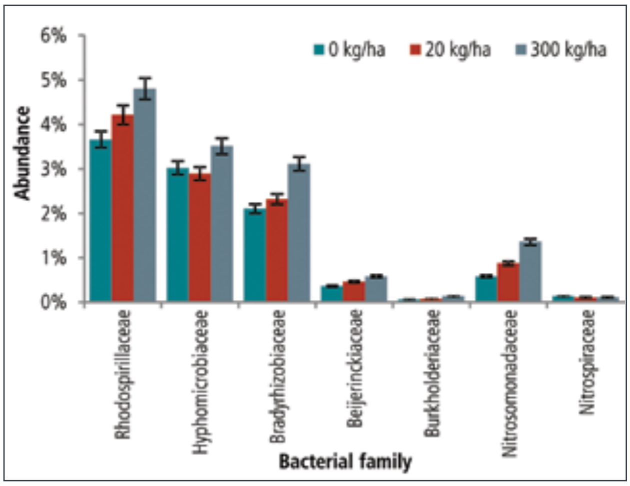
Ms Little demonstrated that ryegrass growth in a limited outdoor trial was significantly stimulated by treating the soil with a commercial potassium humate (Figure 56). However, the stimulation occurred only during the early growth stage, and was not sustained in the longer term. The reasons for this are unclear, although it is possible that the growth of both treatments was ultimately governed by a common limiting nutrient. Further research is required to understand how the initial benefits of treatment with potassium humate may be translated to an increased crop yield.

Figure 56: Ryegrass treated with a commercial potassium humate



Ms Little also used genetic profiling methods to study the effect of potassium humate application on the microbial population in the soil. It was found that the abundance of soil bacterial families associated with nitrogen cycling was altered in response to treatments with the soluble potassium humate granules (Figure 57). The implications of this are not well understood and require further investigation.

Figure 57: Effect of commercial potassium humate on N-cycle soil microbial population



Evaluation of granular humate-phosphate fertilisers on soil phosphorus availability and plant growth

Global use of chemical fertiliser, specifically nitrogen, phosphorus and potassium (N, P and K), is rising steadily, driven largely by China, the US and India. By 2030 fertiliser applications in these regions are expected to increase by about 50%.

However, much of the fertiliser applied to crops is wasted. For example, during 1950–1990, the application of nitrogen fertiliser increased by 15 times, whereas the amount of N utilised by plants increased by only a factor of three. In Australia, it is estimated that more than A$20 billion worth of phosphorus fertiliser has been applied to arable soils and is still present in poorly-available form [(6)].

Urea accounts for about half of world nitrogen fertiliser production. Urea is synthesised from ammonia which, in turn, is produced from hydrogen (from natural gas) and nitrogen (from the air). Production of urea creates significant GHG emissions, equivalent to 1.85kg $CO_{2\text{-}e}$ per kilogram of urea [(7)].

Phosphorus fertilisers, on the other hand, cannot be economically synthesised from chemical precursors but must be mined. Phosphorus is thus a non-renewable resource and is in short supply. Globally, it is expected that peak phosphorus production from mining will occur by around the end of the 21st century [(8)]. More efficient ways to use chemical fertilisers are needed, to make the most of vital but increasingly scarce resources, and to minimise the harmful impacts of fertilisers on the environment.

BCIA has provided scholarship support for Mrs Azita Kargosha, a PhD student working under the supervision of Associate Professor Antonio Patti. Mrs Kargosha is investigating the performance of blends of humic substance products with superphosphate fertiliser.

This project has benefitted from the assistance of two local companies, Torreco and Feeco Australia. Torreco uses a torrefaction process to heat the brown coal briefly in an oxygen-deficient atmosphere, which makes the coal dry and brittle, and thus easier to grind and granulate. Feeco has expertise in granulation technology, and has produced small batches of granules containing blends of brown coal / humates and chemical fertilisers, for testing at Monash University.

The charged ionic groups within humic substances and brown coal can bind to phosphorus fertilisers, making them available in slow-release form. This project will investigate the implications that this has on the movement of phosphorus through the soil and for improved nutrient availability to crops.

It is anticipated that this project will provide a rational scientific basis for the optimisation of improved phosphorus fertilisers which can help preserve scarce phosphorus resources through increased nutrient use efficiency.

Optimising fertiliser composition utilising brown coal, biomass wastes and conventional fertilisers

BCIA is providing scholarship support for another PhD student working with Associate Professor Patti, Mr Biplob Saha, who is investigating the interactions between brown coal and nitrogen fertilisers.

Torreco and Feeco Australia have also provided assistance with preparing the fertiliser granules evaluated in this project. The research seeks to improve the efficiency of nitrogen fertilisers, such as urea, through blending with brown coal or humic substances.

Urea fertiliser is unstable in the environment and can easily be lost through a variety of mechanisms, including leaching, volatilisation, breakdown by microorganisms, as well as chemical processes such as hydrolysis and precipitation.

(6) Cornish PS (2009). Research directions: Improving plant uptake of soil phosphorus, and reducing dependency on input of phosphorus fertiliser. Crop and Pasture Science, 60, 190–196.
(7) Wood S, & Cowie A (2004). A review of GHG emission factors for fertiliser production. In IEA bioenergy task, 38(1), 1–20.
(8) Cordell D, & White S (2011). Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability, 3, 2,027–2,049.

Soil microorganisms transform urea to volatile ammonia and nitrous oxide, which can be lost into the atmosphere. Nitrous oxide is a potent GHG and causes acid rain and the destruction of stratospheric ozone.

Mr Saha has shown that brown coal can bind to ammonia, slowing its release from the soil (Figure 58). Preliminary results have demonstrated the suppression of ammonia release from urea-brown coal blends in water. The release of ammonia gas from soil columns is also suppressed. Retention of ammonia in the soil should make the nitrogen more available for plant use, either directly or through microbial transformation.

Brown coal-urea blends exhibit a remarkable decrease in the daily emissions of nitrous oxide from soil columns (Figure 59). The blends that included brown coal had lower N_2O and NH_3 emissions and maintained higher mineral N in soil.

These results suggest that blending of urea with the coal can reduce gaseous nitrogen emissions, as well as retaining more mineralised N in the soil thus providing greater amounts of available N to crops.

Figure 58: Release of NH_4^+ from urea brown coal blends in water

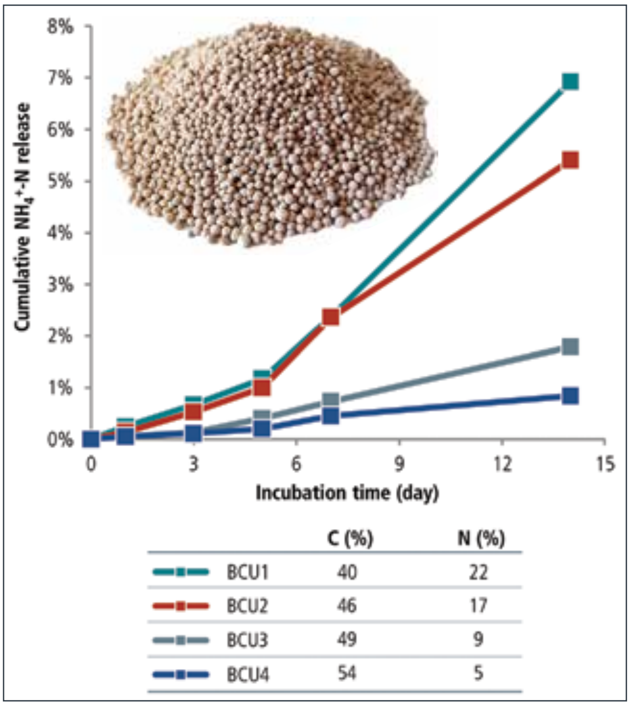
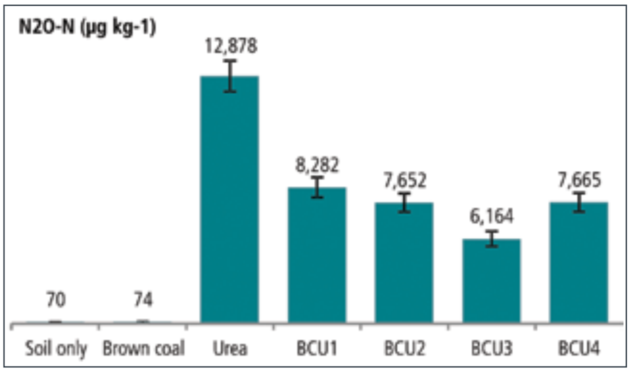


Figure 59: Cumulative nitrous oxide emissions from the surface of the soil columns



This project will provide a scientific basis for the optimisation of improved nitrogen fertilisers based on blends with brown coal or humic substances. It is anticipated that this will support the development of a new manufacturing industry to create new, efficient fertiliser products for use throughout Australia.

Applications for brown coal in Australian agriculture

This project was initiated in response to feedback from a BCIA-run workshop in December 2015, 'Agricultural applications for brown coal', which involved the majority of industry, academic and regulatory experts known to have an interest in this area. Participants at the workshop were aware that a lot of research had been done in this area in the past, but it was not readily accessible. BCIA's Dr David McManus undertook this project as a literature survey on behalf of BCIA members, to inform them of the opportunities that exist for use of brown coal in Australian agriculture.

The literature review showed that there is a range of potential uses for brown coal in Australian agriculture. Coal or extracted humic substances can be used as soil amendments and in organomineral fertilisers. Coal itself can be used as a carrier for microbial biofertilisers and to reduce ammonia and N_2O emissions from beef cattle feedlots and other intensive animal-rearing systems. Humic acids can be used as animal feed supplements to improve animal health and growth rates. The report included recommendations for further research to ensure the quality and reliability of new agricultural products based on Victorian brown coal.

Amendment of farming soils with brown coal can quickly improve soil health, leading to increased plant growth and photosynthesis. In turn, this results in more CO_2 being captured from the atmosphere and stored as soil organic carbon. This is an inexpensive way to help offset Australia's GHG emissions.

The report also considered the agricultural use of Latrobe Valley fly ash. Applications for the fly ash are generally limited because of its strong alkalinity and high concentration of boron. There may be agricultural applications in areas of high rainfall and / or acidic soils, where boron deficiency is likely to be a problem. In these areas, the high boron content of fly ash would actually be an advantage. Further research is required to investigate the potential for applications in such areas.

Due to the strong interest in the agricultural potential for brown coal, BCIA members have given approval for the project report to be made public.

3.3.4. Reversible electrochemical storage of hydrogen in activated carbons from Victorian brown coal

Low-cost and efficient reversible energy storage devices are essential for a sustainable energy future. Renewable energy sources such as solar and wind are intermittent, and require a form of storage to deliver a stable output. One way to store this energy is in batteries. Another way is in the form of hydrogen, produced through the electrolysis of water.

As an energy carrier, hydrogen has a number of advantages. A large volume of hydrogen can be easily stored in different ways. Hydrogen is a high efficiency, low polluting fuel that can be used for transportation, heating, and power generation in places where it is difficult to use electricity. In some instances, it is cheaper to ship hydrogen by pipeline than sending electricity over long distances by wire.

Electrochemical storage of hydrogen within solid-state storage materials is potentially more efficient than storage as compressed hydrogen gas. Since 2001, a number of studies have investigated the potential for electrochemical hydrogen storage in activated carbons and the electrochemical processes involved.

Carbon-based materials, particularly activated carbons, are potentially attractive materials for the reversible storage of hydrogen since they are lightweight, have high internal surface areas, and can be produced from abundant and low-cost coal.

A number of forms of activated carbon have already been made from Victorian brown coal and found to have potential applications such as natural gas storage, carbon dioxide capture, and anode fabrication. However, there has not been any investigation into the reversible electrochemical hydrogen storage potential of activated carbons made from brown coal.

BCIA is providing scholarship support for Mr Amandeep Oberoi, a PhD student at RMIT University under the supervision of Associate Professor John Andrews, to investigate the reversible electrochemical storage of hydrogen in selected activated carbons made from Victorian brown coal. The objectives of this project were as follows.

- Prepare using a variety of methods, and characterise, a selection of activated carbon samples made from Victorian brown coal and other carbon precursors with a range of pore size distributions including especially ultramicropores (<0.7nm diameter).
- Measure the reversible electrochemical hydrogen storage capacities of electrodes made from these samples in both acidic and alkaline electrolytes, in electrochemical cells with different designs.
- Develop a theoretical explanation of the mechanisms of hydrogen storage in these activated carbons, and test this theory against experimental results.
- Select, fabricate and measure the hydrogen storage performance of one or more activated carbon samples that are the most promising.

Preliminary results have shown that a mesoporous activated carbon prepared from Victorian brown coal has an equivalent hydrogen storage capacity of 1.6%, which compares favourably with the metal hydrides used in commercial solid-state hydrogen storage.

3.3.5. Development of brown coal geopolymer concrete

Globally, the cement industry is a major source of CO_2 emissions, representing 5%–7% of the world total. Each tonne of cement releases between 0.7 and 1.0 tonnes of CO_2 as it cures, producing an annual total release of almost 2 billion tonnes of CO_2 into the atmosphere. It is important to find ways to reduce the environmental impact of this industry.

Fly ash is an underused by-product of coal-fired power stations that can serve as a replacement for ordinary cement in some applications. In Victoria, brown coal fired power stations produce more than 500,000 tonnes of fly ash and bottom ash annually, none of which has any commercial value. The majority of this by-product is stored in landfills.

Ordinary Portland cement, the main binder in concrete, is activated by hydration of calcium hydroxide. Fly ash produces 'geopolymer concrete', which is activated by reaction of aluminosilicates with high concentration alkali. It is not clear whether the fly ash produced from Victorian brown coal is suitable for production of geopolymer concrete.

BCIA is providing scholarship support to a PhD student at RMIT University, Mr Rahmat Dirgantara, under the supervision of Dr David Law and Associate Professor Tom Molyneaux.

The aim of Mr Dirgantara's project is to characterise the specific chemical make-up of brown coal fly ash from Victorian power stations and to investigate whether the fly ash can be used to make geopolymer concrete of sufficient mechanical strength.

The fly ash used in this study was recovered directly from the electrostatic precipitators of three power stations in the Latrobe Valley. There were large variations in the chemical composition, due to natural variations in coal.

Initial geopolymer mortars prepared from the fly ash exhibited marked differences in mechanical strength. The maximum strength of the geopolymer mortar obtained from the Loy Yang fly ash was 56MPa, while Yallourn and Hazelwood geopolymer mortars has compressive strengths of approximately 10MPa. The differences in compressive strength relate to the aluminosilicate content of the fly ash.

Further trials were undertaken using Loy Yang fly ash to manufacture concrete specimens. The concretes produced had a maximum compressive strength of 60MPa, more than sufficient for a construction grade concrete. However, there was considerable variability due to the changing composition of the fly ash.

To date, the research has demonstrated that a good quality geopolymer concrete can be manufactured using Loy Yang brown coal fly ash.

Further investigation is under way to determine the optimum mix design, the mechanical properties and the durability characteristics of geopolymer. Options for processing the raw fly ash to standardise the composition are also being evaluated.

Figure 60: Brown coal geopolymer mortar brown coal fly ash from A. Loy Yang; B. Yallourn; and C. Hazelwood

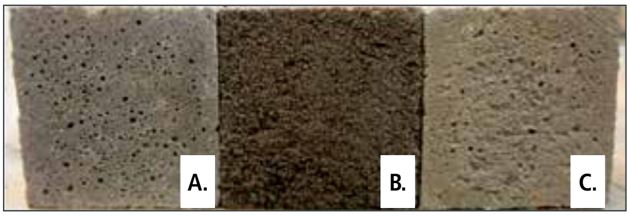


Figure 61: Brown coal geopolymer concrete brown coal fly ash from Loy Yang

Key Publications

Little KR, Rose MT, Jackson WR, Cavagnaro TR, & Patti AF (2014). Do lignite-derived organic amendments improve early-stage pasture growth and key soil biological and physicochemical properties? Crop and Pasture Science, 65, 899–910.

Mollah MM, Jackson WR, Marshall M, & Chaffee AL (2015). An attempt to produce blast furnace coke from Victorian brown coal. Fuel, 148, 104–111.

Patti AF, Jackson WR, Norng S, Rose MT, & Cavagnaro TR (2013). Commercial Humic Substances Stimulate Tomato Growth. In Functions of Natural Organic Matter in Changing Environment (pp. 1,079–1,084). Springer Netherlands.

Patti A, Rose M, Little K, Jackson R, & Cavagnaro T (2014). A meta-analysis of plant-growth response to humic substance applications: Implications for agriculture. Advances in Agronomy, 124, 37–89.

Tang EC, Perkins E, Hoadley AF, & Hapgood KP (2012). Development of lignite granulation regime map. Chemeca 2012: Quality of life through chemical engineering: 23-26 September 2012, Wellington, New Zealand, 665.

Tran CKT, Rose MT, Cavagnaro TR, & Patti AF (2015). Lignite amendment has limited impacts on soil microbial communities and mineral nitrogen availability. Applied Soil Ecology, 95, 140–150.

Skills Development Program

BCIA's skills development program represents a strategic investment to secure the expertise required for new low emissions brown coal technologies. The academic aspect of the program included funding for PhD scholarship support and two Research Leader Fellowships. This is in addition to the PhD, Masters and undergraduate students and postdoctoral fellows supported through the R&D portfolio projects.

Research Leader Fellowships

The BCIA Research Leader Fellowship program recognises outstanding researchers of international repute who can provide a significant leadership and mentoring role in building Australia's internationally-competitive research capacity within the brown coal innovation sector.

In 2010, BCIA awarded two Research Leader Fellowships. One was to Dr Klaus Hein, in joint roles as Professor of Low Emissions Technology at the Department of Chemical Engineering, Monash University, and as Research and Development Manager at HRL Technology Pty Ltd. The second was to Dr Alan Chaffee, as Professor and BCIA Research Leader at the School of Chemistry, Monash University.

Professor Klaus Hein


Prof. Klaus Hein

Professor Hein is one of the world's most eminent brown coal researchers. He was formerly the head of R&D with RWE, a major utility company in Germany, and a professor at both the University of Delft in the Netherlands and the University of Stuttgart in Germany.

He has served as an international consultant and as a coordinator of multi-country, multi-partner research projects.

Professor Hein's Research Leader Fellowship was Australia's first joint industry-university professorial appointment in brown coal-related technology. The aim of Professor Hein's Fellowship was to produce a number of high level PhD and Masters graduates for the future leadership, management and development of Victoria's brown coal resource. A major aim of the program was to leverage Professor Hein's international contacts to bring together key researchers from around the world in industry-focused collaborative projects.

There were two primary activities during Professor Hein's Fellowship. The first was a research, mentoring and educational role at HRL Technology in Mulgrave. There, his principal responsibility was to prepare and conduct a BCIA-supported research project, 'Next generation lower emission gasification systems R&D – Power and Products'. He drew upon his international network to organise visits by HRL Technology engineers to R&D gasification facilities in Europe, the US, Canada and Australia. He also arranged for five engineering students from the University of Melbourne to undertake industrial research projects, supervised by HRL Technology.

The second major activity was a mentoring and educational role within the Energy, Fuels and Reaction Engineering research group at Monash University. There, he led two BCIA-funded research projects: 'Development of chemical looping process for fuels production and CO_2 capture from Victorian brown coals' and 'Development of entrained flow gasification technology with brown coal for generation of power, fuel and chemicals'. Professor Hein acted as co-supervisor and mentor to 10 PhD engineering students at Monash University, and represented Victorian brown coal research at conferences in the United States, China, Germany and Australia.

In addition, Professor Hein arranged visits from representatives from the Japanese agencies Nippon Steel, MHI, Chiyoda, University of Tokyo, IHI Corporation, JPower, JCOAL and Hitachi as well as from the VTT Research Centre, Finland. He also negotiated in-kind partnerships with overseas institutes to facilitate international collaboration on workshops, joint publications in international journals, exchange of researchers, and participation in cluster projects of the European Commission.

Professor Hein has made a significant contribution to the development and bolstering of BCIA's international linkages and networks throughout his Research Leader Fellowship. He has enhanced international collaboration and strengthened the linkages and complementary research capabilities of Monash University with HRL Technology, and contributed to the development of brown coal research at the University's Gippsland campus.

Dr Alan Chaffee

Dr Alan Chaffee

Dr Alan Chaffee is a professor in the School of Chemistry at Monash University and is Australia's premier academic in the science of Victorian brown coal. He has previously worked with CSIRO and BHP Research and has developed expertise in a broad range of research areas relating to Victorian brown coal: both direct and indirect liquefaction, preparation of high surface area activated carbons, improved catalysts for synthesis gas conversion, fundamentals of lignite characterisation, applied aspects of coal use, novel materials for CO_2 capture, and catalysts for CO_2 conversion into valuable products. Dr Chaffee's research focus is on applied science that can be used in subsequent process development work by engineering groups.

As a BCIA Research Leader Fellow, Dr Chaffee has trained young scientists and engineers in the specialist skills required for the development and sustainable use of Victorian brown coal.

His research program sought to address issues that impede the broader use of Victorian brown coal and to facilitate its application in new markets, along four major themes.

1. Understanding spontaneous combustion.
2. Transformation of brown coal into high value products.
3. Coal and coal-derived materials as adsorbents.
4. CO_2 capture and use.

The research sought to generate outcomes that could be used in subsequent process development work by engineering groups. The program also emphasised activities that offered improved environmental outcomes, including reduced energy consumption and the recovery or use of associated CO_2 emissions.

Some highlights of the program are briefly described below.

Although spontaneous combustion has been widely studied, the physico-chemical factors that influence its rate have been poorly characterised. Also, Victorian brown coal is heterogeneous, which has compromised comparisons between prior studies. A significant new finding from Dr Chaffee's work is the identification of an inverse relationship between the volume of micropores present in the coal and the critical ignition temperature. Thus, when the micropore volume was reduced, for example by dewatering, the propensity for spontaneous combustion was also reduced.

Victorian brown coal is potentially a low-cost carbonaceous precursor to a variety of higher value products. Dr Chaffee's group investigated methods for making materials such as blast furnace coke substitute, active carbon products and road bitumen. This work was quite successful and led to the development of valuable intellectual property in the former two cases. Studies of liquefaction of brown coal in comparison with various forms of biomass led to new understanding about the chemical mechanisms involved.

Other work identified a novel way of extracting coal using metastable ionic liquids formed from the condensation of CO_2 and various low molecular weight amines. In certain cases, these ionic liquids can extract as much as 70% of the coal. The ionic liquid can be recovered as its constituent gases by simply heating the liquid to a mild temperature (~60°C). This approach can be selective for specific types of molecular structures (such as triterpenoid components) under certain conditions.

In a substantial program on new materials for CO_2 capture, the group developed a composite amine / silica material that has been patented. This material is prospective for adsorption-based CO_2 capture from flue gas streams using a vacuum-swing adsorption process configuration. Other materials were identified that are have potential for CO_2 capture from synthesisgas at elevated temperatures in a pre-combustion context.

Active carbons prepared from Victorian brown coal have abundant microspores, making them excellent adsorbents for small molecules. The group has investigated the capacity of active carbons to store hydrogen and methane as well as CO_2. The electrical conductivity of carbon gives them a distinctive capability for use in electrical swing adsorption, which is the subject of an ongoing study with a consortium of European collaborators from industry and academia.

The direct conversion of CO_2 into commodity chemicals, such as methanol by gas phase heterogeneous catalysis is being investigated. The group is applying conventional catalysts and novel ones based on a relatively new class of materials known as metal-organic frameworks. (Metal-organic frameworks are also prospective for CO_2 capture).

The fellowship has provided the opportunity to collaborate with many groups domestically and internationally. The group hosted international exchange researchers from Canada, China, Germany, Japan and Spain. There were several reciprocal visits by group members that provided opportunities to use unique facilities in overseas laboratories and to present Australian work at international conferences.

The fellowship also provided a platform that helped generate funding from other sources, including industry and government.

An emphasis of the research program was on conversion routes that offered improved environmental outcomes, including reduced energy consumption and the recovery or use of associated CO_2 emissions.

During the period of his Fellowship, Dr Chaffee was involved in 20 different research projects. BCIA funded eight. Dr Chaffee contributed to 26 conference presentations, 92 conference papers and 67 peer-reviewed journal publications. He was responsible for the supervision of 17 higher degree students and 16 undergraduate research projects. In addition, he hosted 12 international exchange students, from Japan, China, Canada, Germany and Spain.

Some of the significant developments arising from this research include the following.

- Improved understanding of the process of spontaneous combustion in brown coal.
- Development of valuable intellectual property relating to production of a blast furnace coke substitute from Victorian brown coal.
- Solubilisation of brown coal using recyclable, distillable ionic liquids.
- Development of metal-organic frameworks and other novel CO_2 sorbents.
- Development of modified activated carbons from Victorian brown coal for capture of CO_2 and storage of hydrogen.
- Contribution to understanding the degradation of amine sorbents and solvents during post-combustion CO_2 capture.

Dr Chaffee has made a substantial contribution to the training of a new generation of scientists and engineers, and to the creation of new products from brown coal and new technologies for capture of associated CO_2 emissions. He has enhanced Victoria's international research linkages and maintained Monash University's reputation as a leader in brown coal research.

Key Publications

Prof. Klaus Hein

Bhattacharya S, Kabir KB, Hein K (2013). Dimethyl ether synthesis from Victorian brown coal through gasification – Current status, and research and development needs. Progress in Energy and Combustion Science 39: 577–605.

Kabir KB, Hein K, Bhattacharya S (2013). Process modelling of dimethyl ether production from Victorian brown coal – Integrating coal drying, gasification and synthesis processes. Computers & Chemical Engineering 48: 96–104.

Saha C, Rajendran S, Hein K, Bhattacharya S (2012). Experimental investigation of chemical looping combustion of Victorian brown coal using hematite. Chemeca 2012: Quality of life through chemical engineering: 23–26-Sep-2012, Wellington, New Zealand, p 530.

Saha C, Zhang S, Hein K, Xiao R, Bhattacharya S (2013). Chemical looping combustion (CLC) of two Victorian brown coals – Part 1: Assessment of interaction between CuO and minerals inherent in coals during single cycle experiment. Fuel 104: 262–274.

Dr Alan Chaffee

Hawes C S, Nolvachai Y, Kulsing C, Knowles GP, Chaffee AL, Marriott PJ, Batten SR, Turner DR (2014). Metal – organic frameworks as stationary phases for mixed-mode separation applications. Chemical Communications 50: 3,735–3,737.

Mathews JP, Chaffee AL (2012). The molecular representations of coal – a review. Fuel 96: 1–14.

Mollah MM, Jackson WR, Marshall M, Chaffee AL (2015). An attempt to produce blast furnace coke from Victorian brown coal. Fuel 148: 104–111.

Qi Y, Hoadley AF, Chaffee AL, Garnier G (2011). Characterisation of lignite as an industrial adsorbent. Fuel 90: 1,567–1,574.

Qi Y, Verheyen TV, Tikkoo T, Vijayaraghavan R, MacFarlane DR, Chaffee AL (2015). High solubility of Victorian brown coal in 'distillable'ionic liquid DIMCARB. Fuel 158: 23–34.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Evaluation of methods for monitoring MEA degradation during pilot scale post-combustion capture of CO_2. International Journal of GHG Control 39: 407–419.

Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Primary sources and accumulation rates of inorganic anions and dissolved metals in a MEA absorbent during PCC at a brown coal-fired power station. International Journal of GHG Control 41: 239–248.

Subagyono DJ, Liang Z, Knowles GP, Chaffee AL (2011). Amine modified mesocellular siliceous foam (MCF) as a sorbent for CO_2. Chemical Engineering Research and Design 89: 1,647–1,657.

Vogt C, Wild T, Bergins C, Strauß K, Hulston J, Chaffee AL (2012). Mechanical / thermal dewatering of lignite. Part 4: Physico-chemical properties and pore structure during an acid treatment within the MTE process. Fuel 93: 433–442.

Vogt C, Chang SL, Taghavimoghaddam J, Chaffee AL (2014). Improvements in the pre-combustion carbon dioxide sorption capacity of a magnesium oxide – cesium carbonate sorbent. Energy & Fuels 28: 5,284–5,295.

Wang J, Chen H, Zhou H, Liu X, Qiao W, Long D, Ling L (2013). Carbon dioxide capture using polyethylenimine-loaded mesoporous carbons. Journal of Environmental Sciences 25: 124–132.

Wells BA, Chaffee AL (2011). Modeling gas separation in metal-organic frameworks. Adsorption 17: 255–264.

Postgraduate scholarships

BCIA has fully or partly funded research projects undertaken by nearly 40 higher degree students. BCIA has provided direct financial support for 16 PhD scholars, with the remaining higher degree students involved in BCIA's research program.

Of the directly supported students, BCIA provided 60 fully funded scholarships in 2010–2011, as listed in the table below (Figure 62).

Figure 62: 2010–2011 Round BCIA PhD scholarship recipients

PhD candidate	Host institution	Project title
Mr Adam Rady	Monash University	Evaluation of Victorian brown coals as fuel for Direct Carbon Fuel Cells (DCFC).
Ms Alicia Reynolds	Monash University	Identification and monitoring of by-products generated from amine based solvents and adsorbents during post-combustion CO_2 capture (PCC) from brown coal flue gases.
Ms Karen Little	Monash University	Sustainable soil carbon and soil health through brown coal-derived products.
Ms Hirra Azher	University of Melbourne	Development of membrane processes for the recovery of water from flue gas streams.
Ms Hui-En Teo	University of Melbourne	Novel coal dewatering techniques.
Ms Joanne Tanner	Monash University	Producing value-added products by gasification of brown coal.

BCIA has also supported 10 supplementary PhD scholarships, providing funding additional to university and Australian postgraduate scholarship awards.

Figure 63: 2013–2014 Round BCIA PhD scholarship recipients

PhD candidate	Host institution	Project title
Mr Baiqian Dai	Monash University	Coal blending combustion and gasification – the mixing of beneficiated brown coal and high-rank bituminous coal.
Mr Tao Xu	Monash University	Development of oxygen-blown entrained glow gasification for use with a range of Victorian brown coals.
Mr Biplob Saha	Monash University	Optimising fertiliser formulation utilising brown coal, biomass wastes, and conventional fertilisers.
Mr Hiep Thuan Lu	University of Melbourne	The impact of impurities on the performance of cellulose acetate membranes for CO_2 separation.
Mr Anthony De Girolamo	Monash University	Developing advanced computer modelling program for the prediction of brown coal ash slagging / fouling propensity under oxy-fuel combustion mode.
Mr Amandeep Oberoi	RMIT	Reversible electrochemical storage of hydrogen in activated carbons from Victorian brown coal and other precursors.
Mr Rahmat Dirgantara	RMIT	Development of brown coal geopolymer concrete.
Mr Manabendra Saha	University of Adelaide	Experimental and computational study of solid fuels under MILD combustion.
Mr Rahul Chowdrey	Federation University	Degradation of amine solvent by reactions with metal surfaces and fly ash during post-combustion capture of CO_2.
Mr Adeel Ghayur	Federation University	Environmental management of new process streams from post-combustion capture of CO_2 in the Latrobe Valley.

In addition to the above direct funding of PhD students, BCIA's research and fellowship funding has contributed towards the following project activities for PhD, masters and post-doctoral research projects.

Figure 64: BCIA's research and fellowship funding contributions

Researcher	Current status	BCIA project involvement
Dr Trent Harkin	Post-doctoral Fellow	CO2CRC's Carbon Capture Technologies in Brown Coal Fired Power Plants.
Mr Chiranjib Saha	PhD Student	Development of Chemical Looping Process for Fuels Production and CO_2 Capture from Victorian Brown Coals.
Mr Sharmen Rajendran	PhD Student	
Dr Anthony Auxilio	Post-doctoral Fellow	
Dr Srikanth Srivatsa	Post-doctoral Fellow	Development of Entrained Flow Gasification Technology with Brown Coal for Generation of Power, Fuel and Chemicals.
Ms Sunaina Dayal	PhD Student	
Ms Evone Tang	PhD Student	Improved Handling Properties of Lignite-Based Products.
Dr Emily Perkins	Post-doctoral Fellow	
Mr Mohammed Reza Parsa	PhD Student	Improved Handling Properties of Lignite-Based Products / Development of Carbon Monoliths for Capture of CO_2 by Electrical Swing Adsorption.
Mrs Azita Kargosha	PhD Student	Coal-Derived Additives: A Green Option for Improving Soil Carbon, Soil Fertility and Agricultural Productivity?
Ms Tran Tai Kim Cuc	Masters Student	
Dr Mick Rose	Post-doctoral Fellow	
Mr Lachlan Ciddor	PhD Student	Carbon Materials from Victorian Brown Coal for CO_2 Capture.
Mr Mamun Mollah	PhD Student	Blast Furnace Coke from Lignite.
Mr Kazi Bayzid Kabir	PhD Student	Catalytic Steam Gasification and Assessment of Dimethyl Ether.
Mr Wirhan Prationo	PhD Student	Pilot-Scale Oxy-Fuel Combustion of Victorian Brown Coal.
Ms Fiona Low	PhD Student	
Mrs Bharti Gharg	PhD Student	Combined low-cost pre-treatment of flue gas and capture of CO_2 from brown coal-fired power stations using a novel integrated process concept.
Mr Makarios Wong	PhD Student	Advancing Chemical Looping Combustion Technology for Victorian Brown Coals.
Dr Jian Zhang	Post-doctoral Fellow	Accelerating the Deployment of Oxy-Fuel Combustion Technology for Victorian Brown Coal.
Mr Qinghu Zhao	PhD Student	Development of Carbon Monoliths for Capture of CO_2 by Electrical Swing Adsorption.
Ms Sing Yee Yeung	PhD Student	Supervised by Professor Alan Chaffee
Ms Anita d'Angelo	PhD Student	
Mr Ngo Wang Cheung	PhD Student	
Mr Christian Vogt	PhD Student	
Mr Mohammad Amer	PhD Student	
Ms Christine Patzchke	PhD Student	
Ms Dirgarini Julia Subgyono	PhD Student	
Mr Vidura Jayaratne	PhD Student	
Ms Jamileh Moghaddam	PhD Student	
Ms Gulah Yuliani	PhD Student	
Mr James Xiao	PhD Student	
Mr Alexander Haines	PhD Student	

Networks, Linkages and Knowledge Sharing Activities

BCIA's Networks and Linkages program aims to build links to local, national and international groups working on environmentally responsible uses of brown coal.

The program encompasses formal links through membership arrangements and funded research collaborations, informal links for example through sponsorship and attendance at international events, travel support for researchers and visits to international technology development sites. In addition BCIA undertakes a range of knowledge sharing activities such as BCIA's *'Perspectives on Brown Coal'* newsletter and open research seminars.

BCIA has been successful in securing significant interest in the brown coal research activities the company promotes. Over the period covered by this report, 47 government, industrial and research partner organisations have been directly involved in BCIA's R&D activities, including organisations from Australia, China, Japan, US, Germany, France, Denmark, Sweden and Belgium.

The company has established a reputation as a trusted source of information on brown coal technology development, and has an active and growing membership base. Members encompass a mix of stakeholders committed to supporting a brighter future for brown coal, and include two international member companies.

Formal linkages

CO2CRC (member 2009–2015)

BCIA has a strong focus on carbon capture activities as applied to brown coal. BCIA was a full member of the CO2CRC from 2009 to 2015, at which point the CRC changed its focus to look primarily at geological storage, rather than capture, of CO_2. BCIA was the only member of the CRC specifically representing brown coal interests, and as a member of the Program Advisory Committee, provided input into research programs and the direction of the CRC.

BCIA's membership of the CRC granted the company access to results and outcomes of the CRC's work. In addition to gaining access to the core work program of the CRC, BCIA was also able to fund additional programs with the CRC to support brown coal specific activity, including the development and operation of pre- and post- combustion capture facilities operated by the CRC at two sites.

JCOAL (reciprocal membership, 2011 onwards)

The Japan Coal Energy Center (JCOAL) is Japan's main industry group focused on the development and promotion of clean coal technologies. JCOAL supports the development, commercialisation, transfer and dissemination of coal technologies and human resource development, in order to ensure the international coal supply and the harmonisation with the environment. JCOAL also carries out a variety of activities to make coal an even more effective resource. With such strong synergies between the mission of JCOAL and BCIA, the companies formed a reciprocal membership arrangement in 2011.

There is a long history of collaborative R&D activities between Australia and Japan in the area of coal technologies. BCIA has supported JCOAL in its studies around Australian coals, and JCOAL members have been actively involved in BCIA's program of R&D, including research on carbon capture and hydrogen production from brown coal.

Lignite Energy Council (reciprocal membership, 2013 onwards)

The Lignite Energy Council (LEC) is a non-profit trade association that has the goals of maintaining a viable lignite coal industry for North Dakota, and enhancing development of the region's lignite coal resources for use in generating electricity, synthetic natural gas and valuable by-products. Its programs include a state / industry partnership to support development of technologies to accomplish this goal, and the LEC also fund R&D activities.

To support enhanced information sharing and collaborative research efforts in the areas of technologies and skills for environmentally responsible uses of brown coal, the LEC and BCIA established a reciprocal membership agreement in 2013.

BCIA hosted a delegation from the LEC who attended the Low Rank Coal conference in 2014, and has organised information sharing sessions for LEC and BCIA members on progress in the two regions. Through the LEC, BCIA has accessed expertise at the Energy and Environment Research Center (EERC) at the University of North Dakota. With BCIA support, the EERC has brought its coal gasification course to Australia for the first time, and BCIA has benefitted from access to R&D on coal gasification and hydrogen separation technologies.

IEA Clean Coal Centre (member)

BCIA joined the Australian Coal Industry Consortium in 2010, and through this group held membership of the IEA Clean Coal Centre (IEA CCC). The IEA CCC is the world's foremost provider of information on the clean and efficient use of coal, particularly clean coal technologies. They undertake in-depth topical reports and literature reviews and maintain an online database of coal related information, as well as providing advice, facilitating R&D networks and organising workshops and conferences.

During the period covered by this report, BCIA was able to work with the IEA CCC to suggest two reports that were undertaken by the centre, looking at low rank coals and DICE technology. BCIA also participated in the IEA Conference on Clean Coal Technologies in 2015, presenting a paper on Australian progress in brown coal developments.

Global CCS Institute (GCCSI) (member)

BCIA is a member of the GCCSI and through this membership gains access to the GCCSI's knowledge sharing and advocacy. GCCSI supports adoption of CCS as quickly and cost-effectively as possible by sharing expertise, building capacity and providing advice and support so that this vital technology can play its part in reducing GHG emissions.

The GCCSI has supported and publicised two of BCIA's reports, the first being the Novel CO_2 capture taskforce report which focused on non-geological methods for CO_2 sequestration, and the second being "Dispersion modelling for CO_2 pipelines: Fit for purpose and best practice techniques". GCCSI hosts both of these reports in its knowledge repository, and has also run a webinar on the dispersion modelling report to share the outcomes with the global community.

Chronology of major Network and Linkage activities supported by BCIA

2010

- National CCS Week – sponsorship and participation on organising committee
- Membership of the CO2CRC negotiated
- BCIA joins the Australian Coal Industry Consortium
- BCIA launches new website

2011

- Participation in 4th annual Australia-Japan High Level Group on Energy and Minerals Consultations
- Meetings with UK and German coal research groups
- BCIA funded event 'Energy Strategies and Coal Utilisation in China' and 'Brown Coal Use in China', held in Melbourne
- Participation in Australia-China Joint Coordination Group meeting

- 1st BCIA funded Future Skills workshop, Latrobe Valley

2012

- Low Rank Coal Symposium, Melbourne – sponsorship, organising committee, presentation
- Meetings with representatives from China, Japan, Singapore, Korea, Poland
- National CCS Week Conference, Perth – sponsorship and organising committee,
- 8th Annual Clean Coal Forum, Beijing, China – sponsorship
- Participation in International Energy Agency (IEA) Clean Energy Symposium, Sydney
- Presentation to APEC meeting on Clean Fossil Fuels, Brisbane.
- Participation in 6th Australia-China joint coordination group on clean coal technology (JCG) meeting, 6 December, Hangzhou, China
- Participation in JCOAL Clean Coal Day, September
- Research Institute tour, China / Mongolia, September
- Australian Institute of Energy CCS Event in Latrobe Valley – sponsorship and participation
- Sponsor of AIE Melbourne Postgraduate Student Energy Awards 2012
- Brown Coal R&D Stakeholders forum, PowerWorks Morwell
- Clearwater Coal Conference in Florida – presentation

2013

- BCIA student workshop – Taking research out of the laboratory, Melbourne
- Sponsorship of Monash-Tsinghua University workshop on clean coal technology
- BCIA Community Forum, Latrobe valley
- Clearwater Coal Conference in Florida – sponsorship and presentation
- Visits to US National Carbon Capture Center, EERC, Lignite Energy Council, EPRI
- BCIA research forums – Carbon Capture, coal drying and handling
- BCIA Gasification Short Course, Melbourne
- BCIA's Coal to Products Conference, Melbourne
- All Energy Conference – presentation
- BCIA Stakeholders Forum on BCIA's Funding Round

2014

- BCIA Community Forum, Latrobe Valley
- BCIA student workshop – research presentations and industry networking
- Clearwater Clean Coal Conference – presentation and sponsorship of exhibition space
- Low Rank Coal Symposium, Melbourne – sponsorship, organising committee, presentation
- National CCS Week Conference, Sydney – sponsorship and organising committee
- Brown Coal R&D Roundtable forum, Federation University Gippsland
- Participation in JCG Workshop with China focussing on oxy-fuel

2015

- BCIA research seminar – 2013 funding round project update
- Meetings with stakeholders from Japan, China, Poland and the US
- IEA Clean Coal Technologies Conference (Poland) - presentation
- Participation in 8th meeting of the Australia-China Joint Coordination Group on Clean Coal Technology (JCG)
- International Conference on Coal Science and Technology, Melbourne – sponsorship, participation in organising committee

Knowledge sharing – ‘Perspectives’ newsletter and BCIA Research Seminars

One of BCIA’s main communications channels is our regular electronic newsletter, *‘Perspectives on Brown Coal’*, which is distributed to an extensive stakeholder database (currently in excess of 1,000 subscribers) and also published on our website. The newsletter was established in 2010, and to the end of 2015, 15 electronic and four print issues of the newsletter had been produced. The newsletter is well received and supported by our stakeholders, and achieves a response rate of three times the benchmark rate for this communication channel.

BCIA has also initiated a range of seminars and events to share our research findings, update the community on progress towards novel uses of coal, and assist in career planning for students. BCIA has also organised a number of workshops to assist in developing targeted research strategies in areas of common interest for our stakeholders.

On average, BCIA supports three to four major events a year. Our largest single event to date has been the coal to products seminar held in 2013, which was attended by over 120 delegates, including representatives from Europe, India and the US.

BCIA also supports bringing major national and international coal research conferences and events to Melbourne. BCIA representatives have been on the organising committee of the Low Rank Coal Symposium (held in Melbourne in 2012 and 2014), and the International Conference on Coal Science and Technology (held in Melbourne in 2015). The company has sponsored a number of Australia-China research symposiums, as well as supporting the bi-annual National CCS week events.

In addition, BCIA has supported the presentation of Australian R&D and technology on an international stage, both through academic presentations at conferences, and support for technology trade shows, including in Melbourne, Beijing and at the Clearwater Clean Coal Conference in the US.

Figure Source and Copyright Attributions

The sources and copyright attributions of the Figures used in this report are shown below. Where possible, illustrations have been drawn from non-confidential project reports. Otherwise, permission of the copyright holders has been sought.

The authors will be pleased to make good any omissions or rectify any mistakes brought to their attention at the earliest opportunity.

Figure	Source	Page
Figure 1	Brown Coal Innovation Australia financials	12
Figure 2	Brown Coal Innovation Australia financials	12
Figure 3	Brown Coal Innovation Australia financials	13
Figure 4	Brown Coal Innovation Australia financials	22
Figure 5	Allardice Consulting	25
Figure 6	Brown Coal Innovation Australia	25
Figure 7	Brown Coal Innovation Australia	26
Figure 8	© Kawasaki Heavy Industries	27
Figure 9	www.rrpowersystems.com/news/press-releases	31
Figure 10	© HRL Technology Pty Ltd	37
Figure 11	© HRL Technology Pty Ltd	37
Figure 12	© HRL Technology Pty Ltd	39
Figure 13	© HRL Technology Pty Ltd	39
Figure 14	© CSIRO	40
Figure 15	© CSIRO	44
Figure 16	www.microchap.info/fuel_cell.htm	44
Figure 17	© Manabendra Saha, University of Adelaide	47
Figure 18	© Manabendra Saha, University of Adelaide	47
Figure 19	© Manabendra Saha, University of Adelaide	48
Figure 20	© Monash University	50
Figure 21	© Monash University	51
Figure 22	© Monash University	51
Figure 23	Redrawn from: Saha C, Zhang S, Hein K, Xiao R, Bhattacharya S (2013). Chemical looping combustion (CLC) of two Victorian brown coals – Part 1: Assessment of interaction between CuO and minerals inherent in coals during single cycle experiment. fuel, 104: 262–274	52
Figure 24	© Monash University	53
Figure 25	© CSIRO	54
Figure 26	© CSIRO	56
Figure 27	© CSIRO	57
Figure 28	© CSIRO	57
Figure 29	Redrawn from: Beyad Y, Puxty G, Wei S, Yang N, Xu D, Maeder M, Burns R, Meuleman E, & Feron P (2014). An SO_2 tolerant process for CO_2 capture. International Journal of Greenhouse Gas Control, 31, 205–213	58
Figure 30	Reynolds AJ, Verheyen TV, Adeloju SB, Chaffee AL, Meuleman E (2015). Evaluation of methods for monitoring MEA degradation during pilot scale postcombustion capture of CO_2. International Journal of Greenhouse Gas Control 39: 407–419. Used with permission of Alicia Reynolds.	59
Figure 31	© CO2CRC	61
Figure 32	© CO2CRC	62
Figure 33	© CO2CRC	63
Figure 34	Westec Environmental Solutions, LLC. "Regenerative froth technology for unprecedented mass transfer in gas / liquid absorption" (www.wes-worldwide.com/_pdf/WES_White_Paper_9-21-2012.pdf)	64
Figure 35	© CO2CRC	65
Figure 36	© CO2CRC	66
Figure 37	© CO2CRC	66
Figure 38	© Lachlan Ciddor, Monash University	67
Figure 39	www.sintef.no/projectweb/matesa	68
Figure 40	© CO2CRC	69
Figure 41	© CO2CRC	71
Figure 42	© Hirra Azher, University of Melbourne	72
Figure 43	© Dr. Hans-Joachim Bayer (www.pipeline journal.net/sites/default/files/styles/ 540x300/public/news/PipelineConstruction.jpg)	74
Figure 44	© Allma (www.confectioneryproduction.com/11509/news/the-uses-of-chlorella-powder)	75
Figure 45	© CO2CRC	75
Figure 46	© Apple and Pear Australia Limited (www.apal.org.au/trends-carbon-stocks-apple-orchards)	76
Figure 47	www.climatechangeandsifi.wordpress.com/geoengineering/carbon-dioxide-removal-cdr/pyrolysis-of-biomass	76
Figure 48	© Hui-En Teo, University of Melbourne	77
Figure 49	© Alan Chaffee, Monash University	78
Figure 50	Redrawn and rearranged from an original © State Government of Victoria	80
Figure 51	© Kawasaki Heavy Industries (www.nippon.com/en/currents/d00167)	83

Brown Coal Innovation Australia Limited
Suite 420, 1 Queens Road, Melbourne 3004, Australia
Tel +61 3 9653 9601 | Fax +61 3 9653 9026
www.bcinnovation.com.au | ABN 51 141 273 261

BROWN COAL INNOVATION AUSTRALIA