

The unrealised potential of Victorian lignite: Exploring the net-zero emission opportunities





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Chairman's Foreword

Popular opinion would have it that as we “decarbonise the economy” there is no future role for the vast lignite deposits of Gippsland. A flawed, simplistic and general misinterpretation of the term decarbonise has led to a misunderstanding of the fundamental role of carbon as the essential underpinning of all life on our planet and in any future sustainable economy as carbon underpins the vast majority of our world's economic and social activity.

Whilst emitting carbon dioxide to the atmosphere is no longer acceptable, carbon itself remains the basis for food and clothing industries (plants and soils rely on the carbon / nitrogen cycle to maintain and improve food productivity), transport industry (carbon fibre and polymers are used in the manufacture of planes, cars, trains, trams, bicycles), construction industry (steel, glass, cement) and renewable energy (silicon for solar cells, carbon fibre and polymers for wind turbines, electrodes in batteries). We are in fact building our future economy on an increased use of these carbon-based products that we now import to avoid the inclusion of manufacturing emissions in our national accounts.

The 2020 COVID-19 shock to our economic system and the interruption of the supply chain demonstrates how important it is to be self-sufficient in many of these commodities, the availability of which we have taken for granted. Victoria has the opportunity to be at the forefront in developing many of these industries and with a significant carbon resource at its disposal, it is in a unique position compared to other parts of Australia.

The challenge for society is to recognise the fundamental role of carbon in our future and find the best pathway for production of goods and services whilst reducing emissions to the atmosphere. The challenge for Victoria is to make use of the vast carbon resource that it has in ways that contribute to the economic and social good of the state and country, whilst maintaining a healthy environment. There is a pathway to achieve this.

The task given to ACI in 2009 when it was established by the Victorian Government with support from the Commonwealth was to develop this pathway. ACI was tasked with investing in innovation to identify net zero emissions opportunities for new industries that would provide employment and wealth creation in the Latrobe Valley.

Through prudent investment of the funds that were provided by governments we achieved a four-fold multiplier in the value of our innovation program through co-investment with industry, universities and other organisations. The industry standard is to achieve a one to one matching of grant funds.

This investment has led to the identification of the commercial opportunities in low cost hydrogen production; low-cost carbon fibre production; activated carbon to replace imported material to clean drinking water, sewage and other industrial application; fertilisers in the form of humates and urea; and carbon dioxide capture technologies all of which are needed for our net zero emissions future.

ACI has developed the next generation of scientists and leaders through its innovative higher degree program, where in recent times, industry and research institutions have come together under ACI's purview to develop projects that tackle real world problems with the best and brightest intellects. Students work with industry partners on an industry nominated problem in the context of the requirements of a higher degree. Part of the program requires working in the industry partner's company.

This report provides an important reference point for the innovation investment made to underpin these future industrial opportunities and provides a direction for future research and commercialisation.

On behalf of the ACI Board, I wish to commend the work of our staff along with our government, industry and academic partners in developing these opportunities.

Gerry Morvell
ACI Chairman

CEO's Foreword

It has been seven years since I took up the privileged position of CEO to Australian Carbon Innovation – ACI (previously Brown Coal Innovation Australia – BCIA). During this time, and for the previous six years under the stewardship of Dr Phil Gurney, ACI has championed the sustainable utilisation of the single largest natural resource in the state of Victoria – lignite or brown coal. This, paired with the world class storage sites for carbon dioxide (CO₂), means that Victoria is uniquely placed to develop new industries and applications that can achieve net zero emissions or even be net negative.

This vast resource that underpinned the economic and social development of the state for 100 years remains a potential resource for low emission applications for the next 100 years if the opportunities available to the state are grasped.

Our lignite has characteristics that are the envy of the rest of the world: it has a low ash content meaning less waste; it is chemically complex which allows for multiple products to be produced (in contrast to black coal and some other lignites). It carries its own water supply, particularly important for the production of hydrogen into the future, and can be mined in such a way that continuous rehabilitation can occur to mitigate the impact of the mining process.

This report summarises the work done over the past 13 years and points the way to the opportunities for the future. I would like to acknowledge the key supporters over the years and apologise to any organisation inadvertently omitted.

- ▶ The Brumby Labor government who had the vision and passion to recognise the immense importance of the resource in Victoria and provided the initial funding and framework for ACI.
- ▶ To the many institutions and organisations over the years who have supported ACI both in the Latrobe Valley and across the country I would like to thank you for your support and guidance.

- ▶ Members over the years have provided not only funding that allowed the operations of the company to continue but also input into research programs and access to sites for key research. ACI could not have operated without their continued support and enthusiasm.
- ▶ The Australian National Low Emissions Council (ANLEC) was a critical partner in the formative years and provided funding support and expertise to ACI at the Board and research level.
- ▶ The many researchers who have contributed to this report are outstanding in relation to their academic rigour and in the quality of the work produced. This research should provide a springboard for the future development of the industrial and social development of the state.

I would like to take this opportunity to acknowledge the work of an individual, who more than anyone else, has demonstrated the intellectual rigour and commitment to scientific discovery that I would like to think ACI is known for. The Research and Investment Manager for BCIA / ACI since virtually from its inception, has been Dr David McManus. David has displayed a level of achievement that is rare in any organisation. I would like to express my personal thanks for his support and guidance over the years.

As I reflect on the accomplishments contained within this report, I do so with a sense of optimism for the future. It is my sincere hope that the insights gleaned from this body of work will serve as a foundation upon which future generations can build, fostering continued progress and innovation in the years to come. May the knowledge gained through our collective efforts pave the way for a brighter, more enlightened future for all.

Brian Davey
ACI Chief Executive Officer



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Abbreviations

ACALET	ACA Low Emissions Technologies Ltd	K	Potassium
ALDP	Advanced Lignite Demonstration Program (Victorian and Commonwealth Governments)	kg	Kilogram
ANLEC R&D	Australian National Low Emissions Coal Research and Development	kWh	Kilowatt hour
ASU	Air Separation Unit	LNG	Liquefied Natural Gas
BCIA	Brown Coal Innovation Australia	LSCF	Lanthanum Strontium Cobalt Ferrite
C	Carbon	LVPC	Latrobe Valley Post-Combustion Capture
Ca	Calcium	m ²	Metre squared
CCS	Carbon Capture and Storage	MEA	Monoethanolamine
CFD	Computational Fluid Dynamics	Mg	Magnesium
CLC	Chemical Looping Combustion	MILD	Moderate or Intense Low-oxygen Dilution combustion
CO	Carbon Monoxide	MJ	Megajoule
CO ₂	Carbon Dioxide	MRC	Micronised Refined Carbon
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies	Mt	Megatonne
CRC	Cooperative Research Centre	MW	Megawatt
CSIRO	Commonwealth Scientific and Industrial Research Organisation	MWh	Megawatt hours
DCFC	Direct Carbon Fuel Cell	N ₂	Nitrogen
DICE	Direct Injection Carbon Engine	N ₂ O	Nitrous Oxide
DME	Dimethyl Ether	NH ₃	Ammonia
ESA	Electrical Swing Adsorption	NO _x	Nitrogen Oxide
ETIS	Energy Technology Innovation Strategy (Victorian Government)	OHD	Oxidative Hydrothermal Dissolution
Fe	Iron	O ₂	Oxygen
GCCSI	Global Carbon Capture and Storage Institute	P	Phosphorous
GHG	Greenhouse gas	PCC	Post-Combustion Capture
GJ	Gigajoule	PDMS	Poly Dimethyl Siloxane
H ₂	Hydrogen	PF	Pulverised Fuel
H ₂ O	Water	pH	Potential of Hydrogen
H ₂ S	Hydrogen Sulfide	R&D	Research and Development
IEA	International Energy Agency	SECV	State Electricity Commission of Victoria
IPCC	Intergovernmental Panel on Climate Change	SO ₂	Sulfur Dioxide
JCOAL	Japan Coal Energy Center	SO _x	Sulfur Oxide
		T _{crit}	Critical Temperature
		TLDS	Tuneable Laser Diode Spectroscopy
		WES	Westec Environmental Solutions

Executive Summary

Inexpensive power generation from lignite, or brown coal, has been the economic mainstay of the Latrobe Valley for the past 100 years, and has been crucial to Victoria's economic development. Lignite is Victoria's largest natural resource, with 33 billion tonnes being economically recoverable. The proximity of lignite mines in the Latrobe Valley and geological CO₂ storage sites in Bass Strait gives Victoria a unique competitive advantage in a low-emissions future.

Research funded by Brown Coal Innovation Australia (BCIA), now known as Australian Carbon Innovation (ACI), with support from the Victorian and Australian Governments, has established that Victoria's unique lignite and CO₂ storage capacity provide unmatched opportunities for new industries and skilled jobs in the Latrobe Valley.

From 2009–2024, BCIA / ACI demonstrated a successful track record in management of lignite research, leveraging combined Victorian and Australian government funding of A\$15.9 million into a A\$57.5 million research portfolio. The projects funded were in three main areas.

1. Low-emissions power generation.
2. Improved CO₂ capture technologies.
3. Value-added products from lignite.

The research supported around 40 postgraduate students and involved 47 government, industrial and research partner organisations, from Australia, China, Japan, US, Germany, France, Denmark, Sweden and Belgium.

To date, ACI has also provided scholarships to twelve engineering undergraduate students at Federation University located in Churchill. These scholarships support local students to gain qualifications in skills needed as the region's economy transitions away from traditional forms of power generation.

Through its research portfolio, BCIA / ACI opened up new avenues for low-emissions commercial development of lignite. Perhaps the most significant field of research was in oxygen-blown entrained-flow gasification of lignite, which extended from fundamental laboratory research to support for the successful Hydrogen Energy Supply Chain (HESC) Pilot Project in 2020–2021.

ACI commissioned modelling that demonstrated the technical feasibility of building a net zero emissions lignite to hydrogen plant and would provide electrical generation support for the renewable energy transition. This would utilise existing technology as of today. Plans to commercialise the HESC process are under way, which would create a new export industry with potential to boost Victoria's Gross State Product (GSP) by a minimum of A\$1.1 billion per year over its 30-year life. This estimate does not include the value of spin off industries that would flourish if such a facility was built.

BCIA was also a major supporter of CO₂ capture research, supporting demonstrations of CSIRO and CO2CRC technologies at Loy Yang and Hazelwood power stations, in collaboration with international partners.



Source: © CO2CRC.

A spin-off company was created to commercialise the CO2CRC technology, and CSIRO's collaboration with IHI Corporation, Japan, advanced the commercialisation of new solvents and hardware for CO₂ capture. Energy savings of up to 40% were achieved under real-world conditions, significantly advancing the prospects for early deployment of carbon capture and storage (CCS) in Victoria.

Research on new products from Victorian lignite has identified some highly prospective technologies worthy of future development. Supplementation of agricultural soil with lignite and lignite extracts helps to boost soil health and crop productivity, and enhance the drawdown of CO₂ from the atmosphere, but long-term field trials are still required to quantify the benefits.

Victorian lignite can also be converted into a range of valuable carbon products, including monolithic activated carbon, carbon fibres, carbon quantum dots,

and graphene. These are low-volume products with high-value applications in 21st century industries, such as renewable energy, batteries, microelectronics and waste remediation. As such, they offer potential for new industries and job creation in the Latrobe Valley.

Looking further ahead, the anticipated implementation of CO₂ capture to limit emissions from heavy industry in Victoria will create a supply of purified CO₂ that can be transformed into valuable products.

The potential exists for local industries producing low-emissions construction materials and fuels, as well as food ingredients, fertilisers and industrial chemicals. These are valid opportunities, whether the CO₂ is sourced from lignite gasification, cement manufacture or directly from the atmosphere.

These opportunities are being actively developed in the US and Europe, but Australia is lagging in this regard.



There remains a need for forward-looking research to develop these opportunities and nurture the local entrepreneurs needed to take up the challenge of creating new low-emissions industries in Victoria.

Unfortunately, research funding to ACI has been discontinued by both the State and Australian Governments, forcing to wind up its operations as of 30th June 2024. It is hoped that this does not mark the end of lignite research in Victoria, but merely an interlude before a new phase of development is stimulated. Commercialisation of HESC would confirm that Victoria's unique lignite and CO₂ storage capacity have a crucial role to play in decarbonising the Japanese economy, and create a valuable new export industry for Victoria.

Hopefully this will lead to renewed appreciation of the value of lignite for Victoria's continued prosperity, and revived government support for new manufacturing opportunities based on lignite and captured CO₂. At that time, the opportunities identified by BCIA / ACI may be reappraised from a fresh perspective.

In the meantime, this report provides a comprehensive summary of all the projects funded by BCIA / ACI during the 2009–2024 period, with a list of key published references where further information may be found.

It serves as a testimonial to the dedication, commitment and ingenuity of the researchers and industrialists who participated in the research projects funded by BCIA / ACI. It is evidence of the commitment of many bright and talented scientists and engineers to tackle the challenge of climate change through low-emissions lignite technologies.



Introduction

A unique combination of natural resources in Victoria

Victoria is home to two key natural resources, which give it a unique competitive advantage. Firstly, there is an enormous reserve of lignite in the Latrobe Valley, located close to the ground surface with a thin layer of overburden. The 33 billion tonnes of economically recoverable lignite has been the economic mainstay of the Latrobe Valley for the past 100 years, and crucial to Victoria’s economic development.

The lignite contains up to around 60 percentage by weight moisture as-mined, restricting its use to near the mine site, so its price is relatively low and not subject to international commodity trading fluctuations. The lignite in the Loy Yang and Yallourn mines is a very pure source of carbon, containing less than 2% mineral impurities. When dried, the lignite is highly reactive and can be gasified at relatively low temperature with near-complete carbon conversion.

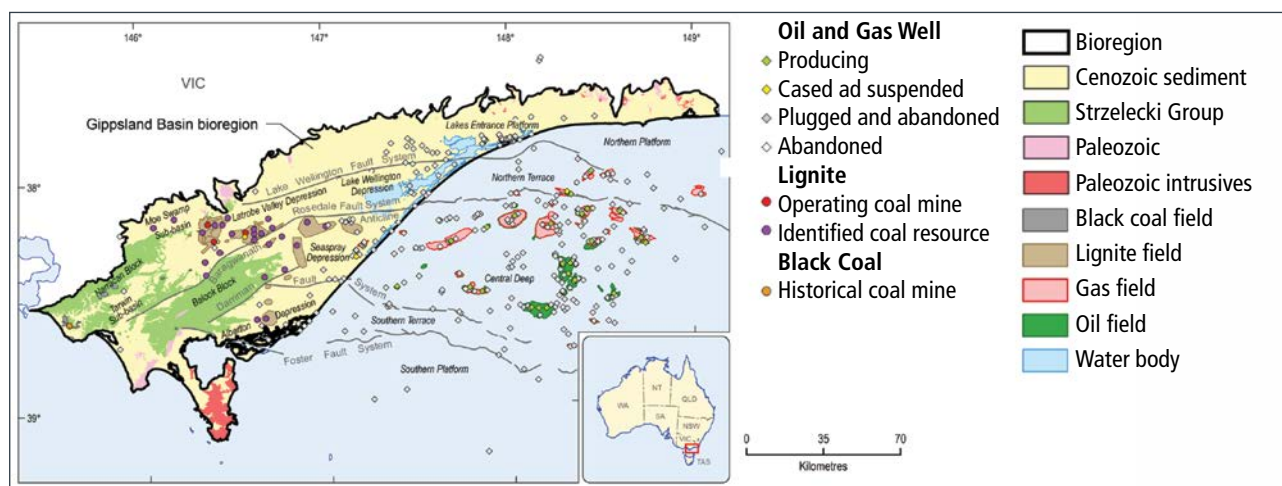
Secondly, the Latrobe Valley is about 100 kilometers away from high quality CO₂ sequestration sites, located in the near-offshore region of the Gippsland

Basin. The CarbonNet Project has established that the Pelican site has a ‘bankable’ CO₂ storage capacity of at least 125 million tonnes, enough to store at least five million tonnes of CO₂ per year for 25 years⁽¹⁾.

In addition, ESSO Australia recently announced the South Eastern Australia CCS Hub, which from 2024 will make existing infrastructure available to third party users, to store up to two megatonne per year CO₂ in the depleted Bream reservoir in Bass Strait. Transportation of CO₂ by pipeline from the Latrobe Valley and storage in the near-offshore Gippsland Basin is one of the lowest-cost options for CO₂ sequestration in Australia, estimated at less than A\$15 per tonne. This is because of the short transport distance and the high porosity and permeability of the storage formation.⁽³⁾

The combination of low-cost lignite as a carbon source and a massive carbon sink in Bass Strait⁽²⁾ provides unmatched opportunities for new industries and skilled jobs in the Latrobe Valley, and the potential for a major new hydrogen export industry.

Figure 1: Distribution of coal, oil and gas fields in the Gippsland region⁽⁴⁾



(1) Earth Resources. The CarbonNet Project. State Government of Victoria.

(2) Kemp S. South Eastern Australia CCS Hub. ESSO Australia. Powerpoint presentation to the Committee for Gippsland, 6 June 2022.

(3) CO2CRC. Australian Power Generation Technology Report. 2015.

(4) Australian Government, Bioregional Assessments. Coal and coal seam gas resource assessment for the Gippsland Basin bioregion, 22 June 2016.

High value products can be manufactured from Victorian lignite

Three of Australia's top four trading partners – Japan, the Republic of Korea and China – have made clear commitments to use clean hydrogen to decarbonise their energy systems. Japan is transitioning to a low-emissions 'hydrogen society', partly through import of low cost, clean hydrogen produced in Victoria by gasification of lignite with CCS.

Victorian lignite is seen as a highly prospective feedstock for inexpensive hydrogen production because it is relatively cheap to extract and, not being a traded commodity, is not subject to price fluctuations.

KPMG has estimated that the HESC project will boost Victoria's Gross State Product (GSP) by A\$1.1 billion per year over the 30-year life of the commercial plant. About A\$919 million of this growth will occur in Gippsland and the Mornington Peninsula.

In Gippsland, the construction phase is expected to create 192 FTE new jobs, with 304 FTE jobs during plant operation. In the Mornington Peninsula, construction will generate 1,231 FTE jobs and the operational phase 511 FTE jobs.⁽⁵⁾

The feasibility of this concept was demonstrated by the Hydrogen Energy Supply Chain (HESC) pilot project in 2020–2021. The governments of Australia and Victoria contributed A\$100 million to the A\$500 million project, with the rest invested by the Japanese Government and project partners.

The HESC Pilot Project produced hydrogen at 99.999% purity by gasification of lignite and lignite-biomass blends, which was liquefied and successfully transported to Japan on the Suiso Frontier, the world's first ocean-going liquid hydrogen carrier ship.

(5) Hopkins, P (2023). Hydrogen contributing to Gippsland economy. Latrobe Valley Express, 12th December 2023.

In addition to hydrogen, there is an array of advanced materials and agriculture inputs that can be manufactured from Victorian lignite.

- ▶ Carbon fibres
- ▶ Graphene
- ▶ Carbon quantum dots
- ▶ Activated carbons and activated carbon monoliths
- ▶ Humic acids
- ▶ Soil Improvers
- ▶ Ammonia

Further manufacturing opportunities arise through recycle of the CO₂ captured during lignite processing.

- ▶ Urea
- ▶ Carbonation of concrete
- ▶ Carbonation of fly ash
- ▶ Calcium and magnesium carbonates
- ▶ Glasshouse horticulture
- ▶ Supercritical CO₂ extraction of food ingredients and pharmaceuticals
- ▶ Ethanol
- ▶ Ethylene carbonate
- ▶ Lignin-based polyurethane
- ▶ Proteins for human and animal food

The Gippsland region has established energy, port, road and rail infrastructure, access to markets, a skilled workforce, and a community with a history of hosting major industries. Victoria has an opportunity to establish a high value-carbon based industry in the Latrobe Valley as lignite power generation is phased out. Carbon neutral or even carbon negative products from this valuable resource would create well paid, high-tech jobs, which can compensate for the loss of regional income.

Figure 2: Lignite is a highly prospective feedstock for manufacturing advanced materials and agriculture inputs in the Latrobe Valley⁽⁶⁾

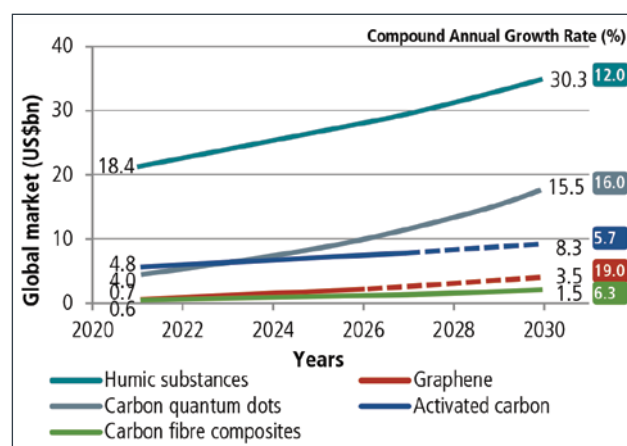


The unique features of advanced carbon materials mean that they are highly sought after, so global demand is growing (Figure 3).

Production technologies for some advanced carbon materials such as graphene and carbon monoliths are still in their infancy, and large-scale commercial supply is still some way off.

Victoria has an opportunity to leverage its lignite resource to secure position itself in these emerging markets and drive market development.

Figure 3: Global demand for advanced carbon materials is growing⁽⁷⁾



(6) Nous Group (2023). Net zero compatible uses for lignite. Report to the Committee for Gippsland.

(7) Nous Group (2023).

The need for low-emissions lignite research

Victoria's combination of high-quality lignite resource and geological CO₂ storage capacity creates numerous opportunities to create well paid, high-tech jobs in the Latrobe Valley. Recognising this opportunity, the Bracks Labor Government established Brown Coal Innovation Australia (BCIA) in 2009, as an independent, not-for-profit company with the mission to invest proactively in the development of technologies and people to broaden the use of lignite for a sustainable future.

In the same year, it co-invested with the Australian Government in the CarbonNet Project, to develop a commercial-scale CCS network in Gippsland. The aim of these initiatives was to enable new jobs and investment in the Gippsland region while supporting a net zero emissions economy in Victoria.

At the time when BCIA was established, the need to transition to a low emissions future was well understood, but it was not clear which energy sources could achieve this at lowest cost. Renewable energy looked promising but was intermittent, and breakthroughs in efficient battery storage were thought to be decades away.

On the other hand, the Victorian government had invested heavily in developing more efficient power generation options to utilise the State's massive lignite (brown coal) resource, firstly through the SECV and later through two Cooperative Research Centres.

Given the uncertainty about the best path forward, the most prudent response was to not pick winners, but to support development of a portfolio of promising new low-emission technologies. With lignite being Victoria's largest natural resource and a major generator of economic prosperity, it was unthinkable that it might one day become a stranded resource. To avoid this, BCIA's mandate included a requirement to investigate new opportunities for products derived

from lignite, to create alternative sources of revenue for the State.

BCIA adopted a portfolio management approach to low-emissions lignite R&D, spreading its investments across the three areas of low-emissions power generation, improved CO₂ capture technologies, and value-added products from lignite.

This rationale was reinforced by a 2017 study, conducted by Gamma Energy Technology and Red Vector, which showed how energy from lignite with CCS could complement renewables to provide the least cost pathway to deep decarbonisation.

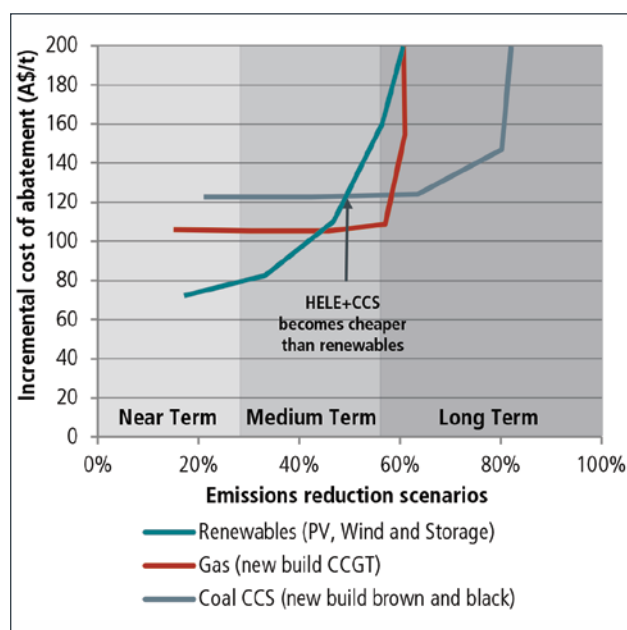
As shown in Figure 4, renewable energy is the cheapest form of energy during the early stages of decarbonisation, but is subject to the "law of diminishing returns". Early-stage renewable infrastructure can be installed with no or minimal new transmission infrastructure, and thus has the lowest incremental cost.

As the distribution system is expanded to access increasingly remote energy sources, the new transmission infrastructure becomes increasingly expensive and transmission losses become greater. The incremental cost of energy must be increased to make the projects financially viable.

At about 45% emissions reduction, new build combined cycle gas turbines (CCGT) become competitive with renewables. The addition of unabated gas to the system helps to displace coal and reduce emissions.

However, at around 55% emissions reduction, when all the coal plants have been shut down, all of the small CCGT plants will have to be fitted with CCS to achieve further emissions reduction, steeply driving up the energy cost. In contrast, energy from lignite or black coal power plants fitted with CCS, although initially more expensive, is the cheapest option at emissions reductions between 60% and 80%.

Figure 4: Cost of abatement pathways with increasing emissions reductions from 2017⁽⁸⁾



Australia is currently in the early stages of decarbonisation, where renewable energy has the biggest impact on energy prices. At this point in time, an emphasis on installing renewable energy makes sense, as it is currently the cheapest form of energy. However, this will not remain the case indefinitely. Over the long term, a hybrid approach offers the least cost pathway to deep decarbonisation.

In Victoria, the combination of inexpensive lignite and abundant CO₂ storage sites in Bass Strait means that low-emissions energy could be generated in the Latrobe Valley using integrated gasification combined cycle (IGCC) technology, without the need for new transmission infrastructure.

In fact, during the 1990s, the Victorian Government – through the SECV – developed an IGCC technology for power generation by fluidised-bed gasification of Victorian lignite, known as integrated drying gasification combined cycle (IDGCC)⁽⁹⁾. This technology was licensed for commercialisation to HRL when the SECV was privatised by the Kennett Coalition Government.

The feasibility of entrained flow gasification of Victorian lignite for IGCC was established for the Shell gasifier by the Monash Energy consortium, and for the EAGLE gasifier by J-POWER.

Pre-commercial IGCC demonstration of the EAGLE gasifier in combination with CCS has been under way since 2016 at the Osaki CoolGen Project in Japan⁽¹⁰⁾. This technology is expected to be used in the first phase of HESC commercialisation in Victoria⁽¹¹⁾.

Active government support is essential to success

The development of low-emissions products and power from Victorian lignite cannot occur without substantial, sustained support from both the Victorian and Australian Governments. This statement reflects the challenges associated with developing new technologies in Australia more broadly.

Australia does not have a good track record in commercialising new technologies. Part of the reason for this is that a funding gap occurs between early-stage university research (often funded by governments) and private sector support for commercialisation (Figure 5).

Good technologies often fail to progress because of a lack of funding for pilot-scale demonstration research. This can be attributed to the following.

1. A dearth of well-funded companies in Australia involved in new technology development.
2. Inadequate funding mechanisms to support pre-commercial demonstration trials.

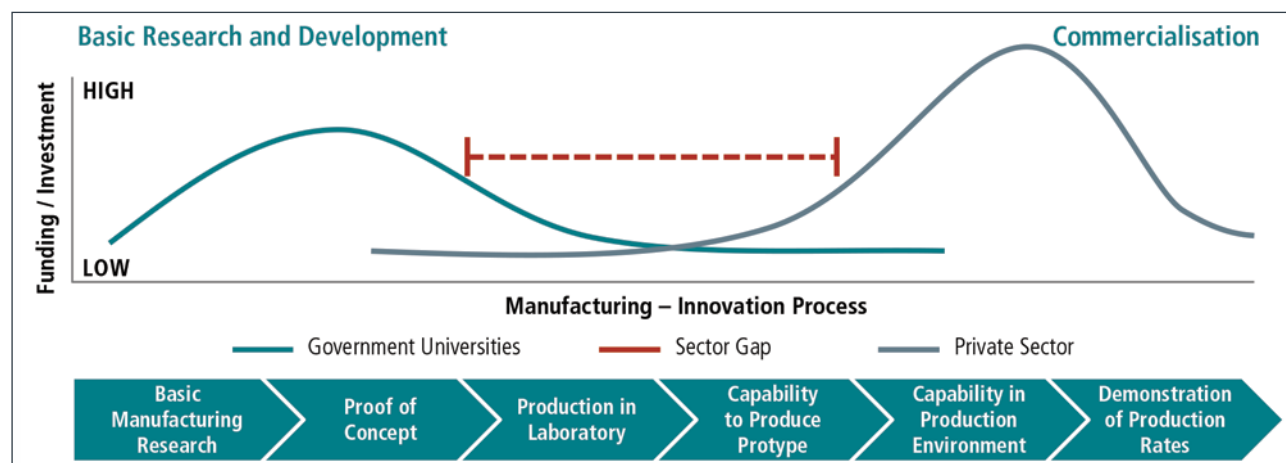
(8) Boston A, Bongers G, Byrom S & Staffell I (2017). Managing Flexibility Whilst Decarbonising Electricity - the Australian NEM is changing, Gamma Energy Technology Pty Ltd, Brisbane, Australia.

(9) Johnson TR, Campisi A, Anderson B, Wilson DM, Huynh DQ, & Pleasance GE (1993). Integrated carbonaceous fuel drying and gasification process and apparatus. International Patent Application WO 93 / 23500, 23 November 1993.

(10) © Osaki CoolGen Corporation (www.osaki-coolgen.jp/en/project/overview.html).

(11) © 2024 HESC (www.hydrogenenergysupplychain.com/about-hesc).

Figure 5: Investment gap in manufacturing innovation



(12) United States Government Accountability Office, Report to Congressional Requesters. Nanomanufacturing - Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health 2014. (www.gao.gov/products/gao-14-181sp).

Even if good technologies are successfully developed and demonstrated at pilot scale, they may still not progress to commercialisation if the market and social conditions are not favourable. Right through to the pre-commercial and commercial phases, the role of government is important. Government support can be both direct, in the form of grants, permitting, etc., and indirect, through the signalling of government attitudes towards further development.

Successive Victorian Governments have certainly made significant investments in low-emissions utilisation of Victorian lignite. The Energy Technology and Innovation Strategy (ETIS), launched by the Bracks Labor Government in 2005, committed more than A\$80 million over five years to support pre-commercial demonstration plants. This included funding for HRL Limited to trial a 400 MW IDGCC gasification facility, a large-scale lignite drying and CO₂ capture plant at International Power Hazelwood, a CO₂ storage trial by CO₂CRC in the Otway Basin. In 2010, the Brumby Labor Government committed A\$15 million of ETIS funding to BCIA.

The Advanced Lignite Demonstration Program (ALDP), funded by the Baillieu-Napthine Coalition Government from 2012, committed a further A\$90 million for projects to convert lignite into synthetic crude oil,

higher grade steel-making coal, briquettes, and hydrogen. For various reasons, none of these projects progressed to commercialisation.

The decline of lignite research in Victoria

Unfortunately, Australia's "climate wars" had a serious impact on the social licence for lignite developments. In 2010, the Rudd government shelved its Carbon Pollution Reduction Scheme proposal, which disincentivised CO₂ capture development. In 2011, the Gillard Labor government achieved passage of a world-leading package of measures to reduce carbon pollution and shift the Australian economy to a clean energy future. However, the relentlessly negative campaign led by Opposition Leader Tony Abbott led against the new "carbon tax" led to this policy being abandoned as well. In 2012, a proposal by HRL to build a new low-emissions power plant in Victoria, using the SECV IDGCC technology, was stymied by a Victorian Civil and Administrative Tribunal (VCAT) ruling.

These developments disincentivised government and industry investment in developing new uses for "dirty brown coal", and funding for research slowed to a trickle. In 2017, the Andrews Labor Government in Victoria signalled that it was still "open for business" for lignite development through its 'Statement on

future uses of brown coal'. Despite this, it adopted an attitude of passive, if not active, resistance to lignite development. The current position as follows.

"Since 2017 there have been significant shifts in the local and global context. The Victorian Government is taking action to achieve net zero emissions by 2045 and transition Victoria's energy sector to 100% renewables."⁽¹³⁾

In April 2019, BCIA adopted the new trading name of Australian Carbon Innovation (ACI), formalising its conviction that development of transformational new technologies that can underpin the development of new industries in the Latrobe Valley, helping to create the employment and prosperity that will be needed as the local power stations reach the end of their working life. However, there is no longer the same welcoming attitude towards new lignite projects, and promised investment from the Victorian government for further research failed to materialise.

The Andrews-Allen Labor government has abandoned the portfolio approach to developing low-emission technologies, and is focused entirely on renewables as the sole pathway to a low-emissions future. It assumes that renewables and batteries can be rolled out indefinitely across the state at uniformly low cost, ignoring the law of diminishing returns.

It ignores the potential for lignite with CCS to play a valuable role in providing system stability and deep decarbonisation, and it sees no value in new technologies to add value to the lignite resource. Research funding to ACI has been discontinued, forcing ACI to wind up its operations in 2024.

Accomplishments of BCIA / ACI

Throughout the period 2009–2024, BCIA actively managed a dwindling portfolio of projects on behalf of the State and Federal governments. Over time, the emphasis shifted exclusively toward value-added

carbon products, which was reflected in a change of the organisation's name to Australian Carbon Innovation (ACI) in 2019.

BCIA / ACI demonstrated a successful track record in management of lignite research, leveraging combined Victorian and Australian government funding of A\$15.9 million into a A\$57.5 million low emissions lignite research portfolio, involving nearly 50 local and international government, industry and research organisations, and supporting around 40 postgraduate students.

Since 2022, ACI has helped support skills development in the Gippsland region through scholarship support for students undertaking the Bachelor of Engineering (Electrical and Information Engineering) Honours Program at Federation University, Churchill. To date, twelve scholarships have been awarded. One of the recipients, Mr Simon Lea, wrote to ACI saying:

"Your belief in my potential and your investment in my future means a great deal. Thanks to your support, I was able to stay focused on my education and pursue my goals, which led to excellent results and receiving a course commendation."

Through its research portfolio, BCIA / ACI opened up new avenues for low-emissions commercial development of lignite. Perhaps the most significant field of research was in oxygen-blown entrained-flow gasification of lignite, which differs significantly from the air-blown fluidised-bed gasification research conducted by the SECV, and is particularly suited to production of value-added products.

BCIA funded a series of projects at Monash University, led by Professor Sankar Bhattacharya, that established the fundamental kinetics of lignite gasification under entrained-flow conditions. This work revealed that Victorian lignite is highly reactive under entrained-flow conditions, with essentially complete carbon conversion possible under relatively mild conditions.

(13) © Victorian Department of Energy, Environment and Climate Action (www.resources.vic.gov.au/geology-exploration/coal/use-of-brown-coal-in-victoria).

BCIA was an early supporter of the HESC concept through a 2011 feasibility study involving KHI and HRL Developments Pty Ltd. Successful pilot-scale demonstration of the HESC concept was demonstrated during the 2020–2021 HESC Pilot Plant trials at AGL Loy Yang power station.

ACI supported this demonstration, in collaboration with Federation University, through data analysis and simulation modelling of the pilot gasifier.

Subsequently, ACI and Monash University verified that both gaseous and liquefied hydrogen can be produced from Victorian lignite, along with all necessary electricity, with specific emissions intensity (SEI) less than the EU Taxonomy limit of 3.0 kg CO₂-e / kg H₂. The emissions intensity can be made net-negative by co-gasification with 1%–2% biomass.

Hydrogen produced from Victorian lignite would have a lower SEI than that from either natural gas or black coal, due to the very low fugitive methane emissions associated with Victorian lignite mining. This is another competitive advantage for Victorian lignite which has not been sufficiently recognised.

BCIA was also a major supporter of CO₂ capture research in Australia, with a focus on demonstration of improved capture efficiency using real lignite flue gas. Demonstrations of CSIRO and CO2CRC capture technologies were supported at Loy Yang and Hazelwood power stations, including amine solvent, membrane and solid adsorbent processes. Energy reductions of up to 40% were achieved, and measures to extend the solvent working life were identified.

The technology developed by CO2CRC, known as UNO MK3, has been commercialised through the Victorian CCS company KC8 Capture Technologies. Barry Hooper, Executive Director, acknowledged the support provided by BCIA during development of this technology:

“KC8 owes a lot to the support of ACI and its predecessor BCIA. The work done through multiple BCIA grants, while part of the CO2CRC, has been critical in allowing us to develop and grow our capture technology, UNO MK3, from bench scale to plant demonstration. The large scale demonstrations we are currently doing in the cement industry (Australia and overseas) and the power sector (in the US) has relied heavily on the foundational research and development funding BCIA and the Victorian Government has provided. Such local support has allowed us to grow a local company, support local research groups, such as The University of Melbourne, and to service the burgeoning CCS market globally from a Melbourne base.”

BCIA also undertook an important piece of work on behalf of CarbonNet, leading a study into the issues involved in designing a transportation pipeline for supercritical CO₂ using Australian Standard 2885, which was developed specifically for flammable gases. It was verified that AS 2885 is fit-for-purpose for CO₂ pipeline design, and guidance was provided on techniques to minimise the risk to as low as reasonably practicable, equivalent to the community expectations for natural gas pipelines.

The research supported by BCIA / ACI on value-added products from lignite identified new opportunities that are still at an early stage of development. The agricultural applications of Victorian lignite and humic products extracted therefrom were investigated through projects at both Monash and Federation Universities. Small-scale plant growth trials were promising, but obtaining statistically significant data from large-scale field trials is a multi-year challenge that has not yet been adequately addressed.

ACI-funded research demonstrated the potential to convert Victorian lignite into a range of valuable carbon products, including monolithic activated

carbon, carbon fibres, carbon quantum dots, and graphene. These are low-volume products with high-value applications in 21st century industries, such as renewable energy, batteries, microelectronics and waste remediation. As such, they offer potential for new industries and job creation in the Latrobe Valley. However, significantly more research is needed to develop these opportunities and nurture the local entrepreneurs needed to take up this challenge.

Taking this another step further, ACI also investigated opportunities to convert captured CO₂ into new value-added products. The potential exists for local industries producing low-emissions construction materials and fuels, as well as food ingredients, fertilisers and industrial chemicals. These are valid opportunities, whether the CO₂ is sourced from lignite gasification, cement manufacture or directly from the atmosphere. These opportunities are being actively developed in the US and Europe, but Australia is lagging in this regard.

A decision to commercialise the HESC project, and granting of all the necessary licences, would signal a new attitude toward the future of Victorian lignite. This would bring a more widespread recognition of the value of lignite for Victoria's continued prosperity, and potentially renewed government support for new manufacturing opportunities based on lignite.

It is hoped that the winding up of ACI does not mark the end of lignite research in Victoria, but merely an interlude before a new phase of development is stimulated. Commercialisation of HESC would confirm that Victoria's unique lignite and CO₂ storage capacity have a crucial role to play in decarbonising the Japanese economy, and create a valuable new export industry for Victoria.

Hopefully this will lead to renewed appreciation of the value of lignite for Victoria's continued prosperity, and revived government support for new manufacturing opportunities based on lignite and captured CO₂. At that time, the opportunities identified by BCIA / ACI may be reappraised from a fresh perspective.

Structure of report

This report provides a comprehensive summary of all the projects funded by BCIA / ACI during the 2009–2024 period, with a list of key published references where further information may be found.

It serves as a testimonial to the dedication, commitment and ingenuity of the researchers and industrialists who participated in the research projects funded by BCIA / ACI. It is evidence of the commitment of many bright and talented scientists and engineers to tackle the challenge of climate change through low-emissions lignite technologies.

The report is structured as follows. Section 3 provides an overview of BCIA / ACI's lignite research portfolio investment profiles, and the achievements of its skills development and network linkage programs.

Section 4 provides summaries of the various funded projects relating to low emissions value-added products from lignite. This includes lignite upgrading (dewatering and drying), agricultural applications of lignite, advanced carbon products (graphene, carbon fibres, activated carbon), and production of value-added products, particularly hydrogen, by gasification (including research on the fundamentals of entrained flow gasification with Victorian lignite).

Section 5 provides summaries of projects relating to CO₂ capture technologies, including solvent, membrane, and adsorption systems. Aspects of CO₂ pipeline design and alternative CO₂ storage processes are also included.

Section 6 provides summaries of projects on CO₂ recycling, a relatively recent area of investigation for ACI.

Section 7 provides summaries of projects on low emissions power generation from lignite, including improved combustion, and combustion in oxygen instead of air.

Overview of BCIA / ACI Portfolio

Technology Portfolio

BCIA was established by the Victorian government in 2009 as an independent, member-based, not-for-profit company with the mission *to invest proactively in the development of technologies and people to broaden the use of lignite for a sustainable future*.

BCIA was responsible for leveraging government funding for lignite research into a portfolio of activities that would support a least-cost transition to a low emissions future. The strategic objectives of BCIA were as follows.

- ▶ 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 lignite 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 the development of the next generation skills base to support industry and the continued development of major lignite 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 lignite into the future.
- ▶ Foster linkages and collaboration between all stakeholders – locally, nationally and internationally.

In November 2010, BCIA entered into a relationship agreement with Australian National Low Emissions Coal Research and Development (ANLEC R&D), a research funding initiative supported equally by the Australian government and the black coal industry through COAL21. In effect, BCIA became the lignite node of ANLEC R&D, providing access to a greater pool of funds for lignite research.

For almost the entire period of its operation, BCIA was ably guided by its Chairman, Mr Gerry Morvell, and the chair of its Research Advisory Committee, Dr John Burgess. Together with their other Board members, they established BCIA as a repository of lignite expertise in Victoria, as a trusted advisor to government, and as a transparent facilitator of collaborative research projects. BCIA never took an intellectual property position in any of the projects it has funded, functioning as an 'honest broker' to develop a research portfolio to meet the funding requirements of the Victorian government and ANLEC R&D.

Dr Burgess championed a strategic approach to research portfolio development, using a 'real options' approach to selecting projects based on time to maturation, risk profile and likely reward. Key to the success of this approach is a willingness to terminate projects that do not perform as expected. This was done on several occasions, allowing funding to be redirected to more prospective projects.

BCIA (ACI from 2019) benefited from the support of its member organisations, and in return provided assistance as required to help them derive benefit from Victoria's lignite resource. The membership of the following organisations is gratefully acknowledged.

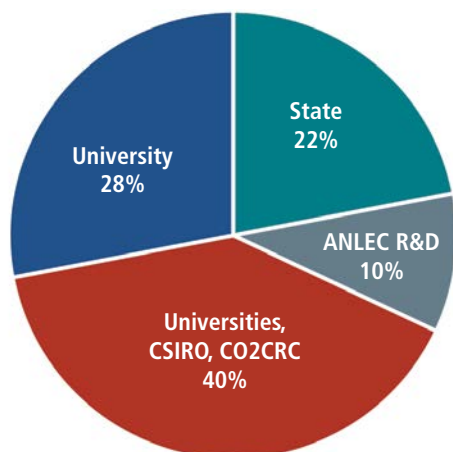
- ▶ State Government of Victoria
- ▶ Australian National Low Emissions Coal Research and Development
- ▶ Japan Coal Energy Centre
- ▶ Lignite Energy Council (North Dakota)
- ▶ CSIRO
- ▶ Monash University
- ▶ Federation University Australia
- ▶ Energy Australia
- ▶ HRL
- ▶ Environmental Clean Technologies

- ▶ Ignite Energy Resources
- ▶ Mantle Mining Corporation
- ▶ Steele Australia
- ▶ Exergen
- ▶ Greenpower Energy
- ▶ Coal Energy Australia (now Cleantech Energy Australia)
- ▶ Sustineri
- ▶ Omnia Specialities
- ▶ J-POWER

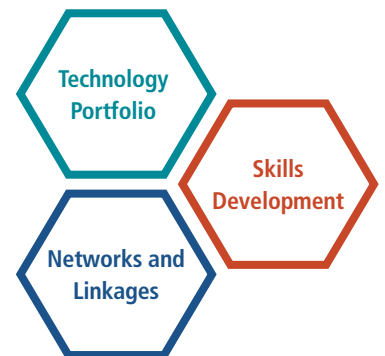
Overall, the Victorian government and ANLEC R&D provided combined funding of A\$19 million for low emissions lignite research, which was leveraged with industry, university and CSIRO funding into a research portfolio worth A\$60 million.

Nearly 50 local and international government, industry and research organisations are represented in this portfolio. The proportion of funding from State, Commonwealth and Industry is shown in Figure 6. In this regard, 'Commonwealth' includes all funding from ANLEC R&D, universities, CSIRO and CO2CRC.

Figure 6: Sources of funding for lignite research



Allocation of resources across three core areas



Technology Portfolio

A diversified R&D portfolio aimed at adapting leading clean coal technologies to increase the use and value of lignite in Australia, both for power generation and the creation of new products and export opportunities.

Skills Development

Establishment of research leader fellowships and PhD scholarship programs to enhance the future knowledge base and technical skills capability in the lignite sector.

Networks and Linkages

Creation of a membership base and securing links between the Victorian, Australian and international energy sectors, and facilitating the exchange of knowledge between industry, government and research communities.

Figure 7: Composition of lignite research portfolio

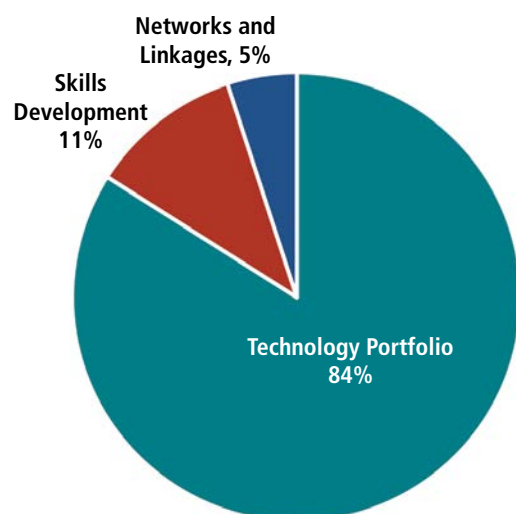


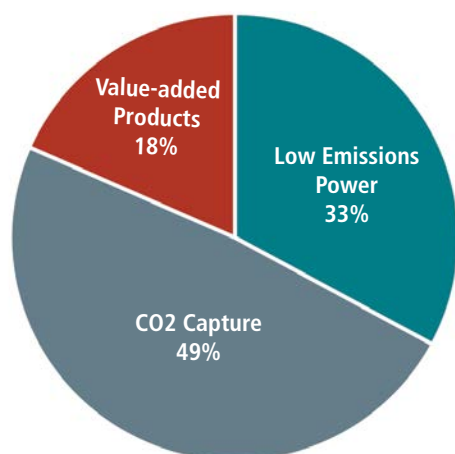
Figure 7 shows the proportion of funding allocated to each of these activities. Technology research and development also includes an additional skills development component, through the training of postgraduate engineers and scientists, and non-academic staff.

The technology research and development aspect of the portfolio comprises projects in three main topics:

1. Value-added Products
2. CO₂ Capture
3. Low Emissions Power

The proportion of total funding allocated to each of these topics is shown in Figure 8. In recent years, funding has been directed predominantly towards value-added products.

Figure 8: Allocation of funding to research project topics



This research portfolio has generated more than 650 publications and presentations. It has contributed to around 40 PhD student projects and two senior research leader fellowships. It has built strong international collaborations with Japan, US, China and Europe, and established a database of over 1,200 individuals representing more than 500 organisations worldwide.

Skills Development

BCIA's skills development program represents a strategic investment to secure the expertise required for new low-emissions lignite 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 lignite 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 lignite 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.

Professor Hein's Research

Leader Fellowship was Australia's first joint industry-university professorial appointment in lignite-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 lignite 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-focussed 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 United States, 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 CO₂ capture from Victorian lignites' and 'Development of entrained flow gasification technology with lignite 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 lignite 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, J-POWER, 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 lignite 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 lignite. He has previously worked with CSIRO and BHP Research and has developed expertise in a broad range of research

areas relating to Victorian lignite: 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 CO₂ capture, and catalysts for CO₂ conversion into valuable products. Professor 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, Professor Chaffee has trained young scientists and engineers in the specialist skills required for the development and sustainable use of Victorian lignite. His research

program sought to address issues that impede the broader use of Victorian lignite and to facilitate its application in new markets, along four major themes.

- ▶ Understanding spontaneous combustion of dried lignite.
- ▶ Transformation of lignite into high value products.
- ▶ Lignite and lignite-derived materials as adsorbents.
- ▶ CO₂ 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 CO₂ 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 lignite is heterogeneous, which has compromised comparisons between prior studies. A significant new finding from Prof. 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 lignite is potentially a low-cost carbonaceous precursor to a variety of higher value products. Prof. 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 lignite in comparison with various forms of biomass led to new understanding about the chemical mechanisms involved.

Other work identified a novel way of extracting lignite using metastable ionic liquids formed from the condensation of CO₂ and various low molecular weight amines. In certain cases, these ionic liquids can extract as much as 70% of the lignite. The ionic liquid can be recovered as its constituent gases by simply heating the liquid to a mild temperature (c.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 CO₂ capture, the group developed a composite amine / silica material that has been patented. This material is prospective for adsorption-based CO₂ capture from flue gas streams using a vacuum-swing adsorption process configuration. Other materials were identified that have potential for CO₂ capture from synthesis gas at elevated temperatures in a pre-combustion context.

Active carbons prepared from Victorian lignite 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 CO₂. The electrical conductivity of carbon gives them a distinctive capability for use in electrical swing adsorption, which was the subject of a study with a consortium of European industrial and academic collaborators.

The direct conversion of CO₂ into commodity chemicals, e.g., methanol, by gas phase heterogeneous catalysis was investigated. The group used conventional catalysts as well as novel ones based on a relatively new class of materials known as metal-organic frameworks. (Metal-organic frameworks are also prospective for CO₂ capture).

The fellowship 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.

During the period of his Fellowship, Prof. Chaffee was involved in 20 different research projects. BCIA funded eight. Prof. Chaffee contributed to 26 conference presentations, 92 conference papers and 67 peer-reviewed journal publications. He was responsible for the supervision of seventeen higher degree students and sixteen undergraduate research projects. In addition, he hosted twelve international exchange students, from Japan, China, Canada, Germany and Spain.

The following are some of the significant developments arising from this research.

- ▶ Improved understanding of the process of spontaneous combustion in lignite.

- ▶ Development of valuable intellectual property relating to production of a blast furnace coke substitute from Victorian lignite.
- ▶ Solubilisation of lignite using recyclable, distillable ionic liquids.
- ▶ Development of metal-organic frameworks and other novel CO₂ sorbents.
- ▶ Development of modified activated carbons from Victorian lignite for capture of CO₂ and storage of hydrogen.
- ▶ Contribution to understanding the degradation of amine sorbents and solvents during post-combustion CO₂ capture.

Prof. Chaffee made a substantial contribution to the training of a new generation of scientists and engineers, and to the creation of new products from lignite and new technologies for capture of associated CO₂ emissions. He enhanced Victoria's international research linkages and maintained Monash University's reputation as a leader in lignite 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 CO₂. *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 CO₂. *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 around forty higher degree students. BCIA has provided direct financial support for sixteen PhD scholars, with the remaining higher degree students involved in BCIA's research program.

Of the directly supported students, BCIA provided six fully funded scholarships in 2010–2011, as listed in Figure 9.

Figure 9: 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 / ACI has also supported seventeen supplementary PhD scholarships, providing funding additional to university and Australian postgraduate scholarship awards.

Figure 10: 2013–2014 Round BCIA PhD scholarship recipients

PhD candidate	Host institution	Project title
Mr Rahul Chowdrey	Federation University	Degradation of amine solvent by reactions with metal surfaces and flyash 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
Mr Anushan Kulendran	Federation University	Use and recycling of Potassium in the production of advanced carbon products
Mr Nauman Ahmad	Monash University	Advanced bio-oil separation for the production of furfural from biomass
Mr Baiqian Dai	Monash University	Coal blending combustion and gasification – the mixing of beneficiated brown coal and high-rank bituminous coal
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
Ms Wei Lin Ng	Monash University	Synthesis of Ethylene Carbonate via the direct catalytic carboxylation of CO ₂ with Ethylene Glycol
Mr Biplob Saha	Monash University	Optimising fertiliser formulation utilising brown coal, biomass wastes, and conventional fertilisers
Mr Amir Sohail	Monash University	Sulphur removal from waste tyre pyrolysis oil using active carbon monoliths
Mr Jingwei Wang	Monash University	Development of advanced catalysts for furfural production from catalytic flash pyrolysis of biomass

PhD candidate	Host institution	Project title
Mr Tao Xu	Monash University	Development of oxygen-blown entrained glow gasification for use with a range of Victorian brown coals
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
Ms Jiahui Li	Swinburne University	3D printed fibre-reinforced composites with nanomaterials
Mr Rahinul Mazumder	Swinburne University	Production and applications of layered graphene sheets from Victorian lignite
Mr Manabendra Saha	University of Adelaide	Experimental and computational study of solid fuels under MILD combustion
Mr Hiep Thuan Lu	University of Melbourne	The impact of impurities on the performance of cellulose acetate membranes for CO ₂ separation

As well as the above direct funding of PhD students, BCIA's research and fellowship funding has supported PhD, masters and post-doctoral research projects through its technology R&D program, as shown in Figure 11.

Figure 11: BCIA's research and fellowship funding contributions

Researcher	Current status	BCIA project involvement
Dr Trent Harkin	Post-doctoral Fellow	CO ₂ CRC'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	
Dr Emily Perkins	Post-doctoral Fellow	Improved Handling Properties of Lignite-Based Products.
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.

Researcher	Current status	BCIA project involvement
Mr Qinghu Zhao	PhD Student	Development of Carbon Monoliths for Capture of CO ₂ by Electrical Swing Adsorption.
Mr Andrew Hood	PhD Student	Enhanced humic acid extraction from Victorian lignite.
Dr Sobhan Fakhrhoseini	Post-doctoral Fellow	Carbon fibres from Victorian lignite.
Dr Mamum Mollah	Post-doctoral Fellow	
Dr Mahmud Kibria	Post-doctoral Fellow	Net zero hydrogen and ammonia from Victorian lignite.
Mr Nima Baghbani	PhD Student	Lignite amendments for sustainable soil development.
Dr Cedar Martin	Post-doctoral Fellow	Nex generation plant bio-stimulant from Victorian lignite.
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	

Undergraduate Scholarships

The Bachelor of Engineering (Electrical and Information Engineering) Honours Program was introduced by Federation University at its Gippsland Campus from 2022 to help address a serious shortage of qualified electrical engineers in the region. The program was developed in response to industry calls to address the skills shortage as the region's economy transitions away from traditional forms of power generation.

To encourage enrolment in this degree, ACI has offered up to eight scholarships per year of A\$7,000 each for local students to continue their studies in the Gippsland region.

Six scholarships were awarded in 2022, three in 2023, and three in 2024.

Networks and Linkages

BCIA's Networks and Linkages program created relationships with local, national and international groups working on environmentally responsible uses of lignite. The program encompassed both formal links through membership arrangements and funded research collaborations, and 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 undertook a range of knowledge sharing activities such as BCIA's Perspectives newsletter and open research seminars.

BCIA / ACI established a reputation as a trusted source of information on lignite technology development, and was successful in securing significant interest in its lignite research activities. Over the period covered

by this report, 47 government, industrial and research partner organisations were directly involved in the R&D activities, including organisations from Australia, China, Japan, US, Germany, France, Denmark, Sweden and Belgium.

Formal linkages

CO2CRC (member 2009–2015)

BCIA has a strong focus on carbon capture activities as applied to lignite. BCIA was a full member of the CO2CRC from 2009 to 2015, at which point CO2CRC changed its focus to look primarily at geological storage, rather than capture, of CO₂. BCIA was the only member of CO2CRC specifically representing lignite interests, and as a member of the Program Advisory Committee, provided input into research programs and direction.

BCIA's membership of CO2CRC granted the company access to results and outcomes of the CRC's work. Building on the core work program of CO2CRC (funded through CRC funding including Commonwealth and member contributions), BCIA funded additional programs to support lignite-specific activity, including the development and operation of pre- and post- combustion capture facilities operated by CO2CRC at two sites.

JCOAL (reciprocal membership, 2011 onwards)

The Japan Coal Energy Center (JCOAL) is Japan's main industry group focussed 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 supported JCOAL in their studies around Australian coals, and JCOAL members were actively involved in BCIA's program of R&D, including research on carbon capture and hydrogen production from lignite.

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 or 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 lignite, 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 organised information sharing sessions for LEC and BCIA members on progress in the two regions. Through the LEC, BCIA accessed expertise at the Energy and Environment Research Center (EERC) at the University of North Dakota. With BCIA support, the EERC brought its coal gasification course to Australia for the first time, and BCIA benefitted from access to R&D on coal gasification and hydrogen separation technologies.

IEA Clean Coal Centre

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.

BCIA worked with the IEA CCC to suggest two reports that were undertaken by the centre, looking at low rank coals and direct injection carbon engine (DICE) technology. BCIA also participated in the IEA Conference on Clean Coal Technologies in 2015, presenting a paper on Australian progress in lignite developments.

Global Carbon Capture and Storage Institute

BCIA was a member of the Global Carbon Capture and Storage Institute (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 greenhouse gas emissions.

The GCCSI supported and publicised two of BCIA's reports, the first being the Novel CO₂ capture taskforce report which focussed on non-geological methods for CO₂ sequestration, and the second being "Dispersion modelling for CO₂ pipelines: Fit for purpose and best practice techniques". GCCSI hosts both of these reports in its knowledge repository, and also ran a webinar on the dispersion modelling report to share the outcomes with the global community.

Chronology of Major Network and Linkage Activities Supported

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

2017

- ▶ Facilitated a Value Engineering Workshop for Cleantech Energy Australia
- ▶ Facilitated a workshop on production of blast furnace coke from lignite
- ▶ Attended 9th Carbon Dioxide Utilisation Summit, Reykjavik, Iceland
- ▶ Presentation to Deputy Vice Chancellor Research and Investment and Federation University management team – BCIA and future directions
- ▶ Presentation to AGL management team – opportunities for alternate use of lignite
- ▶ Presentation to Latrobe Valley New Energy Forum – opportunities for alternate use of lignite
- ▶ Presentation to Latrobe Valley Authority (LVA) on options for the future use of lignite
- ▶ Presentation to Latrobe City Council (LCC) on support for alternate lignite products
- ▶ Presentation to LV Mine Rehabilitation Commissioner and team on options for the utilisation of lignite in mine rehabilitation

- ▶ Presentation to MLC Harriet Shing for support for ongoing use of lignite
- ▶ Panel member at Deakin University energy seminar
- ▶ Attended LVA forum on alternate energy technology for the Latrobe Valley
- ▶ Presented to LCC on new advances in lignite technology
- ▶ Attended Regional Development Victoria (RDV) forum on new lignite technology
- ▶ Presented at Australian Academy of Technological Sciences and Engineering (ATSE) forum on new lignite technology opportunities
- ▶ Attended ARC forum on investment opportunities in Canberra
- ▶ Presented to Federal Govt Resources Department on the opportunities for lignite in Victoria
- ▶ Attended CO2CRC Carbon Capture conference.
- ▶ Presentation to the Resources Minister of Victoria on future options for lignite
- ▶ Attended State government forum to discuss opportunities for KEPCO and JCOAL in Victoria

2018

- ▶ BCIA and Federation University hosted a public seminar on “Carbon to Products” at Traralgon
- ▶ Presented to Federal government Resources Department – opportunities for lignite development and the need for Federal support
- ▶ Briefed opposition Shadow Energy Minister in Victoria on future lignite opportunities
- ▶ Attended RDV roundtable on the Transition from Coal
- ▶ Attended the Advanced Manufacturing Growth Centre (AMGC) funding opportunities workshop
- ▶ Attended Vic govt sponsored workshop with KEPCO from South Korea on opportunities in the Latrobe Valley

- ▶ Presented to Gippsland Regional Executive Forum on opportunities of lignite for Gippsland

2019

- ▶ Presentation on ‘Next generation carbon products from Victorian lignite’ at Carbon Innovation Conference 2019, Swinburne University
- ▶ ACI and Federation University hosted a public Hydrogen Forum at Federation University, Churchill
- ▶ Presented to the Federation University Research Forum on research opportunities for lignite
- ▶ Briefed the Chief Scientist for Australia (Alan Finkel) on lignite opportunities and emerging technology
- ▶ Presented to a Japanese delegation on opportunities to invest in lignite-based technologies
- ▶ Briefed advisor to Minister Pakula (Industry Vic) on the role lignite could play in the energy transition
- ▶ Keynote speaker at the Annual Lignite Energy conference in North Dakota, on ‘Future directions for lignite in Victoria’
- ▶ Briefed Australian Renewable Energy Agency (ARENA) management group on the role of lignite in a low emissions future

2020

- ▶ Presentation to the Soils CRC on the opportunity for lignite in mine rehabilitation
- ▶ Presentation to National Energy Resources Australia (NERA) on the need for a regional hydrogen cluster
- ▶ Attended the DVIR&I Federation University Energy Forum

2021

- ▶ Attended NERA foundation workshop in Gippsland
- ▶ Interview with WIN TV on the opportunities for lignite in Gippsland
- ▶ Attended the LCC Energy Review Forum as panel member

- ▶ Presented to the AGL Community Dialogue group meeting
- ▶ Presented to Gippsland Rotary meeting on the future of lignite
- ▶ Participated in a roundtable – New Energy Industrial Hubs; Barriers and Opportunities
- ▶ Represented ACI as Vice Chair of an Expert Panel on the coal preparation phase of the HESC project
- ▶ Participated in Federation University Electrical Engineering course launch

2022

- ▶ Presentation on ‘Options for net zero hydrogen and ammonia from Victorian lignite’ at “The Energy Transition – The Role for Sustainable Carbon” conference in Sardinia, Italy
- ▶ Presentation on ‘Hydrogen from Lignite – A modelling approach’ at “Positioning Hydrogen 2022” conference in Melbourne
- ▶ Facilitated a stakeholder meeting on ‘Common ground for lignite-based projects’ in Melbourne
- ▶ Presentation to the public hearings on the closure of the Hazelwood power station
- ▶ Presentation to the Committee for Gippsland (C4G) on opportunities for lignite
- ▶ Presented at forum run by LV Mine Rehabilitation Authority on the opportunities for lignite in mine rehabilitation
- ▶ Sat on Expert panel on Gippsland Clean Energy Forum sponsored by C4G
- ▶ Participated in Gippsland Clean Energy Conference
- ▶ Participated in CarbonNet Community Reference Group
- ▶ Participated in Gippsland Regional Skills Network – Energy Forum

- ▶ Participated in a Workshop with Department on Prime Minister and Cabinet committee on Net Zero Taskforce

2023

- ▶ Key note presentation at Ramaco ‘Products from Carbon’ conference in Sheridan, Wyoming US
- ▶ Participated in RDV ‘Lignite Entrepreneurial Discovery Workshop’ in Morwell
- ▶ Attended Federation University Foundation Scholarships presentation event in Churchill
- ▶ Attended workshop on ‘Hydrogen RT&D and Asset Management in Gippsland’, Federation University, Churchill
- ▶ Presentation to LVA on opportunities for hydrogen production in Gippsland
- ▶ Roundtable with ARUP Engineering Group on the opportunities for Industrial Transition and Regional Innovation
- ▶ Attended EnLit Australia conference on Energy Transition
- ▶ Presented to eight Rivers US delegation on the opportunities for lignite in the low emission power generation sector
- ▶ Participated in Cooperative Industry Workshop LV
- ▶ Participated in the Festival of Big Ideas – Panel member on energy options for the LV
- ▶ Participated in Lignite Energy Council Board meeting as Board member – presentation on Victorian activities
- ▶ Panel member at workshop on ‘Transforming Gippsland; Life beyond the Coal mines’

Knowledge sharing

One of BCIA's main communications channels was a regular electronic newsletter 'Perspectives on Brown Coal' (Perspectives), was distributed to an extensive stakeholder database (in excess of 1,000 subscribers) and also published on its website. The newsletter was established in 2010, with 20 electronic and four print issues of the newsletter had been produced. The newsletter was well received and supported by stakeholders, and achieved a response rate of three times the benchmark rate for this communication channel.

BCIA also initiated a range of seminars and events to share the research findings, update the community on progress towards novel uses of lignite, and assist in career planning for students. BCIA organised a number of workshops to assist in developing targeted research strategies in areas of common interest for its stakeholders.

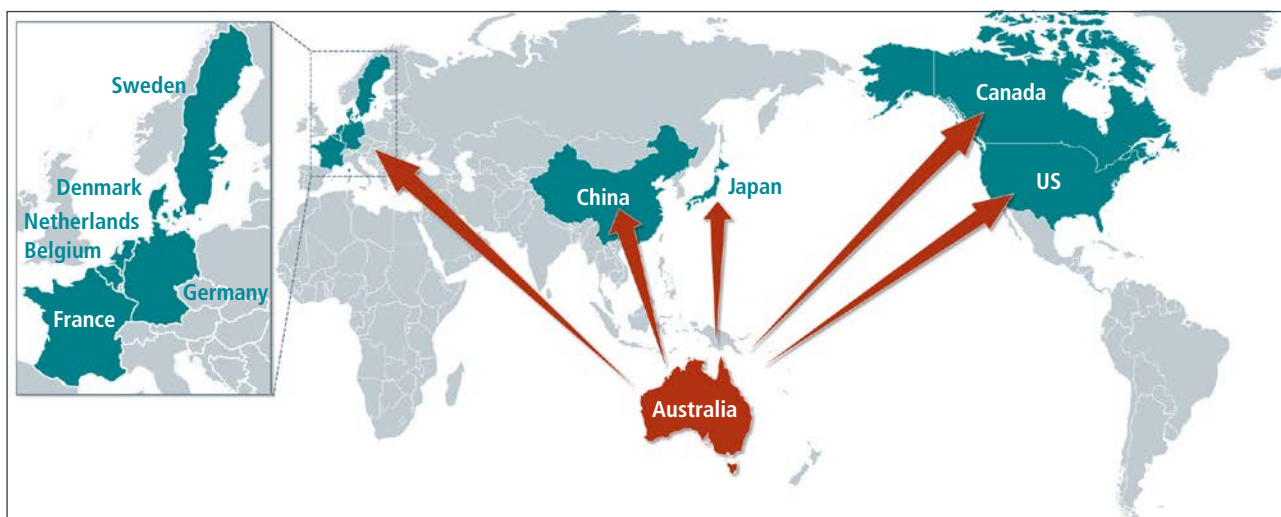
On average, BCIA supported three to four major events a year up to 2015, after which lack of funding became prohibitive. The largest single event was the lignite to products seminar held in 2013, which was attended by over 120 delegates, including representatives from Europe, India and US.

BCIA also supported bringing major national and international coal research conferences and events to Melbourne. BCIA representatives participated 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 sponsored a number of Australia-China research symposiums, as well as supporting the bi-annual National CCS week events. In addition, BCIA 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.

Another form of knowledge sharing undertaken by BCIA was the commissioning and/or preparation of reports for the benefit of its members. The aim was to provide pre-commercial state-of-the-art information to inform future research priorities. Topics included oxygen-blown gasification, the economics of lignite-to-chemicals, applications of lignite in agriculture, and next generation carbon products.

Figure 12: BCIA sponsored workshops with groups in Europe, Asia and the US



Low Emissions Value-Added Products From Lignite

Lignite Upgrading

Utilisation of Victorian lignite in applications at any great distance from the mine site is a challenge. The freshly-mined lignite contains about two-thirds water, making it expensive to transport. The dried lignite 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 lignite for anything other than local power generation. The development of economical new uses for Victorian lignite 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 lignite upgrading techniques.

Novel lignite dewatering techniques

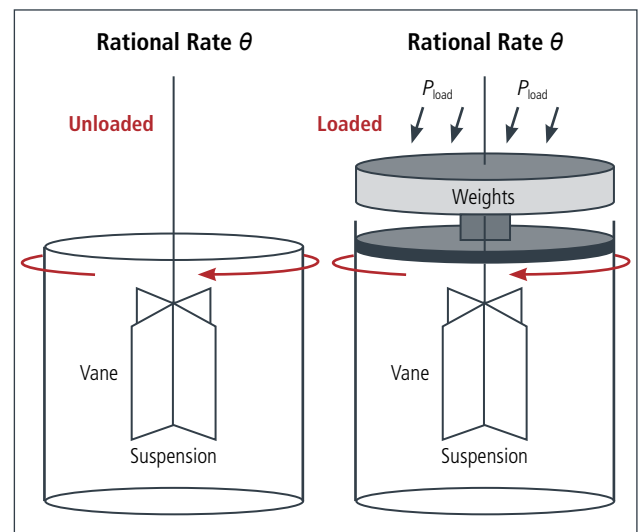
The high energy associated with drying Victorian lignite is a major impediment to its broader use. Researchers at the University of Melbourne have developed a new method for economical dewatering of lignite, which involves compression of the coal between rollers rotating at different speeds. It has been 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 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 13). 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 13: Measurement of combined shear and compression



Ms Teo chose to work initially with a well characterised experimental system before moving on to lignite. 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 lignite has not yet been demonstrated.

Spontaneous combustion propensity of upgraded lignite

The vast majority of lignite 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 lignite has long been of interest.

Handling and transport of lignite 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 lignite briquettes and char was reviewed in 1988⁽¹⁴⁾ and 1991⁽¹⁵⁾.

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 lignite.

In order to improve the understanding of the processes involved in spontaneous combustion, BCIA supported a study at Monash University led by Prof. 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 lignite on its spontaneous combustion behaviour.

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 14.

Figure 14: Treatments applied to lignite samples

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,

(14) 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.

(15) 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.

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 lignite. 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.

Lignite drying status report

In 2018, BCIA was commissioned to prepare a 'Lignite Drying Status Report' for the Electric Power Research Institute (EPRI), an independent, non-profit organization in the United States. EPRI conducts research, development, and demonstration projects on electricity generation, delivery, and use, for the benefit of the public.

The "Lignite Drying Status Report' gave an overview of the lignite drying technologies that are currently available and offered by commercial vendors. It also included some novel technologies that are not yet at commercial offer stage. Two of the novel technologies had been the subject of trials with lignite during BCIA-funded research. These are highlighted in the following sections.

Superheated steam drying technology

Keith Engineering, based in Sydney, specialises in the design, manufacture and installation of processing equipment for the rendering and abattoir industries. Keith Engineering is part of the Pinches Group, based in Melbourne, which owns and operates a number of manufacturing and engineering supply companies.

Keith Engineering has developed a process called Airless Drying, which utilizes direct heat rotary drum drying with superheated steam as the drying medium instead of conventional hot air.

The major benefit of 'airless drying' is that superheated steam has heat transfer properties superior to air at elevated temperatures. The removal of oxygen from the drying process reduces odour and minimises the risk of explosion and fire.

Keith Engineering has constructed a pilot scale superheated steam rotary drum dryer system, shown in Figure 15. The dryer has a drum diameter of 0.37 m and a length of 3.0 m, with an evaporation rate of 125 kg per hour.

Figure 15: Pilot scale superheated steam rotary drum dryer system



BCIA supported a research project at Monash University, led by Associate Professor Andrew Hoadley, to investigate the potential of this drying technology. Loy Yang lignite with a moisture content of 61% was dried to 11% in 30 minutes. Superheated steam at 230°C was passed through the dryer co-currently with the lignite.

After exiting the dryer, the superheated steam was passed through a heater to boost the temperature back to 230°C, and returned to the drum through the action of a fan. A proportion of the steam, equal in mass to the amount evaporated from the lignite, was removed from the system via a condenser. More than 90% of the moisture was removed from Loy Yang lignite in a safe and energy-efficient manner.

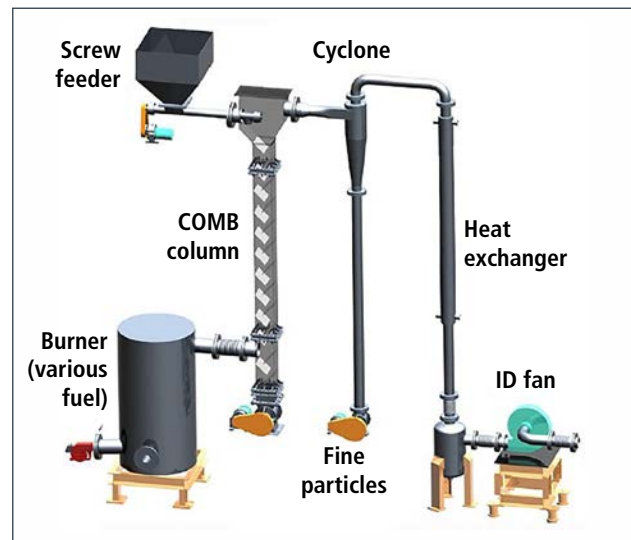
Monash University researchers subsequently utilized this system to produce a slow release nitrogen fertiliser by simultaneous granulation and drying of urea with lignite.

Counter flow multi baffle (COMB) drying technology

The Korean Institute of Energy Research (KIER) has developed a new Counter Flow Multi Baffle dryer (COMB) drying technology, which uses low temperature waste flue gas (rather than high temperature steam) in an efficient counter-current design.

The COMB dryer consists of a vertical series of inclined baffle plates which increase the residence time and mixing of the lignite as it descends. As shown in Figure 16, the solids and gas flow counter-currently, maximising the driving force for drying over the length of the column.

Figure 16: Schematic view of COMB drying system



The shape and arrangement of the inner baffles can be adjusted to maximise contact efficiency, and the residence time of the solids can be adjusted between three to ten minutes. The COMB drying technology is both simple and flexible in operation.

KIER has established a one tonne per day pilot plant COMB dryer at the Dangjin power plant owned by the Korea East-West Power Company. It is operated by Samyang Eco-energy Co., with research support provided by KIER. The COMB drying plant uses hot flue gas for drying, to mimic the low temperature flue gas widely available as waste heat in power stations.

In 2018, BCIA funded a preliminary investigation of drying Victorian lignite using the COMB drying technology. The project, 'Evaluation of COMB dryer technology with Victorian lignite', involved sending a research fellow from the Department of Chemical Engineering, Monash University to Dangjin, to observe the operation and performance of the COMB plant while drying Victorian lignite.

The pilot plant trials proved to be successful, showing that high-moisture (c.60%) lignite can be dried to a moisture content of 6% to 15%, depending on particle size and residence time. A preliminary process simulation model was developed, to be used in the design of a larger system.

During this time, KIER completed construction of a 5 tonnes per day facility, located at the outskirts of Daejeon, Korea. In 2019, ACI funded a second project with Monash University, 'Larger scale testing of COMB drying technology with Victorian lignite, to test the COMB dryer at larger scale and over a longer duration in the new facility.

Each of the tests involved four to eight hours of steady state drying under continuous feeding mode. Residence time was estimated around two minutes. Particle size of the raw coal was <10 mm, inlet gas temperatures 220°C and 270°C and two different gas flow rates were used during the tests. There were no problems in feeding raw coal to the COMB dryer unit. The dried coal came out in two locations – fine particles from the cyclone and very coarse remnants from the bottom. The moisture content at the outlet of the dryer column and at cyclone outlet was uniform, mostly around 6%.

The two test programs demonstrated that smooth operation and acceptable moisture content can be achieved using 200°C flue gas, 4% oxygen concentration in the inlet flue gas, one to two minutes residence time and a gas flow rate of five to six times the coal feed rate. Further optimization would be possible in larger plant.

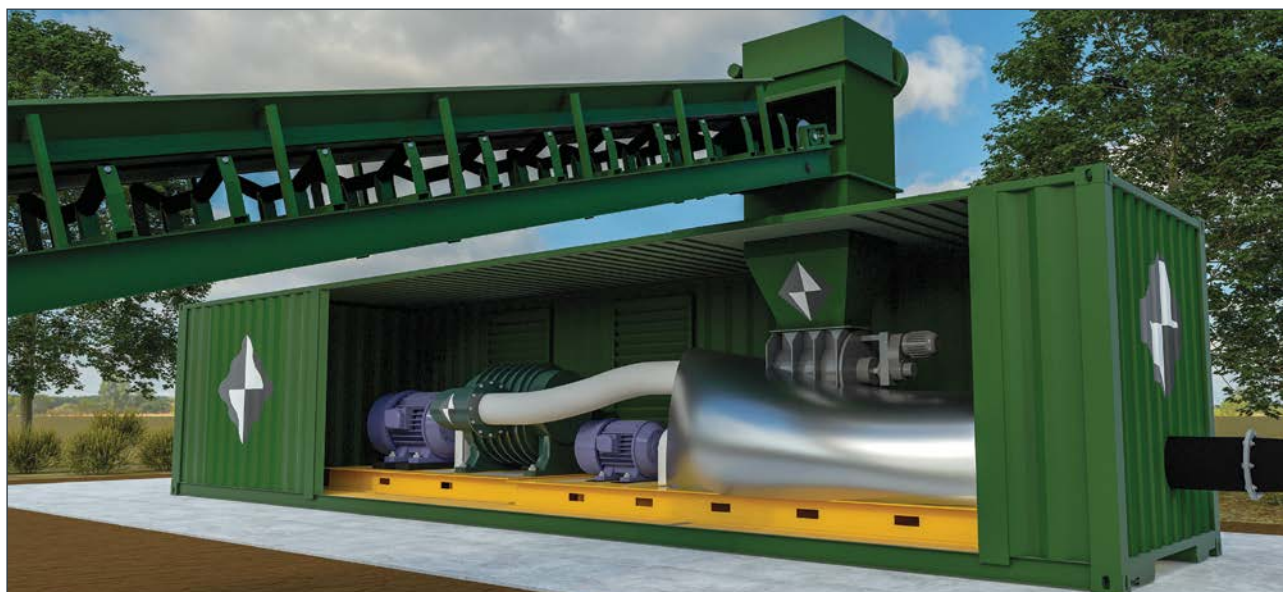
The study concluded that the COMB dryer system is a simple, flexible and scalable system. It is flexible because it can produce variable moisture content of the dried coal depending on the gas flow rate and gas temperature used. The COMB dryer system is also easy to start – both cold start-up and hot start-up – and can operate with semi-skilled personnel. The footprint of the plant is also small and the plant can be transferred to other locations relatively easily. No issues with spontaneous combustion were encountered.

Vortex flash drying

Pneumatic flash drying involves drying of finely milled lignite particles in a co-current stream of superheated steam, combustion gas or syngas. Hot air can also be used, but with an increased risk of dust explosion. It is possible to increase the effectiveness of pneumatic flash drying systems by imparting a swirling motion to the flow, which increases the turbulence of the drying medium, improving heat and mass transfer and reducing power consumption.

Ahrko Systems (www.arkhosystems.com) is a Melbourne-based, private unlisted company that has developed a unique Swirling Pipe Coal Dryer technology for use with Victorian lignite. In this system, swirling is induced by combining air flow from two tangential pipes, and drying is affected via variable temperature air-driven vortices and a specially designed separation cyclone. With funding support from BCIA, Ahrko collaborated with the University of Melbourne to develop a computational fluid dynamics (CFD) model of the drying process, which has been validated at full scale with Yallourn lignite.

Figure 17: Artist's impression of the modular Ahrko swirling flow coal dryer



Ahrko has built a full-scale prototype (shown at www.player.vimeo.com/video/144192336), which is currently being fine-tuned for improved performance. Further developmental work will include optimisation

of air heating to improve the drying performance. The business model of Ahrko Systems is to produce 100 tonne per hour modular drying systems, which it intends to lease rather than sell.

Key Publications

- Buscall R, Kusuma TE, Stickland AD, Rubasingha S, Scales PJ, Teo HE, & Worrall GL (2015). The non-monotonic shear-thinning flow of two strongly cohesive concentrated suspensions. *Journal of Non-Newtonian Fluid Mechanics*, 222, 112-120.
- 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.
- Clayton S, Desai D, & Hoadley A (2007). Drying of brown coal using a superheated steam rotary dryer. In: *The Proceedings of the 5th Asia-Pacific Drying Conference: (In 2 Volumes)*, pp. 179-184.
- Parsa MR, Tsukasaki Y, Perkins EL, & Chaffee AL (2017). The effect of densification on brown coal physical properties and its spontaneous combustion propensity. *Fuel*, 193, 54-64.
- Parsa MR, & Chaffee AL (2018). The effect of densification with NaOH on brown coal thermal oxidation behaviour and structure. *Fuel*, 216, 548-558.
- Parsa MR, & Chaffee AL (2019). The effect of densification with alkali hydroxides on brown coal self-heating behaviour and physico-chemical properties. *Fuel*, 240, 299-308.
- Rose MT, Perkins EL, Saha BK, Tang EC, Cavagnaro TR, Jackson WR, Hapgood KP, Hoadley AFA, & Patti AF (2016). A slow release nitrogen fertiliser produced by simultaneous granulation and superheated steam drying of urea with brown coal. *Chemical and Biological Technologies in Agriculture*, 3(1), 10.
- 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.

Agricultural Applications for Lignite-Derived Products

Opportunities for lignite in agriculture

In December 2015, BCIA ran a workshop on 'Agricultural applications for lignite', attended by 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.

In response, BCIA prepared a literature review for its members, called 'Applications for lignite in Australian agriculture'. The report showed that there is a range of potential uses for lignite in Australian agriculture. Lignite or extracted humic substances can be used as soil amendments and in organomineral fertilisers.

Lignite itself can be used as a carrier for microbial biofertilisers and to reduce ammonia and N₂O 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.

Amendment of farming soils with lignite can quickly improve soil health, leading to increased plant growth and photosynthesis. In turn, this results in more CO₂ being captured from the atmosphere and stored as soil organic carbon. This is an inexpensive way to help offset Australia's greenhouse gas emissions.

The report included recommendations for further research to ensure the quality and reliability of new agricultural products based on Victorian lignite. A major focus for subsequent research funded by BCIA and ACI has been the agricultural application of humic substances from Victorian lignite.

Humic substances are organic compounds that are important components of humus, the major organic fraction of soil, peat, and coal. They are produced by biodegradation of dead organic matter and are complex mixtures of many different organic compounds.

Humic substances are essential for healthy soil. They fix nitrogen, make soil nutrients available to plants through cation exchange, and improve the physical structure of the soil.⁽¹⁶⁾ Humic substances can help to reduce fertiliser application rates, enhance efficiency of nutrient use, replace synthetic plant regulators,

increase water stress tolerance, decrease disease incidence, and enhance early growth and flowering, and serve as a carrier for beneficial microorganisms.⁽¹⁷⁾ 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 CO₂ capture from the atmosphere through the increased photosynthesis resulting from better plant growth conditions.

Lignite can be used to produce a range of commercial humic substance products, such as humic acid and fulvic acid, which are used to increase the growth and yields of a variety of agricultural crops. The advantages of lignite as a soil amendment have been recognised for many years and it is commonly added to potting mixes.⁽¹⁸⁾

Figure 18: Dark brown humic and golden brown fulvic acids



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.⁽¹⁹⁾ However, little research has been conducted in Australia to provide a scientific basis for such claims.

To help fill this knowledge gap, and new manufacturing opportunities in Victoria, BCIA / ACI funded seven projects at Monash University and Federation University on production and application of lignite-derived soil amendments to boost agricultural productivity.

(16) Youngs RW, Frost CM (1963). Humic acids from Leonardite; a soil conditioner and organic fertilizer. *Proceedings of the North Dakota Academy of Science* 17: 76-82.

(17) Canellas LP, Olivares FL, Aguiar NO, Jones DL, Nebbioso A, Mazzei P, Piccolo A (2015). Humic and fulvic acids as biostimulants in horticulture. *Scientia Horticulturae* 196: 15-27.

(18) 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.*

(19) 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).

Coal derived soil additives: A green option for improving soil carbon, soil fertility and agricultural productivity?

This project, led by Associate Professor Tony Patti at Monash University, had the following objectives.

- ▶ To characterise the humic substance content of a range of commercial products.
- ▶ To assess the effects of humic substance products on agricultural plants in glasshouses.
- ▶ To evaluate the impact of humic substance products on degraded soils.
- ▶ To 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 lignite, 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 lignite 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.

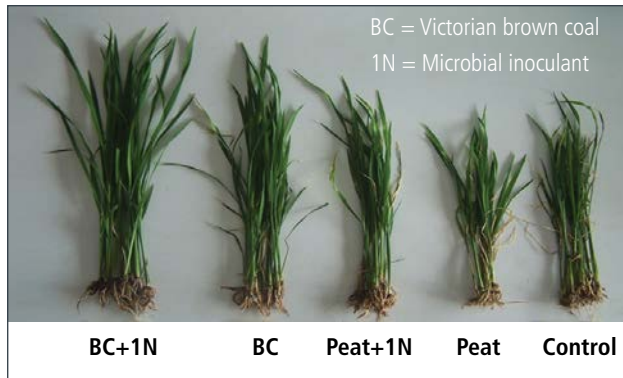
Given the low application rates used, changes in soil characteristics are only likely over longer time periods through cumulative effects. The literature survey and analysis also revealed that humic substances from compost sources (25% to 29% increases in plant growth) significantly outperformed those from lignite (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. A glasshouse pot trial with rice showed significant differences between treatments, with Victorian lignite having the most positive effect on plant growth, particularly when inoculated with nitrogen fixing bacteria (Figure 19).

The combination of lignite 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 lignite also seemed to support increased viability of the microbial inoculant.

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.

Figure 19: Rice in glasshouse trial after 30 days



The research tools developed through this project can help support the development and validation of new commercial agricultural products based on Victorian lignite.

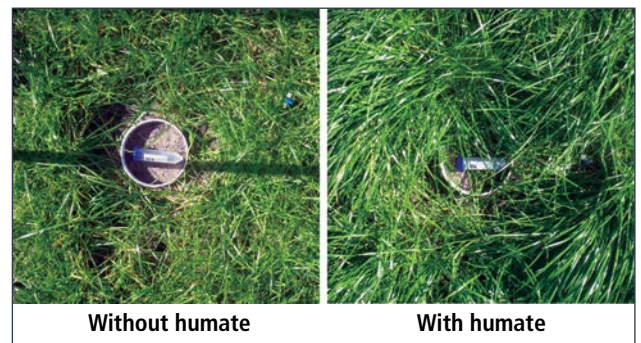
Sustainable soil carbon and soil health through lignite-derived humic products

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 20). However, the stimulation occurred only during the early growth stage, and was not sustained in the longer term.

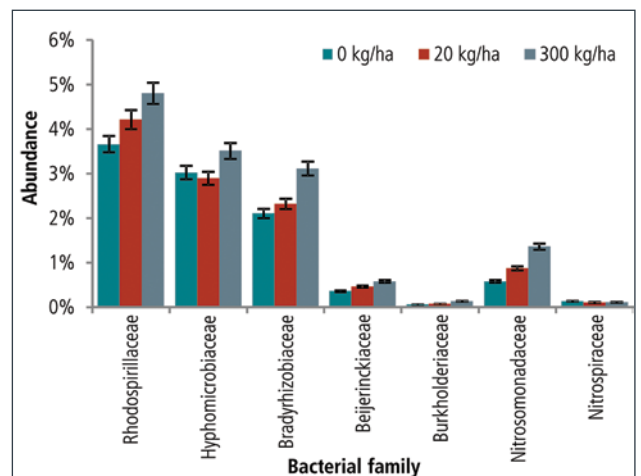
The reasons for this are unclear, although it is possible that the growth of both treatments was ultimately governed by a common limiting nutrient. Further research is required to understand how the initial benefits of treatment with potassium humate may be translated to an increased crop yield.

Figure 20: 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 as shown in Figure 21. The implications of this are not well understood and require further investigation.

Figure 21: Effect of commercial potassium humate on N-cycle soil microbial population



Evaluation of granular humate-phosphate fertilisers

Global use of chemical fertiliser, specifically nitrogen, phosphorus and potassium (N, P and K), is rising steadily, driven largely by China, 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.⁽²⁰⁾

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 greenhouse gas emissions, equivalent to 1.85 kg CO₂-e / kg urea.⁽²¹⁾ 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⁽²²⁾. 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.

(20) 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.

(21) Wood S, & Cowie A (2004). A review of greenhouse gas emission factors for fertiliser production. In IEA bioenergy task, 38(1), 1-20.

(22) Cordell D, & White S (2011). Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability*, 3, 2027-2049.

BCIA 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 benefitted from the assistance of two local companies, Torreco and Feeco Australia. Torreco uses a torrefaction process to heat the lignite briefly in an oxygen-deficient atmosphere, which makes the lignite 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 lignite / humates and chemical fertilisers, for testing at Monash University.

The charged ionic groups within humic substances and lignite 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.

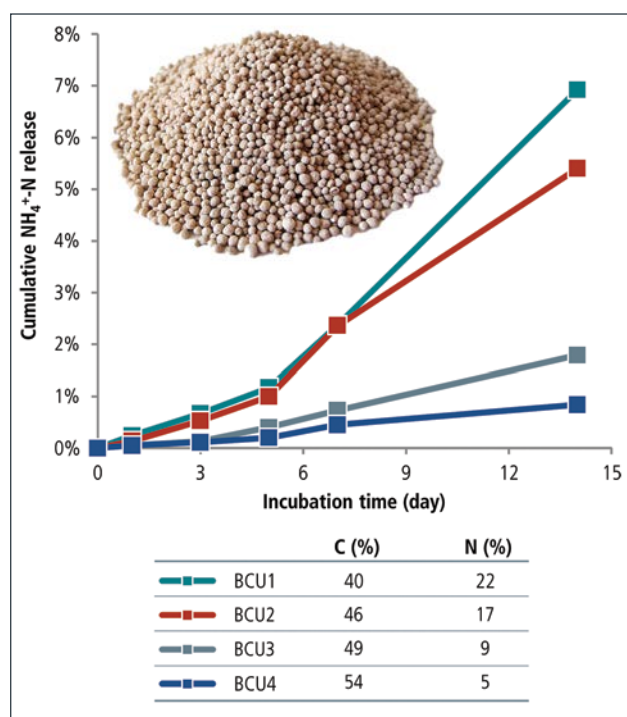
It is anticipated that this project will provide a rational scientific basis for the optimisation of improved phosphorus fertilisers which can help preserve scarce phosphorus resources through increased nutrient use efficiency.

Optimising a lignite-urea fertiliser composition

BCIA provided scholarship support for a PhD student at Monash University, Mr Biplob Saha, who investigated the interactions between lignite and nitrogen fertilisers, under the supervision of Associate Professor Tony Patti.

The project sought to improve the efficiency of nitrogen fertilisers, such as urea, through blending with lignite or humic substances. Mr Saha showed that lignite can bind to ammonia, slowing its release from the soil (Figure 4.9). Retention of ammonia in the soil makes the nitrogen more available for plant use.

Figure 22: Release of ammonia (NH_4^+) from urea lignite blends in water



Glasshouse and field experiments confirmed that blending of urea with lignite showed a beneficial effect on the growth, nitrogen uptake, biomass and economic yield in both silverbeet and corn. The higher availability of mineral nitrogen facilitated better crop growth, and increased biomass and economic yield of the studied crop plants by approximately 30% and 25%, respectively.

Other experiments showed that a granular lignite-urea fertiliser blend, in comparison to urea alone, allowed the use of 25% less fertiliser without any loss of crop yield, and with less wastage of nitrogen to the environment.

These studies clearly highlight the economic value of using lignite as an agricultural input in combination with nitrogen fertilisers. Commercial field trials are currently under way to capitalise on these findings, which may lead to a new manufacturing industry in Victoria.

Improving the extraction of humic products from lignite

Omnia Specialities Australia Pty Ltd (visit website at www.omnia.com.au), a multinational South African-based agrochemical company, produces humic compounds in Morwell from a naturally oxidised fraction of Victorian lignite, which is a particularly rich natural source of humates. Omnia Specialities has recently invested in a multimillion dollar upgrade of its manufacturing plant (Figure 23), making it a key production facility for global export of these lignite-sourced products.

Figure 23: Omnia Specialities Australia production facility, Morwell



The yield and properties of humic compounds exhibit significant variation (20% to 95%) across and within the lignite mines and deposits in the Latrobe Valley. The lignite seams that are rich in humic substances are difficult to identify and access, posing a significant barrier to the expansion of the Victorian humic industry.

ACI supported a collaboration between Omnia Specialities and Federation University to develop a commercially practicable and safe means of oxidising run-of-mine Victorian lignite. The project was being undertaken by PhD student, Mr Andrew Hood, under the supervision of Professor Vince Verheyen. The

aim of the project was to find a way to tailor the preparation of humic and fulvic acids in high yield regardless of lignite source.

A tailored lignite oxidation process was developed at bench scale and shown to increase the humic acid (HA) content of run-of-mine lignite from 13% to 29% to 68% to 75%. Preliminary efforts to increase the capacity of the process to 100 litre scale were also successful. However, a cost analysis indicated that the bench-scale process was likely to be too expensive, indicating the need for an alternative processing approach. Suitable approaches were identified, but are not easy to implement at bench scale.

This project demonstrated that the potential exists to increase the humate content of run-of-mine lignite and boost the manufacturing capacity of Omnia's facility in Morwell. Further R&D investment is required to build upon the preliminary results achieved in this process and implement a cost-effective process suitable for large-scale manufacture.

Next generation plant biostimulant from lignite

This project is a further collaboration between Omnia Specialities and Federation University, involving an exploration of the relation between humic chemical structure and plant growth stimulation. The molecular and physico-chemical properties of humics that are responsible for plant growth regulation are unknown, so this project combines Federation University's humics chemical characterisation expertise with Omnia's manufacturing, agriculture, plant growth and plant regulation expertise to address this knowledge gap. The scientific objectives of the project are as follows.

- ▶ To separate humics into fractions.
- ▶ To characterise humic molecular structure.
- ▶ To develop a protocol that is suitable for evaluating the effects of humics on plant growth.

- ▶ To identify humic molecular structures in the sample set that are most likely to affect plant growth or regulation.

At the time of writing, three selected fractionation techniques (solvent extraction, ester hydrolysis and dialysis) have been used to prepare 10g humic fractions from Victorian lignite and sample analysis is underway. An initial plant growth trial has been completed at the Australian Plant Phenomics Facility in Adelaide, with the next trial planned in the near future.

Lignite as a soil-improving amendment

The amelioration of degraded soils and the rebuilding of soils (e.g. for mine rehabilitation) requires construction of a soil cover, but is often hampered by unavailability of suitable quantities of soil materials. The subsoil materials, such as clays, have inappropriate functional properties for use as topsoil.

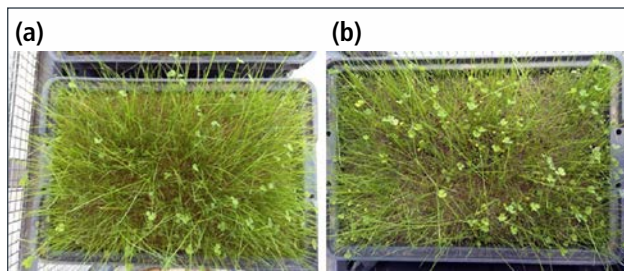
This project, a collaboration between AGL Loy Yang and Federation University, investigates the use of lignite as an amendment to improve soil properties and soil health in general, to develop a sustainable solution for use in mine rehabilitation in the Latrobe Valley.

The aim is to determine the optimal range of lignite concentration for addition to representative subsoil substrates to achieve an improvement of soil properties (physical, chemical, mechanical, microbiological) without any risk of coal combustion.

Testing to date has established that addition of up to 20 wt.% lignite generally improves the compressive strength of the soil, and slightly decreases slope stability. Significantly, it was demonstrated that addition of 20 wt.% lignite did not increase the risk of spontaneous combustion, challenging long-held beliefs in mine rehabilitation.

Further testing and evaluation of plant growth performance is ongoing.

Figure 24: Grass seeded in soil mixtures containing (a) 0% lignite and (b) 20% lignite



Advanced Carbon Products

Carbon is an extremely versatile element that is the basis for all of life on Earth. It has application across the range of human endeavour and all areas of the economic and social wellbeing of people and the planet. For much of human history, only four main types of carbon were known: diamond, graphite, carbon black (as soot) and charcoal.

It is only since the second half of the 20th century that completely new forms of carbon were discovered – carbon fibres, fullerenes, carbon nanotubes and graphene – that are now used in the most advanced emerging technologies of the 21st century; for example, aerospace, energy-efficient automobiles, wind turbine blades, flexible solar panels, energy storage (lithium ion batteries, supercapacitors), smart and wearable electronics, medical diagnostics, etc.

Around the world, the race is on to capitalise on these new developments and to leverage available natural resources into competitive manufacturing industries. Victoria's Latrobe Valley, with its abundant carbon resources and skilled workforce, is well placed to take advantage of these new developments, to create the new industries and jobs needed for continued economic prosperity.

BCIA / ACI has championed the development of high value carbon products from Victorian lignite, as a way to preserve the economy of the Latrobe Valley as coal-fired power stations are progressively retired. The range of products that could potentially be developed is summarised in Figure 25.

The following sections provide a brief overview of the research that has been undertaken in Victoria with BCIA / ACI support.

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.
- Patti AF, Jackson WR, Norg S, Rose MT, & Cavagnaro TR (2013). Commercial Humic Substances Stimulate Tomato Growth. In *Functions of Natural Organic Matter in Changing Environment* (pp. 1079-1084). 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.
- Saha BK, Rose MT, Wong V, Cavagnaro TR, & Patti AF (2017). Hybrid brown coal-urea fertiliser reduces nitrogen loss compared to urea alone. *Science of the Total Environment*, 601, 1496-1504.
- Saha BK, Rose MT, Wong VN, Cavagnaro TR, & Patti AF (2018). Nitrogen dynamics in soil fertilized with slow release brown coal-urea fertilizers. *Scientific reports*, 8(1), 14577.
- Saha BK, Rose MT, Wong VN, Cavagnaro T R, & Patti AF (2019). A slow release brown coal-urea fertiliser reduced gaseous N loss from soil and increased silver beet yield and N uptake. *Science of The Total Environment*, 649, 793-800.
- Saha BK, Rose MT, Van Zwieten L, Wong VN, & Patti AF (2021). Slow release brown coal-urea fertilizer potentially influences greenhouse gas emissions, nitrogen use efficiency, and sweet corn yield in oxisol. *ACS Agricultural Science & Technology*, 1(5), 469-478.
- Saha BK, Rose MT, Van Zwieten L, Wong VN, Rose TJ, & Patti AF. (2023). Fate and recovery of nitrogen applied as slow release brown coal-urea in field microcosms: 15 N tracer study. *Environmental science: processes & impacts*, 25(3), 648-658.
- 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.

Figure 25: Range of potential applications for carbon products that could be produced in Victoria

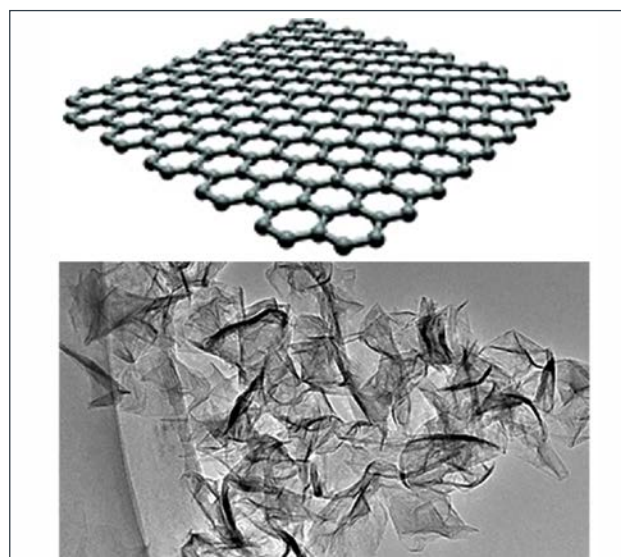
Carbon Product	Potential Applications
Carbon Fibres	
High tensile carbon fibres	Aircraft, automobiles, boats, machine parts, high-grade sporting goods, pressure vessels, wind turbine blades, civil engineering.
Chopped carbon fibres	Disk brake pads, gaskets for gas sealing, seal rings and packings, insulating components.
Electrospun carbon fibres	Textiles, air filters, catalyst supports, medical applications, electrodes for lithium-ion batteries, supercapacitors, in solar cells and sensors, adsorbents.
Activated carbon fibres	Water purification, heavy metal removal, odour control, SO ₂ and NO _x removal, biomedical applications, capacitors, vapour sensing, refrigeration, catalysis, electro-chemical applications, natural gas and biogas storage, wound dressings, medical personnel masks and blood purification.
Graphene-based Products	
Graphene	Conductive ink, flexible touch screens, chemical sensors, solar cells, batteries, supercapacitors, LED lighting, automobile and aircraft components, electromagnetic-interference shielding, gas barrier, flexible and wearable devices, nano-electromechanical systems, superdense data storage, improved performance for light emitting diodes, ultrafast lasers.
Graphene oxide	Water-dispersible precursor for graphene; hydrogen storage, ion conductors, nanofiltration membranes.
Quantum dots	Photovoltaic devices, light-emitting diodes, photodetectors, thermoelectric devices, supercapacitors, rechargeable batteries, catalysis, cellular and in vivo imaging, biosensors.
Carbon Fibres	
High tensile carbon fibres	Aircraft, automobiles, boats, machine parts, high-grade sporting goods, pressure vessels, wind turbine blades, civil engineering.
Chopped carbon fibres	Disk brake pads, gaskets for gas sealing, seal rings and packings, insulating components.
Electrospun carbon fibres	Textiles, air filters, catalyst supports, medical applications, electrodes for lithium-ion batteries, supercapacitors, in solar cells and sensors, adsorbents.

Graphene-based products

Graphene is a two-dimensional monolayer sheet of carbon arranged in a honeycomb network. This unique crystal structure confers a range of valuable properties. Graphene is chemically inert and stable, and conducts heat and electricity better than any metal. In proportion to its thickness, graphene is about 100 times stronger than the strongest steel.

Graphene is nearly transparent and yet has the ability to sustain extremely high densities of electric current (a million times higher than copper), offering the potential for use in transparent electronic devices. Due to its unique spectrum of valuable properties, graphene is expected to have a major impact in advanced 21st century technologies.

Figure 26: Graphene molecular structure and transmission electron microscopy image



The large-scale industrial use of graphene will require cost-effective production methods. Graphene does not occur naturally, and is most commonly synthesised from the carbon mineral, graphite. A solution-based process, known as Hummers' method, is used to chemically modify graphite to produce a water dispersible intermediary, graphite oxide. Graphene can be produced from graphene oxide by thermal annealing or chemical reduction.

Graphene oxide has the same structure as graphene, with the addition of oxygen-containing functional groups that provide reactive sites for chemical modification. Graphene oxide can be easily dispersed in water and is easy to process. It can be deposited on any substrate and then converted into a graphene.

This makes graphene oxide suitable for the use in the production of transparent conductive films, flexible electronics, solar cells and chemical sensors. Graphene oxide has a high surface area and can be suitable for the use as electrode material for batteries and capacitors. It can easily be mixed with different polymers and other materials to enhance their properties like tensile strength, elasticity and conductivity of composite materials.

ACI is currently supporting development of graphene-based products from Victorian lignite through two PhD Top-up Scholarships at Swinburne University. One, supervised by Dr Nisa Salim, involves optimisation and scale-up of a novel process for manufacturing layered graphene sheets from Victorian lignite.

The second, involving GrapheneX, is investigating the applications for graphene in 3D-printed composite materials. GrapheneX is a joint venture collaboration between Swinburne University and Cleantech Energy Australia P / L, which draws upon the skills of Dr Nishar Hameed, who has expertise in graphene nanocomposites and functional materials, and Prof Baohua Jia, who has expertise in fabrication of graphene oxide supercapacitors, graphene

metamaterials, 3D graphene networks and advanced solar cells.

Carbon quantum dots

Carbon quantum dots (CQDs) are very small semiconductor crystals, comprising turbostratic (i.e. misarranged sheets) or graphitic carbon, coated with oxygen-rich moieties which impart high solubility in aqueous solutions. First discovered in 2004, CQDs have been subject to intensive research activity, due to their broad range of potential application in the fields of energy conversion and storage (photovoltaic devices, light-emitting diodes, photodetectors, thermoelectric devices, supercapacitors and rechargeable batteries), synthesis (photocatalysis and electrocatalysis), and biomedical applications (cellular and in vivo imaging, biosensors, photothermal and photodynamic therapy).

ACI funded a six-month collaboration between CSIRO and Yokohama City University (YCU) to investigate the feasibility of producing CQDs from Victorian lignite. Researchers at YCU successfully prepared light-emitting CQDs exhibiting photoluminescence at 408 nm (deep blue colour) from Victorian lignite. A prototype light-emitting diode (LED) device was fabricated at CSIRO Manufacturing's bespoke Flexible Electronics Laboratory clean room facility. The CQD-LED device exhibited a sky-blue luminescence of 100 Cd / m² at an applied voltage of 12 V.

CSIRO and YCU are also interested in the hydrogen storage potential of CQDs, and are collaborating on Gaussian software to design of tailored hydrogen storage materials based on Victorian lignite. Industrial partners are being sought to support follow-on research.

Carbon fibres

Carbon fibres contain at least 92 wt% carbon and have diameters of about five to ten micrometres. Within each fibre, the carbon atoms are bonded

together in crystals that are more or less aligned parallel to the long axis. This results in outstanding specific strength and modulus, almost four times that of steel, making it one of the strongest materials on the planet today.

Carbon fibres are now being used commercially in structural, light-weight composites for a wide range of industries such as aerospace, automotive, bicycles, oil and gas, clean energy and sporting goods, where they are replacing traditional materials such as steel and aluminium.

Figure 27: Individual carbon fibre and a carbon fibre car wheel made in Geelong



The potential for greater market penetration of carbon fibre is currently limited by cost. Almost all carbon fibre is made from polyacrylonitrile (PAN), which gives superior mechanical properties. However, PAN is an expensive petroleum-based polymer contributing to more than 50% of carbon fibre price. Worldwide, there is great interest in reducing the amount of PAN used in carbon fibres by substituting with less expensive precursor materials.

Victoria has the potential to develop a carbon fibre manufacturing industry, due to its low cost lignite resource in the Latrobe Valley and Carbon Nexus, located at Deakin University's Geelong Waurin Ponds Campus. Carbon Nexus is a globally unique carbon fibre and composite materials research facility, which houses an industrial pilot and research scale carbon fibre processing line, a precursor fibre spinning line and composite manufacturing capabilities (Figure 28).

Figure 28: Pilot and research carbon fibre lines at Carbon Nexus



To explore this potential, ACI funded a 12-month exploratory project between Monash and Deakin universities. The team at the School of Chemistry at Monash University, led by Professor Alan Chaffee, contributed expertise in chemical transformation and fractionation of Victorian lignite. The team at Carbon Nexus at Deakin University, led by Associate Professor Mino Naebe, contributed expertise in production and characterisation of carbon fibres and their composites.

This first-of-its-kind project was aimed at proof-of-concept, laboratory-scale preparation of carbon fibres from Victorian lignite with characteristics appropriate to specific applications. The team at Monash University prepared a range of Victorian lignite extracts by different techniques, while the Deakin University team at Carbon Nexus transformed these precursor materials into raw fibres and subsequently into carbon fibre.

Carbon fibres were produced with substitution of up to 40% PAN using three different extracts of Victorian lignite. Two were extracts produced in the laboratory at Monash University, and one was a commercial product modified by a simple chemical treatment.

Based on previous experience, Deakin University is confident that, with further optimisation, carbon fibres containing 50% lignite could be produced to meet the cost and performance requirements of the automotive industry.

Figure 29: Precursor fibre and carbon fibre tows from lignite-PAN blend



It is believed that valuable intellectual property has been produced in this project, which is being treated as a trade secret rather than patentable.

Further work is needed to modify the surface chemistry of the lignite extracts and fine-tune carbon fibre production parameters (c.20 variables) at pilot scale at Carbon Nexus. This could be expected to produce automobile-grade carbon fibres from Victorian lignite within one to two years.

Activated carbon products

Activated carbon is a form of carbon that has been processed to be microporous, with a high surface area available for physical or chemical adsorption. It is produced from carbonaceous source materials such as bamboo, coconut husk, willow peat, wood, coir, lignite, coal, and petroleum pitch.

Activated carbon has a wide diversity of applications in various fields, including the treatment of drinking water, groundwater, municipal wastewater, industrial wastewater; remediation of contaminated groundwater and soil, air and gas cleaning, solvent

recovery, gas storage, and in industrial production processes such as in pharmaceuticals, chemicals, food and beverage production.

Typically, commercial activated carbons are used in the form of powders or granules, requiring the use of packed bed contactors. There are disadvantages with this approach, such as high pressure drop associated with the flow through the packed media, particle entrainment and channelling.

A way to overcome this problem is to utilise an activated carbon contactor with a honeycomb structure, making use of the very high geometric surface area-to-volume ratio of this shape. The high surface area provides high contact efficiencies, with a significantly lower pressure drop.

In 2014, BCIA funded a collaborative project between Monash University and the University of Melbourne, called 'Carbon Monoliths for Capture of CO₂ by Electrical Swing Adsorption', in association with the EU-funded MATESA consortium. The vision of MATESA was to develop a new-generation high-efficiency capture process based on selective adsorption of CO₂ on hybrid honeycomb monoliths.

As part of this project, a group led by Professor Alan Chaffee at Monash University produced activated carbon honeycomb monoliths from Victorian lignite. The lignite was mixed with an alkali to produce a gel material that could be extruded to form a honeycomb monolith, which was subsequently carbonised⁽²³⁾. The resulting activated carbon monolith is shown in Figure 30.

Since then, Professor Chaffee's group has continued to explore applications for honeycomb activated carbon monoliths with more immediate commercial potential. Refined fabrication techniques allow production of high quality, hard extruded monoliths from Victorian lignite at low cost.

(23) Parsa, M. R., & Chaffee, A. L. (2018). Carbon monoliths and a process for producing same. PCT Patent Application WO2018213890.

Figure 30: Honeycomb activated carbon from Victorian lignite



The activated carbon monoliths have potential for use in adsorption of a wide range of organic pollutants, as well as inorganic material such as phosphorous, arsenic or other heavy metals. Additives can be incorporated into the activated carbon monoliths to increase the adsorption / oxidation of targeted contaminants. After use, the monoliths can be efficiently regenerated by applying a low voltage electric current to heat the adsorbent internally.

The products being developed at Monash University offer great potential as viable and effective industrial adsorbents for water treatment. Monash University has lodged patent applications in 8 jurisdictions to date: Australia, US, China, Europe, India, Japan, Singapore and World. In November 2021, Monolith Technologies Pty Ltd acquired an exclusive licence to exploit the patent rights.

Activated carbons for storage of hydrogen

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.

BCIA provided 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 lignite.

The project successfully contributed to improved scientific understanding of reversible electrochemical storage of hydrogen in solid carbon-based material with acid electrolytes, and established the technical feasibility of a proton flow battery incorporating such an electrode.

Figure 31: Prototype proton battery connected to a voltmeter



A mesoporous activated carbon prepared from Victorian lignite had a hydrogen storage capacity of 1.6%, which compares favourably with the metal hydrides used in commercial solid-state hydrogen storage, and in lithium ion and lithium polymer batteries. The performance of the activated carbon was not optimised for this application, so this is a promising area for future research.

Potassium-enhanced activated carbon electrodes

Activated carbons are widely used in electrodes for energy storage (e.g., batteries, supercapacitors). Much is known about steam activation and KOH-mediated activation of Victorian lignites, and this is being leveraged in a current project at Federation University to develop tailored carbons suitable for use in battery and energy storage.

Environmental Clean Technologies and GrapheneX are collaborating with Federation University, with partial funding support from ACI. The postgraduate student, Mr Anushan Kulendran, began working on this project in late 2023, under co-supervision of Dr Surbhi Sharma and Dr Alicia Reynolds.

Blast furnace coke

Globally, the production of steel increases steadily to meet the demands of a growing world population. Production of steel relies on production of iron in blast furnaces, which in turn relies on a steady supply of coke to reduce iron oxides to metal.

The grade of coal used to produce coke is not abundant, is relatively expensive and is subject to frequent price fluctuations, so there is strong interest in developing cheaper alternatives.

Most coals, including many bituminous coals, are not suitable for blast furnace coke production. Coking coals have the unique attribute of softening when heated, agglomerating and forming a plastic phase called mesophase. It solidifies upon cooling to form hard, strong, macroporous lumps of coke.

Low rank coals, including lignite, have long been investigated as potential alternatives for blast furnace coke since the end of World War II. While it has proven possible to produce coke-like materials from lignite having the required strength, they tend to be

too reactive for blast furnace use, quickly breaking down to fines.

In 2009, the Victorian Government and Japan's Kyushu Electric Power Company established a project at Monash University to investigate the production of blast furnace coke from Victorian lignite.

BCIA assumed management of this project at the end of 2010. The 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.

Research efforts in this project were directed toward production of hard, low reactivity cokes from lignite. The research involved evaluation of a range of processing conditions, involving the following.

1. Separation of tarry material from Victorian lignite.
2. Briquetting of the mixture including the residue, a binder and a cementing agent under a carefully regulated heating regime.

Briquettes were produced and tested for compressive strength and reactivity.

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 lignite. The details remain confidential and the university pursued patenting of this material and its method of preparation.

Since completion of the project in 2015, further incremental improvements have been made, including the production of 50 mm briquettes (shown in Figure 32), suitable for evaluation in standard industry tests. Opportunities to commercialise this valuable intellectual property are being explored.

Figure 32: Briquette produced from Victorian lignite



Geopolymer concrete using lignite fly ash

Globally, the cement industry is a major source of CO₂ emissions, representing 5% to 7% of the world total. Each tonne of cement releases between 0.7 and 1.0 tonnes of CO₂ as it cures, producing an annual total release of almost 2 billion tonnes of CO₂ 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, lignite-fired power stations produce more than 500,000 tonnes of flyash 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. In contrast, flyash produces 'geopolymer concrete', which is activated by reaction of aluminosilicates with high concentration alkali. It is not clear whether the flyash produced from Victorian lignite is suitable for production of geopolymer concrete.

To address this question, BCIA provided scholarship support to a PhD student at RMIT University, Mr Rahmat Dirgantara, under the supervision of Dr David Law and Associate Professor Tom Molyneux. The

aim of Mr Dirgantara's project was to characterise the specific chemical make-up of lignite flyash from Victorian power stations and to investigate whether the flyash can be used to make geopolymer concrete of sufficient mechanical strength.

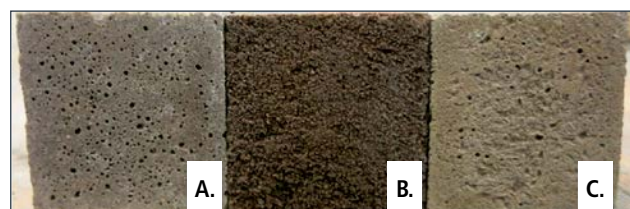
The flyash used in this study was recovered directly from the electrostatic precipitators of three power stations in the Latrobe Valley. There were large variations in the chemical composition, due to natural variations in lignite.

Initial geopolymer mortars prepared from the flyash exhibited marked differences in mechanical strength. The maximum strength of the geopolymer mortar obtained from the Loy Yang flyash was 56 MPa, while Yallourn and Hazelwood geopolymer mortars has compressive strengths of approximately 10 MPa. The differences in compressive strength relate to the aluminosilicate content of the flyash.

Further trials were undertaken using Loy Yang flyash to manufacture concrete specimens. The concretes produced had a maximum compressive strength of 60 MPa, more than sufficient for a construction grade concrete. However, there was considerable variability due to the changing composition of the flyash.

This research demonstrated that a good quality geopolymer concrete can be manufactured using lignite flyash from Loy Yang. Further investigation has been undertaken to determine the optimum mix design, the mechanical properties and the durability characteristics of geopolymer. Options for processing the raw flyash to standardise the composition were also evaluated.

Figure 33: ignite flyash geopolymer mortar from A. Loy Yang; B. Yallourn; and C. Hazelwood



Key Publications

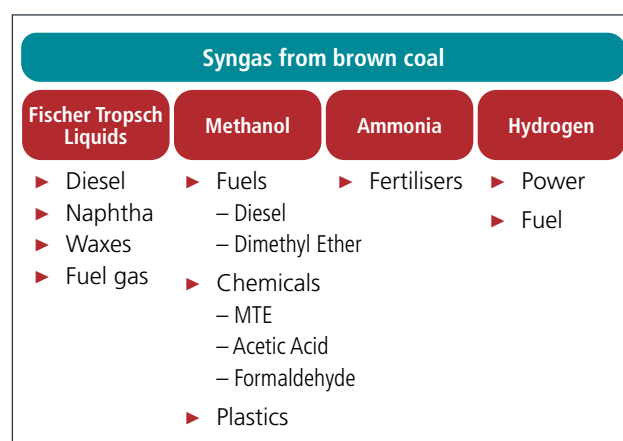
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Products from Gasification

Gasification is a technology that can convert lignite 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, CO₂ and H₂ (and N₂ 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 H₂ can be processed to create a wide range of products, as illustrated in Figure 34.

Figure 34: The diversity of products from syngas, which can be formed from gasification of lignite



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 lignite 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 lignite 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 lignite. The process involved gasification of lignite using a high temperature Winkler fluidised bed gasifier. The integrated drying gasification combined cycle was subsequently licensed to HRL 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 / ACI continued to support lignite gasification research, but shifted the emphasis to the production of value-added products. From a processing perspective, this required a shift from air-blown fluidised bed-type reactors to oxygen-blown entrained flow-type reactors. Entrained flow gasifiers achieve high carbon conversion efficiencies and produce a cleaner syngas product, which is accomplished by operation at higher temperatures and pressures than fluidised bed gasifiers. As such, the previous gasification research is not directly relevant to commercial lignite-to-product gasification processes.

To help fill this knowledge gap, BCIA / ACI oversaw the development of new knowledge and skills relating to lignite gasification under entrained flow conditions. A total of 16 projects were commissioned, 8 relating to the fundamentals of gasification technology and 8 to products from gasification. This created a valuable body of new knowledge relating to the performance of Victorian lignite under entrained flow gasification conditions, and the potential of this route for producing value-added fuels and chemicals.

Entrained flow gasification of Victorian lignite

Oxygen-blown gasification of Victorian lignite: Research and technology review

Air-blown gasification of Victorian lignite 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 lignite 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 lignite. 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 focussed on the key issues anticipated when moving from air-blown to oxygen-blown lignite gasification and produced recommendations for research to address knowledge gaps.

Background paper on solar conversion of lignite

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 CO₂ for sustainable fuels production.

Combining input from lignite gasification and concentrating solar technologies may offer an overall system that improves the environmental sustainability of lignite while accelerating the stand-alone feasibility of solar thermal.

BCIA commissioned a background paper to brief BCIA members on the background to solar gasification. Questions addressed in this study were 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 lignite to a high solar resource be justified?

- To what extent could solar technology reduce production costs and CO₂ 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 lignite 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 / GJ, 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.

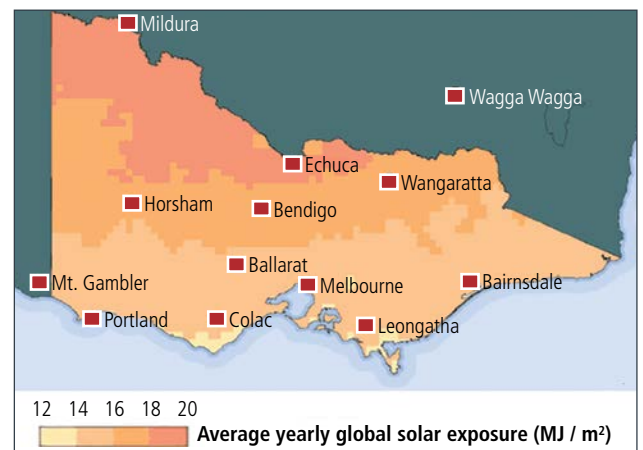
Unfortunately, the Gippsland basin, which is the source of most of Victoria's lignite, has one of the lowest levels of solar radiation in mainland Australia. Figure 35 shows the average annual solar irradiation in Victoria⁽²⁴⁾. The minimum average solar irradiation required for realistic operation of a concentrating solar thermal system is 18–20 MJ / m².

The Latrobe Valley in Victoria's south-east receives 13–15 MJ / m² annually, while Mildura in the north receives about 21 MJ / m². It is not feasible to operate a hybrid solar gasification plant in the Latrobe Valley.

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

Figure 35: Solar exposure across Victoria



Next generation lower emissions gasification systems R&D

This project was led by Professor Klaus Hein at HRL Technology, in collaboration with Monash University and 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 lignite, 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 lignite gasification, gas treatment and use; pre-combustion CO₂ 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.

(24) © Victorian Department of Energy, Environment and Climate Action (www.energyandresources.vic.gov.au/energy/sustainable-energy/solar-energy/what/victorias-solar-resource-details).

- ▶ 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 lignite-derived syngas.
- ▶ An outline of the requirements for technical-scale evaluation of gasification and gas conditioning.

Advanced lignite gasification

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

- ▶ The use of inexpensive catalysts, based on lignite char or flyash, for syngas cleaning and conversion of CO to CO₂.
- ▶ 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 lignite 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 was 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 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 lignites 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.

Development of entrained flow gasification technology with lignite

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 had shown that slag viscosity models developed for high rank coals do not give consistent results with the slag composition expected from gasification of Victorian lignite. Thus, current slag viscosity modelling may not be suitable for the design of an entrained flow gasifier for deployment in Victoria.

This BCIA-supported project was 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 lignite.

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 lignites 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 lignites require different temperatures to achieve a suitable slag viscosity.

Yallourn lignite requires a temperature of 1,450°C, whereas Loy Yang and Morwell lignites require temperatures in excess of 1,500°C. Acceptable performance with Loy Yang and Morwell lignites could be achieved by blending them with Yallourn lignite.

The project also showed that existing models do not accurately predict the slag viscosity of Victorian lignites. 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 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.

Lignite-derived syngas generation for use in higher value product processes

BCIA sponsored a PhD project at Monash University to study the fundamentals of entrained flow gasification of Victorian lignite. The PhD student involved, Ms Joanne Tanner, 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 500 µm diameter at temperatures to 1,600°C (Figure 36).

The rig was used to prepare char samples and measure char conversion and the yield and composition of syngas. A comprehensive matrix of pyrolysis and gasification trials was conducted using Victorian and Rhenish lignites.

Based on the results of this research, efficient carbon conversion, high throughput and tar-free syngas may therefore be expected under industrial conditions.

The maximum char reactivity for the Victorian lignite was observed at 1,200°C, confirming that there exists a fuel-dependant optimum gasification temperature and highlighting the potential for use of Victorian lignites in moderate temperature, entrained flow apparatus with suitable ash handling systems.

Figure 36: HELENA entrained flow reactor at Monash University



Development of oxy-blown entrained flow gasification with Victorian lignite

A second PhD project sponsored by BCIA at Monash University provided a deeper insight into the effect of the mineral components of Victorian lignite on gasification behaviour. The PhD student, Mr Tao Xu, studied under the supervision of Professor Sankar Bhattacharya.

This project extended the analysis of lignite gasification through detailed characterisation of chars and an investigation of the speciation of mineral elements into the gas and slag phases. Mineral transformations during coal pyrolysis and char gasification were observed at high temperatures between 1,000°C and 1,400°C. The decomposition of CaSO₄ and the formation of Fe₃O₄/MgFe₂O₄ were

found in Maddingley and Yallourn lignites. Loy Yang lignite mainly had one major mineral phase, quartz, and had no significant mineral transformation during coal pyrolysis and char gasification.

Kinetic modelling of Victorian lignites (Yallourn and Maddingley) was investigated using thermogravimetric analyser and entrained flow reactor (EFR) data. A modified volumetric model was validated for Victorian lignites by fitting thermogravimetric analysis data, and used to calculate kinetic parameters. A mathematical equation was developed for predicting the carbon conversion of Victorian lignite chars at 1,000°C–1,400°C. It showed good agreement with the experimental EFR data at high temperature.

This study achieved a detailed understanding of the effects of operational variables on gasification performance, the emission of air pollutants, and mineral transformation during entrained flow gasification. The information generated in this study is expected to advance the development of Victorian lignite gasification for commercial applications.

Lignite blending combustion and gasification

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 provided scholarship support for a PhD project at Monash University to investigate the potential benefits of using blends of upgraded lignite and black coal in both gasification and combustion. The PhD student, Mr Baiqian Dai, studied under the supervision of Dr Lian Zhang.

The objectives of this project were to elucidate the optimum mixing ratios between low-rank lignite and high-quality bituminous coal for combustion and gasification, through process flow sheeting and techno-economic analysis; to clarify the ignition, oxidation and gasification reactivity of coal blend, and

the interaction between different coal particles, if any; and to reveal the ash interaction and ash slagging / fouling propensity during coal blend combustion and gasification.

It was found that lignite char has a higher reactivity than bituminous coal char, mainly due to its more porous physical structure. The blending of bituminous coal with Victorian lignite promotes slagging by ash interactions. Production of metallic iron in the slag, an undesirable reaction, is reduced remarkably by the addition of bituminous coal char. This would be beneficial for slag discharge in an entrained flow gasifier.

An integrated pyrolysis and gasification process was developed for Victorian lignite, involving an initial mild pyrolysis process to generate moisture-free char as feed for an entrained flow gasifier. A simulation model for this process was developed using Aspen Plus.

This project contributed to the understanding of coal blend gasification, in terms of process efficiency, reactivity and ash slagging propensity, thereby improving the market potential for upgraded Victorian lignite products.

Products from Gasification

Victorian lignite to chemicals: Economics and technology status

To qualify as a low-emissions technology, the carbon dioxide emissions from a gasification process must be captured and prevented from reaching the atmosphere. This comes at a cost, which will have an impact on the economics of the process. In the absence of a price on carbon, the product must be able to absorb this cost while remaining commercially competitive.

In order to identify the most prospective opportunities for low-emissions lignite-to-chemicals via gasification,

BCIA commissioned a study on behalf of its members, called 'Victorian based lignite to chemicals – economics and technology status'. The report was prepared by Dr Nikolai Kinaev, Strategic Energy Consulting Pty Ltd, and Dr Geoff Bongers, Gamma Energy Technology Pty Ltd.

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. It was found that the feasibility of a lignite-to-chemicals facility is dependent on the particular chemical produced.

- ▶ The levelised cost of hydrogen production is within the upper bound of current market prices, but is sensitive to the cost of CO₂ transportation and storage. Capital subsidies are not likely to be a useful incentive for hydrogen production.
- ▶ Urea production may also be feasible and is relatively insensitive to the cost of CO₂ transportation and storage. 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.
- ▶ Synthetic petroleum products (from a Fischer-Tropsch facility) are not likely to be feasible unless the crude oil price is above A\$130 per barrel for the life of the facility.
- ▶ Both methanol and ammonia require significant subsidies or assistance to become competitive at current market prices.

The study found that a large workforce would be required to construct a lignite-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 would be created, depending upon the specific process involved, and three times that many local jobs to support these operational roles.

Pilot-scale demonstration of hydrogen and CO₂ separation membrane technology

BCIA member funds partially sponsored a pilot-scale evaluation of Praxair's hydrogen separation membrane, in which hydrogen was 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 lignite-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%. Regenerable RVS-1 sulphur sorbent reduced sulphur concentrations from nearly 4000 ppm to below 5 ppm in a single reactor. A hot-side syngas compressor was successfully demonstrated to raise the syngas pressure from 120 psi to above 450 psi 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 550 MW power plant with CO₂ capture from 31.7% to 35.7% (with Selexol as the base case for CO₂ 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 lignites 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 lignite fuels. Experimental testing of the lignites should be undertaken to determine the optimum conditions to achieve high carbon conversion while minimising bed agglomeration issues.

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

Catalytic steam gasification and assessment of dimethyl ether synthesis

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 lignite. DME is a non-toxic, environmentally benign fuel which is being developed overseas as a diesel substitute for motor vehicles. It is produced by catalytic conversion of methanol,

currently using 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.

Three new bi-functional catalysts were developed that performed as well as or better than a mixture of commercial catalysts, giving DME yields of 35-40%. More research is needed to develop improved catalysts for this application.

This project successfully established the principle of one-pot synthesis of DME from lignite syngas. DME is a prospective low-emissions diesel substitute, making it worthy of further study. This is an example of the new opportunities that could arise from lignite gasification research in Victoria.

Options for production of low cost CO₂-free hydrogen from Victorian lignite

Alternative methods for low cost production of CO₂-free hydrogen were investigated by Cleantech

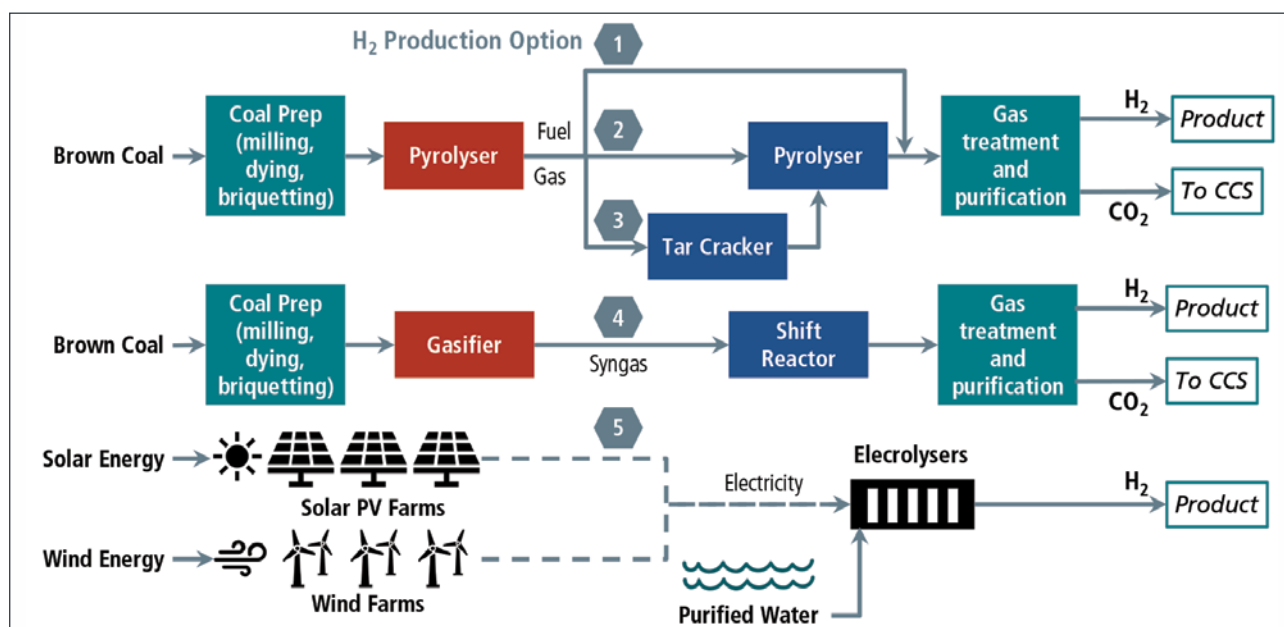
Energy Australia (CEA), a member of ACI. CSIRO was commissioned to conduct a desktop costing study of potential CO₂-free hydrogen production technologies, in collaboration with Monash University and Gamma Energy Technology. The project was funded jointly by ACI, ANLEC R&D and CEA.

Since CEA's interest at the time was focussed on pyrolysis of Victorian lignite, the primary focus was on hydrogen production options based on pyrolysis. Three pyrolysis options were considered.

- ▶ Pressure swing adsorption (PSA) for recovery of hydrogen from pyrolysis gas.
- ▶ Catalytic steam reforming, to convert methane and hydrocarbons in the pyrolysis gas to syngas, followed by PSA for hydrogen recovery.
- ▶ Chemical looping reforming of pyrolysis gas, with recovery of hydrogen and CO₂ as separate process streams.

For comparison, two other hydrogen production technologies were evaluated: (i) lignite gasification with CCS, and (ii) electrolysis of water using renewable (wind and solar) energy generated in Victoria.

Figure 37: Simplified block diagrams for hydrogen production



The project involved a desktop review, supported by process modelling and independent cost estimates. The study assumed a hydrogen production rate of 770 tonnes per day for each option. This equates to the anticipated market demand from Japan in the 2030s.

It was found that, in principle, sufficient CO₂-free hydrogen could be produced by all of the investigated production routes. However, gasification of lignite with CCS was found to be the most economical option for production of CO₂-free hydrogen at the quantity and cost needed by the Japanese market in the 2030s.

The production cost for gasification-based hydrogen was estimated as A\$2.73 / kg to A\$4.64 / kg in 2030. Renewable-based hydrogen is expected to be more expensive (A\$5-60 / kg to A\$8.90 / kg), with the best pyrolysis-based process costing A\$5.10 / kg in 2030.

This project provided strategic advice on options for the development of a high-value export opportunity. The most cost-effective option for producing export quantities of CO₂-free hydrogen was found to be by utilising the State's massive lignite resource in the Latrobe Valley and the proven CO₂ storage capacity in the nearby Gippsland Basin.

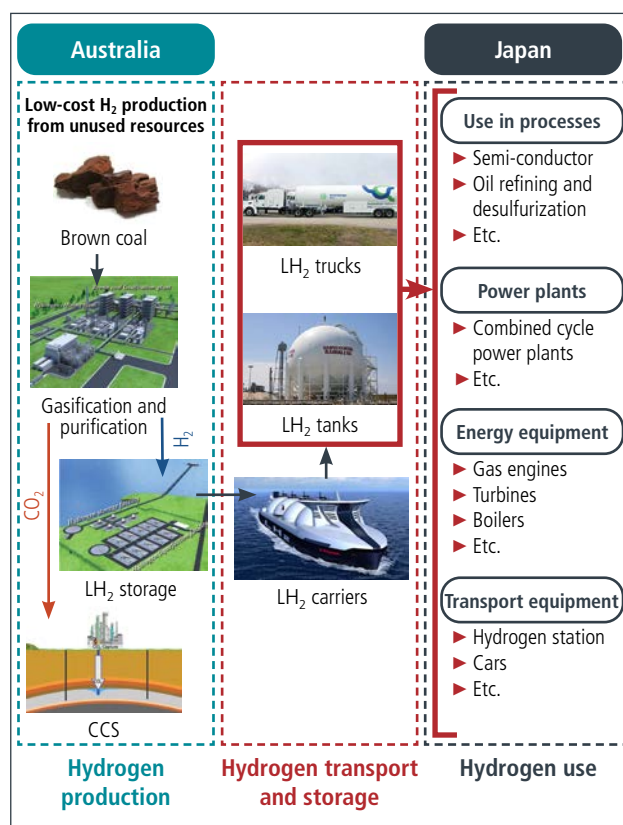
Hydrogen energy supply chain (HESC) concept development

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 lignite produces a mixture of CO, CO₂ and H₂. Further reaction with steam (the water gas shift reaction) can convert these to just CO₂ and H₂. The CO₂ can then be captured and geologically sequestered leaving H₂ 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 greenhouse gas 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.⁽²⁵⁾

Figure 38: The steps involved in producing hydrogen from Victorian lignite and transporting it to Japan as an energy source



Kawasaki Heavy Industries Ltd (KHI) has proposed the concept of a CO₂-free hydrogen energy supply chain based on producing hydrogen from lignite in Australia and transporting it for consumption in Japan (Figure 38). The concept involves gasification of lignite in the Latrobe Valley, separation and sequestration of the CO₂, and transport of the hydrogen gas to a

(25) Yoshino Y, Harada E, Inoue K, Yoshimura K, Yamashita S, & Hakamada K (2012). Feasibility study of 'CO₂ free hydrogen chain' utilizing Australian brown coal linked with CCS. Energy Procedia, 29, 701-709.

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.⁽²⁶⁾

BCIA was an early supporter of the 'CO₂-free hydrogen energy supply chain' concept through a project involving KHI and HRL Developments Pty Ltd. The objective was to develop a conceptual design for production of hydrogen from Victorian lignite using HRL's integrated drying and gasification technology and other commercially-available technologies.

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.

Latrobe Valley HESC pilot project

The research initially funded by BCIA subsequently matured into the Hydrogen Energy Supply Chain (HESC) Project. The HESC Pilot Project commenced in 2018 with the announcement of the plan to build a gasification plant in the Latrobe Valley and a hydrogen liquefaction plant in Hastings. The HESC Pilot Project was created as a partnership between the governments of Japan, Australia and Victoria and experienced industry partners in Japan and Australia.

The industry project partners were Kawasaki Heavy Industries, Ltd (KHI), Electric Power Development Co., Ltd. (J-POWER), Iwatani Corporation (Iwatani), Marubeni Corporation (Marubeni), AGL Energy (AGL) and Sumitomo Corporation (Sumitomo). Royal Dutch

Shell (Shell), ENEOS Corporation and Kawasaki Kisen Kaisha, Ltd. (K-Line) were also involved in the Japanese portion of the project.

The governments of Australia and Victoria contributed A\$100 million in funding to the A\$500 million project. The rest was invested by the Japanese Government and Project Partners.

During 2020–2021, the HESC Pilot Project produced hydrogen at 99.999% purity by gasification of lignite and lignite-biomass blends, which was liquefied and successfully transported to Japan on the Suiso Frontier, the world's first ocean-going liquid hydrogen carrier ship.

Figure 39: HESC Pilot Plant at AGL Loy Yang power station⁽²⁶⁾



ACI, in collaboration with Federation University, Churchill, provided research services in support of the successful HESC Pilot project. The ACI and Federation University team provided data analysis, simulation modelling and data interpretation to inform the operations of the HESC pilot plant. The outputs from this work are as follows.

- ▶ An extensive literature review examining the implications of five unique attributes of Victorian lignite on its utility in entrained flow gasification: (i) its organic matter composition, (ii) its high moisture content, (iii) its high proportion of volatile matter, (iv) its high gasification reactivity, and (v) its low ash content. The literature review identified knowledge gaps in grinding of Victorian lignite, handling of the lignite powder and prediction of slag behaviour.

(26) © HESC (www.hydrogenenergysupplychain.com/about-hesc).

- ▶ A thermodynamic equilibrium process model was developed for the HESC pilot gasifier using Aspen Plus simulation software. The model was designed to predict the average temperature and composition of the synthesis gas (syngas) produced by the gasifier from Loy Yang lignite and lignite / biomass blends under various operating conditions. The developed model could play a valuable role in the scale-up of the gasifier trial results and process optimisation to minimise the cost of hydrogen production.
- ▶ Detailed analysis reports for gasifier runs during both the 'Hot Commissioning' and 'Operational' phases. Comparison of the experimental data with the Aspen Plus simulation results indicated that the HESC pilot gasifier was consistently operated under conditions that maximised the potential for hydrogen production.
- ▶ A laboratory-based investigation into the reactivity implications of porosity and mineral structure of Loy Yang lignite and biomass blend gasifier chars.
- ▶ A desktop review of options for CO₂ capture plants suitable for an EAGLE gasifier in Victoria. The overall conclusion of this review was that there are commercial and emerging technologies that are economic and practical that will contribute to sustainable, low cost zero-emission hydrogen utilising Victorian lignite. Importantly, there are successful commercial examples for each of the currently available processing routes for producing pure hydrogen from gasifier synthesis gas.

Options for net zero emissions hydrogen from Victorian lignite

In 2022, ACI was commissioned by the Victorian Department of Jobs, Precincts and Regions to deliver a feasibility study on production of net zero emissions hydrogen by gasification of Victorian lignite, utilising high efficiency carbon dioxide capture, heat integration, co-gasification with biomass and incorporation of renewable energy.

The project was conducted as a collaboration between Monash University and ACI, under the leadership of Professor Sankar Bhattacharya. A Monash Research Fellow, Dr Mahmud Kibria, was responsible for development of a detailed process simulation model using Aspen Plus software, running the model to investigate a number of different scenarios, and documenting the model for publication. ACI's Research Investment Manager, Dr David McManus, was responsible for conducting literature searches, report drafting and project coordination.

The outcome of this project was a paper published open-access in the International Journal of Hydrogen Energy. The study investigated the feasibility of producing export quantities (770 tonne per day) of clean hydrogen meeting international standards, by gasification of Victorian lignite plus CCS.

This involved a detailed Aspen Plus simulation analysis of the entire production process, focussing on the resources, energy requirements and greenhouse gas emissions associated with production of gaseous and liquefied hydrogen, and taking into account fugitive methane emissions during lignite mining.

The proposed process comprised lignite mining, lignite drying and milling, air separation unit (ASU), dry-feed entrained flow gasification, gas cooling and cleaning, sour water-gas shift reaction, acid gas removal, pressure swing adsorption (PSA) for hydrogen purification, elemental sulphur recovery, CO₂ compression for transport and injection, hydrogen liquefaction, steam and gas turbines to generate all process power, plus an optional post-combustion CO₂ capture step. High grade waste heat was utilised for process heat and power generation.

Three alternative process scenarios were investigated as options to reduce resource utilisation and greenhouse gas emissions: replacing the gas turbine with renewable energy from off-site wind turbines, and co-gasification of lignite with either biomass or biochar.

In each case, the specific net greenhouse gas intensity was estimated and compared to the EU Taxonomy specification for sustainable hydrogen.

This was the first time that a coal-to-hydrogen study had quantified the greenhouse gas emissions across the entire production chain, including upstream fugitive methane emissions. It was found that both gaseous and liquefied hydrogen can be produced from Victorian lignite, along with all necessary electricity, with specific emissions intensity (SEI) of 2.70 kg CO₂-e / kg H₂ and 2.73 kg CO₂-e / kg H₂, respectively. These values conform to the EU Taxonomy limit of 3.0 kg CO₂-e / kg H₂. This result was achieved using a Selexol™ plant for CO₂ capture, operating at 89.5%–91.7% overall capture efficiency. Importantly, the very low fugitive methane emissions associated with Victorian lignite mining was found to be crucial to the low SEI of the process, making this a critical advantage over the alternative natural gas or black coal processes.

This study showed that there are technical options available to further reduce the SEI to meet tightening emissions targets. An additional post-combustion MDEA CO₂ capture unit could be added to increase the capture efficiency to 99.0%–99.2% and reduce the SEI to 0.3 kg CO₂-e / kg H₂. Emissions intensity could be further reduced by utilising renewable energy rather than co-production of electricity on site. Net zero emissions could then be achieved by co-gasification with ≤1.4 dry wt.% biomass, while a higher proportion of biomass would achieve net-negative emissions. Thus, options exist for production of clean hydrogen from Victorian lignite consistent with a ‘net zero by 2050’ target.

Options for net zero emissions ammonia from Victorian lignite

In Japan, leading power companies, manufacturers and research institutes are collaborating toward commercialization of a CO₂-free ammonia value

chain, with significant achievements in development of ammonia-fuelled gas turbine power plant, a direct ammonia-fuelled solid oxide fuel cell, and co-firing of ammonia at a commercial coal power plant.⁽²⁷⁾ Ammonia is already one of the most important industrial chemicals in the world, with the lives of around half of humanity being dependent on ammonia-based fertilisers.⁽²⁸⁾ In 2020, 185 million tonnes of ammonia was produced and around 20 million tonnes was traded globally, so the infrastructure to support safe and reliable storage, distribution and export of ammonia is already highly developed.⁽²⁹⁾

This suggests that there could be potential for production of clean ammonia from Victorian lignite for both the domestic and export markets. To investigate this opportunity, ACI commissioned Monash University to extend the previous lignite-to-hydrogen simulation model to include synthesis and liquefaction of ammonia.

As in the previous study, options were considered in which all the necessary electricity was generated either on-site using lignite or sourced off-site from renewables. The aim was to provide a direct comparison of the resource requirements and CO₂ emissions intensity for production of export-quantities of liquefied hydrogen and ammonia from Victorian lignite.

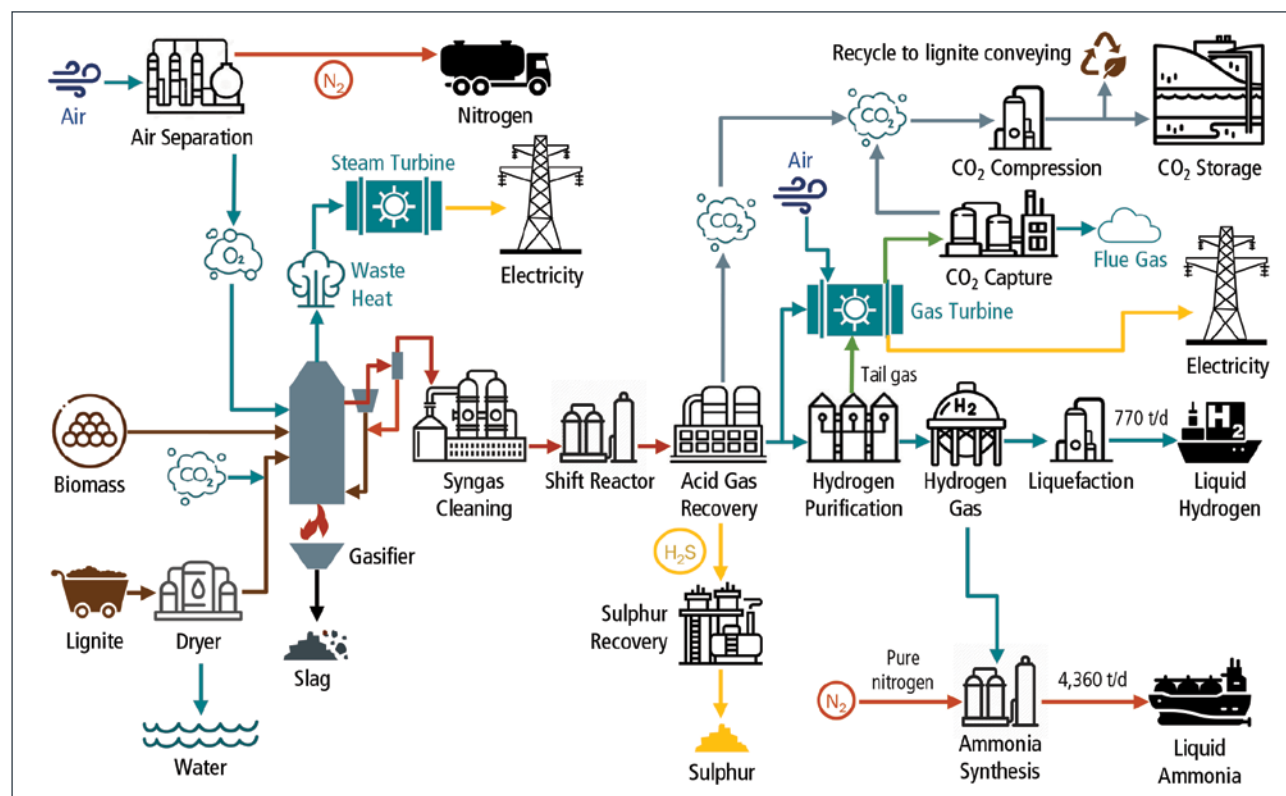
The second objective of this study to utilise the insights gained to also quantify the resource requirements and CO₂ emissions intensity for production of green ammonia using renewable energy. Relevant data is scarce in the literature, so this study offered an opportunity to compare the alternative options on a consistent basis.

(27) Muraki S (2008). Development of technologies to utilize green ammonia in energy market. Presentation at NH₃ Fuel Conference 2018.

(28) Erisman JW, Sutton MA, Galloway J, Klimont Z, Winiwarter W (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, 1(10):636-9.

(29) International Energy Agency. Ammonia technology roadmap. October 2021.

Figure 40: Production of net zero emissions hydrogen and ammonia from Victorian lignite



Surprisingly, this study found that the electrical power requirement for ammonia synthesis is essentially the same as that needed for liquefaction of an equivalent output of hydrogen. On this basis both options are equally attractive, although ammonia synthesis is at a higher level of technological maturity than large-scale hydrogen liquefaction.

It was found that ammonia can be produced from Victorian lignite with very low CO₂ emission intensity (0.49 kg CO₂-e kgNH₃⁻¹), equivalent to that of next-generation natural gas reforming with CCS processes. If required, the emission intensity can be reduced to 0.05 kg CO₂-e kgNH₃⁻¹ with a post-combustion CO₂ capture system, and then made carbon neutral by co-gasification with ≤1.4% biomass.

For comparison, this study also examined the implications of producing the same quantity of green ammonia using renewable energy alone. It was estimated that production of 178.2_{th}⁻¹ green ammonia

would require 1,946 MW renewable energy and associated transmission infrastructure. In Victoria, this could be supplied by a wind farm with a 5.4 GW rated capacity, occupying an area of over 72,000 ha. This is highly unlikely to be a viable option.

This analysis was published in the International Journal of Hydrogen Energy. It indicates that clean hydrogen in the form of ammonia, produced in Victoria by lignite gasification with CCS, can be consistent with global emissions reductions targets over the next few decades. The unique combination of low-cost lignite and high-quality CO₂ storage geology means that Victoria is well placed to become a significant exporter of low-emissions ammonia to the world market. Further research is recommended on recovery of energy from the low grade waste heat streams and opportunities for additional electricity generation using the organic Rankine cycle.

Key Publications

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Carbon Dioxide Capture and Storage Technologies

Introduction

What is carbon capture and storage?

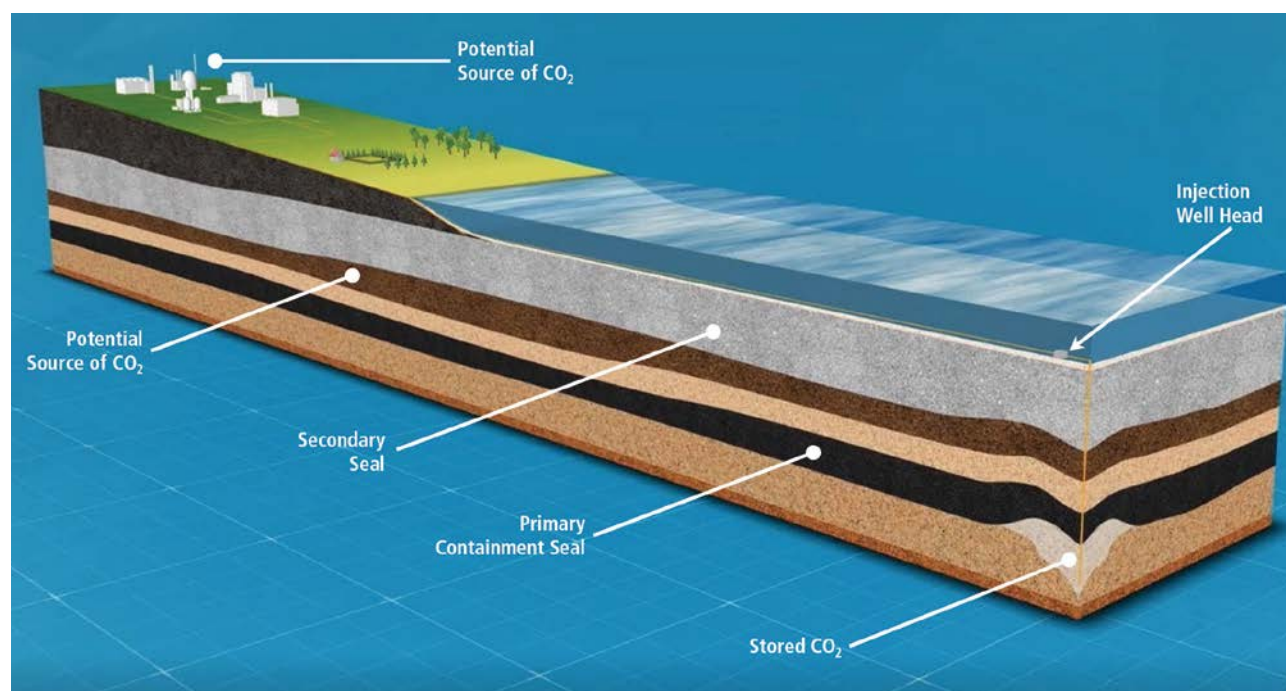
Carbon capture and storage (CCS) involves capturing carbon dioxide (CO₂), from industrial processes and then transporting it to a suitable storage site for safe, long-term storage deep underground. CCS has the potential to play an important role in reducing greenhouse gas emissions from industry and addressing climate change. It is a proven technology and has been in safe, commercial operation for more than 50 years.

CCS presents an important opportunity for new industries in Victoria consistent with the Victorian Government's target of net zero emissions by 2045.

Victoria offers a world-class opportunity for CCS – Bass Strait's offshore geology provides excellent potential to safely store large quantities of CO₂ while also being located close to the Latrobe Valley.⁽³⁰⁾ CCS has a number of key benefits for the state as it will allow industry that may have a high CO₂ emission level such as hydrogen production to flourish, providing high paid local jobs, on a long term sustainable basis.

The CarbonNet Project is investigating the establishment of a commercial-scale CCS network in the Latrobe Valley, with the support of the Australian and Victorian governments. The network would bring together multiple CO₂ capture projects, transporting CO₂ via a shared pipeline and injecting it into deep underground, offshore storage sites in Gippsland (Figure 41).

Figure 41: Diagram showing carbon capture and storage⁽³¹⁾



(30) © Victorian Department of Energy, Environment and Climate Action (www.earthresources.vic.gov.au/projects/carbonnet-project/carbon-capture-and-storage-faq).

(31) © Victorian Department of Energy, Environment and Climate Action; The CarbonNet project – Advancing CCS for Victoria.

The importance of CCS for a low emissions future

The Intergovernmental Panel on Climate Change (IPCC) has advised that limiting global warming to 1.5°C will require that global CO₂ emissions fall to net zero by 2050. In its 2019 report, 'Global Warming of 1.5°C', the IPCC emphasised the importance of CCS for deep mitigation pathways, based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO₂ from the atmosphere when combined with bioenergy.

CCS can be used in two ways in mitigation pathways.

1. To move more rapidly towards the point of carbon neutrality and maintain it afterwards in order to stabilize global mean temperature rise.
2. To produce net negative CO₂ emissions, drawing down anthropogenic CO₂ in the atmosphere in order to decline global mean temperature after an overshoot peak.

The IPCC estimated that a zero emissions pathway, limiting global warming to 1.5°C, requires CO₂ emissions in industry to be about 65%–90% lower in 2050 relative to 2010. This will require storage of up to 1,200 GtCO₂ globally by 2050, well within the proven technical potential of at least about 2,000 GtCO₂ of storage capacity in geological formations. Transitional change is already underway, but limiting warming to 1.5°C will require a rapid escalation in the scale and pace of CCS deployment, particularly in the next 10 to 20 years.

The IPCC stated: "*Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term.*"⁽³²⁾

(32) © IPCC (www.ipcc.ch/sr15).

Development of CCS for use with Victorian Lignite

The IPCC noted that the deployment of CCS is, in general, being held back by uncertainty about the feasibility of timely upscaling, both due to lack of regulatory capacity and concerns about storage safety and cost.

It is fair to say that the development of CCS technologies for use in the combustion and processing of Victorian lignite has been strongly supported by BCIA / ACI, with funding from both the Victorian and Australian governments.

BCIA / ACI has played a prominent role in supporting the development of post-combustion capture technologies suitable for use in lignite power stations, and pre-combustion capture technologies suitable for gasification of lignite, which can also be utilised for capturing CO₂ emissions from lignite upgrading and other industrial processes. They would also be suitable for use for bioenergy production and perhaps for recovery of CO₂ from the atmosphere.

BCIA / ACI has supported CO2CRC, CSIRO, Monash University and the University of Melbourne to investigate advances in carbon capture technologies, including solvents, membranes and solid-phased adsorbents. The emphasis has been on pilot-scale demonstration, making BCIA / ACI one of the largest supporters of CCS development in Australia.

Solvent-Based Systems

BCIA supported the development of two main types of solvent-based CO₂ capture system. One is the CO2CRC precipitating adsorption system, in which CO₂ is captured using potassium carbonate solvent. The CO2CRC process, known as UNO MK 3, became the basis for a start-up company which is commercialising the technology.

The other is the CSIRO amine-based adsorption system. CSIRO has researched new strategies to reduce the cost of CCS through the use of new, efficient solvents with lower energy penalty, and novel processes to avoid sulphur deactivation. The superior performance of CSIRO's solvent technology was demonstrated through a joint pilot CO₂ capture project with IHI Corporation of Japan.

CO2CRC Precipitating Absorption System

Pre-combustion CO₂ capture from a pilot gasifier (UNO MK 1)

The first incarnation of the potassium carbonate absorption process (UNO MK 1) was tested using syngas from an air-blown pilot-scale gasifier (Figure 42). This was an example of the use of 'pre-combustion CO₂ capture, where the syngas (a mixture of CO, CO₂ and H₂) was cleaned before combustion or further processing.

This project, 'Pre-combustion carbon dioxide technologies for lignite power generation' was led Dr Abdul Qader of the CO2CRC, in collaboration with HRL Developments Pty Ltd, Process Group, the University of Melbourne, Monash University and UNSW.

Figure 42: CO2CRC pre-combustion CO₂ capture rig at HRL Developments



This project identified the problem of sulphur and nitrogen impurities in the syngas interacting with the potassium carbonate solvent, altering the CO₂ capture properties. These interactions were incorporated into a simulation model for use in process design and optimisation.

Development of UNO MK 3 for post-combustion CO₂ capture

BCIA subsequently supported further development of the CO2CRC potassium carbonate process for recovery of CO₂ from flue gas at the Hazelwood power station, in the project 'Latrobe Valley Post Combustion Capture (LVPCC) Project – CO2CRC stream' (Figure 43). Under the operating conditions used, the CO₂ capture efficiency was only about 20%, but the experimental data was used to design an optimised system.

Figure 43: CO2CRC pilot plant trials at Hazelwood



This process included a novel strategy for continuous precipitation of the potassium carbonate, to increase the driving force for CO₂ removal and reduce 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 monoethanolamine (MEA) solvent.

Refinement of UNO MK 3 process

This project, 'CO2CRC's Carbon Capture Technologies in Brown-Coal-Fired Power Plants (CCT-BCFPP) - capture demonstration for cost reduction', 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 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 44: UNO MK 3 pilot plant at Hazelwood



Operational data from the pilot plant operating on flue gas from the Hazelwood power station (Figure 44) 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 CO₂ capture efficiency was 50% at best, and persistent foaming problems prevented long-term stable operation. However, the process simulation model was successfully verified, and was 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

(33) Hooper, B. (2018, October). Faster, higher, stronger: A winning solution for a precipitating potassium carbonate capture system. In 14th Greenhouse Gas Control Technologies Conference Melbourne (pp. 21-26).

the UNO MK 3 process retrofitted to a 500 MW lignite-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, now known as KC8 Capture Technologies Ltd (www.kc8capture.com). Since the completion of BCIA-funded research, significant improvements in CO₂ capture efficiency have been achieved with the use of a promoter⁽³³⁾, and the absorber has been modified to allow the process to run at much higher solids concentrations.

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 CO₂ capture. *Energy Procedia*, 63, 1773-1780.

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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, 1668-1675.

Smith KH, Anderson CJ, Tao W, Endo K, Mumford KA, Kentish SE, Qader A, Hooper B, & Stevens GW (2012). Pre-combustion capture of CO₂—Results from solvent absorption pilot plant trials using 30wt% potassium carbonate and boric acid promoted potassium carbonate solvent. *International Journal of Greenhouse Gas 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 CO₂ capture. *Energy & Fuels*, 28, 299-306.

Stevens G, Hooper B, Dugan C and Webley PA (2008). Reactor, plant and process, WO2008138054, November 20, 2008.

Amine Solvent Absorption Systems

Amine solvent scrubbing is based on the chemical absorption of CO₂ using aqueous alkanolamine solutions. It is a robust technology that has been used to separate CO₂ 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 CO₂. In addition, the commercial solvents are quickly 'poisoned' by the sulphur compounds present in coal, usually requiring additional expensive scrubbing equipment.

Desulphurisation equipment is not used in Australian power stations since Australian coals contain low levels of sulphur. Even so, sulphur compounds can accumulate in CO₂ absorption systems over time and will eventually reduce the capacity and efficiency of CO₂ 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 sulphur scrubbing equipment.

In Australia, CSIRO has led 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.⁽³⁴⁾

CSIRO also conducts 'learning by doing' research at post-combustion capture pilot plants in Victoria, NSW, Queensland and China.⁽³⁵⁾

(34) © CSIRO (www.csiro.au/en/Research/EF/Areas/Coal-mining/Carbon-capture-and-storage).

(35) Cottrell A. CSIRO PCC pilot plant research in Australia. PCC Science & Technology seminar, 26 March 2013.

In Victoria, AGL Loy Yang has played a prominent role in supporting the development of post-combustion capture technologies suitable for use in lignite 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 45) that has been used for two BCIA-supported projects. Loy Yang power station also hosted a new pilot plant built and owned by the Japanese technology provider, IHI Corporation. BCIA also supported trials at this plant.

BCIA also supported four PhD projects to complement the pilot scale research. Each of these projects was integrated with the CSIRO research activities, in collaboration with the Churchill campus of Federation University Australia.

Latrobe Valley Post-Combustion Capture (LVPC) Project – CSIRO stream

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

The CSIRO stream of the LVPC project involved an investigation of CO₂ 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 CO₂ 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.
- ▶ 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 CO₂ from the flue gas. One of the amine blends required significantly less heat duty in the stripper reboiler, while maintaining good CO₂ sorption / desorption kinetics, translating to an overall lower energy penalty for CO₂ capture.

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

Figure 45: CSIRO post-combustion capture 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 capital cost of such a system might be 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. Development of more sensitive analytical methods became a focus for on-going work.

Evaluation of advanced PCC process and equipment with two advanced liquid absorbents for application in Victorian lignite-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 involved the installation and operation of a A\$1 million Japanese-built post-combustion capture pilot plant at Loy Yang power station, being the first such pilot plant in Victoria to operate around the clock.

This project entailed 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 represented a significant step forward in post-combustion capture technology application for Victorian lignite-fired power stations.

In the first year, IHI Corporation designed and manufactured a 0.5 tonnes per day CO₂ 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 46).

Figure 46: IHI Corporation's 0.5 tpd pilot plant at AGL Loy Yang power station



IHI Corporation's amine-based technology was evaluated through a parametric study to determine the minimum thermal energy requirement for liquid absorbent regeneration for the two selected absorbents and two process configurations. This was followed by a similar study of an advanced liquid absorbent developed by CSIRO.

This project was a successful collaboration between CSIRO and IHI Corporation in demonstrating long-term 24 / 7, 5000 hr continuous operation of an optimised CO₂ capture pilot plant with each of two distinct amine solvents, using real flue gas slipstream from the AGL Loy Yang power plant.

One of the goals of the project was to demonstrate that a combination of improved amine solvents and IHI Corporation's proprietary process configuration could reduce the reboiler duty to 2.5 MJ / kg CO₂ captured, representing a potential 40% reduction in operating costs compared with conventional MEA solvent. The reboiler duty with IHI Corporation's ISOL-162 solvent was 2.73 MJ / kg CO₂, while CSIRO's CAL008 solvent achieved 2.6 MJ / kg CO₂, representing potential operating cost savings of 34% and 38%, respectively. CAL008 was found to be a more robust absorbent than ISOL-162.

Combined low-cost pretreatment of flue gas and capture of CO₂ from lignite-fired power stations using a novel integrated process concept (coCAPco)

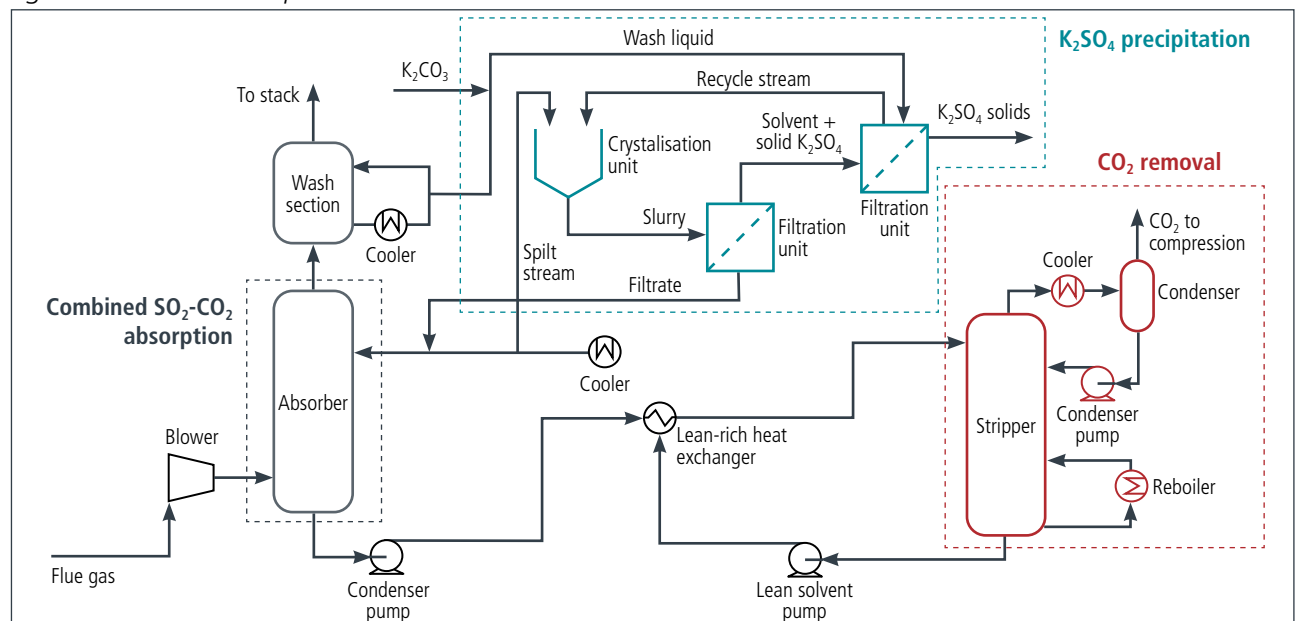
Sulphur dioxide (SO₂) is an acidic gas that is formed as a combustion product from sulphur compounds present in coal. Environmental emissions of SO₂ contribute to 'acid rain', which has led to mandated requirements for SO₂ scrubbers on coal-fired power stations in the US, Europe and Japan. Australian coals, including Victorian lignite, are low in sulphur by world

standards so flue gas desulphurisation is not necessary. However, this creates a local problem when it comes to post-combustion capture using amine solvents. SO₂ is a stronger acid than CO₂ and is absorbed preferentially by amines, reducing the pH. As a result, both the rate of CO₂ absorption and the overall CO₂ capacity of the solvent are decreased.

The objective of this project was to develop a new absorber system to allow effective simultaneous capture of SO₂ and CO₂. This was intended to allow post-combustion capture to be implemented effectively in Australia without the need for an expensive preliminary desulphurisation 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⁽³⁶⁾, 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 47) involves continuous precipitation of SO₂ in the form of K₂SO₄ from a bleed stream off the main amine solvent loop.

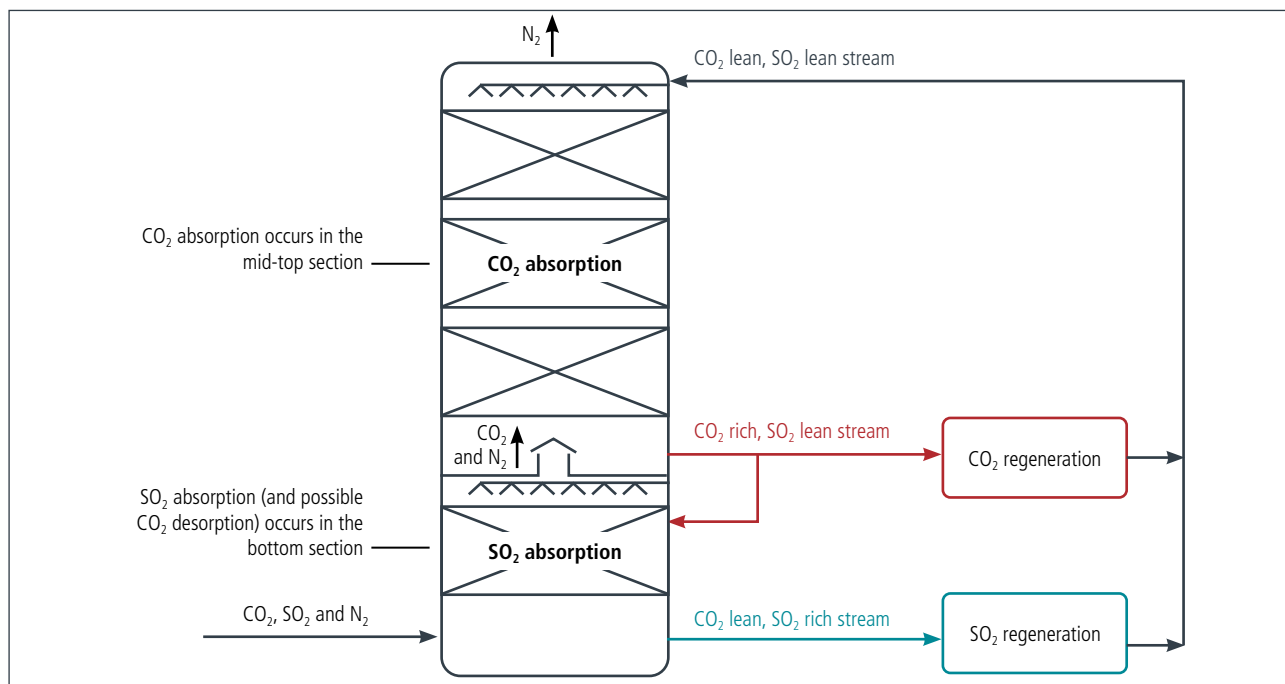
Figure 47: TNO CASPER process



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

The second stream involved pilot scale testing of a novel amine-based solvent developed by CSIRO (building on experience gained in the previous project) and a novel post-combustion capture process configuration, dubbed 'CS-CAP' (Figure 48).

Figure 48: CSIRO CS-CAP process



In this patented process, both CO₂ and SO₂ are removed using a single column and a single solvent. CO₂ is absorbed using the bulk of the solvent in the upper section of the column while SO₂ is absorbed in a fraction of the solvent in the lower section of the column. The concentrated SO₂ stream can be recycled, while the bulk of the solvent remains SO₂ free.

Both the TNO CASPER process and the CSIRO CS-CAP process were able to capture over 90% of the CO₂ in the flue gas and all of the SO₂, irrespective of the concentration in the flue gas. A model for the sulphur chemistry as a function of SO₂, CO₂ and absorbent composition was validated. Both technologies were shown to have the potential to capture SO₂ and CO₂ simultaneously, eliminating the need for a separate flue gas desulphurisation step.

A techno-economic assessment suggested that the CASPER process should represent a cost saving of about A\$200 million for a 500 MW plant fitted with amine-based post-combustion capture. The cost of CO₂ avoidance using the CASPER process, assuming retrofit to a fully amortised 500 MW lignite boiler,

was estimated at A\$78 / tCO₂. Equivalent costings for the CS-CAP process were not possible, as the solvent regeneration process was not optimised.

Combined low-cost pretreatment of flue gas and capture of CO₂ from lignite-fired power stations using a novel integrated process concept; closing the sulphur loop (coCAPCO₂)

This project was led by Dr Erik Meuleman of CSIRO, building upon the previous BCIA-funded coCAPco project. The project examined the feasibility and cost-effectiveness of a range of methods for regeneration of the SO₂-loaded amine solvent produced in CSIRO's CS-CAP process. Ms Bharti Garg, a PhD student

at Federation University, investigated alternative regeneration methods (crystallisation, nanofiltration, electro-dialysis, ion-exchange and distillation) using SO₂-loaded solvent from CSIRO's PCC pilot plant at Loy Yang power station.

Critical assessment of potential regeneration technologies, including their potential for scale-up and incorporation into the CS-Cap process, identified two for additional experimental evaluation: thermal reclamation and reactive crystallisation. Laboratory experiments confirmed the ability of both processes to regenerate the absorbent, and provided data on the chemical requirements and effectiveness of both processes over a range of operating conditions.

An Aspen Plus process simulation was developed for both technologies and validated against experimental data. The simulation was used to size and cost the equipment required for full-scale application of the CS-Cap process. The high-level economic analysis showed that the un-optimised CS-Cap process had a lower capital cost compared to conventional flue gas desulphurisation, but a higher operating cost. Further process optimisation is required.

The next step in the development of this technology will be to design a crystallisation unit that can be evaluated at pilot-scale. Pilot-scale evaluation will provide useful information on the practical operating results of the process, and provide updated information for a more detailed economic comparison.

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

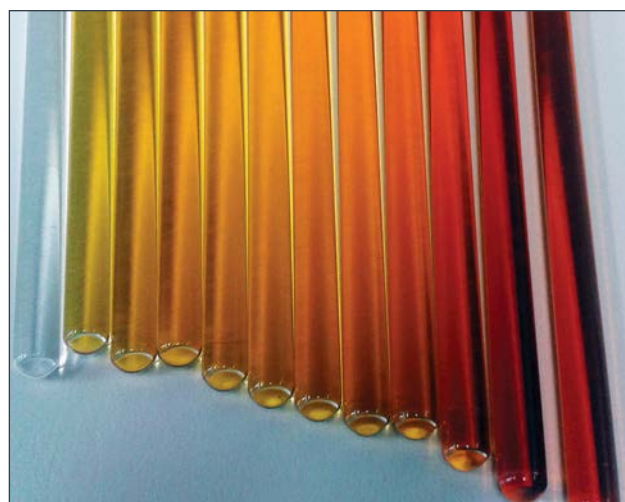
This project was undertaken by Ms Alicia Reynolds, a BCIA-funded PhD scholarship recipient at Monash University Gippsland (now Federation University). The objectives of this study were as follows.

- ▶ 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 amenable to online 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 PCC pilot plant (Figure 49). 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 49: 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.⁽³⁷⁾

(37) Reynolds, A. J., Verheyen, T. V., Adeloju, S. B., Chaffee, A. L., & Meuleman, E. (2015). Monoethanolamine degradation during pilot-scale post-combustion capture of CO₂ from a brown coal-fired power station. *Energy & Fuels*, 29(11), 7441-7455.

Solvent degradation during PCC

BCIA provided scholarship support for this project by Mr Rahul Chowdhury, a PhD student at Federation University. The objectives of this project 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, post-combustion capture plant integrity and environmental effects.
- ▶ Investigate the impact of PCC operating conditions on important heterogeneous reactions and interactions.
- ▶ Develop operation and design guidelines to minimise and manage the impact of heterogeneous interactions on PCC solvent management and plant integrity.

A key finding of this project was that contamination of the solvent with residual fly ash particles is the major cause of corrosion and solvent degradation. The insoluble fly ash component was essentially inert, with minimal impact on MEA oxidation and corrosion.

The soluble ash components (e.g. Na, Ca, Mg) increased corrosion severity and promoted MEA oxidation. This highlights the need for deep fly ash removal prior to PCC, particularly for ashes with high solubility in the solvent system.

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- Artanto Y, Jansen J, Pearson P, Puxty G, Cottrell A, Meuleman E, & Feron P (2014). Pilot-scale evaluation of AMP / PZ to capture CO₂ from flue gas of an Australian brown coal-fired power station. *International Journal of Greenhouse Gas control*, 20, 189-195.
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- Cousins A, Pearson P, Puxty G, Huang S, Feron P, Garg B, & Verheyen V (2018). CS-CAP: Development of an SO₂ tolerant post combustion CO₂ capture process. *Carbon Capture Journal*, July-August 2018, pp. 2-3.
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- Reynolds, AJ, Verheyen, TV, Adeloju, SB, Chaffee, AL, & Meuleman, E (2015). Monoethanolamine degradation during pilot-scale post-combustion capture of CO₂ from a brown coal-fired power station. *Energy & Fuels*, 29(11), 7441-7455.

Improved Solvent Absorption Hardware

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 CO₂ capture.

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

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 CO₂ 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 / CO₂ gas mixture (Figure 50), and in the CO₂CRC pilot plant at the GDF Suez Hazelwood power station.

Figure 50: Internals of laboratory-scale WES froth absorber



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.

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, the complexity of the co-current gas / liquid flow created by the WES internals meant that a workable CFD model was beyond the capability of current programs and hardware. 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 required length of absorber column.

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 & Liu ZB (2012). Absorber, WO2012112224, 23 August, 2012.

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Physical Adsorption Systems

The most widely adopted approach for CO₂ capture is to use chemical solvents, which can absorb CO₂ by chemical reaction during the capture stage and then release the CO₂ 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 CO₂ capture technologies for lignite 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 CO₂ capture, using syngas from HRL's pilot-scale air-blown gasifier. The objectives as follows.

- ▶ Evaluate solvent, adsorbent and membrane pre-combustion capture techniques.
- ▶ Reduce the technical risk and cost of capturing CO₂ from pre-combustion sources.
- ▶ 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 CO₂ capture. This technology has the potential to recover CO₂ with relatively low energy consumption, while CO₂ 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 1 kPa (Figure 51). The pilot rig was operated in conjunction with an in-house process simulator, MINSAs (Monash Integrated Numerical Simulation of Adsorption), a powerful tool for evaluating cycle design and investigating the effects of a large number of variables on CO₂ capture performance. The simulation results were as follows.

- ▶ Design novel pressure vacuum swing adsorption 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 51: Operation of the pilot adsorption system on the HRL Mulgrave gasifier



Preliminary process modelling work with MINSA indicated that pressure swing vacuum adsorption 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 CO₂ capture at high temperatures.

Pilot-scale results of pressure swing vacuum adsorption with zeolite 13X showed that sophisticated operating cycles could produce CO₂ concentration greater than 95%, the target for effective transportation and sequestration of CO₂.

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 CO₂ capture: CO2CRC stream

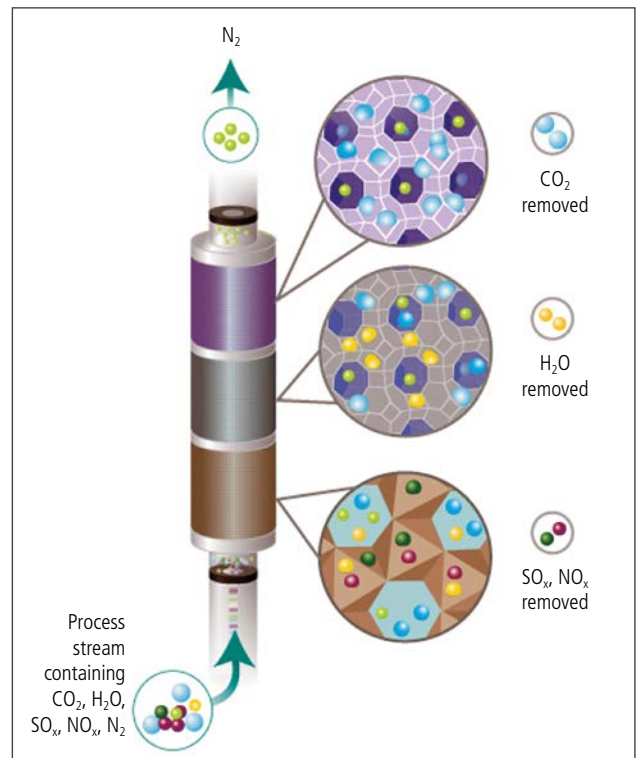
The CO2CRC led a post-combustion capture project at the GDF-SUEZ Hazelwood power station, representing a world first in demonstrating post-combustion capture using three different separation technologies (solvents, membranes and adsorption) in parallel in a real power plant setting. The objective of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

- ▶ Testing solvent, adsorbent and membrane post-combustion capture techniques with real power plant flue gas.
- ▶ Reducing the technical risk and cost of capturing CO₂ 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 CO₂-selective adsorbent materials (Figure 52). Water-selective adsorbents removed the water in the gas stream, and acid resistant adsorbents removed SO_x and NO_x.

Figure 52: Multilayer adsorption



The pilot rig (Figure 53) 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 53: 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 CO₂ capture using vacuum swing adsorption. Simulations indicated that high CO₂ purity and recovery should be possible through careful management of the CO₂ 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 CO₂ 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 lignite for CO₂ capture

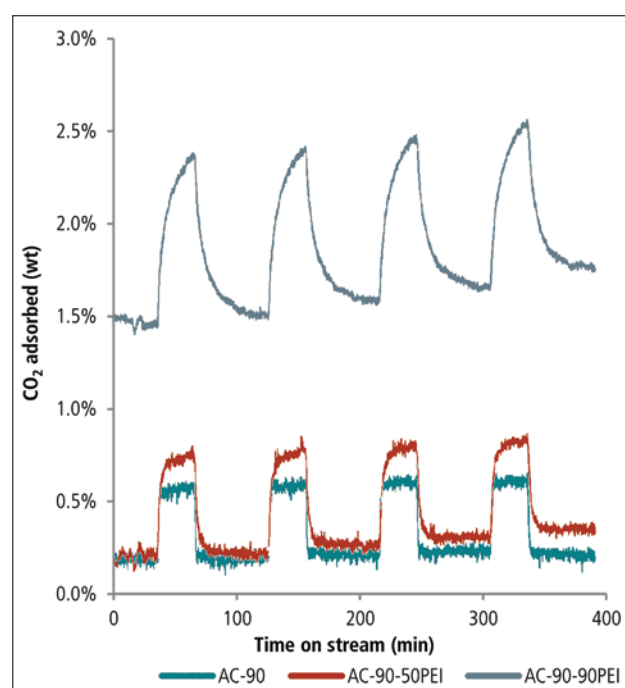
A large part of the cost of adsorption systems is due to the need to regularly replace the adsorbent bed and dispose of the waste materials. Costs could be reduced significantly if the adsorbent bed could be fabricated from low-cost Victorian lignite. Waste disposal costs could then be minimised by burning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

Monash University undertook an investigation of the potential to produce activated carbons from Victorian lignite for use in CO₂ 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. Surface impregnation with polyethyleneimine (PEI) further modified some of the mesoporous carbons, which further increased the CO₂ adsorption capacity (Figure 54). All of the resulting mesoporous carbons showed a higher CO₂ adsorption capacity than the commercial activated carbon standard.

Figure 54: Multi-cycle CO₂ adsorption of modified activated carbons



Evaluation of carbon monoliths for capture of CO₂ by Electrical Swing Adsorption

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

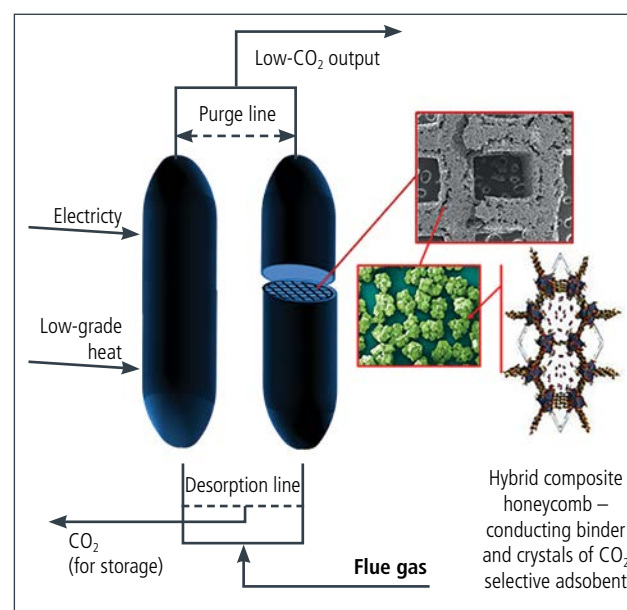
The project focused on the development of carbonaceous adsorbent monolithic solids that could be used to capture CO₂ in a process known as electrical swing adsorption (Figure 55). The monoliths must be electrically conductive so that the CO₂ can be recovered (desorbed) in a concentrated form by applying electrical current.

Research involved the fabrication of improved adsorbents, their evaluation at bench scale and process and process integration modelling. All this was considered in a life cycle analysis context to determine optimum configurations to reduce the environmental impact. This information provided 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, pursued the development of carbon monoliths from Victorian lignite. These were fabricated and tested at laboratory scale for their physical strength and electrical conductivity. Their capacity and selectivity in separating CO₂ from other components of flue gas was evaluated both in their own right and after incorporation of a metal organic framework.

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

Figure 55: Conceptual diagram of electrical swing adsorption



Key Publications

Ciddor LA, Knowles GP, & Chaffee AL (2013). Improving the CO₂ 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, Sept 29, Oct 3, 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 CO₂ 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). CO₂ capture at elevated temperatures by cyclic adsorption processes. RSC Advances, 2, 5291-5297.

Zhang J, Xiao P, Li G, & Webley PA (2009). Effect of flue gas impurities on CO₂ capture performance from flue gas at coal-fired power stations by vacuum swing adsorption. Energy Procedia, 1, 1115-1122.

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 CO₂ from other gases (gas separation membranes) or to allow CO₂ to be absorbed from a gas stream into a solvent (membrane gas absorption).

In the context of power production from lignite, there are two main ways that membranes can be used for CO₂ capture: either for pre-combustion capture or post-combustion capture. The term 'pre-combustion capture' relates specifically to coal gasification processes, in which CO₂ 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 CO₂ from syngas before it is transformed into value-added products. Post-combustion capture involves recovery of CO₂ from the flue gas exiting a furnace or boiler.

The main difference between these two CO₂ 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. sulphur is present as H₂S in syngas and SO₂ 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 supported two research projects and two PhD scholarships to evaluate the potential of membranes in cleaning emissions from lignite processes.

Pre-combustion CO₂ capture technologies for lignite power generation

The Pre-Combustion CO₂ 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 CO₂ capture, using syngas from HRL's pilot-scale air-blown gasifier (Figure 56). The objectives were as follows.

- ▶ Evaluate solvent, adsorbent and membrane pre-combustion capture techniques.
- ▶ Reduce the technical risk and cost of capturing CO₂ from pre-combustion sources.
- ▶ Identify the most cost-effective technologies for deployment in Victoria.

Figure 56: CO₂CRC membrane pilot plant at HRL Mulgrave gasifier



Membranes composed of poly dimethyl siloxane (PDMS), a rubbery polymer, performed best under syngas conditions, exhibiting high CO₂ permeability as well as good CO₂/H₂ and CO₂/N₂ selectivity. The CO₂ permeability of the PDMS membrane decreased over a six to eight 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, H₂S 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 CO₂ 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 CO₂ purity of 96%.

The best performing H₂-selective membrane was a nanoporous carbon membrane, which achieved adequate H₂/CO₂ and H₂/N₂ selectivity at high temperature. Matrimid membranes also showed potential for H₂ 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 CO₂ 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 57).

Figure 57: Membrane pilot plant at Hazelwood power station



The objective of the project was to reduce the technical risk and cost of post-combustion capture for Victorian lignite-fired power stations in the following ways.

- ▶ Testing solvent, adsorbent and membrane post-combustion capture techniques with real power plant flue gas.
- ▶ Reducing the technical risk and cost of capturing CO₂ 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 CO₂ from flue gas, to determine which membrane technology has the greatest potential for successful post-combustion capture.

The membrane pilot plant was designed to separate out around 15 tonnes CO₂ per year, and could operate the following two membrane separation processes in parallel.

- ▶ A gas separation membrane (Air Products PRISM polysulfone membrane), where the membrane is a nonporous polymer selective for CO₂ and the permeate stream is under vacuum.
- ▶ A membrane gas-solvent absorption contactor, where CO₂ 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 CO₂ 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.

With the membrane gas-solvent absorption contactor, 85% of the CO₂ in the flue gas was absorbed into BASF PuraTreat™ F solvent. The potassium carbonate solvent was much less efficient at absorbing CO₂, since 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: N₂, CO, NO, CO₂. The polyimide membranes exhibited higher permeability for each gas than the polysulfone membranes.

With the Matrimid 5218, CO₂ was adsorbed faster than CH₄ and N₂, 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 (<2 µm thick). With use, interaction with CO₂ 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% CO₂ 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% CO₂ 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 lignite flue gases

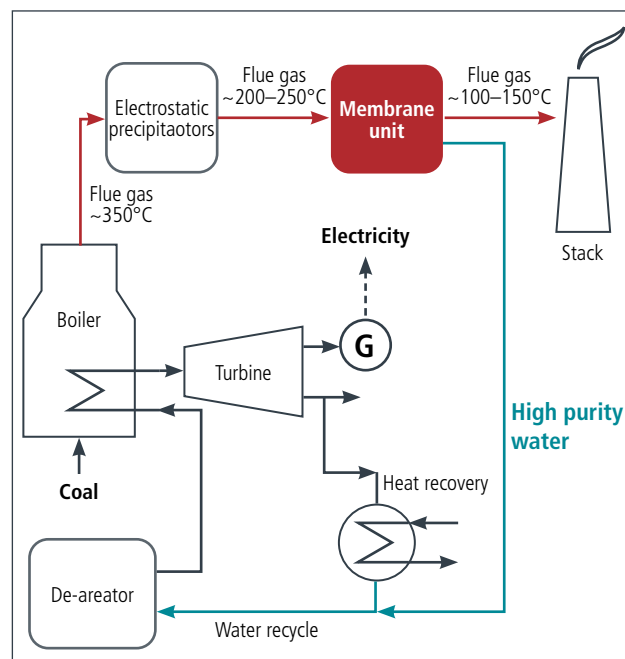
At its peak, approximately 60 million tonnes of lignite was burned for power generation in the Latrobe Valley each year. Since lignite contains about two-thirds moisture, about 40 million tonnes of water was discharged annually to the atmosphere as moisture in the flue gas. This represents a valuable resource that could potentially be recycled for use as boiler feed water, but the water recovered needs to be of a high purity. The presence of CO₂, SO_x and NO_x in the recovered water would make it acidic and cause corrosion problems in the boiler.

Membrane technology can potentially allow recovery of high purity water from boiler flue gas (Figure 58). Membrane materials such as Nafion™ are almost 100% selective for water, allowing production of near-drinking quality water supplies. Previously, studies have focussed 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–150°C.

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, CO₂ and N₂ 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 CO₂ at 150°C were also studied for four other candidate polymers. Nafion 112 exhibited the highest H₂O / CO₂ selectivity.

Figure 58: Schematic diagram of a coal-fired power plant with a membrane unit to recover and recycle water vapour



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.

Impact of impurities on performance of cellulose acetate membranes for CO₂ separation

Cellulose acetate membranes are widely used in industrial gas separation processes and represent over 90% of the capacity of membranes used for H₂S removal from natural gas. Their commercial availability makes them ideal candidates for use in CO₂ capture applications.

However, the effect of gaseous components such as water, H₂S, SO_x and NO_x on the performance of these membranes at flue gas temperatures is unknown.

BCIA provided scholarship support for this project to Mr Hiep Lu, a PhD student at the University of Melbourne. The objectives of this project were to produce data to quantify the effects of flue gas impurities on cellulose acetate membranes and develop a process design modelling tool.

The project established the practical feasibility of using cellulose acetate membranes for CO₂ recovery in lignite power stations. Cellulose acetate is a viable membrane material for post-combustion capture provided it can be formed into an ultrathin supported film to increase permeance.

CO₂ Dispersion Modelling

Effective deployment of carbon capture and storage infrastructure in Australia will require pipelines to transport compressed CO₂ 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 CO₂ are not known and present uncertain risks. Figure 59 shows installation in the US of a pipeline for transporting CO₂.

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 CO₂ 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 CO₂ is that natural gas is lighter than air, while CO₂ is heavier. In any event where gas is released from a pipeline, the dispersion of CO₂ 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 CO₂ is not. However, CO₂ 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 CO₂ pipelines. In order for a CO₂ 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 CO₂ into the atmosphere.

BCIA supported and managed a project that investigated the application of CO₂ dispersion modelling in the context of new CO₂ pipeline

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.

Lu HT, Kanehashi S, Scholes CA, & Kentish SE (2016). The potential for use of cellulose triacetate membranes in post combustion capture. *International Journal of Greenhouse Gas Control*, 55, 97-104.

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.

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 CO₂ release projects.

The investigation considered a series of modelling tools that may be regarded as fit for purpose for simulating the dispersion characteristics of CO₂ gas. The assessment was based on the following criteria.

- ▶ Availability, ease of use, access to technical support.
- ▶ Ability to calculate appropriate source terms for different CO₂ release scenarios.
- ▶ Validation history, particularly with CO₂.
- ▶ 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 CO₂ 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. The project identified appropriate models for each of these.

The project investigated a range of dense gas dispersion models, including empirical correlations, integral models, Lagrangian particle and plume dispersion models and computational fluid dynamics models. Selected models were reviewed and evaluated against the various criteria to determine their suitability.

One of the main conclusions was that sufficient information and modelling tools are available to allow a new CO₂ pipeline to be designed in accordance

with Australian Standard 2885. The project produced a comprehensive report that provided guidance on international best practice in modelling CO₂ dispersion, and identified appropriate 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 allows the risks associated with new CO₂ pipelines to be reduced to as low as reasonably practicable, equivalent to the community expectations for natural gas pipelines.

Figure 59: A CO₂ pipeline being laid in the US



CO₂ Sequestration

Carbon Capture Task Force

In Victoria, the main focus for CO₂ storage has been 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 CO₂. 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.⁽³⁸⁾

- ▶ Bio-sequestration is the capture and storage of atmospheric CO₂ 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 CO₂ from industrial processes.
- ▶ Mineral sequestration, or mineral carbonation, involves reaction of CO₂ 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 made the following recommendations in relation to these novel technologies.⁽³⁹⁾

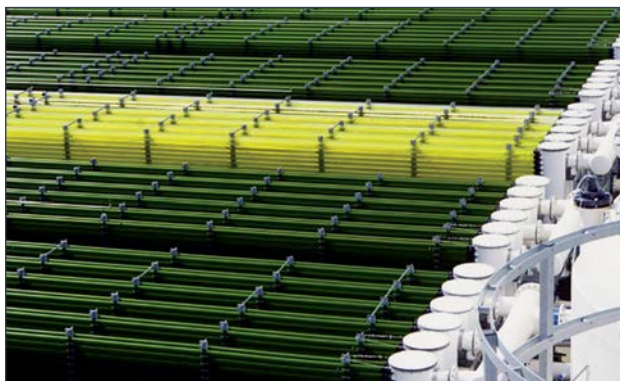
(38) © Global CCS Institute (www.hub.globalccsinstitute.com/publications/novel-co2-capture-taskforce-report/executive-summary).

(39) © Global CCS Institute (www.hub.globalccsinstitute.com/publications/novel-co2-capture-taskforce-report/recommendations).

1. The growth of algae by consumption of CO₂ from coal-fired power stations using photosynthesis can provide a relatively small contribution to the stations' overall CO₂ emissions (Figure 60). The R&D on algae for CO₂ mitigation should be focused on the following.

- ▶ Increased algal productivity, including new algal species research.
- ▶ Reduction of capital costs and raw material requirements.
- ▶ Increased mass transfer efficiency for CO₂ absorption in bio-reactors at low CO₂ concentrations.

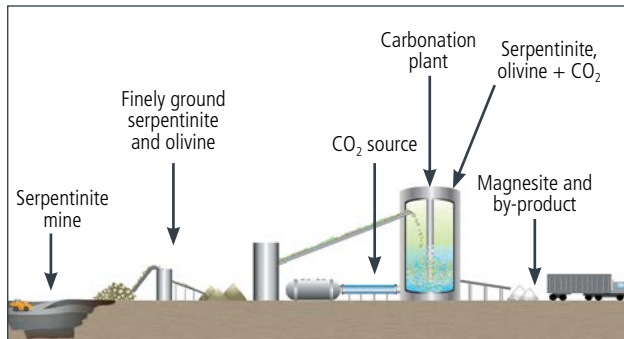
Figure 60: Large-scale cultivation of microalgae



2. Mineral carbonation technology in Australia apparently follows two streams; (i) development of the work undertaken previously in the US on serpentine rock heat activation followed by reaction with CO₂; and (ii) technologies based on novel chemistry and flowsheets (Figure 61). Since the technology offers the scale and permanency required for the capture of CO₂ from coal-fired power stations close to the rock resources, the Task Force recommended that research, development and demonstration in the following areas.
- ▶ 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 61: Conceptual scheme for mineral carbonation



- The regulatory environment for forestry sequestration of CO₂ from the atmosphere in terms of credits for CO₂ 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.
- Sequestration through soil carbon enhancement has potential to make a contribution to CO₂ 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 CO₂ and other greenhouse gas 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 62).

Figure 62: Sampling agricultural soil carbon content



- Biochar is a potential soil amendment that could provide permanence while improving agricultural outcomes (Figure 63). 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 63: Biochar for soil amendment



- Life cycle analysis should be routinely employed in any analysis of CO₂ sequestration by the above technologies.

Catalytic flash pyrolysis of lignocellulosic biomass for furfural synthesis

- ▶ ACI is providing support for a project at Monash university aimed at producing both biochar and value-added furfural from lignocellulosic biomass. The project is led by Professor Lian Zhang, in collaboration with Advanced Fuel Innovation Pty Ltd and CSIRO Energy.
- ▶ Furfural is a bio-based platform chemical with an estimated worldwide production of approximately 300,000 tonnes / year, with Australia importing

5,000 tonnes per year. However, the commercial process based on batch hydrolysis is inefficient, being only able to utilise C5-rich hemicellulose while abundant C6 glucose is wasted. Moreover, the process is environmentally unfriendly, as it discharges plenty of waste acids, and unused organic solvent and solid residues in a black liquor form.

Professor Zhang has developed and patented a new catalytic flash pyrolysis technology that can process biomass with high throughput in a few seconds, thereby potentially increasing the process cost-benefit ratio remarkably. A novel zinc sulphate-rich catalyst has been developed from waste car tyres that can convert both C5 and C6 sugars into furfural, creating a second value-added product in addition to the biochar.

A pilot plant has been built as a step toward commercialisation of the process. ACI is supporting this effort through two PhD Top-up Scholarships. Mr Jingwei Wang is working on development of supported catalysts, and Mr Nauman Ahmad is working on improving the efficiency of bio-oil product separation.

Key Publications

- Burgess J, Jeffery L, Lowe A, Schuck S, & Flentje W (2011). Novel CO₂ Capture Task Force Report.
- Sherpa Consulting (2015). Dispersion modelling techniques for carbon dioxide pipelines in Australia. Available from the Global CCS Institute website.
- Zhou Q, & Zhang L (2022). Process for producing furfural and catalyst for use in same. World Patent Application WO 2022 / 204765.
- Zhou Q, Gu J, Wang J, De Girolamo A, Yang S, & Zhang L (2023). High production of furfural by flash pyrolysis of C6 sugars and lignocellulose by Pd-PdO / ZnSO₄ catalyst. Nature Communications, 14(1), 1563.

Carbon Dioxide Recycling

A variation on the theme of CCS is Carbon Capture and Utilisation (CCU), in which the captured CO₂ is converted into other products with higher economic value (e.g. methanol, plastics, concrete, and reactants for various chemical synthesis). This is also known as 'CO₂ recycling'. The aim of CO₂ recycling is to reduce overall net emissions of greenhouse gases by recycling captured CO₂ back into the production chain and creating revenue to offset to cost of CO₂ capture.

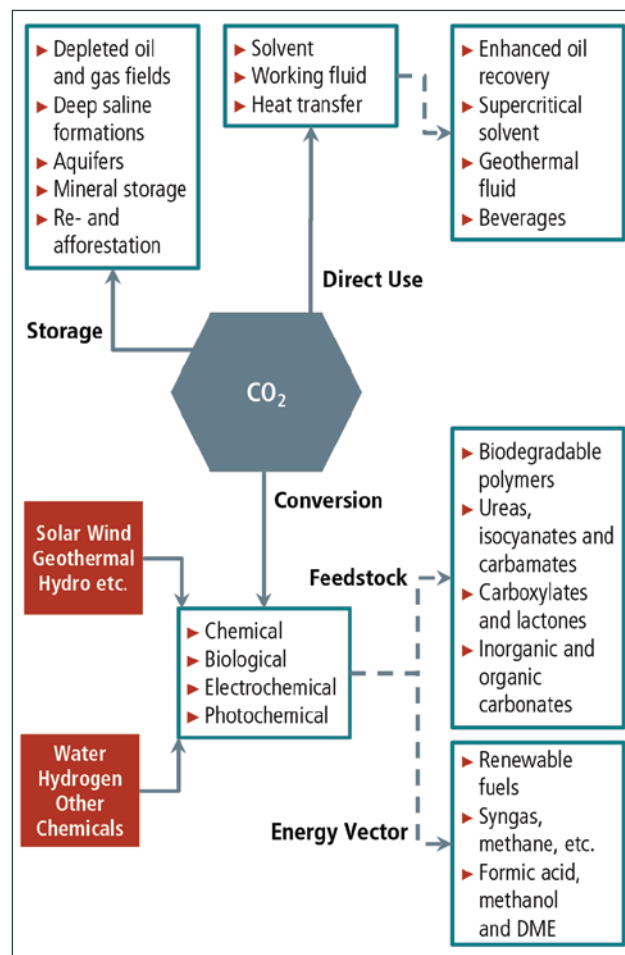
The development of CO₂ recycling technologies, and successful businesses based upon them, is essential to effectively address the collective challenge presented by rapid global warming. To limit global warming to 1.5°C, the IEA warns that CO₂ must be extracted from the atmosphere as a matter of urgency, but the quantities required will require a gargantuan effort over the next 50 years and longer. A global shift of emphasis toward net-negative emissions is needed, which requires large-scale capture of atmospheric CO₂ and permanent storage of the CO₂ both underground and in manufactured products.

While the idea of CO₂ recycling is inherently appealing, in practice it is quite challenging and often quite complex. CO₂ is the end product of combustion and respiration processes, making it a highly oxidised and thermodynamically stable molecule. Upgrading it to more valuable products requires some ingenuity. However, a wide variety of approaches have been developed to add value to captured CO₂, as illustrated in Figure 64.

To date, ACI has invested very limited funds in this area, although the scope is much greater. In 2022, it provided support funding for a PhD project at Monash University, investigating a 'green' synthesis pathway for conversion of CO₂ into an important solvent used in manufacture of storage batteries for renewable energy systems.

In 2023, ACI was commissioned to prepare a report on opportunities for CO₂ recycling in Victoria.

Figure 64: Pathways to utilisation of carbon dioxide



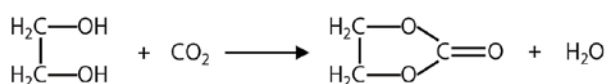
Ethylene carbonate via catalytic carboxylation of CO₂ with ethylene glycol

Ethylene carbonate (EC) is the preferred solvent for use in lithium-ion batteries. The growing demand for electric vehicles is driving growth in the global market for EC, which is expected to grow from US\$288 million in 2019 to US\$418.5 million in 2027.⁽⁴⁰⁾ However, the current industrial process for EC synthesis involves reaction of CO₂ with ethylene oxide, which is a toxic petrochemical.⁽⁴¹⁾

(40) Parihar, Y., & Prasad, E. (2020). Ethylene Carbonate Market (www.alliedmarketresearch.com/ethylene-carbonate-market-A07307).

(41) Clements JH (2003). Reactive applications of cyclic alkylene carbonates. *Industrial & Engineering Chemistry Research*, 42(4), 663-674.

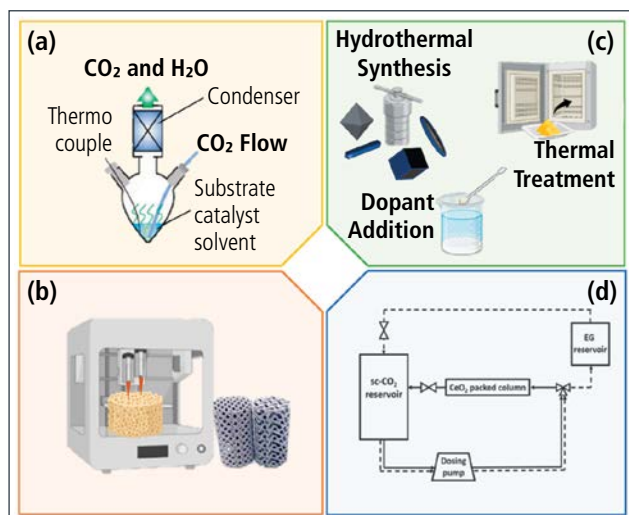
ACI is providing top-up scholarship support for a PhD student at Monash University, Ms Wei Lin Ng, supervised by Professor Sankar Bhattacharya, who is investigating an alternative 'green' synthesis pathway by direct carboxylation of ethylene glycol:



Ethylene glycol (EG) can be readily synthesised from glycerol, which is a byproduct of the biodiesel and soap manufacturing industries, so production of EC by carboxylation of EG is an attractive renewable pathway (Ng et al. 2023).

The research at Monash University is aimed at overcoming the key challenge associated with this reaction pathway, which is end-product limitation due to accumulation of water as byproduct. The experimental strategies being investigated, shown in Figure 65, include catalyst synthesis on a 3D printed support, continuous flow operation and continuous removal of water by sparging with CO₂.

Figure 65: Experimental strategies to overcome the limitations of EC production by carboxylation of EG. (a) Continuous removal of H₂O by gas stripping; (b) 3D-printed catalyst; (c) Catalyst morphology control; (d) Continuous-flow reaction



Source: © CO2CRC.

Opportunities for CO₂ recycling in Victoria

In 2023, ACI was commissioned by CarbonNet to undertake a comprehensive review of the opportunities for CO₂ recycling in Victoria. This report provided an overview of the following five major classes of CO₂ recycling process.

- ▶ Direct Use of CO₂
- ▶ Biological Conversion
- ▶ Inorganic Carbonation
- ▶ Catalytic Chemical Conversion
- ▶ Electrochemical Conversion

In each category, the report included the companies that are championing commercial development of their processes, relevant research work (if any) currently under way in Victoria, plus ACI commentary on their readiness for commercialisation and the opportunities they present for Victoria.

This report found that Victoria is very well placed to take a leading role in addressing the global warming challenge. The report identified thirteen technologies that have potential to make significant and meaningful contributions to Victoria's economic growth and emissions reduction efforts.

The selected technologies, listed in Figure 66, range from ‘fully commercial’ to ‘needs more work’, with projected commercialisation timeframes in the short-, medium-, and long-terms.

Figure 66: Summary of identified opportunities for CO₂ recycling in Victoria

CO ₂ Recycling Technology	Product Opportunities Arising	Developmental Status	Rationale for Selection
Urea	Import replacement of a major fertiliser used in Australian agriculture.	Commercial and gasification tested by two commercial vendors.	Actively being investigated for commercialisation in Victoria.
Carbonation of concrete	Reduced emission intensity of concrete in construction and infrastructure projects.	Commercial and now available in Australia.	CO ₂ alone gives an immediate reduction in a major industry sector. Potential to double the reduction using baking soda. Potential to incorporate DAC or biogenic CO ₂ for greater emissions reduction.
Glasshouse horticulture	Reduced use of CO ₂ produced by natural gas combustion in glasshouse production of tomatoes, herbs, flowers, pharmaceutical cannabis, etc.	Already used commercially in some places overseas, but not yet widespread in Australia.	Immediate boost to an existing horticulture industry in the Latrobe Valley. Many product opportunities. Potential for domestic and/or export markets. Opportunities for value-adding using S-CO ₂ . Biomass waste can be gasified to green hydrogen.
Supercritical CO ₂ processing (S-CO ₂)	Solvent-free extraction of oils and de-fatting of seed proteins for food ingredients; water-free textile dyeing.	A small food ingredients company in Tasmania, but otherwise not yet commercialised in Australia.	New business opportunity in water-free textile dyeing. Potential for opportunities in defatting of hemp seeds, fruit / vegetable powders, natural colours and flavours, edible and pharmaceutical oils, bioingredient extracts (e.g., hop, pharmaceutical cannabinoids).
Bipolar membrane electrodialysis (EDBM)	Production of acids and alkalis from simple salts using renewable energy, producing alkali for use in CO ₂ capture, production of sodium bicarbonate, etc.	Commercially available, used in water industry.	Versatile technology, enabler of new opportunities, compatible with renewable energy. Produces NaOH for production of baking soda, carbonation of fly ash, and DAC.
Ca / Mg carbonate	Additive for ‘green’ concrete and plasterboard.	Commercialised overseas, and being investigated by Mineral Carbonation International in NSW.	Synergistic with baking soda production. Direct link to DAC, and route to adding value to DAC.
Ethanol	Important biofuel and precursor to ethylene, a major industrial feedstock.	Early-stage R&D overseas, but poised to take off.	‘Green’ polyethylene could be produced in Victoria, to make non-biodegradable, recyclable plastics.

CO ₂ Recycling Technology	Product Opportunities Arising	Developmental Status	Rationale for Selection
Carbonated fly ash	Transformation of a hazardous waste into aggregate for 'green' concrete.	Commercialised overseas, but hindered by prescriptive building standards.	Simple chemistry. Ideal way to monetise the massive amount of heritage waste fly ash in the Latrobe Valley. Potential for a variety of low-emissions concretes and building materials for the construction industry. Links to Ca / Mg carbonate and DAC.
Syngas by SOE	High efficiency production of syngas using renewable energy, key enabler for many other products.	Under development by CSIRO and collaborators.	Syngas a versatile industrial chemical feedstock. SOE is more economical at small scale than gasification. Scale appropriate for biological conversion to ethanol or edible biomass.
Methanol	Important chemical industry feedstock.	Commercial overseas, but more expensive than conventional product. Research needed for more efficient catalyst.	A major industrial chemical feedstock. Research interest / expertise in Victoria to build upon.
Ethylene carbonate	Important 'green' chemical industry feedstock and solvent in lithium-ion batteries.	Improved catalyst and reactor design for renewable feedstock being researched at Monash University.	Potential for domestic production of 'green' solvent for lithium-ion batteries. Research interest / expertise in Victoria to build upon.
Lignin-based polurethane	Versatile route to plant-based plastics, rubbers and adhesives.	Early-stage exploratory.	Potential to add value to lignin waste from Latrobe Valley papermaking plant.
Hydrogen-oxidising bacteria	Proteins for human and animal food.	Engineering R&D required to scale up a potentially explosive gas fermentation.	Potential for production of edible biomass / protein for aquafeed and human food products. Alternative to using biological conversion of syngas.

The anticipated timeframe for commercialisation of each technology is shown in Figure 67. The technologies listed as 'short-term' have been commercialised overseas and could form the basis of new businesses in Victoria.

Figure 67: Timeframe for commercialisation of prospective CO₂ recycling opportunities

TRL 1-3		Ethanol Ethylene carbonate Lignin-based polyurethane H ₂ -oxidising bacteria	
TRL 4-6	Carbonated fly ash Ca/Mg carbonates Syngas by SOE Methanol / EDBM		
TRL 7-9	Concrete carbonation Glasshouse Horticulture S-CO ₂ Processing	Urea	
	Short-term	Intermediate	Long-term

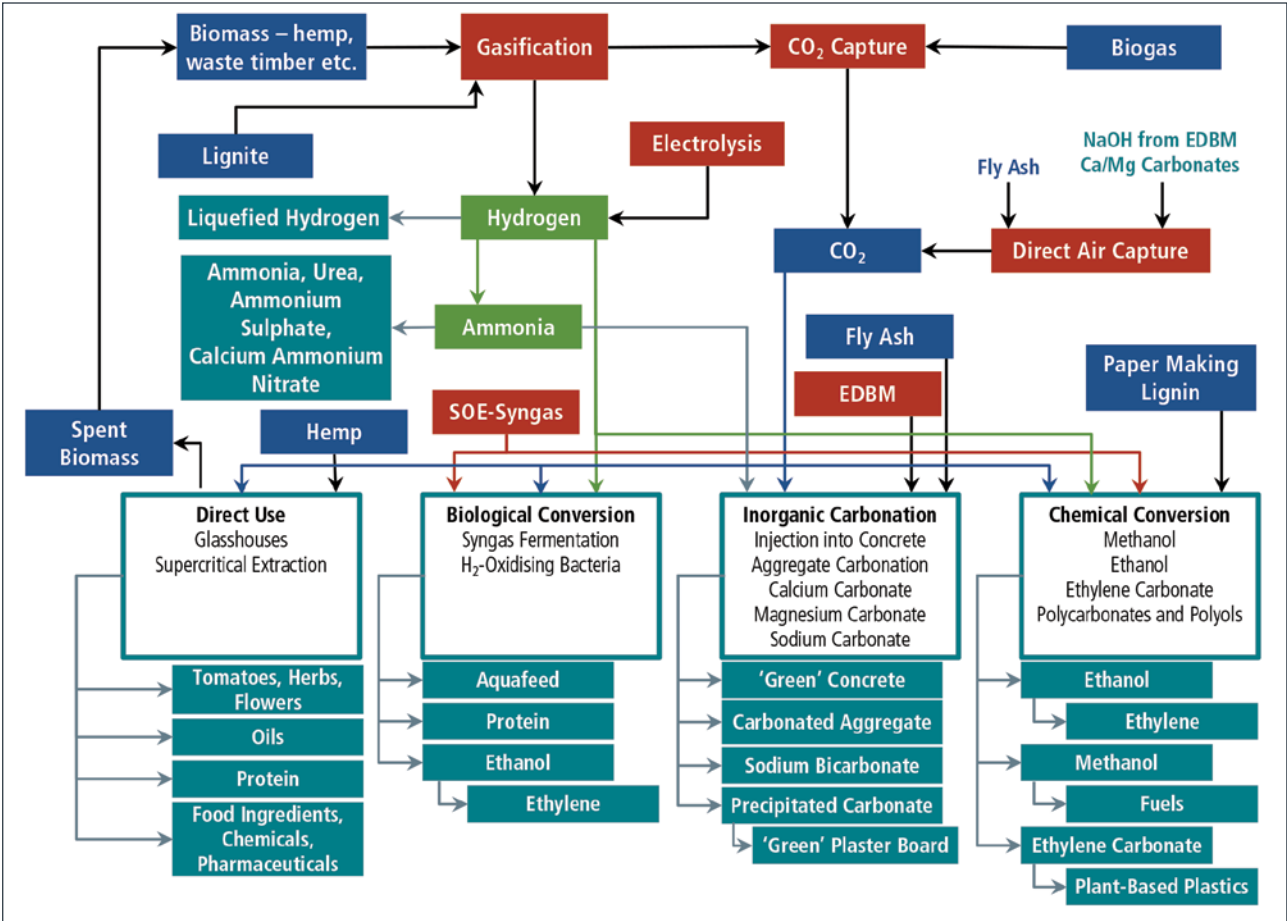
This portfolio of technologies includes a mixture of technologies that are mostly at commercial or pilot scale, with some requiring fundamental research to develop their potential. These technologies were selected because they have the potential to create and support an ecosystem of interdependent new industries in the Latrobe Valley, making use of the resources that could conceivably become available over time. Fortunately, an existing research skills base is available in Victoria to support this technology development pathway for CO₂ recycling, and work is already occurring on some of the nominated technologies.

Valley. It is assumed that low-emissions hydrogen and/or ammonia will be commercialised in the Latrobe Valley in the not-too-distant future, and that there is an abundant supply of CO₂ that can be tapped off from a transport pipeline for recycling.

It is also assumed that barriers to remediation of the massive stockpiles of power station fly ash are successfully overcome. Local sources of renewable energy (wind, solar, geothermal) could be used for electricity and heat, and strategically-planted crops of plantation timber and/or industrial hemp are a potential source of biomass. Both direct air capture (DAC) and biogas could produce carbon-neutral CO₂ for upgrading.

Figure 68 shows the types of connections that could be made, and the range of products that could be produced, in a green technology hub in the Latrobe

Figure 68: Identified prospective opportunities for CO₂ recycling in Victoria



The identified CO₂ recycling opportunities are broadly aligned with the findings of previous reviewers, including CSIRO's 'CO₂ Utilisation Roadmap', while also reflecting the unique resources available in Victoria; in terms of natural resources, commercial interests, and existing research activities.

A key finding of this report is that a variety of technologies for inorganic carbonation have already passed through the R&D phase and been successfully commercialised overseas. CarbonCure has standardised its system for injection of CO₂ into concrete slurry and sold more than 650 units in thirty countries, producing about 5 million truckloads of low-carbon concrete.

Systems for producing low-carbon concrete blocks, slabs, pavers and tiles have been commercialised by Solidia, Carbicrete, CarbonBuilt. Carbon8 Systems has commercialised its process for direct carbonation of solid wastes, and Blue Planet has commercialised its process for continuous extraction of Ca / Mg from solids and precipitation as Ca / Mg carbonates. CarbonFree has commercialised its process for producing baking soda using hydroxide extracted from low-cost salts.

This is significant, because these represent high-volume low-value markets that can achieve significant CO₂ emission reductions, mostly for the construction sector, including concrete formwork, pre-formed concrete blocks, slabs, etc., insulation and plasterboard. This is an ideal way to foster a low-emissions economy, because the captured CO₂ is permanently sequestered into valuable products in a sector that is large and continually growing.

As such, inorganic carbonation is an area of R&D that urgently needs to be kick-started in Australia. Coordinated research by both industry and academia is required, supported by policy direction from the government. The scale of the opportunity is significant, with Victoria using around 16 million

tonnes of cementitious product each year. Reducing the associated GHG emissions, and preferably reaching net-negative, is essential for the state to meet its net zero by 2045 target.

Victoria is well placed to capitalise on this opportunity. The power stations in the Latrobe Valley have produced tens of millions of tonnes of Ca / Mg-rich fly ash, which could be upgraded by carbonation into a supplementary cementitious material, creating a new revenue stream for the power companies. The fly ash could be further value-added by solubilising the Ca / Mg components for reaction with CO₂ or sodium bicarbonate, with possible separation of the Ca and Mg components, to produce Ca, Mg or Ca / Mg carbonates as individual products.

The CarbonCure CO₂ injection system is a short-term opportunity that is now available in Victoria through BOC Gases. This technology is commercially available and easily deployable, and has the potential to make a significant contribution to reducing greenhouse gas emissions in Victoria if widely deployed in the construction industry and Government infrastructure projects. Injection of captured CO₂ into fresh concrete has the potential to reduce the State's consumption of cement by about 1.3 Mt and eliminating 1 Mt of CO₂ emissions, equivalent to taking 11%, or c.350,000, cars off Victoria's roads.

ACI recommends that policymakers assess whether there are any barriers, e.g., building standards, that would preclude the deployment of CarbonCure technology in Victoria. If not, then this should become part of standard practice and mandated for all new infrastructure projects. If barriers are identified, then Government-sanctioned trials should be undertaken to validate this process for inclusion in the relevant codes and standards. The Victorian Government could also provide essential support through public procurement of low-carbon products with verifiable climate benefits, and incentives for the public and

private sectors to invest in and consume these products. The “Big Build” initiative is a once-in-a-generation opportunity to demonstrate innovation in the materials procurement process for Victoria.

This study has also identified, for the first time, that three water treatments plants in the Melbourne metropolitan area (Western, Eastern and Yarra Valley) collectively produce about 100,000 t / y CO₂ which, if captured and stored, would qualify as carbon-negative emissions. CO₂ capture systems suited to this scale of operation are commercially available, prefabricated for easy installation. Injection of this biogenic CO₂ into concrete would significantly help the construction sector reduce its greenhouse gas emissions. **ACI recommends that a study be undertaken to investigate the issues and likely costs involved in implanting CO₂ capture at municipal water plants, identify any policy barriers that need to be addressed, and identify or suggest possible incentives that could assist in bringing this to reality.**

Also, Boral's Blue Circle Southern cement works in Waurn Ponds produces cement kiln dust as a by-product. Modular CO₂ capture systems could also be used to capture CO₂ emissions from the kiln flue gas for carbonation of the kiln dust. This combination would make the cement from Blue Circle Southern close to carbon neutral. **ACI recommends that this option be included in the above recommended study.**

The second short-term opportunity identified in this study, use of CO₂ in glasshouse horticulture, represents a potential customer for CO₂ captured from water treatment biogas. There are existing glasshouse horticulture businesses in Victoria which rely on gas burners to generate CO₂, and require alternatives to help transition away from natural gas use. Overseas, CO₂ from biogas is trucked or piped to glasshouse horticulture facilities. In principle, there is no reason why this could not be done in Victoria.

ACI recommends that a study be undertaken to engage with Victorian glasshouse horticulturalists and investigate the potential business case for using captured biogenic CO₂ to enhance crop production while reducing the emissions intensity of glasshouse horticulture.

The third short-term opportunity identified in this study, supercritical CO₂ (S-CO₂) processing, is commercially available technology but has no local business uptake. This is an instance where a pilot-scale development facility would encourage local entrepreneurship and development of new business opportunities. Federation University in Churchill would be an ideal location for such a facility, to encourage monetisation of existing and new plant crops, and production of new food and pharmaceutical ingredients. **ACI recommends that a business plan be developed for a S-CO₂ R&D facility located at Federation University.**

Production of urea is listed as an intermediate-term opportunity in Victoria, even though it is an established commercial process. This is because it is secondary technology, being dependent on commercial availability of sufficient quantities of hydrogen (green or blue) and CO₂ (fossil or biogenic). Over time, increasing demand from Japan for hydrogen and ammonia as clean fuels will stimulate investment in both hydrogen and ammonia production in Victoria, predominantly from lignite but supplemented by renewable energy and biomass.

Establishment of these capabilities is likely to be a necessary precursor for urea production in Victoria. As is done elsewhere, the balance of production could be shifted between ammonia and urea in response to market demand and relative prices, to maximise profitability. **ACI recommends continued development of skills in industrial pilot scale gasification of lignite and biomass, and the associated skills in CO₂ capture and processing and hydrogen processing.**

The other opportunities placed in the intermediate-term category (carbonated fly ash, calcium / magnesium carbonates, methanol, syngas by SOE, EDBM) are not yet ready for commercialisation in Victoria. In some cases, appropriate technologies have been developed overseas and could potentially be utilised in Victoria, e.g., Carbon8 Systems, Blue Planet, or could be adapted from other industries, e.g., EDBM. Some are being investigated by local researchers. However, in the absence of support from government and the community, these opportunities will not materialise.

The opportunities placed in the long-term category (ethanol, ethylene carbonate, lignin-based polyurethane, H₂-oxidising bacteria) are seen as having potential to be the basis for new manufacturing industries in Victoria, including green fuels, plastics and food ingredients. These require further research at lab scale and then scale-up, and currently lack any industrial support. Research is also required on development of compact solar thermal heat storage systems, to provide the high temperatures (c.600°C) needed to overcome the energy barrier of CO₂ conversion. **ACI recommends that government funding be allocated to support strategic research to underpin the creation of these new manufacturing industries in Victoria.**

Beyond this, there are likely to be opportunities for conversion of CO₂ into high-value low-volume fine chemicals (e.g., acetic acid, benzoic acid, acrylic acid, carbonic acids, esters and lactones), all of which are precursors to many industrial products, but these are beyond the scope of this report. **ACI recommends that an independent review of developments in this area be undertaken by a qualified expert, to provide guidance on the opportunities that exist for strategic research efforts. This review should include detailed consultations with representatives of the relevant chemicals and plastics industries.**

Given the urgency with which the climate change emergency must be addressed, new thinking is required on how to stimulate and support the development, demonstration and commercialisation of new CO₂ capture and recycle technologies in Australia. In the absence of any kind of pricing mechanism that reflects the value to society of CO₂ capture and recycle, market forces alone will not deliver the necessary outcomes.

Previous reviews have shown this to be a global challenge. It is broadly understood that CO₂ recycling technologies can only be successfully introduced if they are seen as desirable and are actively supported and coordinated at all levels – policy, industry and public. To this end, it is worth repeating the key recommendations made by previous reviewers.

- ▶ Awareness of CO₂ recycling and its role in the decarbonisation challenge needs to be raised within government, the private sector and the wider public.
- ▶ At the same time, public awareness needs to be raised of the life cycle emissions associated with existing fossil-based products, highlighting the changes that individuals can bring about through their collective choices.
- ▶ Early opportunities, such as the use of CO₂ in building materials, can be stimulated through Government support for product testing trials and updating of standards, and through public procurement of low-carbon products with verifiable climate benefits, further supported by incentives for the public and private sectors to invest in and consume these products.
- ▶ Financial incentives and mechanisms are needed to accelerate investment in CO₂ recycling technology research and development, as well as demonstration at the scale needed to attract further investment.

- ▶ Support mechanisms are needed that allow CO₂ recycling to receive recognition for sustainability benefits and compete on a more level-playing field with conventional products, including integration with existing strategies and green mechanisms.
- ▶ A piecemeal approach will not be successful. Engagement and close collaboration between all interested parties is required, and knowledge transfer must be facilitated.

An additional issue faced by technology developers in Australia is that there are insufficient support mechanisms to help bridge the “chasm of death” between laboratory research and pre-commercial demonstration. A new approach is needed.

Following the successful example of the NRG COSIA Carbon XPRIZE in the US, which brought together technology developers with large industry and private philanthropists, it is suggested that a similar competition could be run in Victoria to actively encourage the commercial deployment of CO₂ recycling in the Latrobe Valley. This would kick-start the scale-up of promising new technologies and draw established technologies to Victoria, create new businesses and jobs, and lay the foundation for a green industrial ecosystem in the Latrobe Valley.

ACI recommends that a scoping study be undertaken to investigate how a competition of this nature might be set up and run in Victoria. A working group of interested parties should be established to oversee this process, including representatives of relevant State government departments, to ensure that any regulatory hurdles are identified and addressed.

Key Publications

Ng WL, Minh Loy AC, McManus D, Gupta AK, Sarmah AK, & Bhattacharya S (2023). Exploring greener pathways and catalytic systems for ethylene carbonate production. *ACS Sustainable Chemistry & Engineering*, 11(39), 14287-14307.

Low Emissions Power from Lignite

Improved Efficiency of Lignite Combustion

Pulverised fuel steam boilers

All coal-fired power stations in Australia employ pulverised fuel (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 22 MPa and temperature is below 540°C. Supercritical PF boilers, which are used in other Australian states, operate at pressures greater than 22 MPa and temperatures of 600°C and above, resulting in higher efficiencies and lower greenhouse gas emissions.

The Latrobe Valley power stations were designed to produce inexpensive electricity by burning lignite fresh from the adjacent mines, but this benefit came at the expense of high greenhouse gas emissions. The average greenhouse gas intensity of Victorian lignite-fired power stations is around 1.35 tonnes CO₂-equivalent per MWh, which is 50% higher than the Australian average.⁽⁴²⁾ The power stations are all old, but that does not mean that efforts to reduce greenhouse gas 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 CO₂ 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.

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

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 (O₂) 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 O₂ 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 CO₂ emissions and lower cost of operations. A challenge for Australian coal-fired 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 O₂ 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 coal- and lignite-fired power stations.

This project involved long-term trials of two Siemens SITRANS-SL Tuneable Laser Diode Spectroscopy (TLDS) gas analysers, one measuring O₂ and one measuring CO. 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 lignite- 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 Energy Australia 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 greenhouse gas emissions.

The project involved the installation of O₂ 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 O₂ 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 69 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 70 shows the corresponding estimation of CO concentrations along the laser path, which was used to calculate the average concentration.

Figure 69: Measured CO distribution in the duct

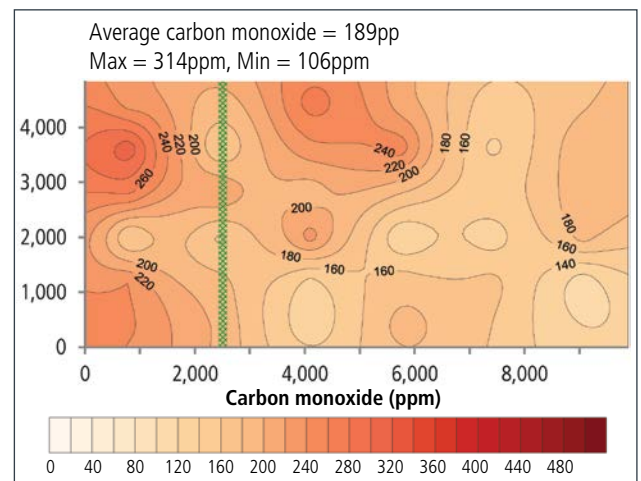
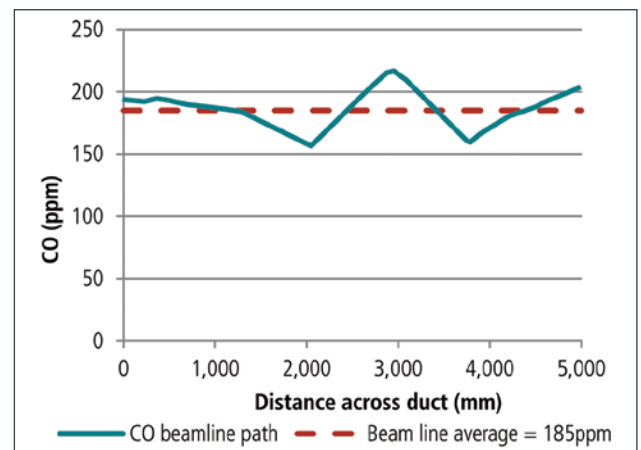


Figure 70: Estimated CO concentration profile



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 O₂ laser produced readings that were more representative of actual O₂ concentrations than the existing sensors used in the power station. When air was used as the purge gas, however, the O₂ readings fluctuated widely.

The project concluded that the O₂ 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 O₂ 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 300 ppm.

This would save 2,365 MWh 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 CO₂-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 O₂ 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 greenhouse gas 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 O₂ monitor for boiler control would deliver more accurate results than current O₂ probes, but requires installation of an on-site nitrogen generator to produce the necessary purge gas for accurate results.

Advanced Materials Assessment

Modern ultra-supercritical power stations use higher temperature boilers to deliver greater efficiency, and reduced greenhouse gas emissions. The higher temperatures require the use of different metal alloys from those currently used in Victoria. Local knowledge of how these alloys operate under the conditions that might exist in a new ultra-supercritical brown coal power stations is lacking, 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 Energy Australia 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 use 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 of 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 Monash University and at Loy Yang B power station (Figure 71). These facilities allowed samples of advanced steel alloys to be exposed to ultra-supercritical steam temperatures (c.790°C) for up to 12,000 hours.

Figure 71: 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. Researchers measured the resulting build-up of oxide scale and developed a predictive model for oxide growth. 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, HRL Technology Pty Ltd commissioned a suite of advanced assessment equipment 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. New predictive methods were assessed, offering the potential to reduce the time for such analysis from months to weeks, representing a significant improvement.

Strand 4 evaluated methods for welding and repairing the high-performance steel alloys. The knowledge gained will help reduce 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 measurement 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 around 1,000 hours of testing rather than from 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.

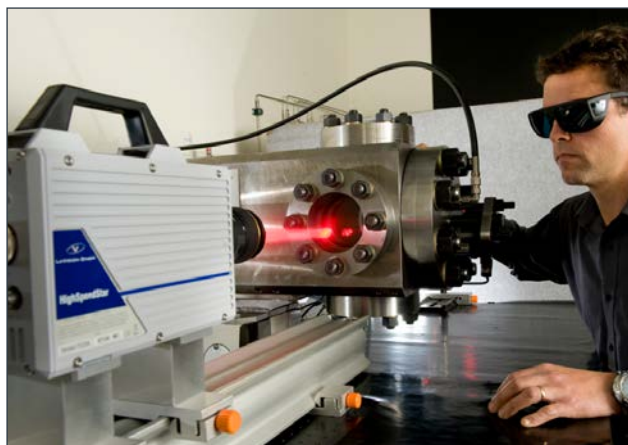
- ▶ More information on the risks of weld cracking in CMV steel (which are widely used in the Latrobe Valley) as components exceed 200,000 hours of service, and of appropriate methods to manage risk.
- ▶ An opportunity for Latrobe Valley power generators to discuss problems and share technical information.

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 to undertake research on oxidation.

Direct Injection Carbon Engine

The direct injection carbon engine (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 1 MW to 100 MW, can be used to generate electricity. Victorian lignite has the potential to make an excellent fuel for DICE engines, as it has low mineral content, high moisture and high reactivity.

Figure 72: 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 lignite should be capable of fuel cycle efficiencies of 48%–50%, producing greenhouse gas emissions of less than 700 kg CO₂.MWh⁻¹.

DICE has the potential to provide a distributed electricity generation option at a 45% reduction in CO₂ 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 lignite 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), thereby 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 1.8 MW 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 CRC for Coal in Sustainable Development. CSIRO Energy Technology subsequently began the development of DICE technology for Australian black coal and lignite in separate projects with Yancoal, Exergen, Ignite Energy Resources, Newcrest, JCG and Xstrata. The outcomes from these projects remain confidential.

Between 2011 and 2018, BCIA supported three projects to further advance the development of DICE technology and move the technology along its commercialisation pathway.

High efficiency power from Victorian lignites

BCIA's first DICE project involved fundamental studies to establish methodology for producing high quality MRC fuel from Victorian lignite 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 investigations with the following aims.

- ▶ Establish the procedures required to manufacture a stable, high quality MRC fuel from Victorian lignite.
- ▶ Evaluate the atomisation and combustion performance of the MRC fuel.

- ▶ Investigate the likely effects of coal ash on engine components.
- ▶ Develop 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 lignite and upgraded lignite 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 lignite 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 lignite MRC 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 6 MW / cylinder. Subsequent modelling work suggested that the efficiency of a diesel engine correctly configured to operate on lignite 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–A\$2,000 per kW, 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 GJ, the preliminary economic analysis concluded that, for natural gas prices of more than A\$8 per GJ, the cost of electricity is lower from DICE than natural gas combined cycle, irrespective of CO₂ 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 lignite-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 (www.dice-net.org). Members of DICEnet include MAN Diesel & Turbo (Denmark), AGL Loy Yang, Energy Australia, 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 was to support the international development of DICE.

MRC-DICE Risk Review

Having demonstrated the potential for use of Victorian lignite 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:

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

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

- ▶ 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 was 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 would need to be monitored and addressed during the commercialisation pathway.

Victorian DICE development – Derisking and small scale demonstration

BCIA's third DICE project involved 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.

The expectation was that successful completion of these funded trials would 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 lignite and black coal MRC fuels in a test engine in Japan.
- ▶ Create sufficient data to allow an engine manufacturer to implement a development program.
- ▶ Define the specification parameters and initial acceptable ranges for both lignite 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 lignite and black coal) in a contemporary low- or medium-speed diesel engine are acceptably low.

CSIRO Energy Technology led and coordinated the joint DICE Development program, in collaboration with MAN Diesel & Turbo and supported by local electricity generators (AGL Loy Yang, Energy Australia)

and developers of lignite upgrading technologies (Ignite Energy Resources, Exergen). The program was funded through two separate but coordinated research agreements, one with BCIA and the other with ANLEC R&D.

Each project contained black coal or lignite-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 was 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 coal and lignite MRC fuels in a test engine in Japan. MAN Diesel & Turbo undertook this work with support from CSIRO Energy Technology.

Initially, good progress was made toward scale-up of acceptable MRC fuels from both lignite and black coal. However, experimental trials in a custom-build fuel injection rig revealed that the high abrasiveness of MRC slurries meant that the MAN injector nozzles could not survive the 20 hours of the planned Mitsui engine test.

The project reached a roadblock when it became apparent that suitably hardened injector nozzles could be fabricated using readily available materials and coatings, requiring a significant new research project to develop more robust nozzle materials. At the same time, MAN signalled a loss of appetite for continued development of coal-fired engines. Consequently, the joint collaborative project was terminated in late 2018.

Key Publications

Wibberley LJ (2011). Coal base-load power using Micronised Refined Coal (MRC). *Energy Generation*, 35-39 (Jan-Mar 2011).

Wibberley LJ (2011). Future low CO₂ power from Victorian brown coal. *Energy Generation*, 35-39 (Jul-Sep 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.

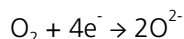
Wibberley LJ (2013). DICE – Emerging technology for ultra-efficient carbon power. *Energy Generation*, 1-5 (Jan-Mar 2103).

Direct Carbon Fuel Cell

The direct carbon fuel cell (DCFC) is an emerging technology that has the potential to increase the efficiency of power generation from lignite to 65%–70%. This is higher than any other carbon fuel technology, and would lead to a significant reduction in the production of CO₂ per MW 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 73. 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:



The oxygen ions flow across the membrane and react with the solid carbon fuel to produce CO₂ at the anode:

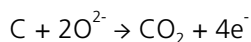
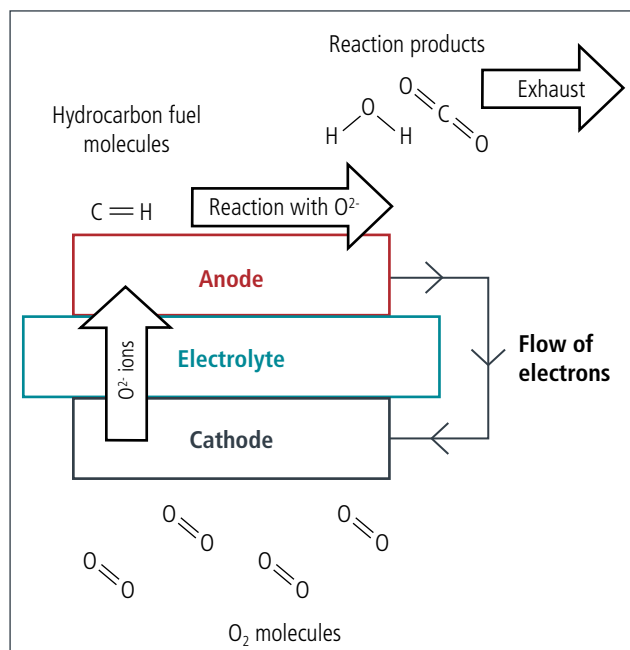


Figure 73: Operation of a direct carbon fuel cell



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.

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 consensus yet as to which would be most applicable for use with lignite.

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 74), is sufficient to power a house or small office.

Figure 74: BlueGen® converts natural gas into 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 lignite is a particularly attractive option.

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

Evaluation of Victorian lignite 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 lignite 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 lignite 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 lignite, 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 lignite char and ash at 850°C. He discovered that mineral impurities in the lignite 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 is needed to investigate the interactions between lignite mineral matter and alternative anode materials.

Feasibility study for DCFC operation on Victorian lignite

Following the initial demonstration that Victorian lignite, exemplified by Morwell lignite, 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 lignite 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 lignite on the materials of construction of the high temperature fuel cells and how these impurities interact with materials at these high temperatures. It 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 lignite minerals. The cell design was changed to avoid this problem, resulting in an increase in performance of over 40%.

Lignites from the Morwell and Yallourn regions presented 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 lignite 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 CO₂. CSIRO has recently demonstrated this process using carbon black, so further research to explore the potential with lignite is warranted.

MILD Combustion

The push for higher efficiency and lower CO₂ emissions from applications of coal has typically focussed 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.

The development of 'Moderate or Intense Low-oxygen Dilution' (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,

Key Publications

Rady AC, Giddey S, Badwal SP, Ladewig BP, & Bhattacharya S (2012). Review of fuels for direct carbon fuel cells. *Energy & Fuels*, 26(3), 1471-1488.

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.

Mr Manabendra Saha, under the supervision of Professor Dally to investigate the MILD combustion characteristics of both SA and Victorian lignites.

Mr Saha's project involved an investigation of the operating conditions required to achieve stable MILD combustion with lignite, including the influence of jet inlet velocities of a stream of CO₂ and lignite (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 lignite 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 75. Flameless combustion was successfully achieved with lignite (Figure 76). 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 established that MILD combustion of Victorian lignite is feasible, and 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 lignite for power generation.

Figure 75: Schematic of the Adelaide MILD combustion furnace

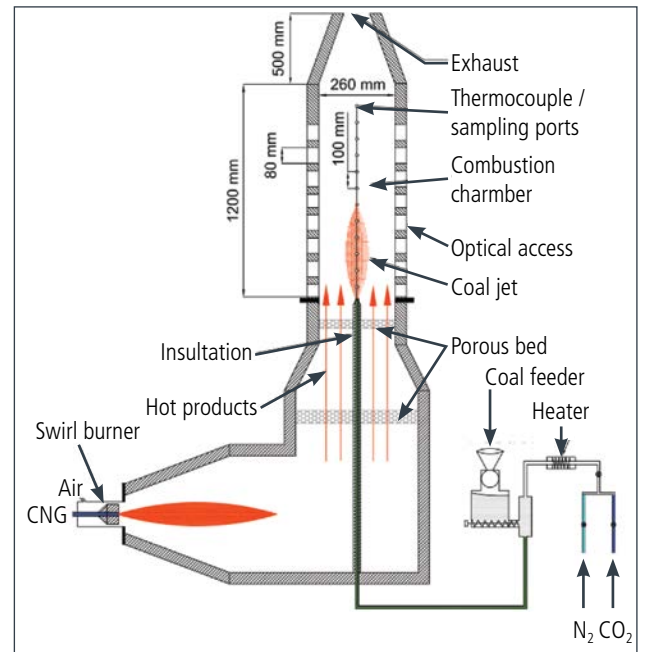
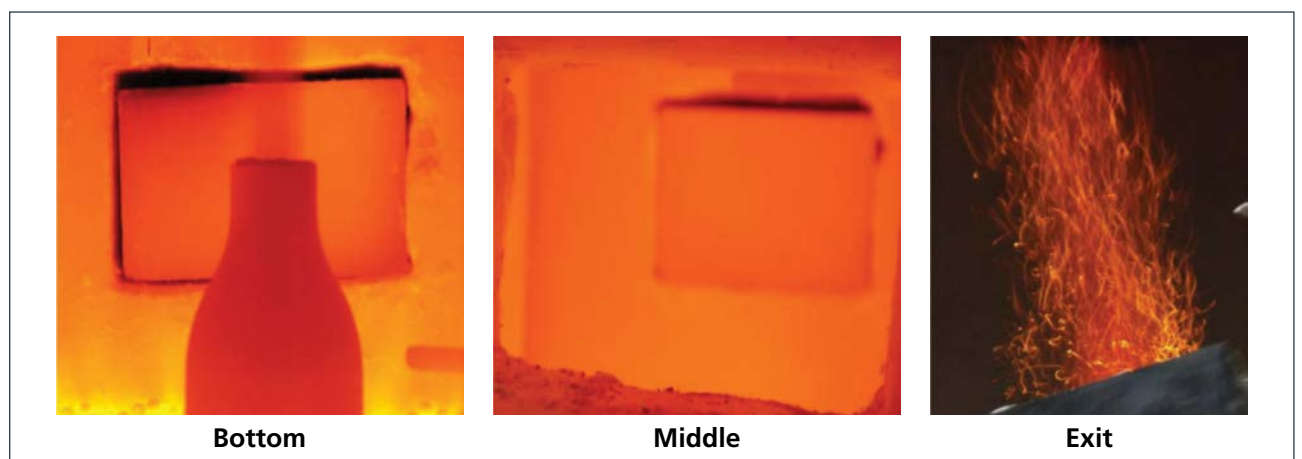


Figure 76: Photograph of the bottom, middle, and exit of the furnace when operating under MILD combustion condition with Loy Yang lignite carried by CO₂



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* (www.dx.doi.org/10.1016/j.fuproc.2016.04.003).

Combustion in Oxygen Instead of Air

Oxy-fuel combustion of lignite

A major aim of BCIA's low-emissions power activity was 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 lignite with little to no greenhouse gas emissions. Indeed, the research and modelling to date shows that oxy-fuel combustion, in combination with CO₂ storage, could deliver power with near-zero emissions at almost zero net efficiency penalty compared to today's Victorian lignite-fired power stations.

Essentially, the process involves burning lignite 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 CO₂. Recovery of CO₂ 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 CO₂ from lignite combustion, without the need for an expensive, intermediate CO₂-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 CO₂. 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 NO_x mass emission rates; and (iii) almost

complete removal of all toxic gaseous emissions including SO_x, NO_x, particulates and trace elements from the flue gas stream in the CO₂ capture plant.⁽⁴³⁾ In 2007, Monash University undertook studies into the feasibility of applying oxy-fuel combustion technology to Victorian lignite, 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 lignite under oxy-fuel conditions and to determine the likely feasibility of deploying oxy-fuel technology.

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 lignite

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 lignite-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 CO₂ capture to Unit 7 at International Power Hazelwood, while the other focussed on Unit B at Loy Yang International Power.

Both studies suggested that oxy-fuel combustion could be cost-competitive with post-combustion CO₂ 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 lignite

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. Such CFD models are vital to understanding the challenges and opportunities in scale-up of these technologies.

As suitable pilot-scale facilities do not exist in Australia, the trials were conducted using a 3 MW_{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 (Energy Australia 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 lignite that had been dried to moisture contents ranging from 12% to 40% (Figure 76).

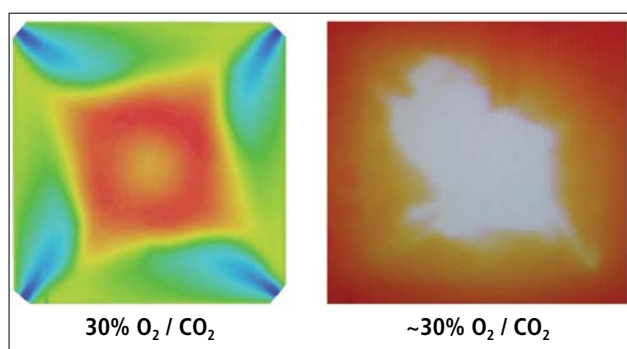
The research established a range of outcomes including the stable and faster combustion of Victorian brown coal under oxy-fuel conditions, production of high purity CO₂ (up to 80%) in flue gases, and led to a greater understanding of the distinct slagging / fouling propensities of Victorian lignite in oxy-fuel mode.

(43) © Global CCS Institute (www.globalccsinstitute.com/publications/callide-oxyfuel-project-lessons-learned).

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 CO₂ and steam; the higher char-CO₂ and char-steam reactivity of Victorian lignite; 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 77: Comparison of CFD model and 3 MW_{th} boiler flame for Yallourn lignite in oxy-firing mode



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 lignite 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 lignite 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 CO₂ compression processes.

An energy efficiency of 25%–28% can be achieved, equivalent to current lignite-fired power stations, but with no CO₂ emissions.

Computer modelling for prediction of lignite ash slagging / fouling propensity under oxy-fuel combustion mode

The pilot-scale oxy-fuel experimental work was complemented by efforts to develop advanced CFD simulation tools to assist in further scale-up. This work was 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 were as follows.

- ▶ Develop and validate a sub-model for the vapourisation 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 contributed 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

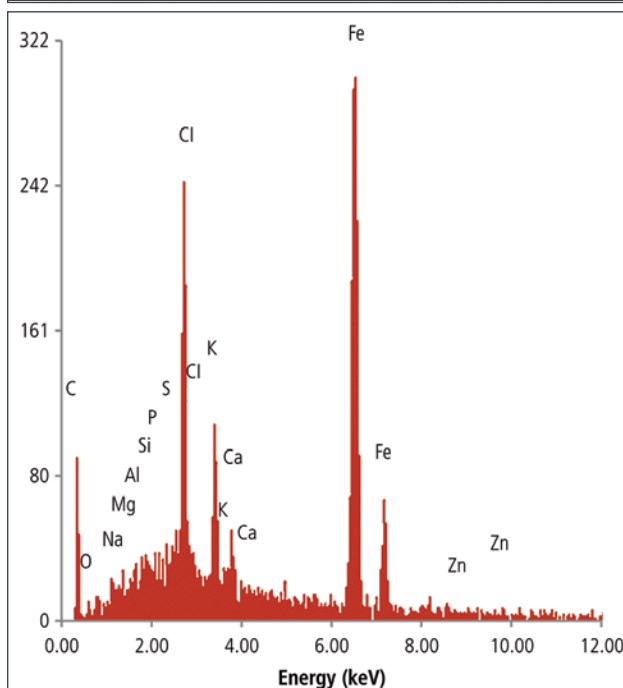
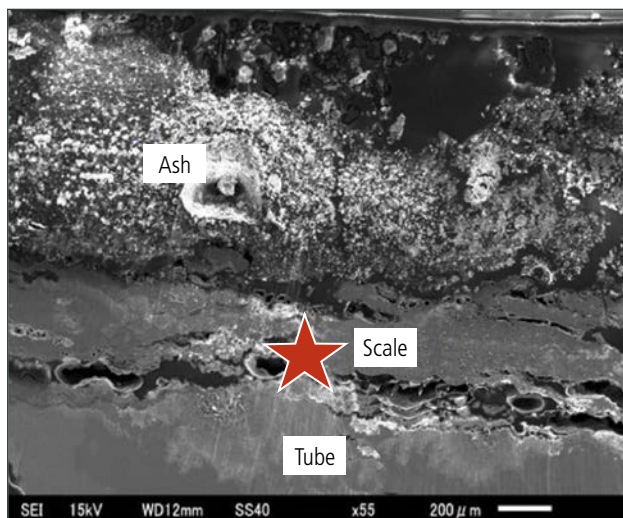
Since 2014, BCIA supported further collaboration between Monash University and SBWL to accelerate the deployment of oxy-fuel technology in Victoria. This project investigated the ash fouling and water tube corrosion occurring under optimised oxy-firing conditions. Understanding the coal-specific factors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

The focus of the project was on oxy-fuel combustion of dried Victorian lignite under supercritical and ultra-supercritical conditions. The project involved long-term ash exposure experiments in the 3 MW_{th} 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 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.

Figure 78: SEM-EDS analysis of Hazelwood ash deposit, collected at 700°C



Experiments in a lab-scale horizontal tube furnace at Chubu University in Japan allowed the interactions between lignite ash and water tubes to be studied under simulated oxy-firing conditions.

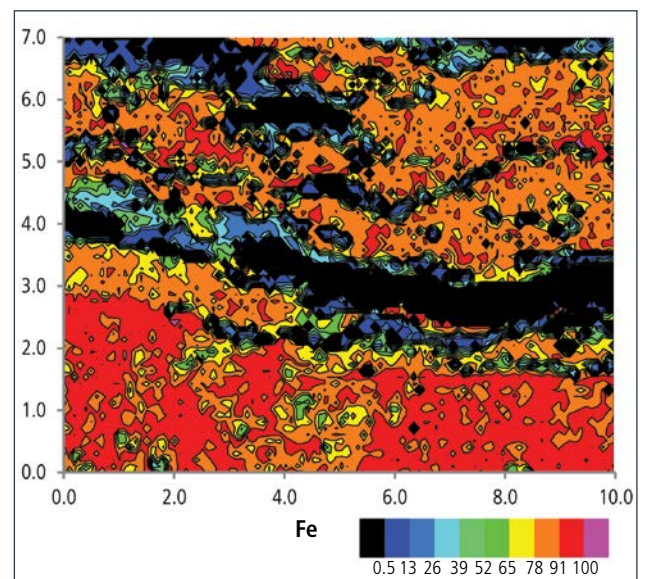
Figure 78 shows the elemental composition of the corroded metal samples measured using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS).

Detailed mapping of the elemental composition over a two-dimensional grid allowed the production of detailed distribution profiles for each element. Figure 79 shows a representation of the distribution of iron 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 lignite.

A CFD model was developed for predicting the composition of flue gas, ash and slag within a boiler under oxy-firing conditions.

Figure 79: Iron distribution in ash deposit at 700°C



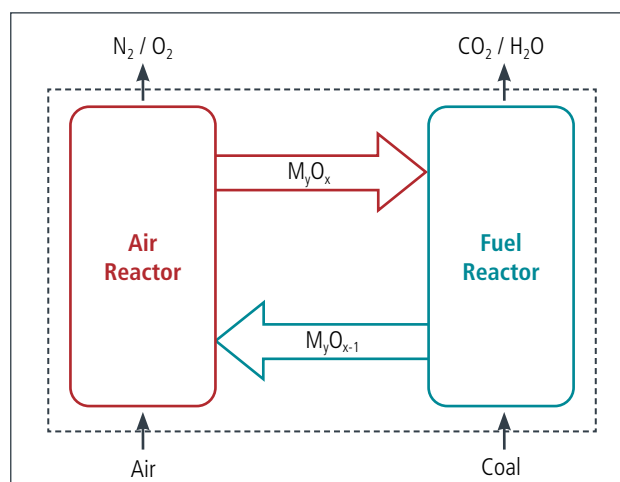
Chemical looping combustion of lignite

Combustion of lignite in a pure oxygen atmosphere allows the generation of power with almost no CO₂ emissions. The flue gas in such a system consists primarily of CO₂ and steam, and it is possible to easily dehydrate and compress the CO₂ 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.

Chemical looping combustion (CLC) is an emerging technology to facilitate capture of CO₂ 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 80. In the fuel reactor the metal oxides serve as an oxygen source for the lignite. The reduced metal particles then pass into the air reactor where they are oxidised back into the oxide form.

Figure 80: Schematic of chemical looping combustion



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Direct contact between air and the lignite is avoided, creating a flue gas that is rich in CO₂. By condensing the associated water vapour, the CO₂ 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 lignite.

Chemical looping has been widely studied for the combustion of natural gas but research into its application for solid fuels commenced only in the past decade.

Victorian lignite 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 lignite in a chemical looping system is unknown.

To address this knowledge gap, BCIA supported two consecutive projects on CLC at Monash University, led by Professor Sankar Bhattacharya. The first project generated baseline information and established the feasibility of CLC with Victorian lignite.

The second project aimed to advance the commercial prospects of this emerging technology through an evaluation of lignite 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 CO₂ capture from Victorian lignite

BCIA's first project on CLC was led by Monash University, in collaboration with Energy Australia, 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 lignite (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 500 Wth 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 lignite 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 10 kW_{th} fluidised bed reactor was designed and constructed in the Department of Chemical Engineering at Monash University (Figure 80).

Carbon conversion efficiencies of greater than 92% were achieved in this reactor, producing flue gas containing more than 82% CO₂. Efficiencies improved with increasing scale, so better results may be expected at pilot scale.

Figure 81: 10 kW_{th} CLC reactor at Monash University



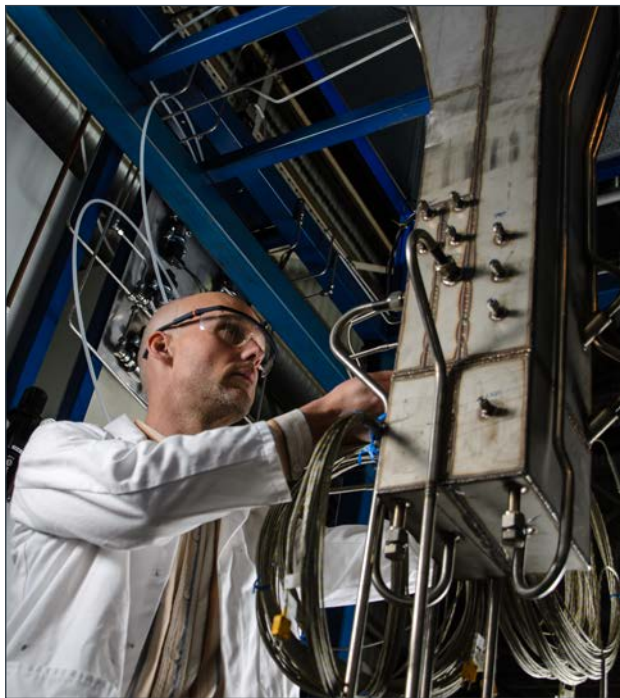
Advancing CLC technology for Victorian lignite

The promising results achieved in the initial CLC project led to BCIA support for a second project with a more applied focus. This project extended the preliminary research through bench-scale research and experiments using a Victorian purpose-built, compact fully looped and continuously fed reactor system (Figure 82).

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

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

Figure 82: Continuous looping CLC rig



Three metal oxides were selected for evaluation as oxygen carriers – iron ore (Fe₂O₃), ilmenite (FeTiO₃), and a synthetic Mn-Fe oxygen carrier. Each oxygen carrier was evaluated at bench scale over 50 oxidation-reduction cycles, to determine its effective working life and deactivation mechanisms.

The bench- and pilot-scale trials established that Victorian lignite is an ideal fuel for CLC in combination with abundant, low-cost ores such as hematite and ilmenite as oxygen carriers. The synthetic Mn-Fe oxygen carrier also performed well, but is currently too expensive to be a practical option. The high reactivity and low ash content of Victorian lignite makes it eminently suitable for CLC and is key for the technical and economic feasibility of the process.

A techno-economic study of a 550 MWe CLC plant using Victorian lignite was completed, drawing upon Alstom's expertise in this area. The HHV, net efficiency was estimated as 31% with 97% CO₂ capture, including the energy required for CO₂ compression. Total plant cost was estimated as A\$4,200 per net kW.

At a capacity factor of 85%, the levelised cost of electricity (LCOE) was estimated as approximately A\$143 per MWh. This is similar to the estimated 2020 LCOE for supercritical pulverised coal combustion of Victorian lignite (with CCS) reported in the Australian Energy Technology Assessment 2012 .

This project established that a 550 MWe CLC plant using Victorian lignite would meet the US Department of Energy's target of 90% CO₂ capture and <35% increase in electricity cost. This is a major development in the progression of CLC technology in Australia.

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