# Energy Security and Prosperity in Australia

## A ROADMAP FOR CARBON CAPTURE & STORAGE

The University of Queensland
Australia
Create change

## Contact

**Professor Chris Greig**
Director UQ Energy Initiative

The University of Queensland
St Lucia QLD 4072 | Australia

**Office:** +61 (0) 7 3346 0656
**Email:** uqenergy@uq.edu.au

# ACKNOWLEDGEMENTS


The authors would like to thank the Steering Committee, Funders and Feedback Contributors who supported, contributed to, and provided feedback on this report. The robust review, challenge, diverse opinions and honest engagement we have received has strengthened this report.

We would particularly like to acknowledge and thank CO2CRC, CSIRO, ANLEC R&D, ACALET, Coal Innovation NSW and the Federal Department of Industry, Innovation and Science for their considerable enabling support of this project.

We would also like to acknowledge the advice and feedback from various industry leaders and subject matter experts from Government, Oil & Gas, Coal and Power industries.


## Steering Committee

Australian Government Department of Industry, Innovation and Science; CSIRO; anlecr&d www.anlecrd.com.au; COAL21; CO2CRC Building a Low Emissions Future; NSW Government Department of Industry Resources & Energy

## Report Authors


> **Professor Chris Greig**
The University of Queensland

> **Dr Geoffrey Bongers**
Gamma Energy Technology

> **Ms Caroline Stott**
The University of Queensland

> **Ms Stephanie Byrom**
Gamma Energy Technology


## Who should read this report

This report provides a roadmap to assure Carbon Capture and Storage (CCS) as an option for achieving emissions reductions in a timely manner in Australia. It is intended for policy-makers associated with energy, emissions-intensive industry and trade sectors in state and Federal Government departments across Australia. It is also for investment decision makers, and those involved in upcoming energy and climate reviews.


Greig, C., Bongers, G., Stott, C. and Byrom, S. (2016) Energy Security and Prosperity in Australia: A Roadmap for CCS, The University of Queensland, Brisbane. ISBN 978-1-74272-175-0

# KEY MESSAGES

1. **Deployment of Carbon Capture and Storage (CCS) is vital to Australia's long-term economic prosperity and energy security.**

2. **CCS must be available on its merits in Australia's energy mix to assure energy system security** and affordability so that future emissions reductions targets are delivered at the lowest economic cost.

3. **CCS is required beyond use in the power sector as it will play a vital role in decarbonising energy intensive industries**, which involve the continued use of fossil fuels.

4. **CCS is not an experimental technology. It is being deployed or available now at commercial scale to:**
   - **provide a competitive, carbon reduction option for reliable 24-7 power from fossil fuels.**
   - **decarbonise a number of existing and prospective emissions-intensive industries** including natural gas and LNG production, iron and steel making, cement production, fertilisers, chemicals and textiles.

5. **The deployment of CCS globally is critical for Australia's trade balance and jobs** that underpin coal and gas exports.

6. **Leadership in CCS could enable new industrial production in Australia and provide an opportunity to increase competitiveness and create jobs** in high value adding sectors, while achieving emissions reduction targets.

7. **Urgent early investment in CCS is required** to assure that CCS can be deployed to achieve the deep reduction in greenhouse gas emissions required to achieve national and global targets.

8. **This Roadmap is a call for significant additional funding for CCS Research, Development and Demonstration (RD&D)** from Government and Industry.

9. **Government and Industry should consider significant ongoing investment in CCS for:**
   - $CO_2$ storage characterisation
   - Legal and regulatory capacity
   - Monitoring international CCS deployment
   - Techno-economic assessments
   - Engagement to achieve public acceptance.

   Such investments may require $CO_2$ storage demonstrations.

10. The Australian Government currently has a range of energy security and climate change reviews planned or in progress. **CCS must be one of the technologies considered in such reviews.**

## Urgency for CCS in Australia

As the world makes the necessary and urgent transition to a low carbon future, resource and system diversity will be key to maintaining a resilient, competitive energy economy.[1] Australia's abundant, cost competitive and high quality coal and gas resources have long underpinned the economic strength and high standard of living achieved in Australia.

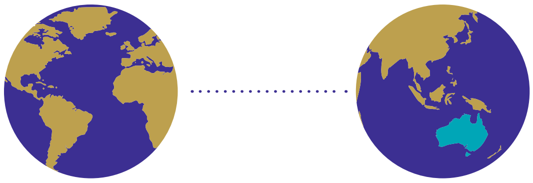
The challenge that Australia and the world face is to continue to realise the benefits and value of fossil energy resources without the associated emissions. It is therefore imperative that commercial-scale Carbon Capture and Storage (CCS) is developed and available. This assures that Australia and its trading partners can maintain energy security and meet future emissions reduction targets at the lowest economic cost.

Australia has the capability to provide leadership in CCS, especially $CO_2$ storage with the Otway and Gorgon projects. These are considered leading examples of $CO_2$ storage research, development and demonstration (RD&D) and commercial-scale deployment.

Urgent investment in $CO_2$ storage site characterisation, CCS projects, techno-economic assessments, and public engagement is required to ensure that CCS can be deployed to achieve the deep reduction in greenhouse gas emissions required to meet national and global targets.

**Figure 1: The global emissions budget**

The carbon budget is the finite amount of greenhouse gases that should be emitted if we are to limit global temperature rise to 2°C.



The global emissions budget for the period 2000-2050 is **1,700 Gt $CO_2$-e**

The national budget for the period 2013–2050 is **10.1 Gt $CO_2$-e**

Australia is responsible for <1% of global carbon budget. By 2030, under business-as-usual Australia's carbon budget will be exhausted. To remain within its budget, deployment of low emissions technologies must be accelerated.

*Source: Climate Change Authority*

*Source: United Nations Environment Programme, The Emissions Gap Report 2014*

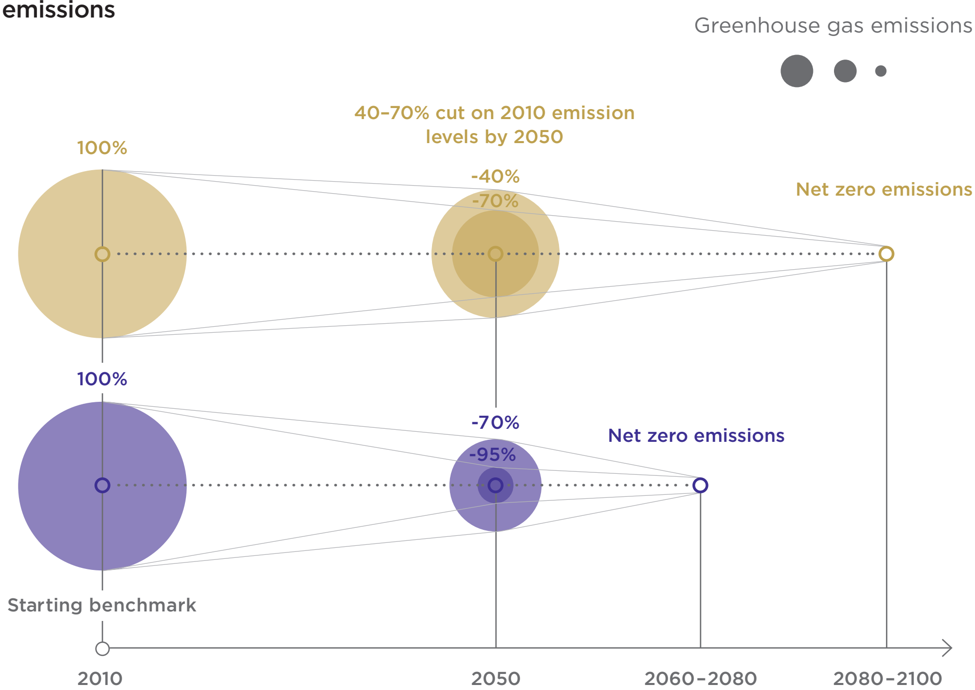
**Figure 2: A timeline for net zero emissions**

**2°C TARGET**

66% chance of limiting warming to below 2°C in the 21st century

**1.5°C TARGET**

More than 50% chance of limiting warming to below 1.5°C in 2100




*Source: The Carbon Brief*

## Energy, Development and Climate Change

Governments, industry and civil society around the world are attempting to resolve the trilemma of providing reliable, affordable and sustainable energy while combating the threat of global temperature rise and the broader impacts of climate change.

However, progress to date has been inadequate. Energy and climate policies in Australia need to be more cohesive and recognise the trade-offs between energy security, cost and emissions reductions.

The world needs to achieve energy security and climate change trade-offs at the lowest economic cost to society. It is therefore essential for governments to recognise that policy settings must be based on emissions reduction potential, not a predilection for particular energy resources or power generation technologies.[2]

Critical to the global response is recognition of the remaining carbon budget and pathways to achieve net zero emissions.

In December 2015, the United Nations Framework Convention on Climate Change (UNFCCC) 21st session of the Conference of the Parties (COP) in Paris agreed to limit the increase in the global average temperature to below 2°C above pre-industrial levels, and to pursue efforts to limit the increase to 1.5°C.

This agreement marked a new era in negotiations as countries came together to acknowledge the risk of climate change and accept the need for action via Intended Nationally Determined Contributions (INDCs). The overarching Paris Agreement encourages governments to assess, legislate and modify existing policy mechanisms to realise emissions reduction targets. Such policy changes will need to be considered across all sectors of economic activity.

All low emissions technologies are coming down the cost curve and future costs are uncertain.[a] Preserving emissions reduction options and diversity is therefore critical to optimise the future energy portfolio and minimise associated costs.

The abundance, cost competitiveness and high energy density of fossil fuels continue to make them an attractive source of energy. CCS can enable their continued use without the associated emissions.

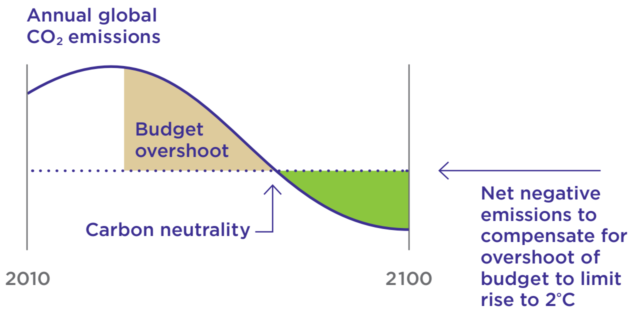
Several climate and decarbonisation models suggest that achieving a 2°C outcome will ultimately require a period of negative emissions. The most prospective negative emissions systems require CCS.

Australia's INDC to reduce greenhouse gas emissions by 26 to 28 per cent below 2005 levels by 2030[3] is potentially within reach. But more substantial reductions will be required post 2030. Accordingly, Australia must pursue options that allow it to contribute to global efforts to achieve a net zero emissions position in the second half of this century.

Hence, from an energy security and economic perspective, Australia and the world will ultimately benefit from deploying CCS, especially if negative emissions solutions are required.

### Figure 3: Achieving carbon neutrality

To achieve carbon neutrality will require net zero emissions, and possibly net negative emissions in the future.




*Source: Climate Change Authority*

*Source: United Nations Environment Programme, The Emissions Gap Report 2014*

[a] *Refer to Appendix Section 2.*

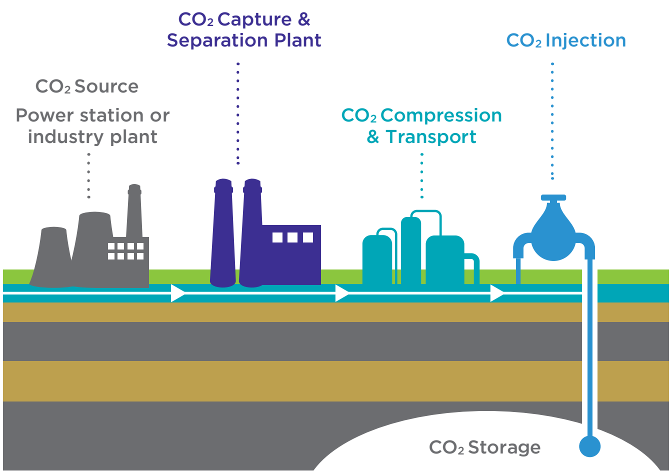
## CCS in a Carbon-Constrained World

Unabated $CO_2$ emissions from fossil fuel use must be limited in a carbon-constrained world. When considering global emissions reserves and implications for climate change, analysis suggests that a significant portion of current proven fossil fuel reserves and the majority of non-reserve resources should not be produced. In the absence of abatement solutions, these should be unused if the world is to have a chance of keeping temperature rise below 2°C.[4]

The primary purpose of CCS is to mitigate $CO_2$ emissions from fossil fuel use in a carbon-constrained world. It enables continued utilisation of global carbon reserves.

CCS is a carbon abatement technology that involves capturing $CO_2$ and other greenhouse gas emissions, transporting them to a suitable geological site and permanently storing them in a manner that prevents emissions from being released to the atmosphere. Storing $CO_2$, the most common greenhouse gas, in deep, underground geological strata is viewed as the most prospective method of storage in Australia.[5]

**Figure 4: What is CCS?**




CCS has potential applications across the power, industrial and (indirectly) transport sectors, including:

- Stationary fossil fuel-fired power generation;
- Manufacturing including cement, steel and biofuels;
- Production of liquid hydrocarbons and chemicals from coal and gas;
- Removal of naturally occurring $CO_2$ from reservoir gas as part of gas processing operations; and
- Electrification of the transport sector (in particular light vehicles) where power is generated using fossil fuels.

### CCS is proven and ready for deployment at commercial scale

**Over 20 years' experience** with commercial scale CCS

Today **15 large-scale projects** (1 in power, 14 industrial) in operation storing 28Mtpa $CO_2$

By end 2017, **22 large-scale projects** (3 in power, 19 industrial) storing 40Mtpa $CO_2$

The IPCC expressed a **high level of confidence that 99% of $CO_2$ stored** in an appropriate storage reservoir will remain there for at least 1000 years.

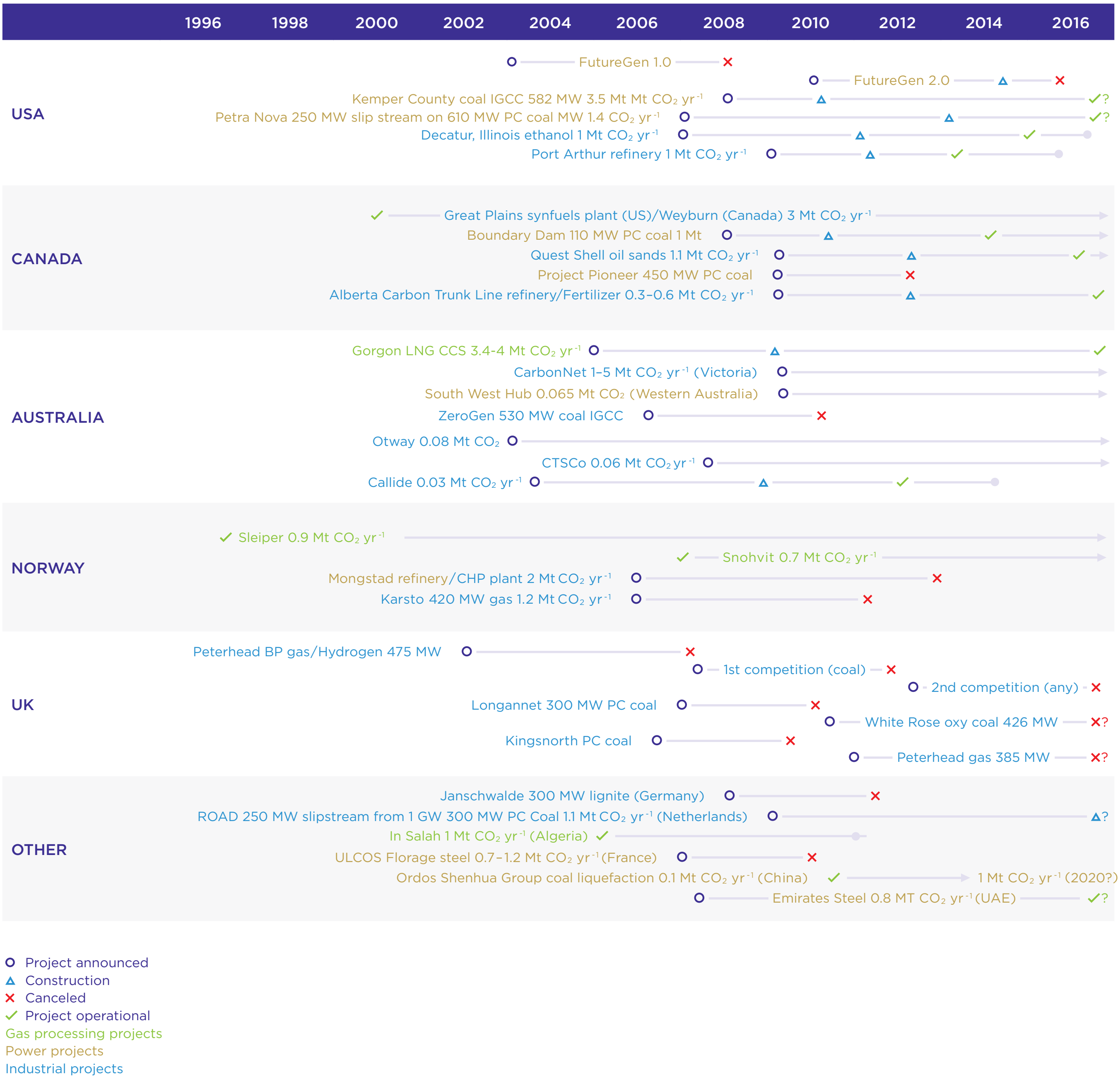
*Source: Global CCS Institute, Re-Powering NSW 2016 Conference*

## Current Status of CCS

Significant integrated CCS projects have been built over the last few decades.[7] Many countries with multiple advanced CCS demonstration projects have published CCS roadmaps.

There are many individual elements of CCS technology each with different levels of development, from early stage research to fully mature. The Australian Power Generation Report[6] provides an overview of the status of the various learning curves for individual technological components.

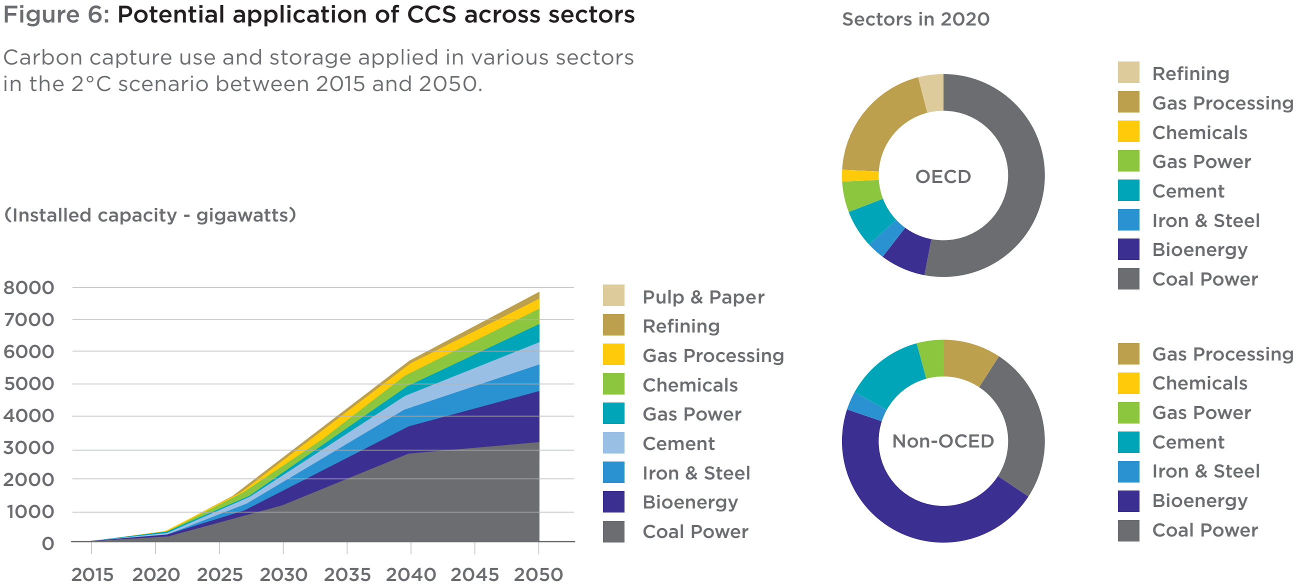
**Figure 5: Portfolio of CCS projects**




*Source: Modified from Reiner, M. (2016) Learning through a portfolio of carbon capture and storage demonstration projects. Nature Energy 1, Article number: 15011.*

Figure 6: **Potential application of CCS across sectors**

Carbon capture use and storage applied in various sectors in the 2°C scenario between 2015 and 2050.




*Source: International Energy Agency. Technology Roadmap Carbon Capture and Storage 2013*

## Power, Industrial and Transport Considerations for Australia

Power generation accounts for 33 per cent of Australia's emissions and is the largest share of emissions in the national greenhouse gas inventory.[8] CCS has the potential to make a substantial contribution to decarbonising the Australian power sector.[a] Today the power sector remains heavily reliant on fossil fuels with coal and gas accounting for approximately 83 per cent of electricity generated.[9]

A gradual uptake of modern, large-scale renewable generation is occurring.[10] Renewable technologies such as wind and solar photovoltaic (PV) have low variable operating costs and generate low emissions, but have intermittent availability. Other renewable technologies, such as geothermal, solar thermal, wave and tidal energy, could potentially operate continuously. But they face difficulties with cost and scale, or are remote and require large transmission infrastructure investments.

Power systems depend on there being sufficient generators to continuously adjust their power generation to follow varying demand over time; with the flexibility to ramp their output up and down.

Intermittent renewable sources such as wind and solar PV cannot perform the roles that are essential for reliable, secure and low-cost electricity supply. Costs of renewable integration increase progressively above 10 per cent penetration and, at 30 to 40 per cent, poses serious risks to system reliability.[12]

Coal, gas and hydro provide reliable, high volume 24-7 power to support renewable generation. Despite suffering reduced revenues, which can threaten their viability, this firm capacity is essential for power systems security and to avoid major disruptions to power supply.

Industrial processes can be integrated with CCS to decarbonise their operations. Direct combustion, industrial processes and product use account for 22 per cent[7] of Australia's emissions. Iron and steel production accounts for 30 per cent of industrial emissions and 6-7 per cent of global anthropogenic emissions, exposing Australia's important iron ore and metallurgical coal exports to future decarbonisation policies.[13]

Due to the inherent chemical reactions and physical properties involved in industrial processes renewable sources cannot currently replace coal and gas. For many industrial processes carbon is an essential raw material in the manufacturing process; for example, fertiliser, plastic, textile, steel and cement production.

Deploying CCS across new industrial sectors could provide an opportunity for new industry, and to grow employment in high value sectors while achieving emissions reduction targets.

Transportation can also benefit from CCS where electric vehicles replace petrol, gas and diesel ones. Transport accounts for almost 16 per cent[7] of Australia's emissions. An electrified transport sector, predominantly applied to light vehicles, would increase electricity demand. This will require low emissions power with 24-7 reliability. CCS thus has the potential to contribute indirectly to the decarbonisation of an (electrified) transport sector.

The CCS industry could have a direct economic impact in Australia. It has the potential to create a large number of high value employment opportunities. This includes direct and indirect employment that would flow through the economy from the supply of goods and services on a broader scale.

[a] *Refer to Appendix Section 3.*

## Export and Trade Considerations

Australia is rich in primary energy resources. In 2013-2014, coal accounted for 66 per cent of Australia's primary energy production with gas accounting for 13 per cent.[8] Net exports of energy, primarily to Asia, accounted for 72 per cent of total primary production.[8] Moreover, energy production for both domestic consumption and export is forecast to more than double over the next 30 years.[14]

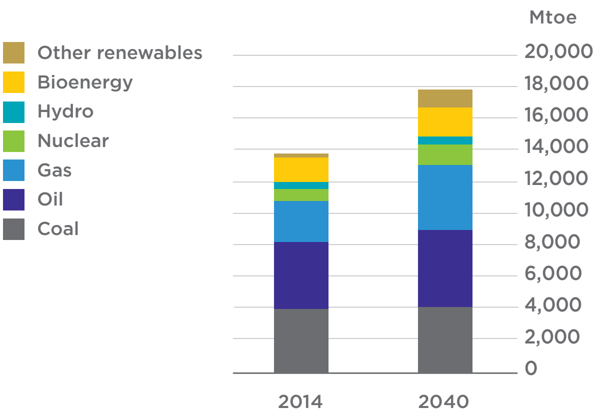
The energy sector plays a vital role in the Australian economy, accounting for approximately $67 billion in export earnings and 6 per cent share of the economy.[8] Australia is the world's largest coal exporter,[15] the second largest liquefied natural gas (LNG) exporter[16] (projected to become the world's largest LNG exporter by 2020)[18] and the third-largest uranium exporter.[19] Coal and gas exports underpin Australia's trade balance with coal accounting for 11.7 per cent and gas accounting for 5.2 per cent.[20] Furthermore, the value of Australia's resources and energy exports is projected to increase by around 50 per cent by 2020.[16] Fossil fuel demand in south east Asia is projected to grow even further to 2040.[17]

Australia has very significant reserves of coal and gas and vast resources. These reserves have expected economic values, and restrictions on production of reserves could greatly impact the energy sector and affect investment in Australia. The widespread deployment of CCS would enable proved and probable reserves to be produced and monetised in a carbon-constrained world.

Continued growth in the energy sector amid the uncertainty and changes taking place across the Australian and global energy markets requires a long-term, stable policy framework to attract energy resource investment. Australia is likely to be a key beneficiary of the development and global deployment of cost-effective CCS. This would essentially provide greater support to continue the responsible production and export of coal and gas in a carbon-constrained world, and reduce the risk of asset stranding.

### Figure 7: **Reliance on fossil fuels**

The world will potentially remain heavily reliant on energy from fossil fuels for several decades to come.




*Source: International Energy Agency, World Energy Outlook 2016*

## When should Australia be CCS-Ready?

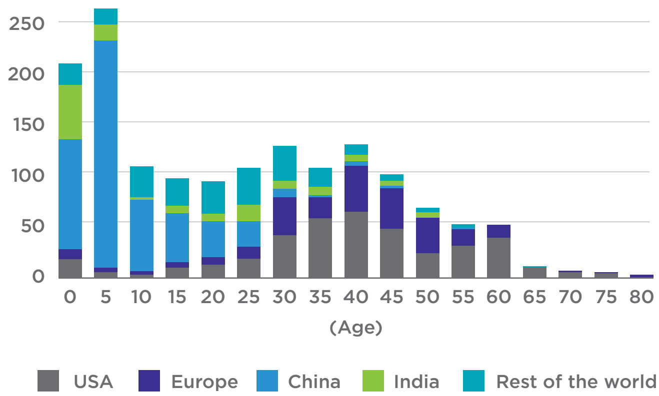
Australia's key trading partners (who are also coal and gas importers) are predominantly Asian economies. They are committed to various emissions mitigation approaches ranging from reductions in emissions intensity (emissions per unit of GDP), reductions from projected business-as-usual emissions, and reductions in per-capita emissions.[3]

Many of these economies have or are currently investing in High Efficiency-Low Emission (HELE) fossil fuel-fired power generation, which is designed to last for 30 to 50 years. HELE technologies provide significant emissions reductions compared with existing coal- and gas-fired generation.

Building on the improvements of HELE, CCS will be required for the deep emissions reductions consistent with a global net zero emissions target. Accordingly, it is critical that those economies also plan and invest now to be in in a position to deploy CCS in the medium and longer term, subject to the technology being cost competitive in their regions.

### Figure 8: **Investment in coal-fired power**

**(Installed capacity - gigawatts)**




*Source: Lane, J. L., Smart, S., Schmeda-Lopez, D., Hoegh-Guldberg, O., Garnett, A., Greig, C. and McFarland, E. (2016), Understanding constraints to the transformation rate of global energy infrastructure. WIREs Energy Environ, 5: 33–48.*

Current projections indicate more than 2,400 new coal-fired power plants are planned for construction by the year 2030.[21] Two main drivers influence construction – growth in future electricity demand due to population increases, and retirement/replacement of infrastructure. Given the age of coal-fired plants it does not appear as through business-as-usual retirements will drive a dramatic reduction in coal use. Continued investment in unabated coal will consume a large proportion of the global emissions budget, unless CCS is applied.[22]

Australia's international obligations, as a signatory to the Paris Agreement, will need to contribute to the global goal of achieving net zero emissions in the second half of this century. The current, firm intermediate target is to reduce economy-wide emissions to 26 to 28 per cent below 2005 levels by 2030.[2] Current policies suggest that this intermediate target is expected to be achieved by a combination of expectations for very low demand growth, large-scale renewable generation, energy productivity improvements, growth in residential and commercial rooftop solar PV backed by grid augmentation, electricity storage, gas-fired generation and retirement of aging coal plants.

Australia's domestic power supply has an increasing focus on energy security and 24-7 system reliability as the proportion of intermittent electricity generation increases. Australia currently has an aging fleet of power generation assets with approximately 21 GW of coal and gas-fired generation in service for more than 30 years. As large, 24-7 coal and gas-fired assets are retired, investment in HELE coal-fired power generation should be considered on its merits. Such an investment case would depend on CCS being deployed in the future.

Looking beyond 2030, there remains the real likelihood that Australia (and the world) will continue to be reliant on fossil fuels (a mix of coal and natural gas) for significant power generation, heavy transport, aviation, agriculture and industrial production.[17] Depending on technological progress among the full suite of low emissions technologies, CCS is likely to be the lowest cost option to achieve the deep cuts in emissions consistent with a global net zero emissions position in the second half of the century.

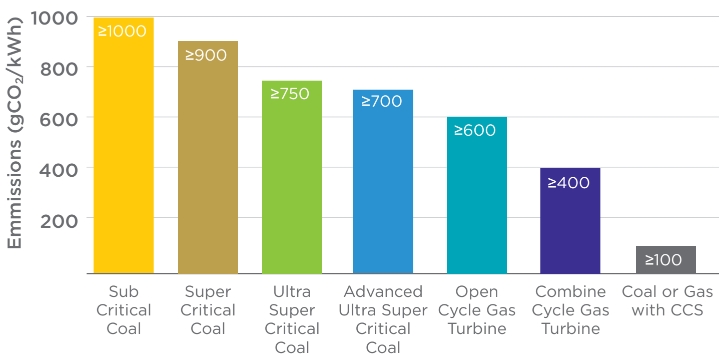
Australia is a leading energy producer and exporter. Australia would benefit from the deployment of HELE and CCS technologies so that it can continue to earn export revenues from fossil fuels.

Accordingly, there is a compelling case that Australia should make the necessary investment now to be ready to deploy CCS commercially in the medium term (post 2030), scaling to potential widespread deployment by 2050. This would enable CCS to compete on an equal footing with alternative step change, low emission technologies (such as solar thermal, geothermal, hydro and bioenergy).

Australia must act now and invest in $CO_2$ storage site characterisation including investment-ready appraisal of priority sites, full-chain CCS demonstration, techno-economic assessments, regulation alignment and public engagement to ensure CCS as a legitimate large-scale emissions reduction option for commercial deployment.

**Figure 9:**

**HELE technologies for coal and gas are a precursor to facilitate the transition to a low carbon future**




*Emissions intensities apply to generation only and exclude upstream and fugitive emissions.*

## Roadmap to CCS-Readiness

The pathway to achieving commercial readiness for CCS will take further investment on a global scale.[17] This investment is required from government and industry to stimulate the necessary development, demonstration and early mover deployment needed to drive down costs. It will also require consistent enabling policy to address project-specific risks along the CCS value chain especially at the interfaces between participants.

### What is CCS-ready?

> A CCS-ready facility is a large-scale industrial or power source of $CO_2$ which could and is intended to be retrofitted with CCS technology when the necessary regulatory and economic drivers are in place. The aim of building new facilities or modifying existing facilities to be CCS-ready is to reduce the risk of carbon emission lock-in or of being unable to fully utilise the facilities in the future without CCS (stranded assets). CCS-ready is not a $CO_2$ mitigation option, but a way to facilitate $CO_2$ mitigation in the future. CCS-ready ceases to be applicable in jurisdictions where the necessary drivers are already in place, or once they come in place.

*Source: Global CCS Institute*

The CCS Roadmap indicates what activities and milestones are required to get Australia ready for widespread commercial deployment without attempting to predict when CCS might become a commercially viable carbon mitigation option.

It must be acknowledged that the roadmap builds on substantial work in the past both internationally and in Australia.[7]

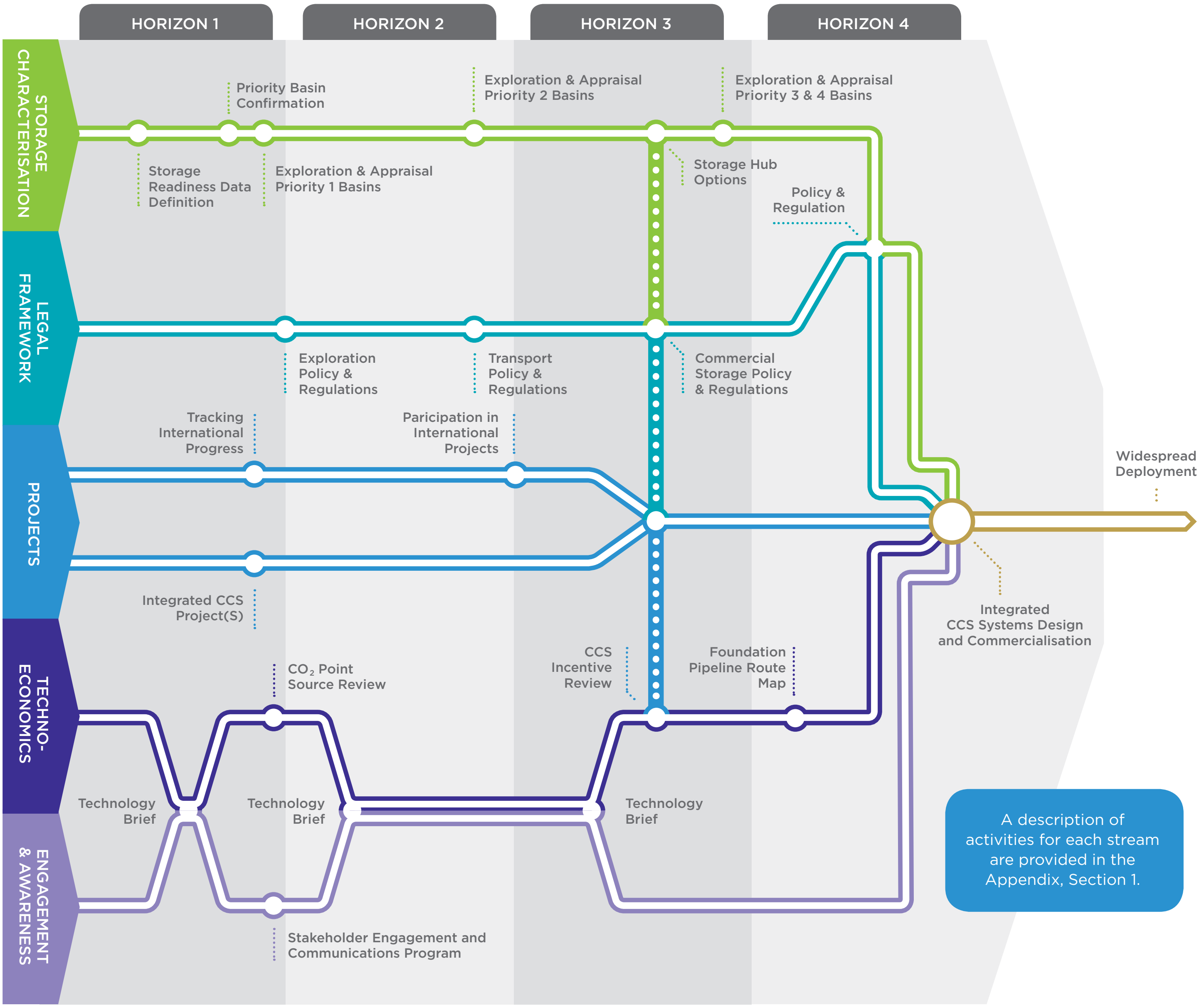
The roadmap is divided into 4 time horizons, which are nominally 5 years in duration. Changes in policy, available funding or other factors may result in the fast-tracking or delaying of individual tracks. Changes may make some tasks redundant or require the addition of tasks not considered necessary at present. Accordingly, the roadmap should be reviewed and revised periodically.

The key elements include:

- Building investment-ready confidence in storage resources;
- Aligning legal and regulatory frameworks and stress testing them;
- Monitoring and participation in international projects;
- Completing techno-economic studies along the full CCS value chain and establishing appropriate investment incentives;
- Securing continuing support through public engagement and storage demonstration projects; and
- Analysis and planning of full value chain CCS systems.

CCS must also be included in a much broader campaign of education and engagement of the public around energy and environment.

## Roadmap




### Progress

**Storage Characterisation (Basin-wide)**

- Gorgon Carbon Dioxide Injection Project
- QLD Storage Assessment (CGI)
- NSW Storage Assessment
- Darling Basin Drilling Project
- Geoscience Australia Pre-Competitive Studies
- Surat Deep Aquifer Appraisal Project

**Legal Framework**

- Offshore Petroleum and Greenhouse Gas Storage Act 2010
- Queensland Greenhouse Gas Storage Act 2009
- Victorian Greenhouse Gas Geological Sequestration Act 2008
- The Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2008
- Australian Gas Greenhouse Geological Sequestration Act 2008
- The Barrow Island Act of 2003

**International Projects**

Power sector

- Boundary Dam
- Petra Nova
- Kemper County IGCC
- Sinopec Shengli
- GreenGen IGCC
- ROAD
- Haifeng Power

Gas and oil

- Val Verde Gas Plants
- Sleipner
- Snøhvit
- Century Plant
- Lula Oil Field
- Uthmaniyah CCS Demonstration Project

Industrial sector

- Illinois Industrial CCS Project
- Quest
- Great Plains Synfuel
- Coffeyville Gasification
- Air Products, Port Arthur
- Texas Clean Energy Project
- Abu Dhabi CC(U)S Project
- Tomakomai Project

**Techno-economics**

- Australian Power Generation Technology Report
- Australian Energy Technology Assessments
- ZeroGen
- Wandoan
- Tarong
- Munmorah/ Vales Point
- Hazelwood
- H3
- Loy Yang
- Mulgrave

**Engagement & Awareness (Australian Projects)**

- Otway Project
- CarbonNet Project
- South West Hub
- CTSCo Surat Basin
- Callide Oxyfuel Project (completed)
- Gorgon Carbon Dioxide Injection Project
- ZeroGen (completed)

## Business Models & Incentives for CCS

The rationale for CCS centres on risk mitigation by preserving options and diversity to assure energy security, achieve emissions reduction targets at the lowest cost, and to preserve the future value of fossil fuel assets.

Incentives and regulatory mechanisms are vital for the development of viable CCS business models to encourage investment and provide an opportunity for competitive advantage.

Current policies are weighted heavily to support renewable technologies. To assure energy security and the value of fossil fuel reserves, government should provide equivalent support to all low emission technologies including CCS.

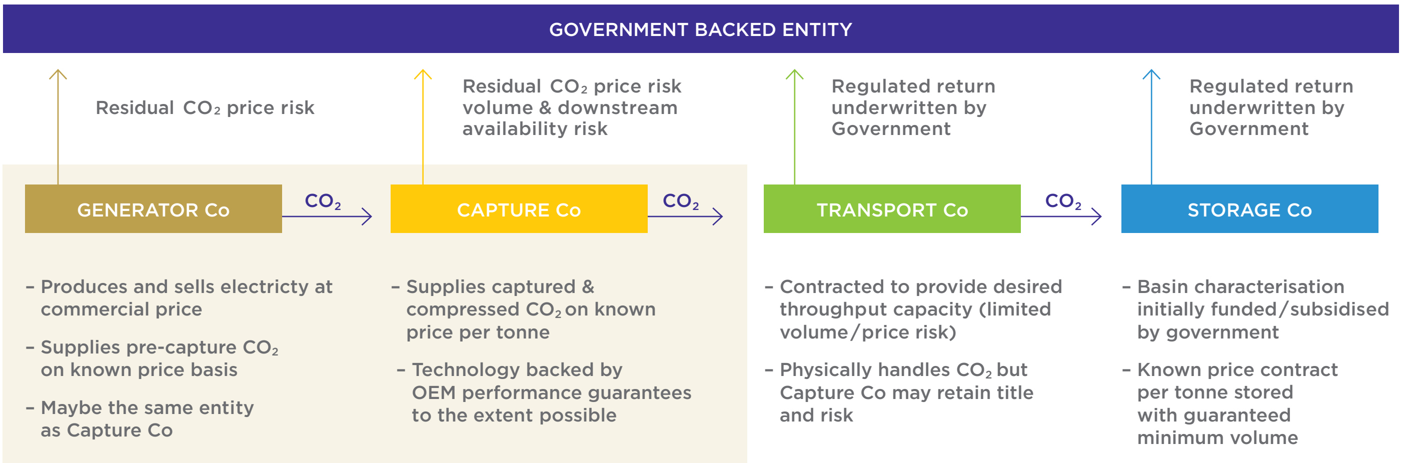
Support should be targeted appropriately, which will require identification of the skill sets and risk profiles along the CCS value chain and across sectors. This may evolve as industry compares the cost of CCS versus changes in opportunity costs. Those include the impacts on export revenues from coal and gas assets and implications for Australia's energy security, that is, adequacy, reliability and competitiveness consistent with sustainable resource development.[23]

Activities to achieve CCS readiness in Australia must have access to a range of transitional government support options. A detailed watching brief on international initiatives is recommended, but support is likely to include mechanisms that:

1. Facilitate development of $CO_2$ storage resources in advance of integrated projects;
2. Lower the amount of capital that needs to be raised by project proponents and support operating-phase cash flows; and
3. Mitigate specific project-related risks along the value chain, especially at party interfaces through a government backed entity.

Furthermore, policies that incentivise low emission technologies should not be based on specific technology types. Rather, policies must be designed to deliver 24-7 reliable power and maintain energy security.

Figure 10: **A possible business model for incentives**




A potential arrangement between corporate operators with four CCS components. The government would have risk backstop arrangements with each company to support project returns. This crucially limits each company's exposure to the operational performance of other elements in the chain.

# WORKING PAPERS AND SUPPORTING REPORTS

A number of working papers were drafted during the development of this study. These provide context for the study but are also designed to be discrete reference documents.

1. Greig, C., Bongers, G., Stott, C. and Byrom, S. (2016). Energy Scenarios, Outlooks and Climate Policies, The University of Queensland, Brisbane. ISBN 978-1-74272-176-7

   This working paper provides an overview of global energy scenarios developed by the International Energy Agency, Shell and BP; an Australian outlook, including the electricity sector, natural gas processing operations and other industrial $CO_2$ sources; and an overview of climate change polices and targets.

2. Greig, C., Baird, J. and Zervos, T. (2016) Financial Incentives for the Acceleration of CCS Projects, The University of Queensland, Brisbane. ISBN 978-1-74272-177-4

   This working paper provides an overview of incentives and regulatory mechanisms to accelerate CCS projects.

3. Greig, C., Bongers, G., Stott, C. and Byrom, S. (2016). Overview of CCS Roadmaps and Projects, The University of Queensland, Brisbane. ISBN 978-1-74272-178-1

   This working paper provides an overview of published CCS roadmaps; Australian CCS projects; and international CCS projects.

4. Bongers, G. (2016) Australian Power Generation Technology Report, CO2CRC, Melbourne.

   This report provides an unbiased, technology-neutral review of a broad range of generation technologies, their capabilities and their costs for 2015 and out to 2030.

# REFERENCES


1. Molyneaux, L., Wagner, L., Froome, C., and Foster, J. (2012) Resilience and electricity systems: A comparative analysis. Energy Policy 47: 188-201.

2. Oxburgh (2016): LOWEST COST DECARBONISATION FOR THE UK: THE CRITICAL ROLE OF CCS. Report to the Secretary of State for Business, Energy and Industrial Strategy from the Parliamentary Advisory Group on Carbon Capture and Storage (CCS).

3. Australian Government Department of Foreign Affairs and Trade (2015) Australia's Intended Nationally Determined Contribution to a new Climate Change Agreement, Canberra, August.

4. McGlade, C. and Ekins, P. (2015) The geographical distribution of fossil fuels unused when limiting global warming to 2°C. Nature 517: 187-190.

5. Carbon Storage Taskforce (2009) Australia's Potential for the Geological Storage of $CO_2$, www.industry.gov.au/Energy/Documents/cei/cst/Aus_Potential_co2_Brochure.pdf (accessed November 2016).

6. Bongers, G. (2016) Australian Power Generation Technology Report, www.co2crc.com.au/wp-content/uploads/2016/04/LCOE_Report_final_web.pdf (accessed November 2016)

7. Reiner, M. (2016) Learning through a portfolio of carbon capture and storage demonstration projects. Nature Energy 1, Article number: 15011.

8. Australian Government Department of Environment (2015) Tracking to 2020: An interim update of Australia's greenhouse gas emissions projections, Canberra.

9. Australian Government Department of Industry, Innovation and Science (2016) Energy in Australia 2015, Canberra, January.

10. Australian Energy Regulator (2015) State of the Energy Market 2015, ISBN 978 1 922145 67 3.

11. Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2015): "Integration Costs Revisited – An economic framework of wind and solar variability", Renewable Energy 74, 925–939.

12. Preliminary Report of the Independent Review into the Future Security of the National Electricity Market, Commonwealth of Australia 2016.

13. EPA (2003) Economic Impact Analysis of Final Iron and Steel Foundries NESHAP. North Carolina : Research Triangle Institute, EPA-452/R-03-012.

14. Australian Energy Projections to 2049-50, BREE, Canberra, November.

15. World Coal Association (2016) Coal market & pricing, www.worldcoal.org/coal/coal-market-pricing (accessed November 2016).

16. Australian Government Department of Industry, Innovation and Science (2016) Resources and Energy Quarterly, June quarter 2016, Canberra.

17. International Energy Agency (2016) World Energy Outlook, IEA/OECD, Paris.

18. Australian Government Department of Industry, Innovation and Science (2015) Resources and Energy Quarterly, September quarter 2015, Canberra

19. World Nuclear Association (2016) World uranium Mining Production, www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx (accessed November 2016).

20. Australian Government Department of Foreign Affairs and Trade (2015) Composition of Trade Australia 2015, Canberra.

21. Lane, J.L., Smart, S., Schmeda-Lopez, d., Hoegh-Guldberg, O., Garnett, A., Greig, C. and McFarland, E. (2015) Understanding constraints to the transformation of global energy infrastructure. WIREs Energy Environ, 5: 33-48.

22. Pfeiffer, A., Millar, R., Hepburn, C. and Beinhocker, E. (2016) The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy, 179: 1395-1408.

23. Australian Government Department of the Environment and Energy (2016) Energy Security www.environment.gov.au/energy/energy-security-office (accessed November 2016).

# Energy Security and Prosperity in Australia

**APPENDIX**

# APPENDIX

This appendix further describes activities required as part of the CCS Roadmap. These will need to link to other CCS activities in progress.

## 1. Roadmap to CCS-Readiness Workplan Outline

The pathway to achieving commercial readiness for CCS will take further investment globally from government and industry to drive the necessary development, demonstration and early mover deployment needed to drive down costs. It will also require consistent enabling policy in the form of risk reduction measures along the CCS value chain.

Without attempting to predict when CCS might become a commercially viable carbon mitigation option, the CCS Roadmap has sought to show what is required to get Australia ready for widespread commercial deployment. It must be acknowledged that this roadmap builds upon the substantial past work carried out both internationally and in Australia.

The key elements include:

- Building investment-ready confidence in storage resources;
- Aligning legal and regulatory frameworks;
- Monitoring and participation in international projects;
- Completing techno-economic studies along the full CCS value chain and establishing appropriate investment incentives;
- Securing the license to operater through public engagement and storage demonstration projects; and
- Analysis and planning of full value chain CCS systems.

The roadmap is divided into 4 time horizons, which are nominally 5 years in duration. Changes in policy, available funding, or other factors may result in the fast-tracking or delaying of individual tracks. Changes may make some tasks redundant or require the addition of tasks not considered necessary at present. Accordingly, the roadmap should be reviewed and revised periodically.

### 1.1 Storage Characterisation

An independent organisation is needed to have oversight of the characterisation of Australia's geological storage resources including the prioritisation and allocation of funding. Further pre-competitive exploration as well as exploration and appraisal of priority basins is required to advance further commercial investment into storage reserves and to mature second-tier storage resources.

Such an organisation may be an existing agency or done in partnership with multiple agencies. It would provide advice to state and Federal government ministers on the commercial, technical, policy and regulatory barriers to CCS. It would also be accountable to coordinate a national approach to prioritising and gathering pre-competitive exploration. As a coordinating body it would act as a stakeholder reference group for government agencies and commercial organisations.

It is envisaged that this oversight complements the pre-competitive storage exploration of the state geological surveys and, while the commercial gap for CCS remains, facilitates necessary exploration and appraisal work in the priority basins across Federal and state jurisdictions.

**Investment-Ready $CO_2$ Storage Exploration and Appraisal Data**

Pre-competitive geoscience data acquisition refers to the collection, collation and integration of basic geoscientific data for subsequent use by government agencies and commercial organisation to determine commercial prospects. The aim of pre-competitive data release is to stimulate exploration by attracting new exploration investment opportunities revealed through the interpretation of the new and expanded datasets. Just as minerals sector and the petroleum sector have different needs for precompetitive data to ensure their medium-term resource exploration success, so too does the $CO_2$ storage sector.

Given the different risk and return on investment profile of the $CO_2$ storage sector, more advanced. extensive data will be required initially to facilitate investment. An updated and detailed definition of the level of data required to assure the medium-term resource exploration success should be developed and agreed upon by Government agencies and industry that covers both on- and off-shore data sets.

Initially this activity would require confirmation of priority basins based on the 2009 Carbon Storage Taskforce Report[1] and any subsequent work.[2] $CO_2$ storage resources should also be added to the 'National Map System.' This should also identify non-technical risks such overlapping and neighbouring tenements, restricted land (mainly national parks) and the distribution of strategic cropping land.

**Exploration and Appraisal in Priority Basins**

There is a need to explore and appraise priority storage basins to facilitate (by de-risking) subsequent commercial investment to further appraise and commercialise large-scale $CO_2$ storage. Work is required to examine the existing data and new data acquired from a drilling, seismic and test program to form an updated and commercially relevant pre-competitive data set.

It should be noted that if the data for a particular basin does not indicate the economic potential for sufficient storage to support significant long-term commercial $CO_2$ injection, then work on the next most prospective basin would commence ahead of schedule; i.e. it is important to recognise and budget for potential exploration failure cases.

It is anticipated that four basins will require this level of exploration and appraisal, the data from which will all be considered pre-competitive and publicly available.

**Storage Hub Options Study**

The injectivity and economic capacity of potential $CO_2$ storage reservoirs impacts the design of end-to-end CCS systems. Injection site locations, storage capacities and reservoir properties of a combination of storage sites in a hub configuration can all affect the design of $CO_2$ pipelines as well as transport and storage costs. A storage hub options study should contain information to inform potential (both capture and storage) project proponents of the hub characteristics to decrease the risks associated with a full-chain CCS project.

[1] *Carbon Storage Taskforce 2009, National Carbon Mapping and Infrastructure Plan – Australia: Full Report, Department of Resources, Energy and Tourism, Canberra.*

[2] *For example, NSW $CO_2$ Storage Assessment Program. Final Report on Stage 1B - Darling Basin Drilling Program. Division of Resources & Energy, NSW Department of Trade and Investment, Regional Infrastructure and Services. December 2014.*

It should cover the priority basins and incorporate and build on the previous storage hub studies.

In addition, a foundation pipeline route map focused on identifying the potential $CO_2$ pipeline routes for storage basins and hubs is recommended. It should contain information for policymakers and the energy sector to use for policy and investment decisions and for further modelling of source matching to storage locations.

## 1.2 Legal Framework

CCS deployment requires a legal and regulatory framework which regulates development and operation and prescribe the potential liabilities it may incur during and after is operation. Various jurisdictions have taken different approaches to the legal and regulatory environment for full-chain CCS and are at different levels of maturity.

As both Federal and state governments have jurisdiction over various elements of the CCS value chain an optimum legal and regulatory environment would be a harmonized framework under which projects would operate nationally. While a considerable number of legal instruments for the elements of the CCS value chain will have been developed, an emphasis on best national practice should be used to inform legislators and regulators. This includes exploration, transport and commercial policy and regulations. This work would provide the relevant governments and agencies the data and recommendations that would enable these bodies to adopt a more unified national approach.

**Exploration Policy and Regulations**

Exploration policy and regulations play an important role in supporting the establishment of verified storage resources. While a considerable number of legal instruments for storage exploration have established, there remains a need to further develop legislation and regulations – with a particular emphasis on a more uniformed approached in all jurisdictions.

**Transport Policy and Regulation**

Tailored, end-to-end policies, laws and regulations which are harmonised across all (state, territory and Federal) jurisdictions offer a pathway to efficiently enable CCS. While policy and law reform is often an iterative in each jurisdiction, a national and coordinated review of the current elements of all CCS policies, laws and regulations should be conducted; the results of which should be used to determine nationally consistent $CO_2$ transport (but preferably end-to-end CCS) policy and regulation.

**Commercial Storage Policy and Regulations**

Commercial storage policy and regulations play an important role in supporting the establishment and usage of verified storage resources. While a considerable number of legal instruments for storage have established, there remains a need to further develop legislation and regulations – with a particular emphasis on a more uniformed approached in all jurisdictions. This includes establishing elements that cover the definition of a leak, and clarity on timeframes, scope and parameters for the monitoring required to establish a baseline. Consideration should also be given to defining when a $CO_2$ plume is behaving as expected.[3]

## 1.3 Projects

**Integrated CCS Project(s)**

While the successful storage of $CO_2$ has been demonstrated at commercial quantities in overseas jurisdictions, a successful, high profile, on shore project, in Australia may prove to be important in assuring public understanding and acceptance of CCS. The lack of visible or accessible activity risks reinforcing the view that CCS is a technology that has 'missed its chance' noting that of course a negative incident associated with such activity might prove fatal for CCS. A medium scale $CO_2$ storage demonstration that is accessible to the general public could build upon the success of the Otway storage project and the Gorgon project. The timing of such an activity needs to be carefully considered. It should only be carried out in a priority basin for which the exploration and appraisal activity has established a level of confidence in large-scale storage economic potential.

**Tracking International Projects**

To assist in the development, demonstration and deployment of CCS knowledge sharing and understanding international project outcomes is essential. This will result in the increased understanding and acceptance of CCS, increased commercial opportunities for CCS and support for CCS in international and national energy and climate change policies. This is currently conducted by the GCSSI.

**Integrated CCS Systems Design and Commercialisation**

The option to combine multiple sources of $CO_2$ into a single transportation system for subsequent storage impacts the design of end-to-end CCS systems. The total quantity and quality of the $CO_2$ along with potential production variations of a combination of sources in a hub configuration can all affect the design of $CO_2$ pipelines and storage systems. In addition to collection hubs, storage hubs should also be identified. Injection site locations, storage capacities and reservoir properties of a combination of storage sites in a hub configuration can all affect the design of $CO_2$ pipelines as well as transport and storage costs. The linkage of sources and sinks, whether single sites or hubs via a pipeline presents the opportunity to have an optimised and effective transportation system. The study should also examine the selection of least cost transport designs for a range of collection hub and storage hubs designs which provide important data on optimum $CO_2$ transportation routes.

A comprehensive collection, transport and storage study should contain information to inform potential project proponents of the potential system characteristics to decrease the risks associated with a full-chain CCS project. It should also inform Federal and state governments of the system requirements.

*[3] Gibbs, M.K., Effective enforcement of underground storage of carbon dioxide, HWL Ebsworth Lawyers, Melbourne, June 2016.*

*[4] Australian Government Department of Environment and Energy, Publications and Resources, https://www.environment.gov.au/climate-change/greenhouse-gas-measurement/publications#quarterly (accessed November 2016).*

## 1.4 Techno-economics

**Technology and International Projects Watching Brief**

There is a need for up-to-date cost and performance data of the full range of low emissions electricity options, including fossil energy systems equipped with CCS, to ensure Australia's energy sector investors and policy makers have an accurate and up-to-date database. An Australian focused low emissions technology-watching brief (with a primary focus on power generation) would provide credible technology cost and performance data for the current year of study and 15- and 25- year projections. It should contain data 'building blocks' for policymakers and energy sector investors to use for policy and investment decisions and for further modelling of Australian emissions reduction options. It should also contain data for a wide range of technologies, including current and projected capital costs, operation and maintenance costs, and detailed performance data.

This work could be carried out in conjunction with the Australian Energy Technology Assessment (AETA) conducted by the Federal Government.

**$CO_2$ Point Source Review**

A review focused on identifying and building on the main greenhouse gas emission point sources and potential project $CO_2$ storage opportunities would provide valuable information for policy makers and potential early mover projects more generally. The review will consider both the current[4] and future scenarios (to 2050) for industrial and power sector emission point sources: this will include location, volume and range of emissions. It should contain data and modelling outcomes for policymakers and the energy sector to use for policy and investment decisions and for further modelling of potential source matching to potential storage locations.

**CCS Incentive Review**

The pathway to achieving commercial readiness for CCS will take further investment globally from government and industry to drive the necessary development, demonstration and early mover deployment needed to drive down costs. It is likely additional investment/financial incentives and consistent enabling policy in the form of risk reduction measures along the CCS value chain.

## 1.5 Engagement and Awareness

**Stakeholder Engagement and Communications Program**

Modern political environments mean that there is a strong need to ensure that the Australian community are well positioned to make informed decisions regarding the current and future energy options. There is a need for increased knowledge within the broader Australian community – the voters, tax payers, current and future workforce, thought leaders, decision makers – both within industry and governments – on the importance and complexity of energy. This should include a wide ranging energy education campaign – including a specific secondary school focus to provide world class teaching resources covering electricity, energy resources and exports, and industrial applications including CCS options.

[5] *Bongers, G. (2016) Australian Power Generation Technology Report, CO2CRC, Melbourne.*

# 2. Low Emission Technology Options

The majority of section is taken from the Australian Power Generation Technology (APGT) Report executive summary.[5]

The APGT Report cost of electricity study provides credible technology cost and performance data for 2015 to 2030. It contains data 'building blocks' for policymakers, power professionals and the energy sector to use for policy and investment decisions and for further modelling of Australian electricity generation options. For a wide range of technologies, the study includes current and projected capital costs, operation and maintenance costs, and detailed performance data.

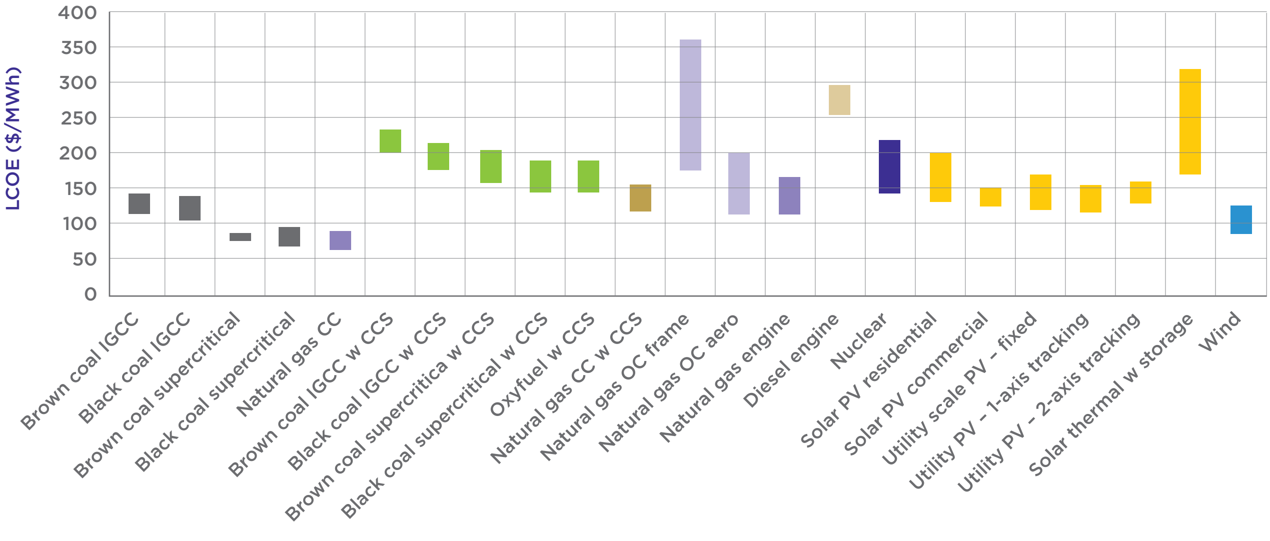
The APGT Report did not attempt to forecast the likely future make-up of the generation suite used in Australia in 2030 scenarios. It was not designed to be used for choosing a 'winning' technology, but as a source of data as an input to further modelling and assessment work.

## 2.1 Comparing our Technology Options

The APGT Report presents a set of important 'building blocks' that enable different generation technologies to be compared on a common basis. It provides industry, government and consumers with the tools needed to evaluate all relevant factors related to cost (both capital and operating costs) and performance (including carbon emissions, water usage and capacity factors).

Figure A1 shows the levelised cost of electricity (LCOE) for a range of technologies if they were to be built in Australia today, under today's conditions. The LCOE captures the average cost of producing electricity from a technology over its entire life, given assumptions about how the generator will operate. It allows the comparison of technologies with very different cost profiles, such as solar photovoltaic (PV) (high upfront cost, but very low running costs) and gas-fired generators (moderate upfront cost, but ongoing fuel and operation costs).

Figure A1: **2015 LCOE ($/MWh) - built in Australia**




### The Cost of Generation in 2015

No single technology is optimal across all metrics, so the ideal grid should include a mix of technologies. Of the renewable technologies, wind power has the lowest LCOE in 2015. Of the fossil-fuel technologies, natural gas combined cycle and supercritical coal-fired generation have the lowest LCOEs.

All new technologies have significantly higher LCOEs than the current Australian grid average wholesale price. A levelised cost does not capture the total cost of operating an electricity grid. For that reason, the LCOE and current electricity pool prices are not comparable, as LCOE covers long-run costs but pool prices often do not.

The LCOE of a technology is the average cost of producing electricity from that technology over its entire life, given assumptions about how the power station will operate; it is the cost of power as delivered to the plant boundary.

A levelised cost does not capture the total cost of operating an electricity grid. For that reason, the LCOE and current electricity pool prices are not comparable, as LCOE covers long-run costs but pool prices often do not.

[6] *Taxation ruling TR 2015/2*

[7] *The focus of current hydropower investment in Australia is on the refurbishment and modernisation of existing assets and in some cases the addition of mini- and micro-hydro units to waterways. The costs of refurbishments and small hydro are too site-specific for inclusion in this study.*

Recognising the limits of the current LCOE methodology, CSIRO has begun research to develop an extended methodology so that technologies can be compared on a more 'like for like' basis. The initial focus of the research is to determine how to take into account the costs of integrating intermittent renewables into the electricity system.

However, LCOEs allow comparisons of technologies with very different cost profiles, such as solar PV versus gas- or coal-fired generation.

Straight-line tax life depreciation was assumed for this Australian study. The tax life for fossil fuel, nuclear and solar plants is assumed to be 30 years, and for a wind plant 20 years. These tax lives are consistent with the depreciation guidelines from the Australian Taxation Office.[6]

The spread of costs for each technology reflects a range of project-specific factors that can affect the costs. This includes the cost of bringing fuel to the plant, the local wind or solar resource levels, and site-specific factors that affect construction costs. The cost of new hydropower generation was not assessed, as it is unlikely that new large-scale hydropower projects will be deployed in Australia.[7]

## 2.2 The Advantages and Disadvantages of Each Technology

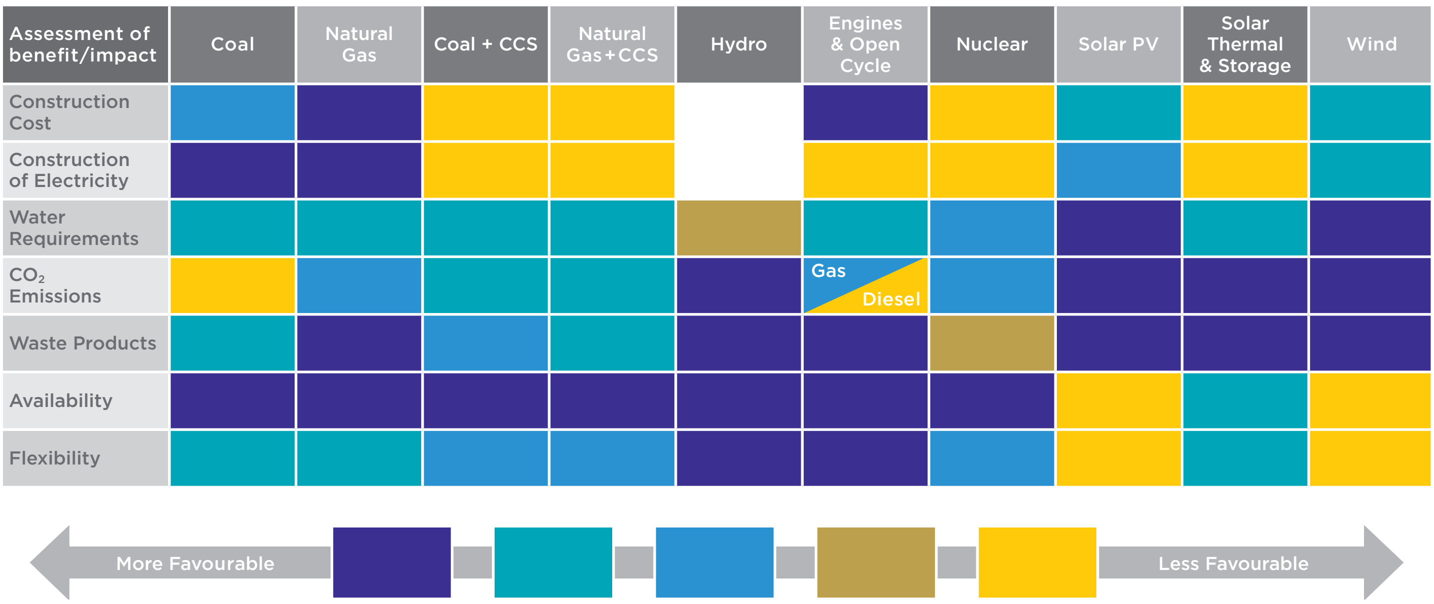
Beyond the range of costs considered above, each technology has operational advantages and limitations that must be considered. Designers of reliable power systems must take all the attributes listed in Table A2 into account, as well as the integration of combinations of low-cost generation and flexible generation and emissions reduction obligations.

## 2.3 Technology Maturity, Costs and Abatement Potential

Figure A3 and Figure A4 are a graphical representation of technologies in terms of maturity, cost and abatement potential:

- Maturity is reflected in the size of the bubbles (refer to Table 2 for details on TRL). The bubbles are also colour coded reflecting the flexibility of a particular technology or the ability to have its output controlled and varied at short notice.
- Cost is expressed as LCOE (Figure A3) and $/tonne of $CO_2$ avoided relative to subcritical brown coal (Figure A4).
- Abatement potential is expressed as the reduction in $CO_2$ emissions per MWh relative to a subcritical brown coal power plant.[8]

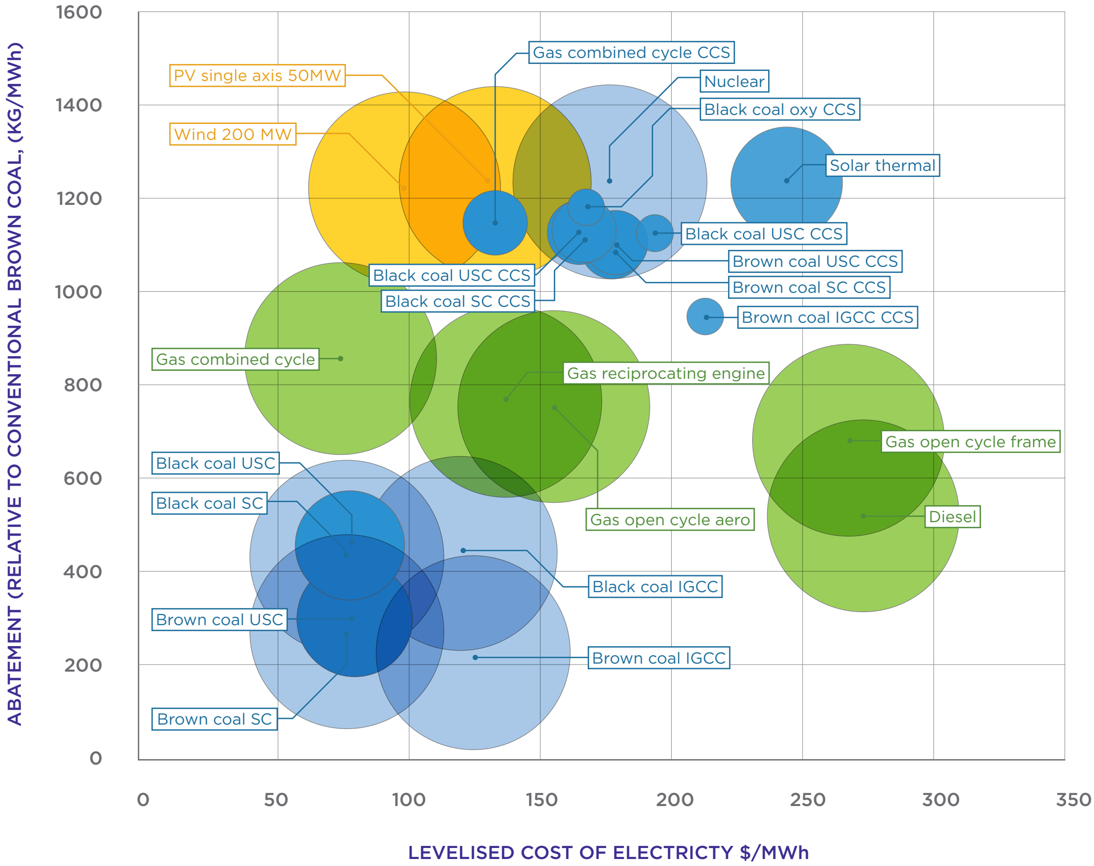
Figure A2: **Electricity technology comparison**




*Source: Bongers, G. (2016) Australian Power Generation Technology Report, CO2CRC, Melbourne.*

*[8] This section based on a GCCSI Private communication 2016 - LETFF Stocktake of Technologies and R&D Activities.*

**Figure A3: Technology prioritisation matrix – LCOE ($/MWh, 2015)**




How to read this chart:

The location of each bubble reflects a technology's relative cost and abatement potential.

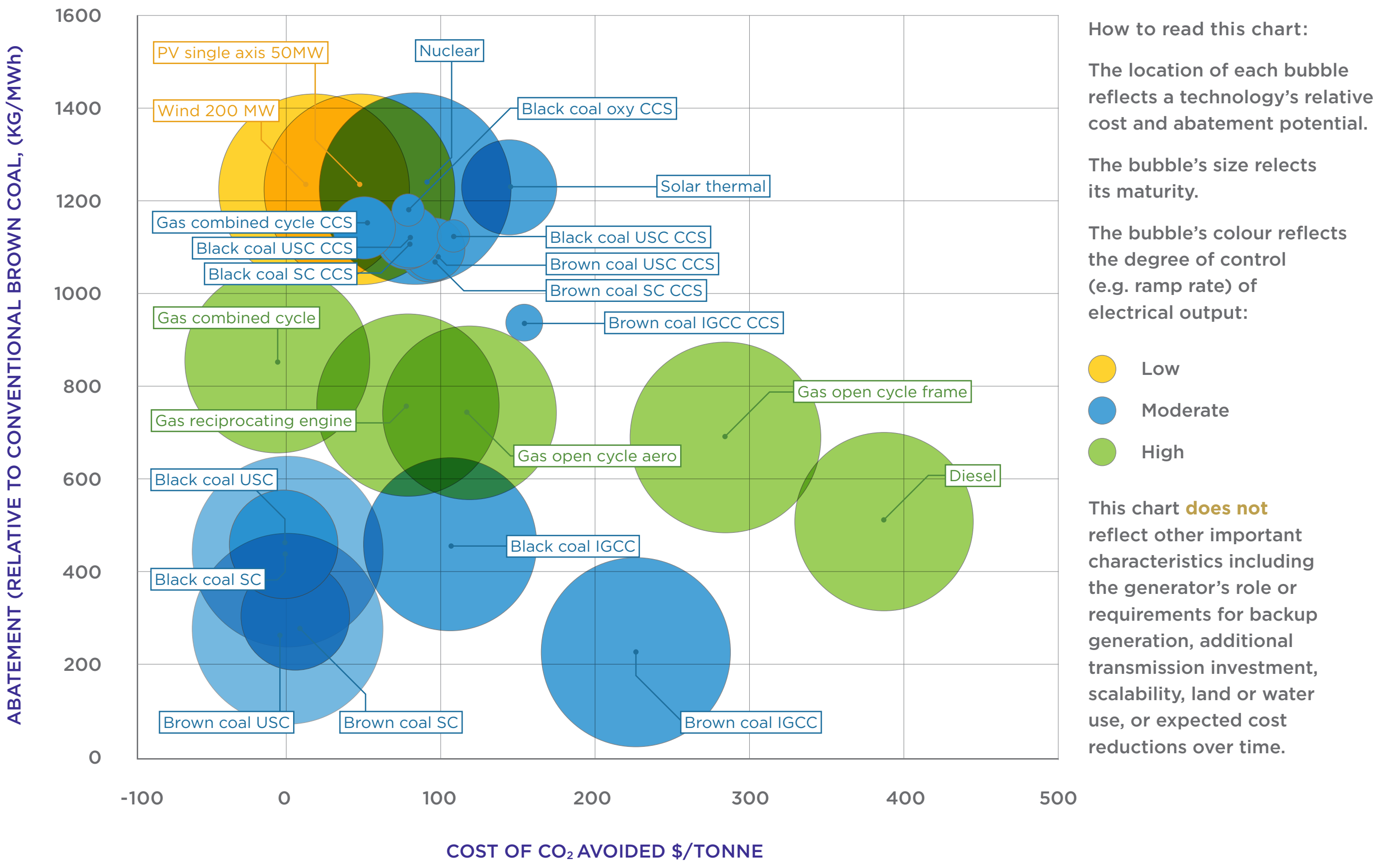
The bubble's size relects its maturity.

The bubble's colour reflects the degree of control (e.g. ramp rate) of electrical output:

- Low
- Moderate
- High

This chart **does not** reflect other important characteristics including the generator's role or requirements for backup generation, additional transmission investment, scalability, land or water use, or expected cost reductions over time.

Figure A4: **Technology prioritisation matrix – Avoided Cost ($/tonne $CO_2$, 2015)**




## 2.4 Future Cost Reductions by 2030

All new low- and zero-emissions technologies are projected to reduce in cost by 2030. In general, the more mature the technology, the less opportunity for further cost reductions.

The scope of cost reduction for a given technology depends heavily on the global take-up of that technology, along with learning-by-doing in local projects.

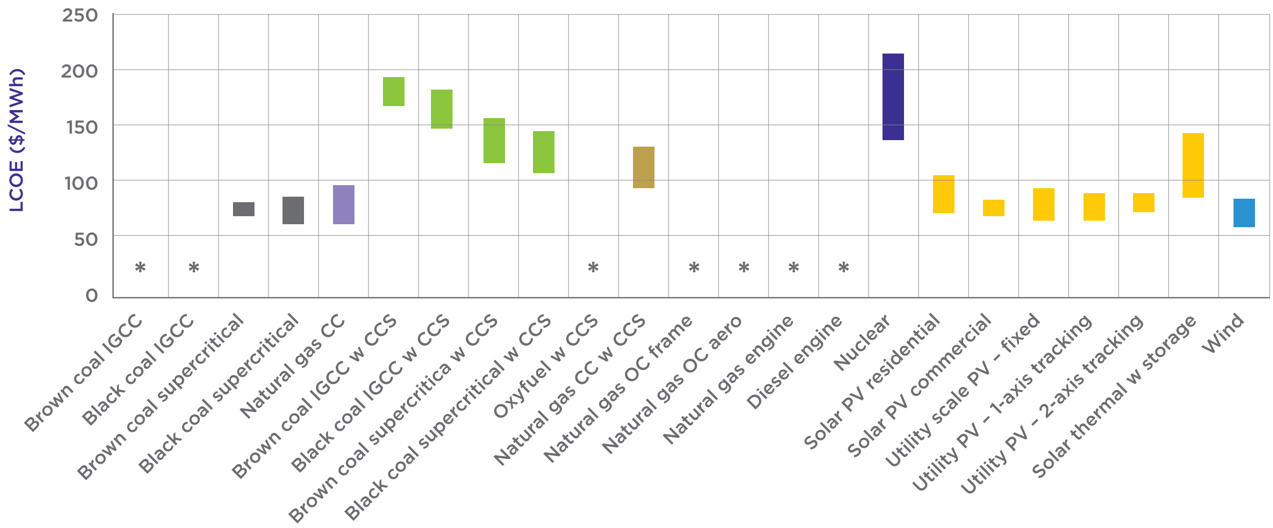
The overall ranking of LCOEs for technologies in 2030 is not projected to change from 2015, but there is likely to be convergence in LCOEs across most technologies.

Just as critical as assessing the current market is understanding of technology costs and capabilities are likely to go in the future. The scope and rate of technology improvements, whether incremental or breakthrough, depend on how much of each technology is deployed—which itself depends on the technology cost—so iterative modelling is needed.

Because all technologies used in Australia are also deployed globally, it is the global deployment levels that will drive technology and manufacturing cost breakthroughs. To capture these learning-by-doing effects, this study used GALLM, a global and local model from the CSIRO, informed by data from the Electric Power Research Institute (EPRI) and industry partners (Figure A5). GALLM considers learning curves for each technology in a global context and projects future costs under various scenarios.

A key input is the current development status of the technology: more mature technologies are less likely to experience future cost reductions.

Figure A5: **2030 LCOE ($/MWh) - built in Australia**




*Technology not considered by GALLM

EPRI has also conducted a separate assessment of each technology to identify explicit cost reductions achievable through focused R&D for each component. Both approaches have merit: the component-based approach identifies readily achievable cost savings, while the learning curve approach captures the more significant cost reductions that have been observed historically for many emerging technologies.

The APGT Report's findings on costs to 2030 include the following:

### Solar PV

Solar PV capital costs are projected to reduce by 35– 50%. As more solar PV plants are built, the cost of PV modules will continue to decline due to mass production. Other system costs and inverter costs are also expected to decrease over time. In laboratories, researchers are continuing to develop new PV configurations that promise to increase cell and module efficiency.

### Solar Thermal

Solar thermal capital costs may halve, depending on the volume of global installations.

### CCS Plant

CCS plant capital costs are projected to reduce by 30– 50%, which translates into a reduction in levelised cost of 10–25% when operating costs are taken into account. There are likely to be improvements in both base plant efficiency and capture technology. However, if there is a lack of deployment at the global level this may inhibit learning by doing and therefore not lead to reductions in costs for CCS.

### Combined Cycle Gas

Combined cycle gas generation is projected to become the cheapest fossil-fuel traditional baseload technology. Natural gas combined cycle plants are likely to benefit from higher firing temperatures, leading to increased efficiencies and reduced capital costs. It is projected that these developments will be used to reduce the cost and improve the performance of integrated gasification combined cycle units.

## 2.5 Changes to LCOE Rankings Caused by Pricing Carbon Emissions

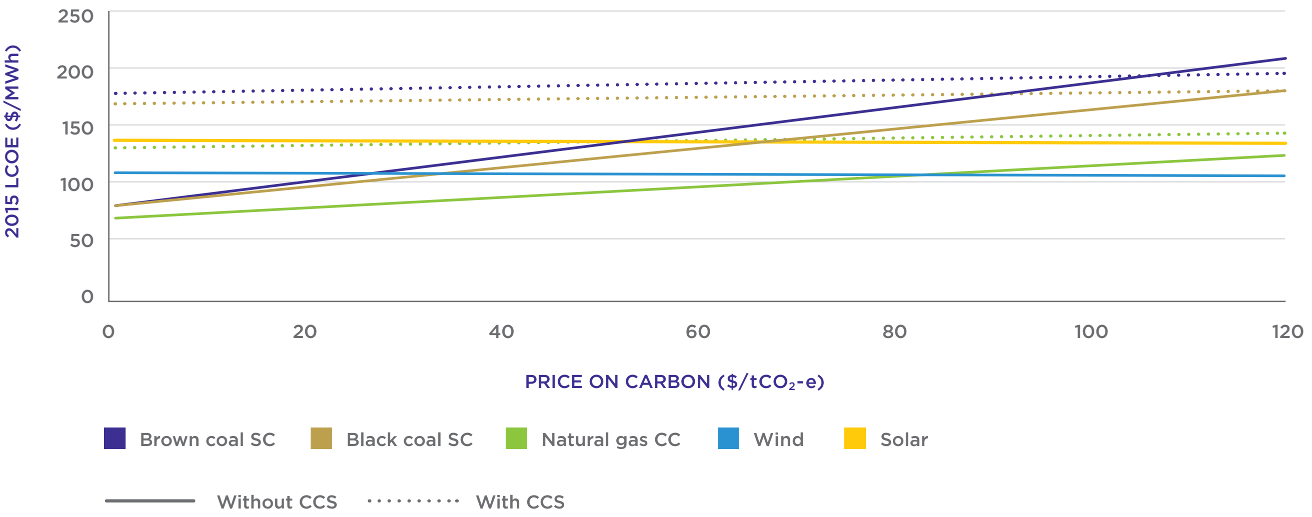
To examine the effect of pricing carbon emissions on the LCOE ranking, the study applied a carbon price to 2015 LCOEs. In the base case studied in this report, fossil-fuel technologies are the lowest cost generators, being lower than wind and significantly lower than solar PV. In order to alter the LCOE ranking of carbon-emitting technologies, a sensitivity analysis on pricing carbon emissions was conducted (Figure A6).

The sensitivity cases showed that a high carbon price is currently required to significantly change the ranking of low-emissions generation technologies:

- Wind is competitive with supercritical coal with a $30/tCO_2$-e price on $CO_2$ emissions.
- Solar PV is competitive with supercritical coal with a $70/tCO_2$-e price.
- Supercritical coal with and without CCS are equivalent with a $130/ tCO_2$-e price.

This situation is likely to change by 2030.

Figure A6: **LCOE sensitivity to emissions pricing**




## 2.6 Carbon Dioxide Transport and Storage

To facilitate the implementation of CCS in Australia, one or more $CO_2$ transport and storage networks need to be developed.

The cost for transport and storage of $CO_2$ (excluding owner's and risk-adjusted costs) from power plants in Australia is likely to vary from $5–14/t $CO_2$ to almost $70/t $CO_2$. Variations in factors such as operating conditions, engineering assumptions, material costs, topography and geological characteristics may lead to different costs. The integrated design of capture systems, transport routes, operating conditions and injection strategies may lead to lower costs.

CCS is an enabling technology for reducing emissions from large stationary sources of $CO_2$, such as power plants and other industrial plants. The implementation of CCS requires a $CO_2$ transport and storage network involving pipelines, booster pumps, wells, storage site facilities and storage site monitoring. Such a network does not currently exist in Australia.

The lowest projected cost for transport and storage from power plants in Australia ($5–14/t $CO_2$) is for cases involving a short transport distance to sites with good storage characteristics. The highest projected cost (up to $70/t $CO_2$) is for cases involving transport over long distances to storage formations with poorer characteristics.

Variations in industry activity, exchange rates, macroeconomic cycles and owner's costs all have a significant effect on estimated CCS costs. Other major factors affecting the costs are related to variability in storage site characteristics (especially for larger and longer term injection of $CO_2$) and the incorporation of trade-offs in pipeline network design and storage site design. In a dynamic operating environment in which the amount of $CO_2$ for injection increases over time, accounting for these trade-offs becomes even more critical.

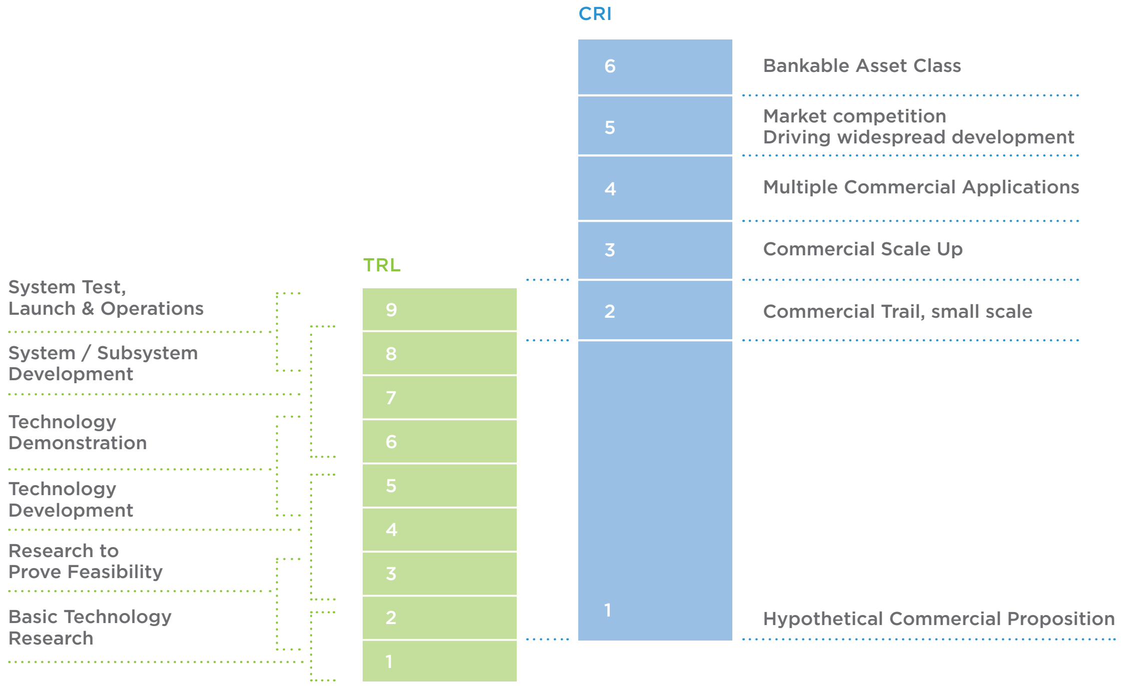
# 3. Low Emission Fossil Fuel Research and Development

## 3.1 Technology and Commercial Readiness

The technology readiness level (TRL) index is a globally accepted benchmarking tool for tracking progress and supporting development of a specific technology through the early stages of the innovation chain. Once a technology has progressed to demonstration and deployment a set of separate factors are introduced to assist in the determination of the commercial readiness of a technology or project. Commercial readiness is sometimes described as a pathway to commercialisation.

Commercial readiness index (CRI) provides a rigorous structure for evaluating where one or more industry sectors are facing barriers, and enables us to structure our funding support to best reduce risks and barriers at the various stages of the pathway to commercialisation.

Figure A7: **Technical and commercial readiness level indication scale**




Source: ARENA (Australian Renewable Energy Agency) 2014,
Commercial Readiness Index for Renewable Energy Sectors, Commonwealth of Australia

## 3.2 Australian Low Emissions Fossil Fuel Stocktake

The high level assessment of the fossil fuel low emissions technologies in Australia are presented in Table A1.

### Table A1: Fossil fuel low emissions technology stocktake

*Source: GCCSI Private communication 2016. LETFF Stocktake of Technologies and R&D Activities*

| Technology | | Emissions Intensity | Readiness | | | Advantage | Top Australian R&D activities |
|---|---|---|---|---|---|---|---|
| | Short description | $kgCO_2e$/ MWh | Short description | TRL | CRL | | |
| **Gas Combustion technologies:** Combined Cycle Gas Turbine (CCGT) | CCGT technology is based on generating electricity by combining gas-fired and steam turbine technologies. It uses two thermodynamic cycles. Electricity is first generated in open-cycle gas turbines by burning natural gas. The exhaust heat is then used to make steam to generate additional electricity using a steam turbine | 373 | - Immediately deployable<br>- Commercial readiness dependent on gas prices/ ability to secure long-term gas supply contracts | 9 | 6 | Australia has large and growing gas resources, and experience in developing major fossil fuel reserves<br>- Potential competition for new electricity demand and replacement as existing generation fleet is retired<br>- Modular designs more readily accommodated in existing grids<br>- Increase the share of rapid load following capacity in the electricity market (but note when used for this purpose the $CO_2$ intensity is much higher) | - Mature commercial technology<br>- Mostly global activities |
| **Pulverised Coal combustion technologies:** Supercritical steam cycle<br>Ultra-supercritical (USC) steam cycle | Pulverised coal-fired plants generate thermal energy by burning pulverised coal and are broken down into three categories: subcritical, supercritical and ultra- supercritical. The primary difference between the three types are the operating temperatures and pressures of the steam that is raised, with supercritical and ultra- supercritical operating above the critical point of water. As the pressures and temperatures increase, so does the operating efficiency, leading to lower emissions | SC – 800<br>USC – 760<br>Adv USC - <750 | - Immediately deployable<br>- Advanced USC requires the development of new materials to enable operation at high temperatures and pressures | SC – 9<br>USC – 8<br>Adv USC - 5 | SC -6<br>USC – 5<br>Adv USC - 2 | - World class coal resources<br>- Expertise in developing and operating major coal resources<br>- 8-10% abatement potential from coal fired power generation through efficiency improvements with SC, USC technologies<br>- Load following capacity<br>- Coal price<br>- Potential competition for new electricity demand and replacement as existing generation fleet is retired | **All PC technologies:**<br>- Mostly global activities<br>- Coal combustion research for coal use in pf boilers: burnout studies and ash behaviour<br>- Brown coal drying technologies have the potential to improve efficiency of conventional combustion technologies<br>- Several demonstration projects in Victoria for advanced dewatering and conversion of brown coals, some of which produce a coal residue product suitable for combustion (and other) applications<br>**SCPC technology:**<br>- Mature technology- little combustion research in Australia<br>- Boiler manufacturers and international utilities are conducting long duration materials testing and development for higher temperature steam boiler tubes for supercritical steam service; engagement of Australian groups is through materials research on relevant stainless steel alloys for steam tubes<br>- Emission control (SOx, NOx, particulates relate to operational issues with existing plant and technologies)<br>**USCPC technology**<br>- Australian research mainly in fundamentals of materials properties and performance<br>- International utility groups and boiler manufacturers are investigating alternative alloys for high T,P steam tubes |

To find out more about ANLEC R&D's contribution to PCC please refer to the ANLEC R&D Catalogue

| Technology | | Emissions Intensity | Readiness | | | Advantage | Top Australian R&D activities |
|---|---|---|---|---|---|---|---|
| | Short description | $kgCO_2e$/ MWh | Short description | TRL | CRL | | |
| **Coal Conversion technologies:** Integrated Gasification Combined Cycle (IGCC) | IGCC power plants use coal gasification - reacting coal with air or oxygen at high temperatures and pressures - to create a synthetic gas (syngas) which is a mixture of carbon monoxide and hydrogen. The syngas can either be used as a chemical feedstock or combusted directly is a gas turbine. Heat recovered from combustion gases is used in a steam turbine to produce additional electrical power. | 792 | - Immediately deployable, with new plants recently commissioned<br>- High capital cost and operational complexity offset by significant efficiency gains<br>- $CO_2$ capture can be integrated in the process to produce $CO_2$ stream at high pressure with lower efficiency penalty than combustion systems | 9 | 5 | - World class coal resources<br>- World leading capability in coal R&D<br>- Reduce emissions from coal-fired power generation<br>- Capable of effectively utilising low-grade coals, refinery residues, organic wastes and biomass<br>- Potential for multiple products means there is an opportunity for new industries to develop from industrial scale deployment (e.g. production of liquid fuels, chemicals, hydrogen, fertilisers, etc) | **All IGCC technologies**<br>- Mostly global activities, some domestic e.g. ANLEC R&D<br>- Coal performance data for Australian and international coals supporting the design, development and deployment of a range of gasification technologies<br>- Gasification reactions and slag behaviour for Australian and international coals, applied to industrial systems through models and validated using international pilot-scale results<br>- Integration of power generation and value added processes (fuels, chemical, fertilisers, explosives, SNG, etc) through gasification and syngas conversion technologies<br>**Brown coal IGCC**<br>Management of high-moisture coals in thermal energy processes; advanced drying technologies for brown coals, including integrated drying processes (including IDGCC)<br>- Major challenges being addressed include effective oxygen- blown gasification of brown coal which is required to facilitate $CO_2$ capture and for production of fuels, chemicals and hydrogen<br>**Black coal IGCC**<br>- Assessment of coal resources (currently not commercially exploited) to develop new market opportunities for coals that are suitable for gasification technology markets and which are not appropriate for current combustion markets |
| **Modular High efficiency technologies:** Direct Injection Carbon Engine (DICE)<br>Direct Carbon Fuel Cells (DCFC) | DICE uses coal in an adapted diesel engine to generate electricity. The fuel, a micronised refined carbon (MRC), is a water-based slurry of finely ground, low ash solid carbons. Suitable diesel engines (5-100 MW) are low to medium speed and adapted to directly inject carbon slurry fuels.<br>A DCFC is a fuel cell that uses a carbon rich material such as biomass or coal to produce energy by combining carbon and oxygen (early stages of development). | Not available as the technology is in development | **Various technical and commercial barriers:**<br>- Cost<br>- Not yet demonstrated at full commercial scale<br>- Optimise injection and engine performance and durability<br>- Improve fuel quality and handling | DICE - 5<br>DCFC - 2 | DICE - 2 | - World class coal resources<br>- World leading capability in coal R&D<br>- Create new market for Australia's coal resources<br>- Provide ability to utilise low grade or waste coal as fuel source<br>- Potentially provide a cost competitive generation alternative in a high gas price future for centralised, distributed and backup power<br>- Increase the share of load following capacity in the electricity market, particularly important in a system with a high share of renewables<br>- Potentially an avenue to utilise biomass resources | - Domestic and global research<br>o CSIRO<br>o IEA Clean Coal Centre<br>o ANLEC R&D<br>- Development of fuels and adaptation of large diesel engines for coal-fired power generation applications<br>- Biomass co-firing with coal in DICE applications to further reduce $CO_2$ emissions in high efficiency systems<br>- Commercial scale engine trials with coal-water slurry fuels, in collaboration with international engine manufacturers |

| Technology | | Emissions Intensity | Readiness | | | Advantage | Top Australian R&D activities |
|---|---|---|---|---|---|---|---|
| | Short description | $kgCO_2e$/ MWh | Short description | TRL | CRL | | |
| **$CO_2$ Capture:** Post Combustion Capture (PCC | PCC is based on technology widely used in the chemical industry and involves the separation of $CO_2$ from the flue gases released in the combustion process at a power plant. This is generally done by contacting the gases with a chemically reactive liquid (commonly an amine or ammonia solution) to capture the $CO_2$. The $CO_2$ is then removed from the absorbing solution by heating. As capture occurs after the combustion process, this technology can be deployed in modules to progressively reduce emissions over time. | **Black Coal:** USC - 106 | **Some technical and commercial barriers:**<br>- Cost<br>- Demonstrate at scale at a power station (preferably integration with storage)<br>- Adapt existing commercial design packages to Australian conditions | 7 | 4 | Can be applied in incremental unit sizes and operated to reduce capture load penalty during peak demand (advantage over other capture technologies)<br>- World class coal resources<br>- World leading capability in coal R&D, including pilot scale operation at coal-fired power stations<br>- Provide baseload or load following near-zero emission electricity supply<br>- Can be retrofitted to existing gas and coal-fired plants reducing stranded assets | **All post-combustion capture technologies**<br>- Pilot scale operation at coal fired power stations and focus on operation in flue gases with impurities<br>- Development of new and more robust absorbents to reduce energy requirement for $CO_2$ recovery<br>- Development of solid sorbent materials and technologies<br>- Development of robust, high flux membrane materials, membrane process and equipment<br>- Smart management of multiple emissions (SOX, NOX, alkalis) in $CO_2$ capture systems<br>- Advanced gas/liquid contactors to reduce capital costs in $CO_2$ capture<br>- Pilot scale testing of processes and solvents on a range of power plants in Australia and internationally<br>- Emission studies to ensure environmental benign $CO_2$ capture<br>**Black coal SCPC with CCS**<br>- Integration with renewable energy sources such as solar thermal<br>**NGCC with CCS**<br>- Process engineering and solvent R&D to consider $CO_2$ capture from very dilute flue gas streams |
| **$CO_2$ Capture:** IGCC with CCS (pre-combustion capture) | Pre-combustion capture typically refers to IGCC power plants which convert the syngas to hydrogen and $CO_2$ and remove the $CO_2$ (e.g., by regenerative stripping) from the syngas stream at elevated pressure prior to the combustion of the hydrogen rich gas in the gas turbine. $CO_2$ capture is integrated into the process providing higher efficiency capture of $CO_2$ at elevated pressures (hence greater output, lower cost and lower emissions CCS). Implementation of CCS can be staged through progressive installation of syngas treatment modules. | **Black Coal:** 109 | - Commercially mature in the chemical industry and needs to be commercially demonstrated in the power sector. | 7 | 3 | - World class coal resources<br>- World leading capability in coal R&D<br>- Reduce emissions from coal-fired power generation<br>- Capable of effectively utilising low-grade coals, refinery residues, organic wastes and biomass<br>- Potential for multiple products means there is an opportunity for new industries to develop from industrial scale deployment (e.g. production of liquid fuels, chemicals, hydrogen, fertilisers, etc)<br>- Can be directly integrated with fuel cell technologies offering very high efficiencies and abatement with integrated $CO_2$ capture. | **All IGCC with CCS technologies**<br>- Advanced membrane separation technologies and catalytic membrane reactor systems for simplified $CO_2$ capture and hydrogen production for power and energy systems<br>- Pilot industrial scale durability testing using syngas slipstreams from several international pilot scale gasification systems<br>**Brown coal IGCC with CCS**<br>- Gas cleaning systems and gas separation membranes for $CO_2$ capture from gasification-derived syngas, including new sorbents for high temperature cleaning, as well as metal and ceramic membranes for $CO_2$ separation, combined water-gas- shift and $CO_2$ separation, as well as O2 production<br>- Advanced hydrogen energy systems using brown coals<br>**Black coal IGCC with CCS**<br>- Performance data in support of advanced gasification technologies for power generation coals<br>- Advanced syngas conversion and separation processes to reduce cost and improve reliability and integration of $CO_2$ capture and hydrogen/power production from coals.<br>- High efficiency gasification and syngas processing technologies (e.g. low temperature, membrane assisted gasification) for very high efficiency, low emissions energy processes. |

| Technology | | Emissions Intensity | Readiness | | | Advantage | Top Australian R&D activities |
|---|---|---|---|---|---|---|---|
| | Short description | $kgCO_2e$/ MWh | Short description | TRL | CRL | | |
| **$CO_2$ Capture:** Oxyfuel | Oxyfuel combustion involves firing a conventional coal fired power station boiler with oxygen diluted with recycled exhaust gases instead of air to produce a stream of highly concentrated $CO_2$ in the flue gas. This $CO_2$ can then be more easily captured by cooling and compression. Oxyfuel combustion and capture has the advantages of relative simplicity of the process and potentially lower costs compared with other emergent $CO_2$ capture technologies. It can also be retrofitted to existing boilers in pulverised coal plants. | **Black Coal:** 53 | Need to demonstrate at larger scale, preferably integrated with storage, prior to developing commercial packages with performance warranties | 6 | 2 | - World class coal resources<br>- World leading capability in coal R&D<br>- Provide baseload or load following near-zero emission electricity supply<br>- Can be retrofitted to existing coal-fired plants reducing stranded assets | **Black coal Oxy with CCS**<br>- Coal combustion studies investigating the effect of $CO_2$ replacement of N2 on flame performance, heat transfer, and boiler performance<br>- Demonstration of oxy-combustion on a retrofitted power station (no capture)<br>- Mercury behaviour and deportment in capture process<br>- Engagement with international groups developing advanced oxy-fired technologies such as pressurised, staged oxygen combustion (process & technology development, coal combustion behaviour in high pressure oxygen environments). These approaches offer oxy-combustion technology without the need for flue gas recycle and the associated issues regarding sulphur etc |

# AUTHORS' RESPONSIBILITY & DISCLAIMERS

## Authors' Responsiblities

Work commenced on 6 July 2016 and was completed on 16 November 2016. Therefore, the Report does not take into account events or circumstances arising after 16 November 2016. The Report's authors take no responsibility to update the Report.

The authors of the Report highlight that the Report, does not constitute investment advice or a recommendation to you on your future course of action. The authors provide no assurance that any relevant authority or third party will accept the scenarios modelled.

No listed author, company or supporter of this report, nor any member or employee thereof undertakes responsibility in any way whatsoever to any person in respect of errors in this Report arising from information that may be later be proven to be incorrect.

In the preparation of this Report the authors have considered and relied upon information sourced from a range of sources believed after due enquiry to be reliable and accurate. The authors have no reason to believe that any information supplied, or obtained from public sources, was false or that any material information has been withheld. The authors do not imply and it should not be construed that they have verified any of the information provided, or that the author's enquiries could have identified any matter, which a more extensive examination might disclose.

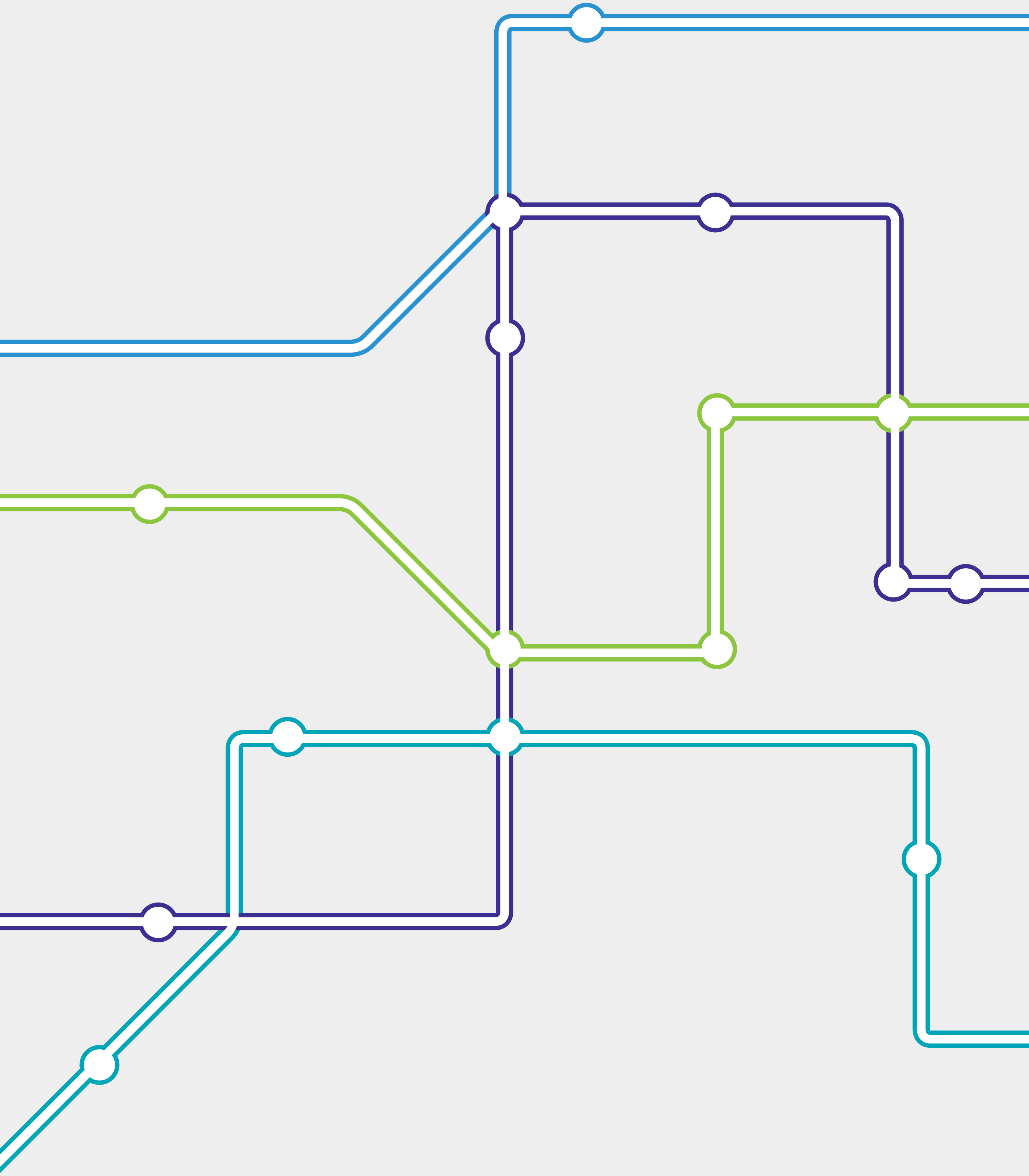
While every effort is made by the authors to ensure that the facts and opinions contained in this document are accurate, the authors do not make any representation about the content and suitability of this information for any particular purpose. The document is not intended to comprise advice, and is provided "as is" without express or implied warranty. Readers should form their own conclusion as to its applicability and suitability. The authors reserve the right to alter or amend this document without prior notice.

## Disclaimer of Warranties and Limitation of Liabilities

This document was prepared by The University of Queensland (UQ). Neither UQ, any member of UQ, any subcontractors engaged, any sponsor, nor any person acting on behalf of any of them:

- makes any warranty or representation whatsoever, express or implied, (i) with respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or (ii) that such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or (iii) that this document is suitable to any particular user's circumstance; or
- assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if UQ or any UQ representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favouring by UQ.



uq.edu.au/energy