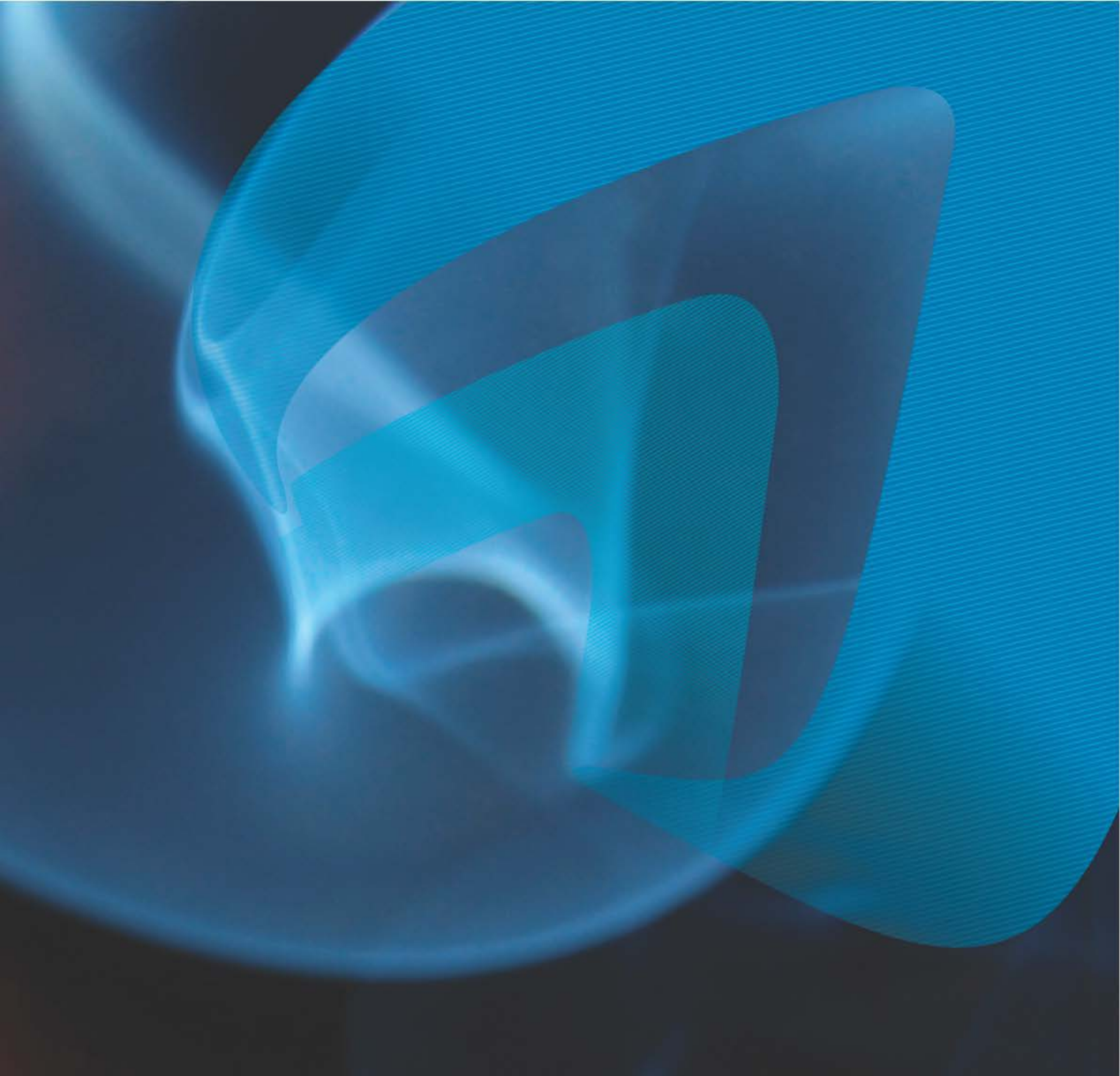

RETROFITTING AUSTRALIAN GAS POWER PLANTS WITH POST COMBUSTION CAPTURE

CO2CRC BUILDING A LOW EMISSIONS FUTURE

Gamma Energy Technology
EXPERIENCE THINKING INNOVATION

Disclaimer

The analysis for this Report was completed on 28th of April 2017 and therefore the Report does not take into account events or circumstances arising after that time. The authors of the Report take no responsibility to update the Report.

The Report's modelling considers only a single set of input assumptions which should not be considered entirely exhaustive. Modelling inherently requires assumptions about future behaviours and market interactions, which may result in forecasts that deviate from actual events. There will usually be differences between estimated and actual results, because events and circumstances frequently do not occur as expected, and those differences may be material. The authors of the Report take no responsibility for the modelling presented to be considered as a definitive account.

The authors 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 the scenarios modelled will be accepted by any relevant authority or third party.

Conclusions in the report are based, in part, on the assumptions stated and on information which is publicly available. 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.

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About CO2CRC Limited:

CO2CRC Limited is Australia's leading CCS research organisation, having invested $100m in CCS research over the past decade. CO2CRC is the first organisation in Australia to have demonstrated CCS end-to-end, and has successfully stored more than 80,000 tonnes of CO_2 at its renowned Otway Research Facility in Victoria. CO2CRC engages the world's leading researchers to collaborate on benchtop and in-field research in Australia, delivering improvements and cost efficiencies in CCS technology.

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About Gamma Energy Technology P/L:

Gamma Energy Technology P/L is an independent energy consulting service, offering a range of technical and support services, including but not limited to power generation technology.

Gamma Energy Technology P/L is proud to contribute to the on-going discussions on energy in Australia as we seek to solve the trilemma of energy supply - to assure energy system security and affordability so that emissions reduction targets are delivered.

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Key Messages

1. As a signatory to the Paris Agreement, Australia has agreed to take action to contribute to limit the increase in global average temperature to well below 2 degrees. This can only be achieved at the lowest cost through a contribution from carbon capture and storage technology.

2. Diverse methods of electricity production are essential to optimise consistency and security of supply, lowest possible cost, and environmental outcomes for Australia.

3. Carbon capture and storage must commence deployment by 2030 across carbon emitting industries broadly, to achieve net zero emissions by Australia beyond 2050.

4. Secure baseload, low carbon emissions electricity will be achieved from natural gas combined cycle plants retrofitted with carbon capture and storage.

5. Retrofit of natural gas combined cycle gas turbines with carbon capture and storage has capital costs significantly lower than comparable solar photovoltaic arrays and may act as an affordable step in establishing a carbon capture and storage industry in Australia.

6. A carbon capture and storage hub will represent the lowest cost pathway for natural gas and coal based electricity generation and other carbon intensive industries to begin the transition to full decarbonisation given the unique geology requirements of storage.

7. All new low or zero emission technologies deployed internationally and in Australia will cost consumers more than the current electricity mix.

8. High value direct and indirect jobs will be created in some regions and new jobs created for transport and storage.

9. Immediate decisions need to be made to facilitate grid scale, and a 24/7 diverse electricity sector able to deliver reliable and available energy to support ongoing economic prosperity with zero emissions by 2050.

Executive Briefing

This report provides an overview of retrofitting Post Combustion Capture (PCC) technology to existing Natural Gas Combined Cycle (NGCC) power plants in Australia. It examines the opportunities to apply carbon capture and storage (CCS) to natural gas power plants, with a view to understanding the role of fossil fuels more broadly with carbon capture and storage in a diverse, clean and robust electricity sector.

As the economy undertakes the urgent task of transitioning to a low carbon future, its electricity supply needs to remain secure and reliable. In addition, it needs to be affordable; and it needs to lower emissions over time.[a] *Retrofitting Australian Gas Power Plants with Post Combustion Capture* is the second in a two part series along with retrofitting coal power plant report,[b] which supplement the 2015 Australian Power Generation Technology report.[c]

The Australian Power Generation Technology Report is an unbiased, technology-neutral review of the cost of a broad range of renewable and non-renewable power generation technologies. The study was the result of a collaboration of 45 industry, government and environment organisations, and compares different technologies, and remains the most up to date review of Australian power generation technologies, their capabilities and costs for 2015, looking out to 2030.[c]

[a] Finkel, A., 2016, "*Electric Future: Wiring for Progress.*" Zunz Lecture – 3/11/16, Powerhouse Museum, Sydney. www.chiefscientist.gov.au/wp-content/uploads/3-Nov-2016-Australias-Chief-Scientist-SPEECH-Electric-Future-Wiring-for-progress.pdf. (Accessed Apr 2017).

[b] First report in the study: Bongers, G.D., Byrom, S. and Constable, T. (2017), *Retrofitting CCS to Coal: Enhancing Australia's Energy Security.* CO2CRC Limited, Vic. Australia.

[c] CO2CRC (2015), *Australian Power Generation Technology Report.* CO2CRC Limited, Vic. Australia. www.co2crc.com.au/wp-content/uploads/2016/04/LCOEReportfinalweb.pdf (Accessed Apr 2017).

Climate Change Agreements

As the international community strives to achieve energy security and climate change at the lowest economic cost to society, both resource and system diversity will be key to achieving a sustainable long-term energy outcome. Australia, as a signatory to the Paris Agreement, has agreed to hold the increase in global temperature to well below 2°C above pre-industrial levels. Australia's Intended Nationally Determined Contribution (INDC) is to reduce greenhouse gas emissions by 26 – 28% below 2005 levels by 2030.[d]

In addition to the 2030 contribution, Australia must pursue options that allow it to contribute its fair share to the global effort towards net zero emissions by the second half of this century.

It is estimated by the International Energy Agency (IEA) that a total of 94 gigatonnes of CO_2 emissions reductions will be required before 2050.[e] The Intergovernmental Panel on Climate Change (IPCC) has determined that without CCS, the cost of achieving a 2°C outcome increases by 138% by the end of this century.[f] Hence, from an International and Australian perspective the world would ultimately benefit from deploying CCS as soon as possible, especially if negative emission solutions are required in the future.

While the future costs of all low emissions technologies are uncertain, they are continuing to come down the cost curve.[c] Preserving options and diversity is critical to enable appropriate technology selections that will aid meeting both the short and longer term targets required to achieve a better than 2°C outcome for the world.

[d] Australian Government Department of Foreign Affairs and Trade, (2015). "*Australia's Intended Nationally Determined Contribution to a New Climate Change Agreement.*" Canberra, Australia.

[e] International Energy Agency (IEA), (2016), "*20 years of carbon capture and storage. Accelerating future deployment.*" Paris, France.

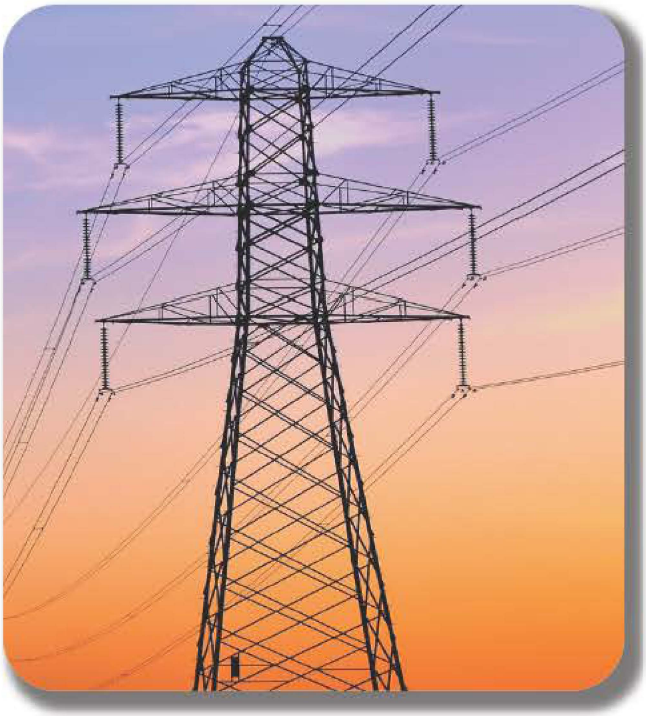
[f] Intergovernmental Panel on Climate Change (IPCC), (2014), "*IPCC 5th Assessment Report.*" www.ipcc.ch/pdf/assessment-report/ar5/syr/SYRAR5FINALfullwcover.pdf. (Accessed Apr 2017).

Electricity Supply Diversity

Electricity generation accounts for a third of Australia's emissions, and as a sector is the largest contributor to the national greenhouse gas inventory.[g] Today, the sector remains heavily reliant on both gas and coal based power plants, together accounting for more than 80% of electricity generated.[h] Retrofitting CCS has the potential to make rapid and large-scale contributions to decarbonising the Australian electricity sector. At present, natural gas is often a supplementary baseload supplier of electricity. However, retrofitting natural gas combined cycle plants with CCS will provide additional baseload power that is available 24/7 with very low carbon emissions.

Electricity systems depend on there being sufficient generation capacity to supply electricity as demand continuously increases and decreases over time, with flexibility to ramp up and down critical to system stability. While intermittent renewable sources such as wind and solar photovoltaic electricity generation plants don't contribute to CO_2 emissions, they cannot perform the key roles that are essential for reliable, secure and low-cost electricity supply alone. No single technology can achieve this by itself; all technologies including NGCC power plants with CCS have significant capabilities and limitations.[c]

With strong State based renewable energy targets being pursued above the Australian Federal Government's renewable energy target, it is essential that baseload electricity remains in the mix to provide the required level of security. Retrofitting natural gas power plants with CCS would provide both low-emissions electricity and system strength to the grid.



Shaping Technology Choices Now for Beyond 2030

The changing electricity generation mix in Australia has resulted in an increasing focus on all three aspects of the energy trilemma – reliable, affordable and sustainable electricity. This increased focus on all elements of the trilemma is in the context of a changing electricity system. The proportion of intermittent electricity generation has rapidly increased, while the coal and gas based generation available within the system is decreasing. This rapid change has placed pressure on the reliability of the national system.

Looking beyond the voluntary 2030 contribution Australia has committed to, there remains a very high likelihood that Australia's energy mix will rely heavily on an existing mix of coal and gas based electricity generation.[i] Carbon capture and storage will need to be part of the lowest cost options to achieve deep cuts in emissions while maintaining a stable grid.

[g] Australian Government Department of Environment, (2015), "*Tracking to 2020: An Interim Update of Australia's Greenhouse Gas Emissions Projections.*" Canberra, Australia.

[h] Australian Government Department of Industry, Innovation and Science, (2016), "*Energy In Australia 2015.*" Canberra, Australia.

[i] International Energy Agency (IEA), (2016), "*World Energy Outlook.*" IEA, Paris, France.

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.[j] This would enable all low emissions technologies to compete on an equal footing in the energy transition.

Carbon capture and storage must be deployed in Australia by 2030 to achieve net zero emissions beyond 2050, and retrofitting current natural gas and coal plants will enable the establishment of the CCS industry. Australia must act now and invest in CO_2 storage site characterisation including investment ready appraisal of priority storage 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.[j]

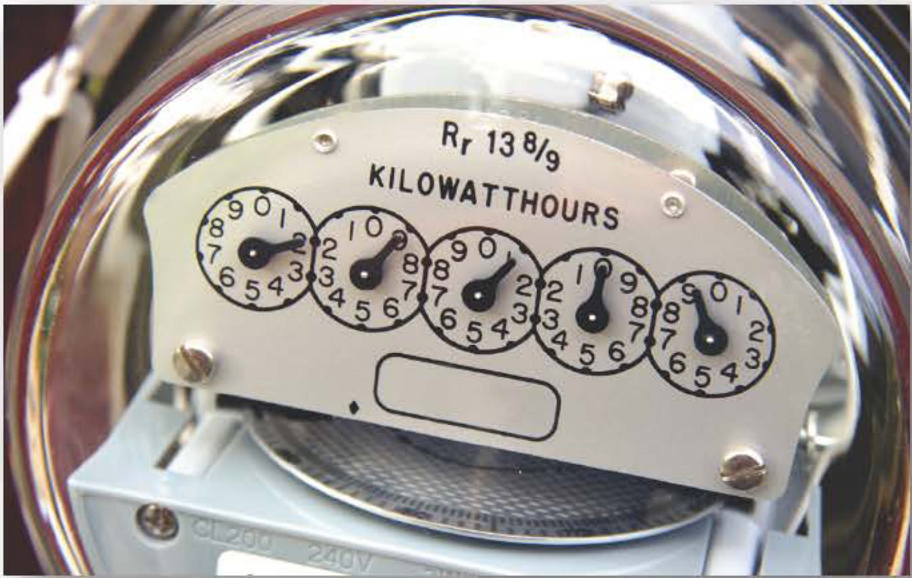
Australia, as a leading energy producer (both coal and gas) would benefit significantly from the national and international deployment of CCS so that it can continue to earn export revenues from natural gas and coal in a world transitioning toward net zero.

Retrofit Costs

The capital cost for post combustion capture (PCC) retrofit for natural gas combined cycle (NGCC) plants is significantly lower than the corresponding amount of solar PV. Retrofitting a 250 megawatts (MW) NGCC plant with CCS would achieve 193MW of low carbon electricity and cost $0.34 billion. This would power approximately 190,000 households per annum and would be equivalent to the output of 480MW of solar PV installed capacity at cost of $1.01 billion.

The figure over shows the Levelised Cost of Electricity (LCOE) range for differing capacity factors, fuel costs and capture rates for both a new build NGCC PCC plant and a retrofit. The base case of a new build NGCC plant delivers electricity at an average LCOE of $78/MWh, which increases to $136/MWh with PCC added. The retrofit of an existing NGCC results in an average LCOE of $115/MWh at a 65% capacity factor and the APGT gas price range.

The increase in capacity factor decreases the LCOE, as there is more generation to amortize costs. However, the largest factor is gas price sensitivity. The APGT previous used a range of $5 – $8/GJ, as there has been an increase in average prices in Australia, this report used a $8 – $13/GJ range, with an approximately $30/MWh increase in the average LCOE.

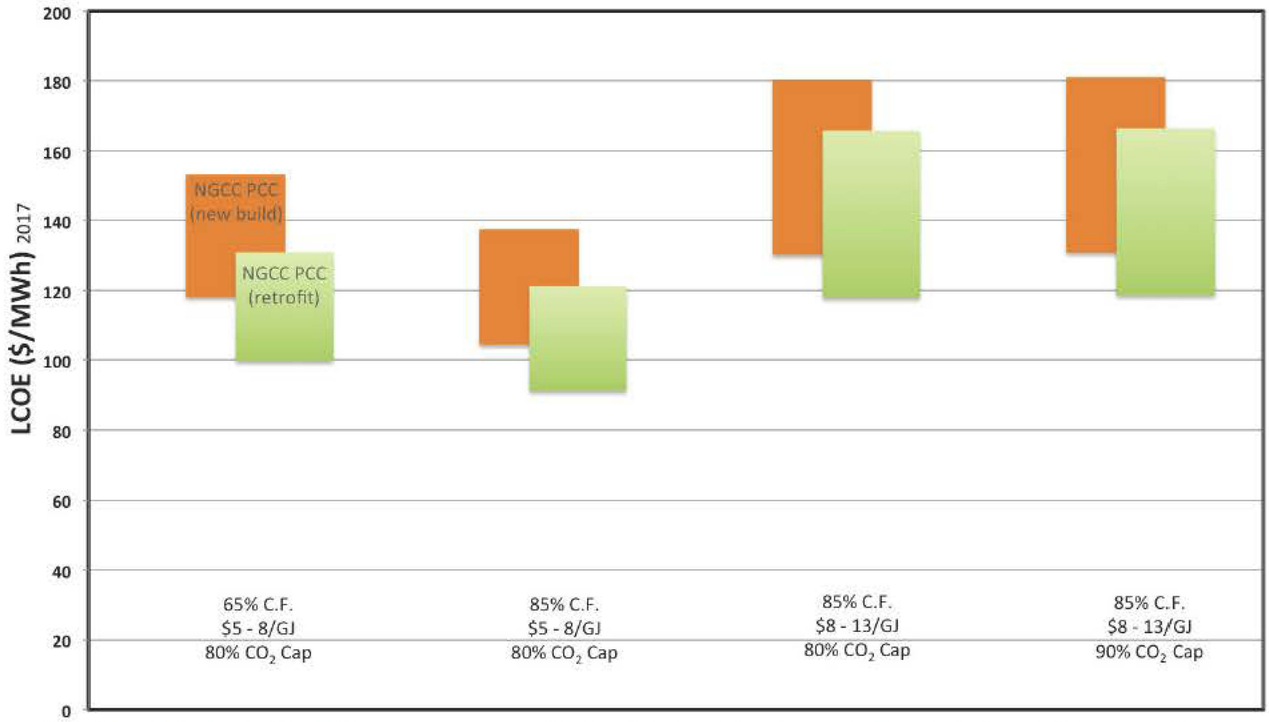


[j] Grieg, C, Bongers, G., Stot, C. and Byrom, S., (2016), "*Energy Security and Prosperity in Australia: A Roadmap for CCS.*" The University of Queensland, Brisbane. ISBN 978-1-73272-175-0.

A retrofit of an existing NGCC plant using an advanced solvent PCC configuration at the $8-13/GJ, 85% capacity factor and a 90% capture rate results in an average LCOE of $108/MWh.

The gas price range of $8 – 13/GJ used in this study reflects a 'very strong' gas price outlook compared to the Australian Energy Market Operator's 2016 National Planning and Forecasting review's strong case at $8.50/GJ.[k] A finely balanced natural gas market will continue to place upward pressure on prices – beyond the strong case predicted in 2016. New natural gas supply tranches are becoming harder to extract and more costly - at a time when low cost reserves in eastern Australia are in decline – again placing upward pressure on prices.[l]

The relatively large range in LCOE's is due to the impact of gas price range.



Levelised cost of electricity comparisons with differing fuel costs, capacity factor and CO_2 capture rates

Securing a Sustainable Electricity Future

There is a particular issue with respect to electricity generation on the east coast, home to greater than 86 per cent of total power demand and where typically 85 per cent of this demand is consistently met through coal and gas.[h] While there has been an oversupply of electricity in the market over the last few years this has turned around rapidly. Actual, announced and planned closures of coal and gas-fired power plants have recently seen a tightening of the National Electricity Market (NEM).

The lead times for all substantial electricity infrastructure development are long and unlikely to be less than five to six years for gas with CCS. Assessment and approval processes, including public consultation, financing, feasibility and front-end engineering design, are required leading up to a decision to begin construction on a power plant. Significant cracks have already emerged in the electricity system and decisions need to be made now to meet Australia's future energy needs.

[k] Core Energy Group, (2016), *"NGFR Gas Price Assessment."* Adelaide, South Australia.

[l] Australian Energy Market Operator (AEMO), (2017). "Gas Statement of Opportunities for Eastern and South-Easter Australia."

Collection and Storage Hubs

A CCS hub will represent the lowest cost pathway for natural gas and coal based electricity generation and other carbon intensive industries to begin the transition to full decarbonisation.

CCS hubs are central collection or distribution systems for CO_2 and a concept schematic is shown below.[m] A collection hub could serve to connect several large and small sources of CO_2 in an efficient collection system. Similarly, a distribution hub could distribute CO_2 from a larger pipeline to a range of storage or utilisation sites. Hubs could be located at the capture end or the storage end of a multi-user pipeline.

Collection hubs could form a connective element among a wide range of captured CO_2 sources with a retrofit natural gas and coal power generation plant being a foundation customer.

A CO_2 hub system, showing a collection and storage hub

Conclusion

Retrofitting carbon capture and storage is an ideal pathway to make rapid and large-scale contributions to decarbonising the Australian economy. Retrofitting natural gas combined cycle plants will enable the provision additional baseload power that is available 24/7 with very low carbon emissions.

[m] Global CCS Institute (2016), "*The Global Status of CCS. Special Report: Understanding Industrial CCS Hubs and Clusters*", Melbourne, Australia.

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Tables and Figures

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1.0 Introduction

This report examines the cost and performance of retrofitting post-combustion capture (PCC) technology to existing natural gas combined cycle (NGCC) plants. It aims to extend the Post Combustion Retrofit chapter in the Australian Power Generation Technology[1] report and is a companion to Retrofitting CCS to Coal: Enhancing Australia's Energy Security report. [2] In summary, we seek to highlight the technical and economic issues associated with retrofitting existing plant with an amine-based PCC technology.

Natural gas is set to play a central role in meeting the world's energy needs for at least the next two-and-a-half decades. Demand for natural gas is anticipated to grow by more than half, faster than any other fossil fuel, and become the leading fuel in the OECD (Organisation for Economic Co-operation and Development) energy mix by around 2030. [3]

There are technical differences between Carbon Capture and Storage (CCS) demonstration on coal and gas-fired plant, and to-date it has primarily been focused on coal-fired plant[3] with limited work on gas-fired plant.[4, 5, 6] Retrofitting PCC to an existing NGCC plant presents significant challenges, such as the following:

- Limited space for new plant equipment
- Limitations of the existing steam turbine
- Cooling water limitations
- Replacement power considerations
- Complicated pipe routings
- Current economics within the power generation sector

Retrofitting CCS has the potential to make large-scale contributions to decarbonising the Australian electricity sector. At present, natural gas is often a supplementary baseload supplier of electricity. Retrofitting NGCC plants will enable the provision additional baseload power that is available 24/7 with very low carbon emissions

The current suite of carbon dioxide (CO_2) capture technologies decreases plant power output and increases the cost of electricity. The challenge is to continually improve these processes to reduce the capture penalties in both efficiency and cost of electricity.

Achieving CO_2 emission control while keeping electricity prices competitive and sustaining economic growth presents society with unprecedented economic and technical challenges. CO_2 capture retrofit technologies are considered one of the important means of reducing natural gas and coal-derived CO_2 emissions. With the majority of Australia's power generation coming from fossil-fuel based generation, CO_2 will need to be removed from existing and future fossil-fuelled plant flue gases to significantly reduce CO_2 emissions.

[1] Gamma Energy Technology (2017), *Power Factbook*, www.powerfactbook.com.

[2] Bongers, G.D., Byrom, S. and Constable, T. (2017), *Retrofitting CCS to Coal: Enhancing Australia's Energy Security*. CO2CRC Limited, Vic. Australia.

[3] Shell U.K. Limited (2015), FEED Summary Report for Full CCS Chain.

[4] IEAGHG (2012), CO_2 Capture at Gas Fired Power Plants.

[5] EPRI (2015), *Post-Combustion Capture on NGCC Plants: Evaluation of Retrofit, New Build, and the Application of Exhaust Gas Recycle*, Californian Energy Commission Workshop on Natural Gas Power Plants with CO_2 Capture, April 16th, 2015.

[6] Nextant Inc. (2016), *Pre - Feasibility Study for Establishing a Carbon Capture Pilot Plant in Mexico (World Bank Contract 7175527)*. Danvers, MA 01923, USA. www.gob.mx/cms/uploads/attachment/file/107318/CCPP_Final_Report.pdf (Accessed Apr 2017).

1.1. Natural Gas Power Technology

Natural gas power plants are a firm capacity generation technology that can act as peaking, load following and base load applications. Gas turbines are used in three different power plant configurations; open cycle, combined cycle and combined heat and power (refer also to Figure 1):[1]

- Open or single cycle is when the gas turbine is connected directly to a generator with no energy recovery from the exhaust stream – typically these plants operate at low capacity factors.
- Combined heat and power, also known as cogeneration, is when the plant is configured to generate power and thermal energy, for non-power applications – these plants tend to operate as base load plants to meet the needs of the steam host.
- Combined Cycle power systems combines the open cycle with a heat recovery steam generator (HRSG) and a steam turbine and generator – these plants operate typically as mid merit to base load (dependent upon natural gas pricing) at capacity factors of greater than 40%.

Utility scale power generation uses combined cycle for base load and open cycles for peak plants or grid support, as a combined cycle power plant is more efficient than open cycle configurations.

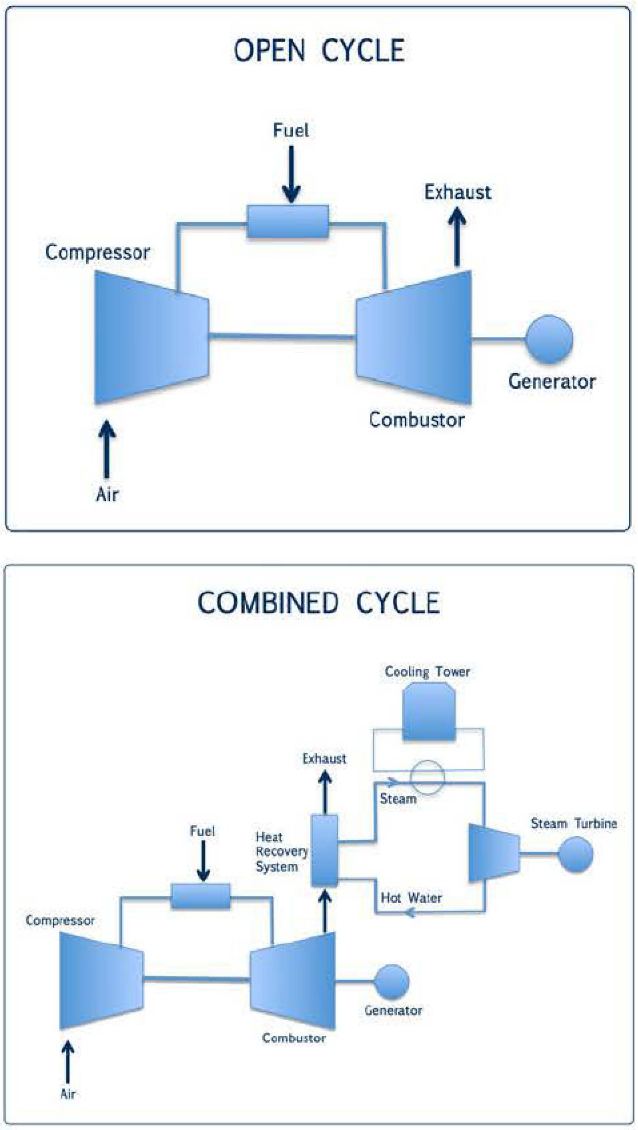

Figure 1: Natural Gas Power Plant Configurations

1.2. What is Post Combustion Capture and Retrofitting

Post combustion capture or PCC refers to the separation of CO_2 from flue gas derived from combusting carbon based fuel. PCC captures the CO_2 after the combustion of the natural gas or coal (refer to Figure 2). At the forefront of the currently available, large scale technology is absorption-based systems that utilise solvents, such as amine, to remove CO_2. To retrofit an existing combined cycle gas plant with a post combustion absorption process would require significant modifications to the steam cycle. A PCC retrofit may be unsuitable for some power plants, as even with energy optimisations, the resulting energy penalty maybe too significant.[7]

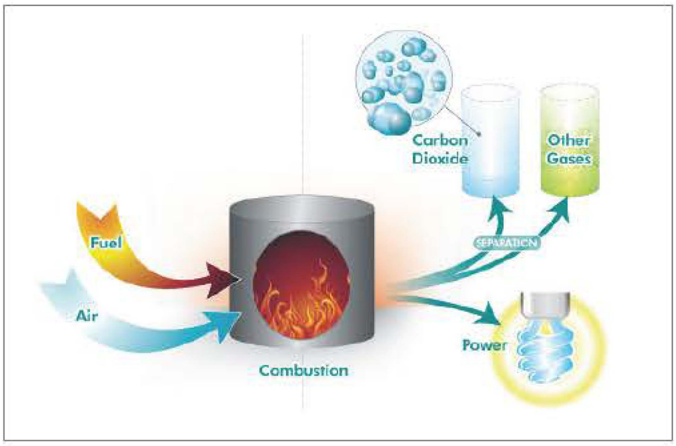

Figure 2: PCC simplified process

PCC applied on Natural Gas Combined Cycle (NGCC) plant also has the option of adding Exhaust Gas Recirculation (EGR), which is included in the base case retrofit in this study. EGR involves recycling a portion of the flue gas from the plant back to the inlet of the compressor section of the turbine, while the remainder is sent to the capture plant. The purpose of the recycle stream is to concentrate the CO_2 level in the flue gas being treated by the capture plant to improve capture efficiency. This efficiency improvement at the capture plant may potentially reduce the size, and cost, associated with the capture plant.[4]

1.3. Plant Equipment and Layout

The post-combustion chemical absorption flue gas capture process can be divided into two main parts: absorption and desorption. The chemical absorption process takes place in the absorber column, while the desorption process takes place in the stripper column.

The PCC design used for a typical, 550 MW sized (two gas turbines on one steam turbine design) NGCC power station consists of:

- 2 absorber train;
- 1 desorber train;
- 4 reboilers per desorber; and
- 2 compression trains.

[7] CO2CRC (2015), *Australian Power Generation Technology Report*. CO2CRC Limited, Vic. Australia. www.co2crc.com.au/wp-content/uploads/2016/04/LCOE_Report_final_web.pdf (Accessed Apr 2017).

1.4. Integration of Post Combustion Capture into existing NGCC Plant

For an existing plant the combustion and power generation systems are not significantly affected, as modifications will be required in the steam cycle due to a diversion of steam to the post combustion capture system.[7] The main interfaces between the NGCC and the capture plant involve low-pressure steam extraction for the capture plant re-boilers and the HRSG flue gas diversion to the capture plant. If EGR is added along with the PCC, further modifications may be required to the gas turbine combustors, to ensure that operability, turndown, emission levels and combustion efficiency remain unaffected in comparison with using fresh air, as opposed to EGR. Figure 3 shows the schematics of a CCGT base plant, while Figure 4 demonstrates the integration of the PCC and EGR.[5]

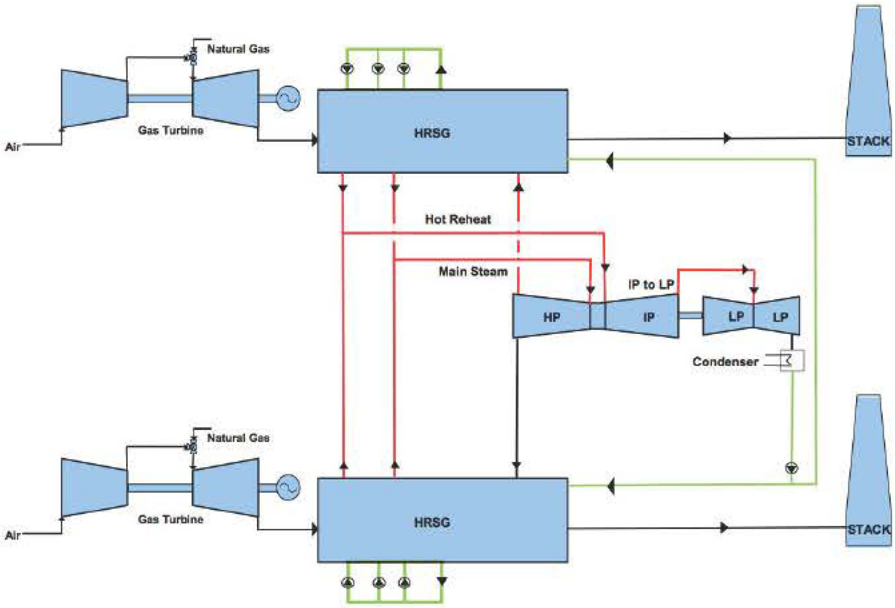

Figure 3: NGCC base plant schematic

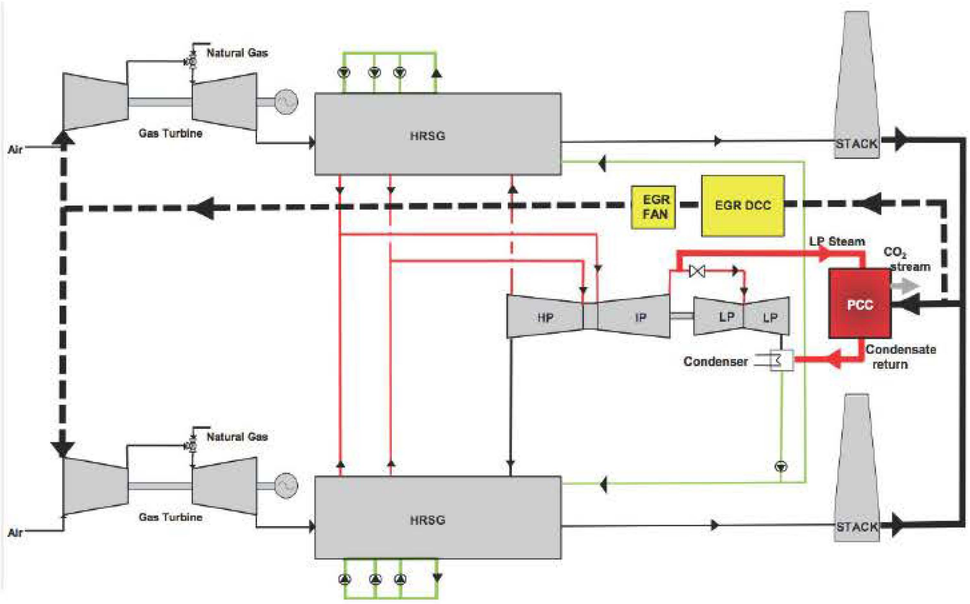

Figure 4: NGCC base plant with PCC and EGR

1.5. Review of Post Combustion Capture Solvent Technologies

Post combustion capture of CO_2 from flue gas stream from carbon based fuel plants (natural gas, coal or biomass) generally involves the chemical or physical absorption of CO_2. Once absorbed, it is regenerated, producing a high purity stream of CO_2. Traditionally this was a very energy intensive process, requiring significant energy from the base power plant. Since the 1990's however, the regeneration energy has reduced from 4.0 – 4.5 down to 2.0 – 2.3MJ/Kg CO_2 due to advancements in solvent technologies.[8]

The current commercial PCC processes are based on chemical absorption. The processes listed in Table 1[9] show many different solvents, manufacturers and locations are active in the application of PCC in power generation applications. Of the amine based technologies examined by Nexant[6] for a full-scale retrofit of a NGCC plant in Poza Rica, Mexico, they concluded that with the level of data accuracy for their study, it was reasonable to conclude that the top five PCC technologies all had similar economic performances and it cannot be determined, with certainty, that one is clearly superior to the rest.

Table 1: Commercial PCC based on chemical absorption processes

PCC process	Developer	Solvent	Demonstration	Commercial project
KM-CDRTM	MHI/KEPCO	KS-1 (Hindered amine)	Plant Barry, Alabama Plant Yates, Georgia	Petra-Nova CCS, Texas (Operational)
CanSolv®	Shell	Amine-based	TCM Norway Aberthaw PCC Wales	Boundary Dam Canada (Operational) Bow City Canada (Planning)
Advanced Capture Process	Aker Clean Carbon	Amine-based	TCM Norway	Longannet UK[10] Porto Tolle Italy[10]
PostCap™	Siemens	Amino acid salt	TCM Norway Big Bend PCC Florida	ROAD Netherlands (Planning) Masdar Abu Dhabi (Planning)
Econamine FG Plus℠	Fluor	Amine-based	TCM Norway Wilhelmshaven PCC Germany	Trailblazer, Texas[10]
Advanced Amine Process	Alstom Power/Dow Chemical	DOW UCARSOLTM FGC 3000	EDF PCC Le Havre, France Charleston PCC, West Virginia	Elektownia Belchatow, Poland (Planning) [10] GETICA Romania (on-hold)
CAP®	Alstom Power	Chilled ammonia	TCM Norway Pleasant Prairie PCC Milwaukee Karlshamn PCC Sweden Mountaineer CCS Phase I, West Virginia	AEP Mountaineer CCS Phase II, West Virginia[10] Project Pioneer Alberta[10]
ECO_2™	Powerspan	Amine-based	Burger PCC, Ohio	
HTC	HTC Purenergy/ Doosan Babcock	Amine-based	International Test Centre, Canada	Antelope Valley CCS, North Dakota[10]
CO_2 Solution	CO_2 Solutions Ltd	Enzyme-based solvent	Pikes Peak South PCC, Saskatchewan, Canada[11]	
DMX™	IFPEN/PROS ERNA	Biphasic solvent	ENEL's Brindisi Pilot PCC, Italy	
RSATTM	Babcock and Wilcox	OptiCap®		

[8] Gale, J (2016), *A global perspective on the status of Carbon Capture*. 2016 NETL CO_2 Capture Technology Project Review Meeting, Pittsburg, USA.

[9] Oko, E., Wang, M. and Joel, A. (2017), *Current status and future development of solvent-based carbon capture*. International Journal of Coal Science & Technology.

[10] These projects were finalised at various study stages and did not progress to commercial operation.

[11] Not listed in original article, also tested at Salaberry-de-Valleyfield, Quebec. GCCSI (2017), *CO_2 Solutions Valleyfield Carbon Capture Demonstration Project*. www.globalccsinstitute.com/projects/co2-solutions-valleyfield-carbon-capture-demonstration-project (Accessed Apr 2017).

Research and demonstration projects are currently underway to improve currently commercially available solvents, as well as into new and novel technologies such as membranes and adsorption processes. Figure 5[12] graphically shows the various aspects that may facilitate improved solvent performance, with many of the current advancements focusing on absorption rate and capacity as well as the heat of regeneration.

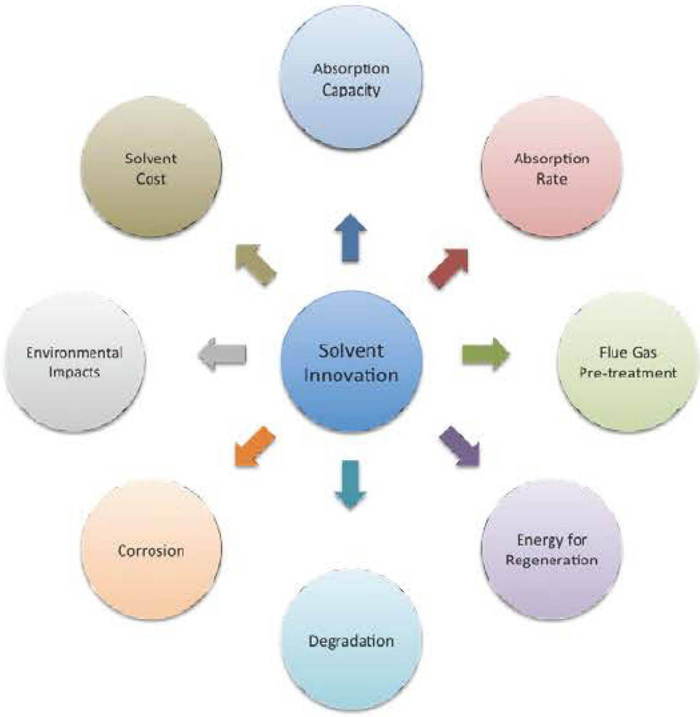

Figure 5: Important factors to be considered when developing a solvent for a CO_2 absorption process

Table 2[13] summarises the Carbon Sequestration Leadership Forum's (CSLF) analysis of 2nd and 3rd generation PCC technologies, with an estimate of the Technical Readiness Level (TRL) range for each technology class. The CSLF identified around 30 groups of 2nd and 3rd generation or emerging CO_2 capture technologies. The majority of which were 3rd generation – tested at laboratory or bench scale, and only a minority were 2nd generation, with a TRL of 4-5.[13]

[12] Based on: IEAGHG (2014), *Assessment of Emerging CO_2 Capture Technologies and their Potential to Reduce Costs*. 2014/TR4, Dec 2014. Added flue gas pre-treatment as an innovation focus area.

[13] Carbon Sequestration Leadership Forum (2017), Supporting Development of 2nd and 3rd Generation Carbon Capture Technologies: Mapping technologies and relevant test facilities.

Table 2: Preliminary evaluation of future generation PCC technologies compared with conventional MEA

PCC Approach	Technology Group	Technical Readiness Level	Potential for Energy Savings
Solvents	Precipitating solvents	4 - 6	2.3 – 3.6GJ/t CO_2
	Two-phase liquid system	4 - 5	2.0 – 2.3GJ/t CO_2
	Enzymes	1 - 2	30 – 35% relative to MEA
	Ionic fluids	1 - 4	15 – 20% relative to MEA
	Encapsulated solvents	1 - 2	Unknown
	Electrochemical solvents	1 - 2	Uncertain
Sorbents	Calcium looping system	5 - 6	Coal: efficiency penalties 5-10% Gas: no benefits
	Vacuum pressure swing	2 - 5	Uncertain, could be good
	Temperature swing	1 - 4	Uncertain, appears limited
Membranes	Polymeric membranes	5 - 6	Fuel consumption: ~50% relative to MEA
	Polymeric membranes with cryogenics	2 - 6	Better than without
	Other membranes	2 - 4	Unknown
"Other"	Cryogenic (low temp)	3 - 5	Competitive MEA
	Supersonic	1 - 2	Unknown
	Hydrates	1 - 2	Unknown
	Algae	1 - 3	Unknown
	CO_2 enriched flue gas	5 - 6	Unknown
	Pressurised post combustion	2 - 5	Unknown

The 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, and is shown in Figure 6.[14] 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.

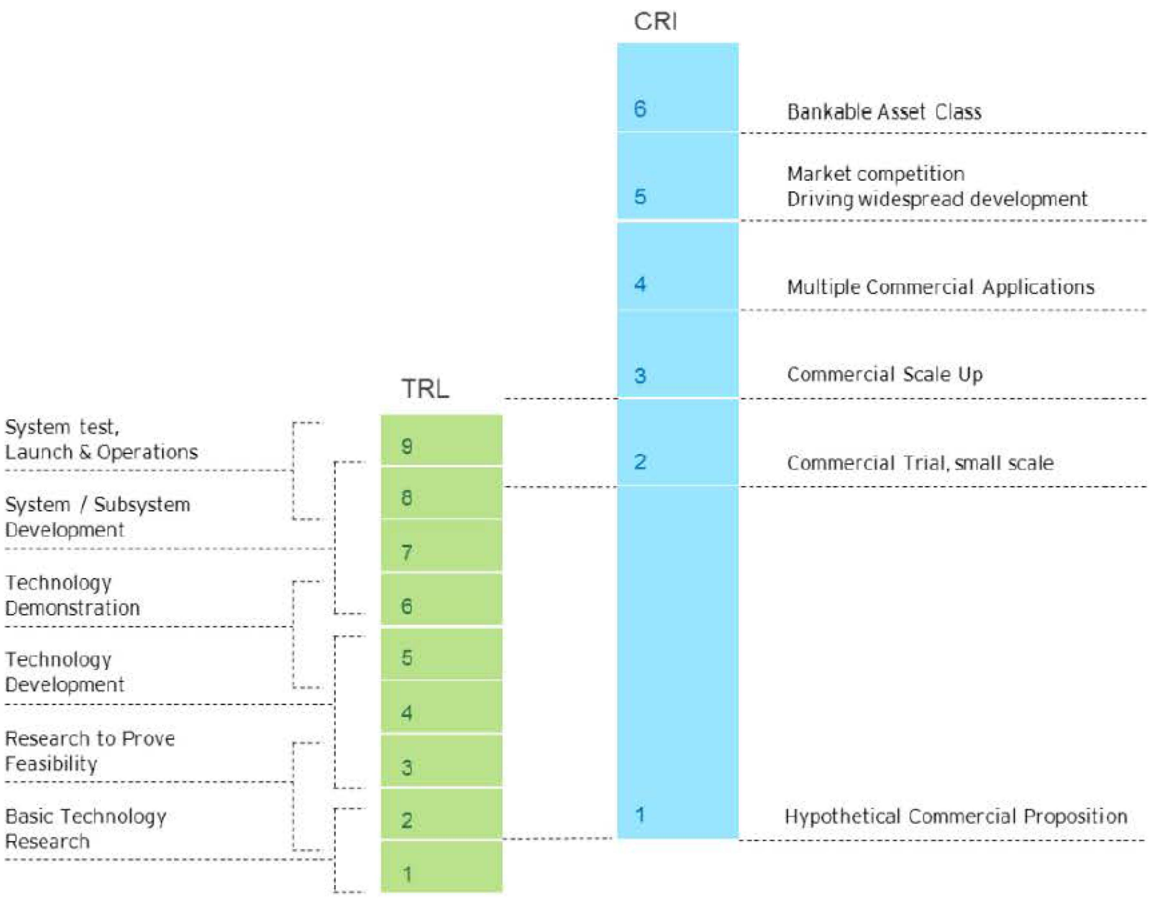

Figure 6: Technical and commercial readiness level indication scale

In summary, PCC is a technology leader in the power generation carbon capture sector, with the prospect of it becoming an even more effective technology. It has been demonstrated to work at scale in both the power sector and industry and cost reductions are occurring from "learn by doing". In addition, significant progress is being made in reducing energy of regeneration for amine based processes from 4.0 – 4.5 (in the 1990's) to 2.0 – 2.3MJ/Kg CO_2 due to:

- Several commercial vendors for existing (and improving) technologies
- Strong competition between vendors
- Different solvent configurations afford some technology choice and optimisation

Apart from the commercial solvents, the next tier of advanced solvents is getting close to commercial scale trials. These next generation solvents and other novel technologies are being tested at small scale and niche applications in industry. With continued R&D support it is possible that these 2nd and 3rd generation solvents will be ready for demonstration scale testing in the next 5 and 10 years respectively.

[14] Australian Renewable Energy Agency (ARENA), (2014), "*Commercial Readiness Index for Renewable Energy Sector.*" Canberra, Commonwealth of Australia

2.0 Natural Gas Combined Cycle PCC Retrofit

2.1. Retrofit Cost and Performance

Table 3 shows the total plant costs on a $/KW$_e$ basis for new build NGCC with and without PCC, based on previous published data.[7] Additional costs for this study were developed for the retrofit of an existing 250MW NGCC plant, assuming it to be a fully paid off asset, in good condition with a suitably long life with access to suitable gas volumes. No base plant upgrades are included in this analysis, neither is the provision of alternative sources of energy to support the retrofitted plant.[15]

Table 3: Natural gas combined cycle (NGCC) with post combustion capture (PCC) costs

	New NGCC[7]		NGCC Retrofit	
	No PCC	With PCC	Base Case	Advanced Solvent
Total Plant Cost (A$/kW sent out)	1,450	3,050	1,775	1,600
Fixed O&M (A$/kW-year)	20	35	37	35
Variable O&M (A$/MWh)	1.5	12.0	13.5	11.5
Efficiency (%HHV)	50	42	41	42

The base case NGCC PCC retrofit case is a fully integrated MEA solvent facility with EGR. The gross power output drops significantly as a result of the steam and electricity diverted to the capture and compression systems. The advanced solvent case benefits from an improvement in the potential regeneration energy required and resulting decreases in auxiliary load required compared with the base case.

Although not proven at scale, EPRI believes these 'advanced solvents' will be commercially available in the near term.[7] In Section 1.5, Table 2 summarises many of the potential of 2nd and 3rd generation PCC solvent technologies, with an estimate of the TRL range for each technology class.

NGCC plants emit virtual no SOx and require no additional controls to be incorporated into a PCC retrofit. In most cases water steam injection and the use of low NOx burners is more than sufficient to reduce emissions to acceptable levels with very little capital cost if not already incorporated into the base NGCC plant.[16]

[15] The design basis, capital cost and estimating basis and cost of electricity (levelised cost of electricity or LCOE) methodologies are consistent with those used in the Australian Power Generation Technology report 2015.

[16] IEAGHG, (2012). "*Emissions of Substances other than CO_2 from power plants with CCS.*" 2012/02, Cheltenham, UK.

2.2. Retrofit Cost of Electricity

The new build NGCC plants are compared with a base case retrofit and an advanced solvent and solar PV.[2] The costs of electricity for a new NGCC with and without PCC have been calculated using the common assumptions[7, 17] and shown in Figure 7. Under APGT assumptions the base new build NGCC plant delivers an average LCOE of $78/MWh, with a new NGCC with PCC plant an LCOE of $136/MWh.

Given the development times associated with a PCC plant, it is likely that the advanced solvents would be available to be incorporated into the design. The base case and advanced solvent retrofit have an average LCOE of $115 and $108/MWh respectively – similar to solar PV.

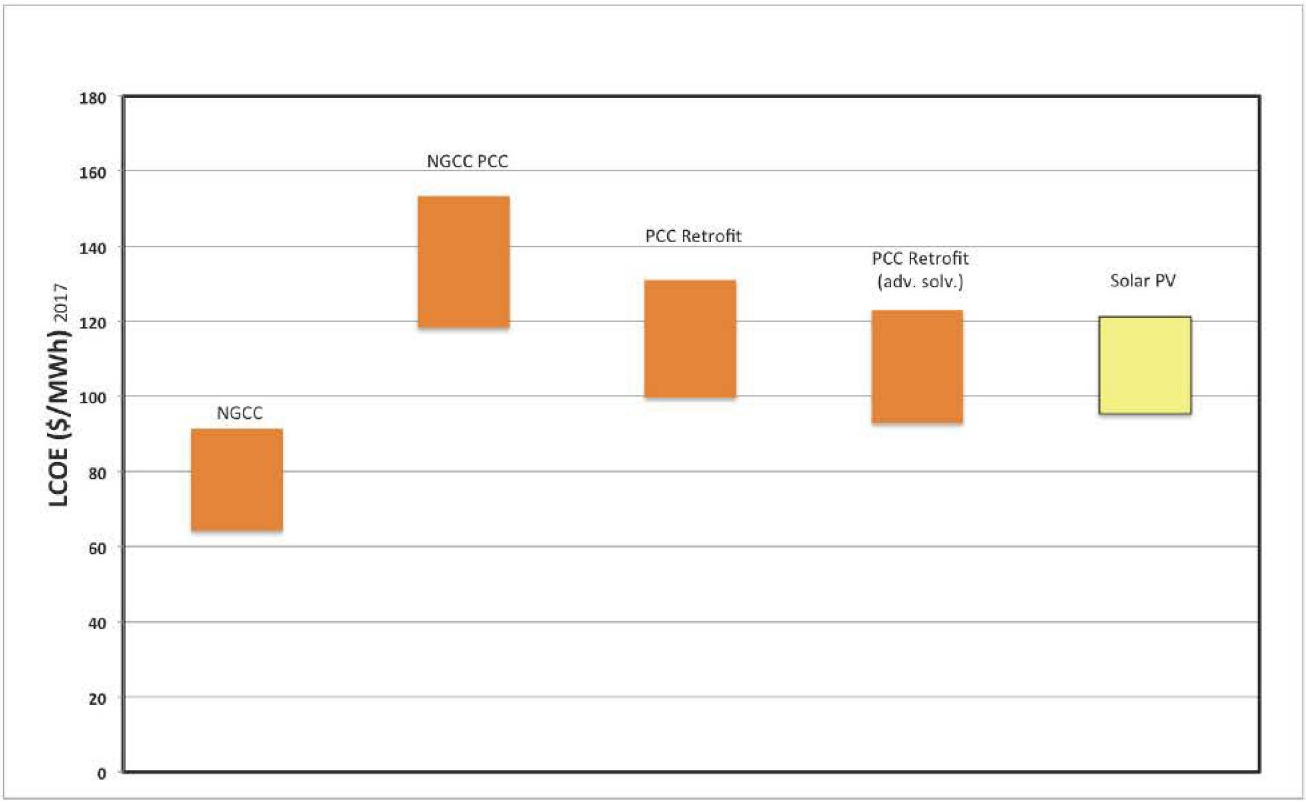

Figure 7: Natural gas combined cycle with PCC LCOE range comparison – APGT assumptions (note: APGT costs for solar updated to 2017)

Table 4 summarises the impact of post combustion capture retrofit on existing plant and the effect of advanced solvents.

Figure 8 shows the same data, broken down into the various Levelised Cost of Electricity (LCOE) elements. As shown in Figure 8, the primary element in the increase in the LCOE between the two new NGCC plants with and without PCC is the significant increase, more than double, in the financing charges associated with the more capital intense NGCC PCC plant.

While the capital charges for a retrofit are similar to a new NGCC plant, the extra energy required to capture the CO_2 reduces the overall plant efficiency, increasing the proportion of fuel costs as part of the LCOE.

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[17] Bongers, G.D., Byrom, S. and Constable, T. (2017), *Retrofitting CCS to Coal: Enhancing Australia's Energy Security*. CO2CRC Limited, Victoria. Australia.

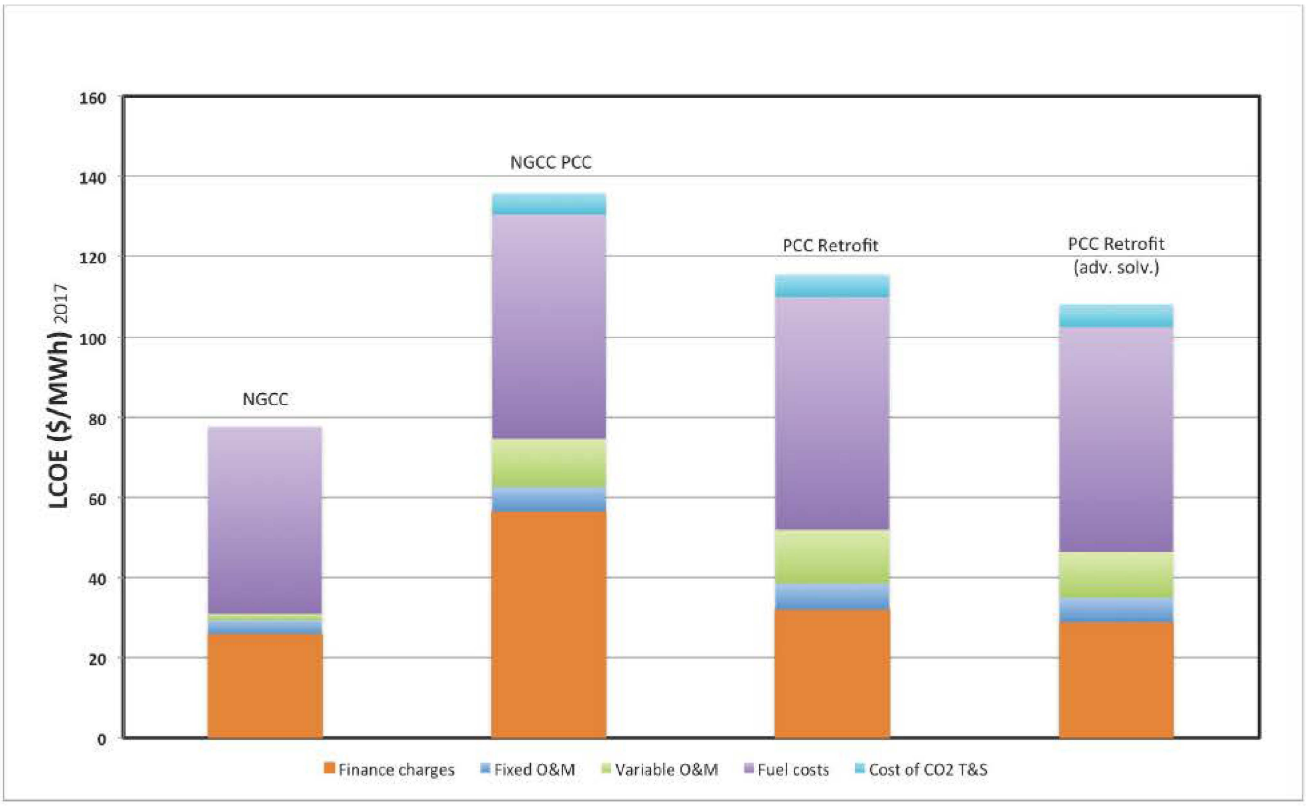

Figure 8: Natural gas combined cycle with PCC LCOE breakdown comparison – APGT assumptions

Table 4: Natural gas combined cycle with PCC costs (APGT assumptions)

	Plant Efficiency (% HHV)	**LCOE** ($/MWh)	**Total Capital** ($bn)	**CO_2 Emitted** (mil t/yr)	**Number of Households Powered**
New Build NGCC (440 MWe)	50	78	0.64	0.93	430,000
New Build NGCC with PCC (375 MWe)	42	136	1.14	0.19	370,000
PCC Retrofit (193 MWe)	41	115	0.34	0.10	190,000
PCC Retrofit – Adv Solvent (198 MWe)	42	108	0.32	0.10	190,000

All of the LCOE's for the natural gas power plants in Figure 7 and Figure 8 use relatively old assumptions in terms of gas price and a low Capacity Factor (C.F.). Figure 9 shows the LCOE range for differing capacity factors, fuel costs, and capture rates for both a new build NGCC PCC plant and a retrofit. The new build NGCC with PCC delivers electricity at an average LCOE $136/MWh. The retrofit of an existing NGCC results in an average LCOE of $115/MWh at a 65% capacity factor and the APGT gas price range.

The increase in capacity factor decreases the LCOE as there is more generation to amortize the costs over. However the largest factor is the increase in the gas price from $5 – $8/GJ to $8 – $13/GJ, with an approximately $30/MWh increase in the average LCOE.

The gas price range of $8 – 13/GJ used in this study reflects a 'very strong' gas price outlook compared to the Australian Energy Market Operator's 2016 National Planning and Forecasting review's strong case at $8.50/GJ.[18] A finely balanced natural gas market will continue to place upward pressure on prices – beyond the strong case predicted in 2016. New natural gas supply tranches are becoming harder to extract and more costly - at a time when low cost reserves in eastern Australia are in decline – again placing upward pressure on prices.[19]

The increase in capacity factor decreases the LCOE, as there is more generation to amortize costs. However the largest factor is gas price sensitivity. The APGT previous used a range of $5 – $8/GJ, as there has been an increase in average prices in Australia, this report used a $8 – $13/GJ range, with an approximately $30/MWh increase in the average LCOE.

A retrofit of an existing NGCC plant using an advanced solvent PCC configuration at the $8-13/GJ, 85% capacity factor and a 90% capture rate results in an average LCOE of $108/MWh.

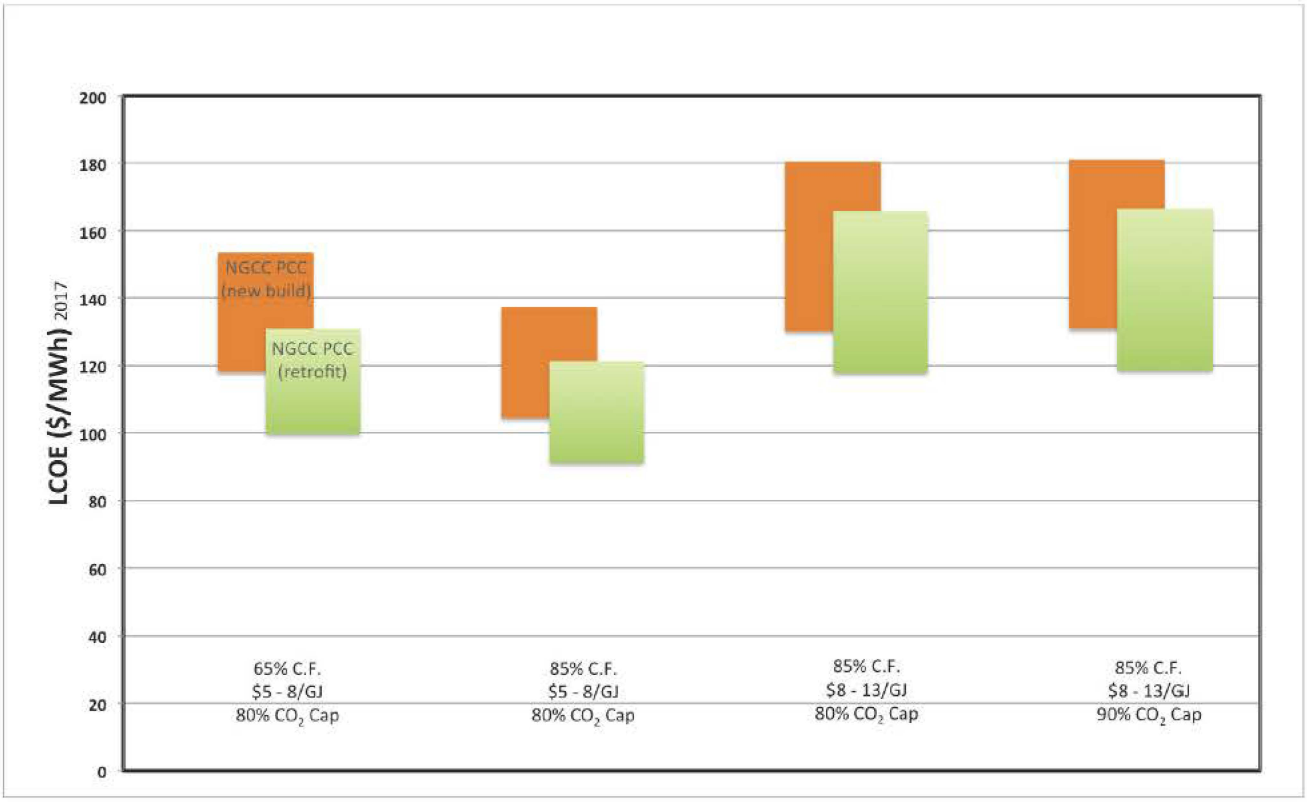

Figure 9: LCOE comparisons with differing fuel costs, capacity factor and CO_2 capture rates

[18] Core Energy Group, (2016), "*NGFR Gas Price Assessment.*" Adelaide, South Australia.

[19] Australian Energy Market Operator (AEMO), (2017). "Gas Statement of Opportunities for Eastern and South-Easter Australia."

Table 5: LCOE comparisons with differing fuel costs, capacity factor and CO_2 capture rates

	65% C.F. $5-8/GJ 80% CO_2 Capture	85% C.F. $5-8/GJ 80% CO_2 Capture	85% C.F. $8-13/GJ 80% CO_2 Capture	85% C.F. $8-13/GJ 90% CO_2 Capture
New Build NGCC with PCC (375 MWe)	118 - 153	105 - 137	130 - 180	131 - 181
PCC Retrofit (193 MWe)	100 - 131	90 - 121	118 - 166	119 - 166

As shown in Figure 10, the capital costs for post combustion capture options are significantly less than a solar PV system of equivalent output.[20] Retrofitting an existing 250MW NGCC cycle plant with PCC would result in a 193MW plant, which would power approximately 190,000 households annually. The equivalent annual average output from a solar PV system requires 480MW of installed capacity.

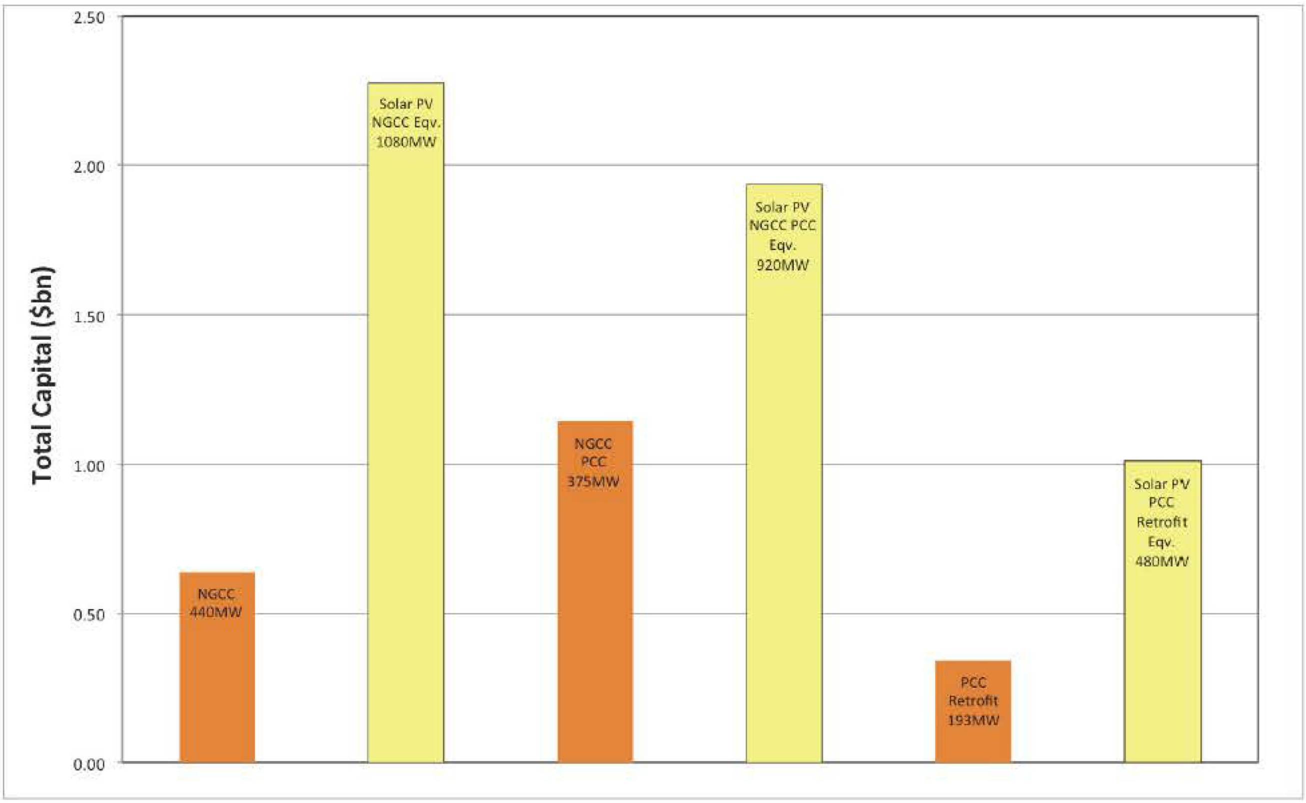

Figure 10: Total capital plant costs – with 'equivalent' households supplied

A new build 375MW NGCC with PCC plant would power 430,000 homes – which is more than the entire Central Coast of NSW[21]. A 193MW NGCC with an advanced solvent retrofit would power 190,000 homes – which is more than Townsville, Qld.[22]

[20] Average Household energy use 5,817kWh average household (which does not include any self generation). https://www.billrepublic.com/average-electricity-usage/ (Accessed Apr 2017).

[21] .id community Demographic Resources, (2017). http://profile.id.com.au/central-coast-nsw/households. (Accessed Apr 2017).

[22] Australian Bureau of Statistics, (2017). http://stat.abs.gov.au. (Accessed Apr 2017).

2.3. Potential Capital Cost Improvements

Figure 11 shows the decrease in LCOE associated with the application of 'learn by doing' capital cost reductions. Following the completion of the Boundary Dam[23] project the project owners have claimed that there is substantial capital cost savings that would be materialised on future projects. Given that the two recently completed projects are coal based[23, 24] and that limited public studies are available for NGCC with PCC (including Poza Rica - Mexico[6], IEA GHG[4], and EPRI[5]), only a 10% and 20% capital saving was calculated for the base case and advanced solvent case retrofit.

As shown in Figure 11, there is only a small effect from the capital savings from 'learn by doing' process improvements. This is primarily due to the relatively small impact of capital finance charges on the LCOE compared with fuel costs.

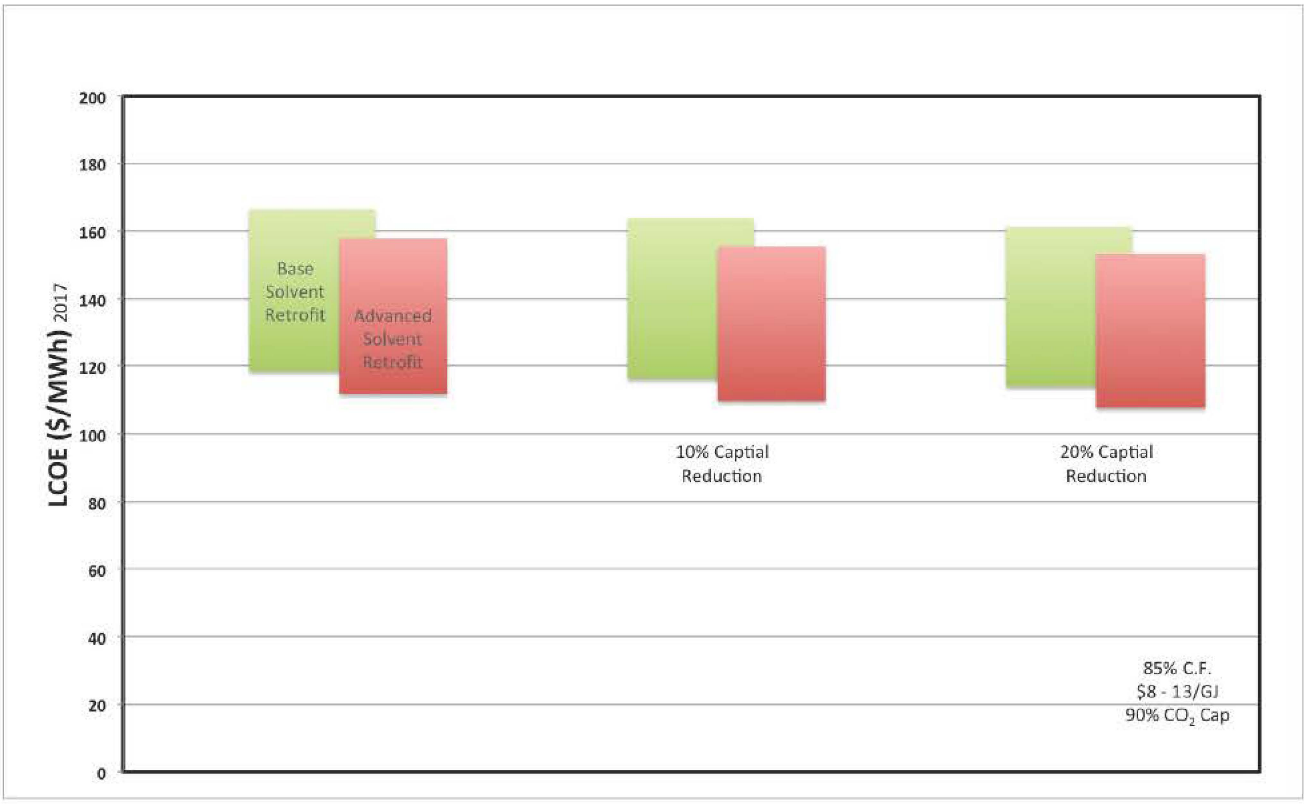

Figure 11: Learn by doing capital cost reduction potential

[23] Monea, M. 2015. SaskPower's Boundary Dam CCS project - Proof that coal is part of the future, https://www.worldcoal.org/saskpowers-boundary-dam-ccs-project-proof-coal-part-future (Accessed Apr 2017)

[24] MIT Carbon Capture and Sequestration Technologies Program, https://sequestration.mit.edu/tools/projects/wa_parish.html (Accessed Apr 2017).

2.4. Natural Gas Australian Plant Listing

Natural gas turbines may be used in as open cycle or combined cycle configurations. The open (or simple) cycle is when the gas turbine is connected directly to a generator with no energy recovery from the exhaust stream. The open cycle gas turbine configurations are not suitable for PCC retrofit, with no heat recovery systems in place. A combined cycle configuration power system combines the gas turbine with a HRSG, a steam turbine and generator. Figure 12 shows a range of configurations for NGCC power plants.[1]

The Australian NGCC facilities connected to the National Energy Market (NEM)[25] and South West Interconnected Service (SWIS)[25, 26, 27] are listed in Table 6 and on Figure 13.

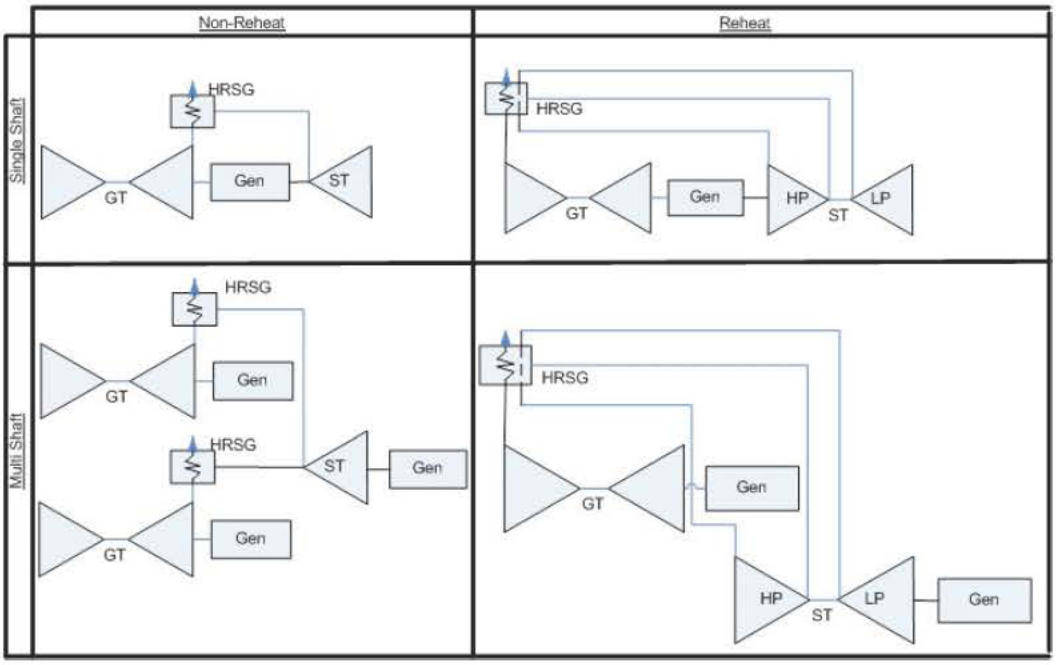

Figure 12: Alternative configurations for NGCC power plants

[25] Base data from AEMO and industry experts: Australian Energy Market Operator, (2013). Existing Generator Data. www.aemo.com.au/media/Files/Other/planning/2013Consultation/PlanningStudies2013EsistingGeneratorTechnicalData.xlsx. (Accessed Apr 2017)

[26] Suynoto, A, and Falcon, N., 2013, "*2014/15 Margin Peak and Margin Off-Peak Review Assumptions Report.*" Document No SH43499, SKM, Melbourne, Victoria.

[27] Environmental Protection Authority, 2005, "*Kwinana Gas-Fired Power Station (Water Cooled Condenser).*" Perth, Western Australia, ISBN. 0 7307 6830 9.

Table 6: Combined cycle natural gas plants on the NEM and SWIS (over 100MW)

Station	Year Commissioned	Capacity (MW)	Thermal Efficiency (% HHV)	Emissions Factor (tCO_2/MWh)
Tallawarra (NSW)	2009	435	54.0%	0.36
Condamine (Qld)	2009	135	48.0%	0.45
Darling Downs (Qld)	2010	630	46.0%	0.42
Swanbank E (Qld)	2002	370	52.0%	0.37
Townsville (Yabulu) (Qld)	2005	244	46.0%	0.45
Osborne (SA)	1998	192	42.0%	0.46
Pelican Point (SA)	2000	474	48.0%	0.40
Tamar Valley (Tas)	2010	208	48.0%	0.41
Kwinana Newgen (WA)	2008	320	47.0%	0.39
Cockburn (WA)	2003	240	47.0%	0.4

The technologies involved with CCS are not inherently new, however they have only recently been applied to emissions reductions in the electricity sector. The results presented in this study are generic, not specially applied to an individual plant – and each plants suitability for a retrofit will be dependent a range of factors including available area for the PCC equipment, the condition of the base plant, access to suitable storage and a range of other factors.

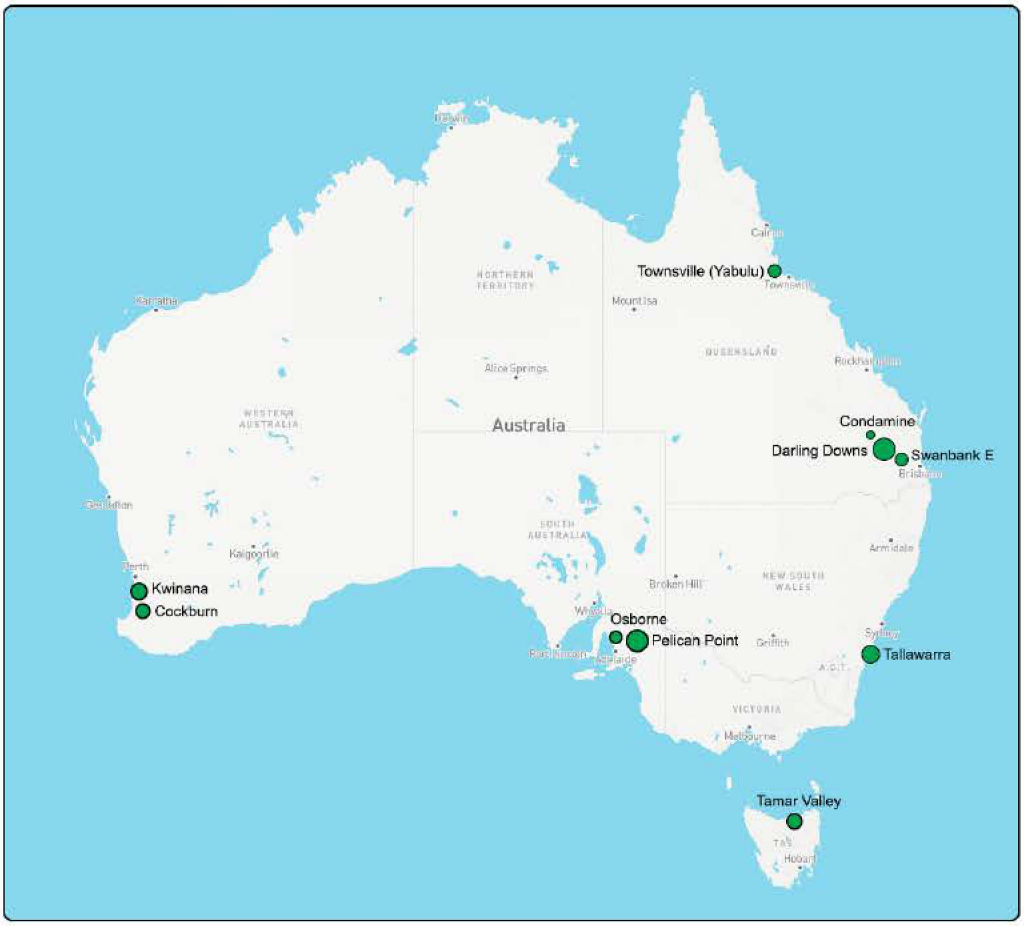

Figure 13: Map of Australian NGCC plants

2.5. Electricity Supply Diversity

Energy security remains a high priority for Australia and retrofitting gas-fired firm capacity with carbon capture and storage will help achieve reliable 24/7, lowest cost and a clean energy future for Australia. When looking to maintain a secure and environmentally sustainable electricity supply system, every electricity generation technology with its various operational and environmental advantages and limitations must be considered. Designers of reliable electricity systems must take the attributes listed in Figure 14[7] as well as capital and operating costs into account.

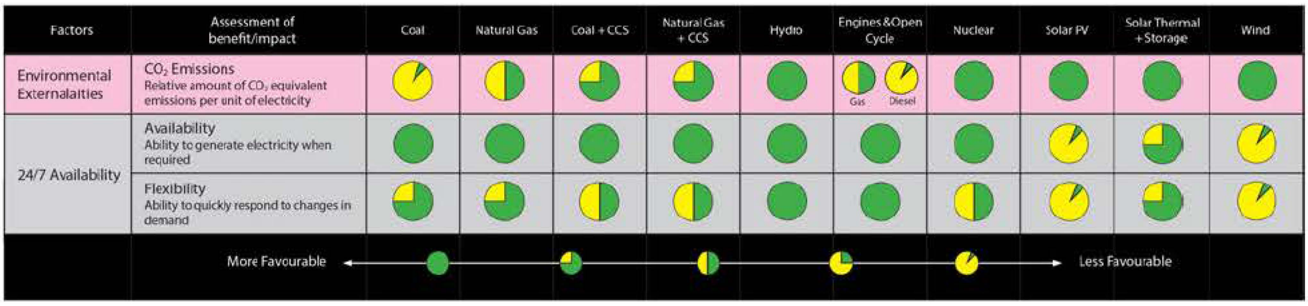

Figure 14: Electricity technology comparisons

In this report we have endeavored to establish quality data for the retrofit NGCC with carbon capture and storage power stations. Undoubtedly however, the most accurate way to generate retrofit cost and performance numbers is to undertake individual studies on existing Australian full-size plants by engineering companies (this was the approach EPRI took in its North American studies for coal, using an engineering team from Nexant and Bechtel).[7]

Notes

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