Meeting Australia's Paris greenhouse commitment at zero net cost

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Summary: ***continued construction of wind and PV at current rates yields a reliable predominantly renewable electricity system by 2030 that meets the Paris greenhouse targets at zero net cost.***

Currently, Australia is installing about 3 Gigawatts (GW) per year of wind and solar photovoltaics (PV). This rate is sufficient (if continued until 2030) for renewable energy to meet more than **half** of Australia's electricity consumption and **all** of Australia's Paris greenhouse emissions reduction target.

The net cost of meeting the Paris target is **zero** because the cost of electricity from new-build wind and PV is **below** (i) the cost of electricity from new-build coal generators and (ii) the cost of electricity from existing gas generators and (iii) the wholesale price in the National Electricity Market (NEM).

The cost of renewables includes the cost of hourly balancing of the grid to retain the **same reliability** as at present. Hourly balancing comprises pumped hydro energy storage, stronger interstate high voltage power lines and the cost of PV and wind spillage on windy, sunny days when the energy stores are full.

Snowy 2.0 provides half the new storage required to support 67% renewables in the NEM.

Figure 1 shows the all-in cost of electricity under three scenarios:

- Renewables: replace enough old coal generators by renewables to meet the Paris target
- Gas: premature retirement of most existing coal plant and replacement by new gas generators to meet the Paris target. Gas is uncompetitive at today's gas prices ($8/GJ). The gas scenario requires a large increase in gas consumption, placing upwards pressure on prices.
- Status Quo: like-for-like replacement of retiring coal generators with supercritical coal. This **FAILS** to meet the Paris target by a wide margin and has similar cost to the renewables scenario.

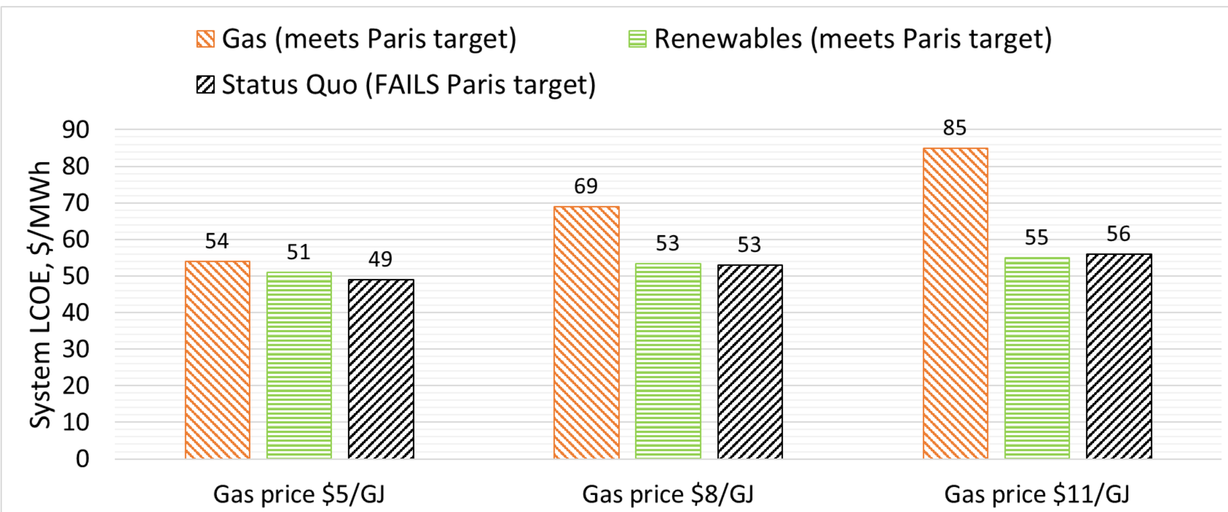

Figure 1: Cost of electricity ($/MWh) for three scenarios and a range of gas prices. See text for details.

Meeting the Paris greenhouse emissions target

The cheapest way to meet the Paris emissions reduction target is by large scale substitution of zero emission wind and solar PV into the electricity system in place of retiring coal and gas.

Australian Greenhouse gas emissions in 2016 were 543 Megatonnes (MT) [1]. Under the Paris agreement Australia will reduce greenhouse gas emissions to 441 MT/year by 2030 [2], a reduction of 102 MT/year from current emissions. Electricity sector emissions in 2016 were 192 MT. We assume that all emission reductions are obtained within the National Electricity Market (NEM). Emissions from electricity production outside the NEM (in WA, NT and remote areas) are about 24 MT/yr.

Thus the 2030 NEM emissions target is 66 MT/yr (= 192 – 24 – 102).

Snowy 2.0 provides half the new storage required to balance the NEM

Snowy 2.0 [3] provides half the new storage required to balance the NEM up to a renewable penetration of 67% (two thirds). Snowy 2.0 has 2 GW power capacity and 350 Gigawatt-hours (GWh) of energy storage [1]. The additional storage needed to reliably balance the NEM when it reaches 67% renewables is Snowy 2.0 plus an additional 2 GW of new storage capacity elsewhere with 6 hours of storage (12 GWh). This may come from pumped hydro, batteries (houses, electric cars) and demand management.

Indeed, Snowy 3.0 [4] with 4 GW capacity could reliably balance a 67% renewables NEM.

Cost of hourly balancing remains low for <75% renewables in the NEM

Hourly balancing ensures that there is enough power available to meet demand for every hour of the year. The hourly balancing cost comprises energy storage, stronger interstate high voltage power lines and the cost of PV/wind spillage on sunny/windy days when the storages are full.

The cost of hourly balancing of the NEM is only about $5/MWh for 67% renewable energy fraction, and rises to about $25/MWh for 100% renewable electricity as shown in Figure 2 [5]. The total cost of renewables is the cost of generation ($50/MWh) plus the cost of balancing (i.e. $55/MWh for 67% renewables). The current wholesale price of electricity in Australia is $70-100/MWh.

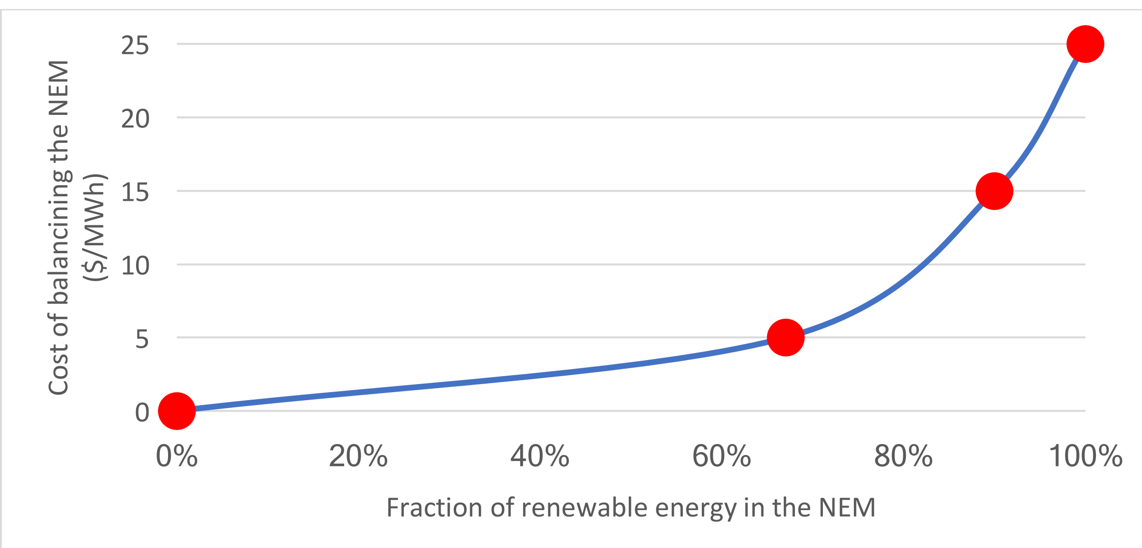

Figure 2: Cost of hourly balancing of the NEM ($/MWh) as a function of renewable energy fraction

Cost of renewable energy is low and falling

The current cost of new-build wind and PV in Australia is around $60/MWh and $70/MWh respectively. We assume that in the 2020s both wind and PV fall to an average of $50/MWh. There are numerous reports of such prices (and lower) already being achieved in overseas locations that have similar wind and solar resources [6-9]. It would be surprising if such prices were not achieved in Australia by 2025.

Renewable energy dominates new generation capacity

PV and wind have 1st and 2nd place in the world's net new generation capacity installed in 2016 (Figure 2), pushing coal into 3rd spot. Wind and PV provide nearly all new capacity installed in Australia.

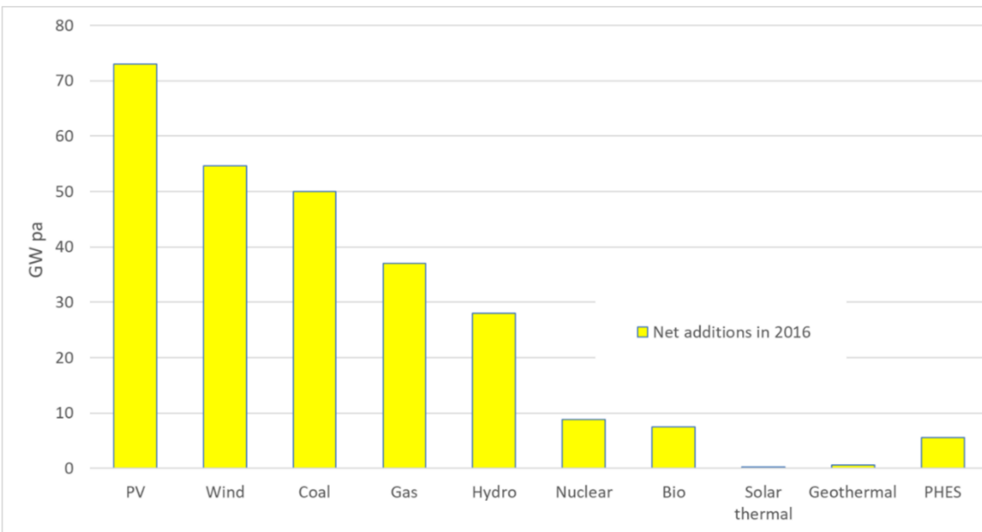

Figure 2: Net new generation capacity installed worldwide in 2016 [10-12]

Stability and reliability remain high under all scenarios

The Renewables scenario is likely to be highly stable because of the wide geographical distribution and highly diverse mix of generators: PV (26 GW), wind (24 GW), coal (9 GW), gas (5 GW), pumped hydro storage (5 GW) and existing hydro/bio (8 GW). Within this mix, a large amount (27 GW) of traditional capacity (coal, gas, hydro and bio) is retained. Inertial energy, spinning reserve, rapid start, black start capability, voltage regulation and frequency control can be provided by a combination of pumped hydro, batteries, demand management and synthetic inertia (from PV and wind farms operated in a conservative fashion at times of grid stress).

All scenarios meet the National Electricity Market standard for unmet energy demand (0.002%) and are likely to achieve stability that matches the current system. A substantial amount of residual coal remains in the Renewables scenarios (9 GW), but only 3 GW remains in the Gas scenario.

Because a renewable electricity system comprises thousands of small generators spread over a million square kilometres, sudden shocks to the electricity system from generator failure, such as occur with aging large coal generators, are unlikely. Neither does cloudy and calm weather cause shocks, because it is predictable and weather patterns take days to move over the Australian continent. Increased interstate interconnection (part of the cost of balancing) reduces the probability of transmission failure, which was the prime cause of the 2016 South Australian blackout.

Retirement of existing coal power stations is gathering speed

Two thirds of Australia's fossil fuel generators will reach the end of their technical lifetimes by 2036, and will need to be replaced either by fossil or renewable energy generators. Data for technical lifetime of each power station is taken from a 2013 report to Government by ACIL Allen [13].

Five coal fired power stations are closed early in the Renewables scenario (Table 2). Coal capacity in 2030 falls from 19 GW (Status Quo) to 9 GW. Brown coal power stations have the highest emission intensity but the lowest operational cost. The Renewables scenario envisages retention of Loy Yang because of its low cost and also its role in supporting Victoria, South Australia and Tasmania.

For the Gas scenario to meet the Paris target requires premature closure of all brown coal power stations and most black coal power stations by 2030 (Table 2), and their replacement with new Combined Cycle Gas Turbines (CCGT) which have lower emissions but higher cost. Coal capacity in 2030 falls from 19 GW (Status Quo) to 4 GW in the Gas scenario.

The coal power stations that would close prematurely in our modelling relative to the ACIL Allen Report [13] are tabulated below.

Power station	**Capacity (GW)**	**Fuel (coal type)**	**Renewables scenario**	**Gas scenario**
Liddell	2.1	Black	2022	2022
Eraring	2.9	Black	2030 (3 years early)	2030 (3 years early)
Yallourn	1.5	Brown	2030 (5 years early)	2030 (5 years early)
Tarong	1.4	Black	2030 (5 years early)	2030 (5 years early)
Bayswater	2.7	Black	2030 (6 years early)	2030 (6 years early)
Callide B	0.7	Black	2030 (9 years early)	2030 (9 years early)
Loy Yang A	2.2	Brown		2030 (6 years early)
Loy Yang B	1.1	Brown		2030 (15 years early)
Stanwell	1.4	Black		2030 (15 years early)
Callide C	0.8	Black		2030 (21 years early)
Tarong North	0.4	Black		2030 (22 years early)

Table 1: premature closure of coal power stations under the Renewables and Gas scenarios

DETAILS

- Renewable energy technology: We avoid heroic assumptions about future technology development: we only consider technology that has already been deployed in large quantities (> 200 GW) with annual deployment rates above 50 GW/year, namely PV and wind. On this basis, we exclude solar thermal, geothermal and ocean energy. We also exclude nuclear energy because of the unlikelihood of its deployment in Australia.
- Wind and PV is being installed at around 3 GW per year [14] to meet the Renewable Energy Target (RET) in 2020. We assume a similar deployment rate until 2030, with 1.5 GW/year each for wind and PV. In all scenarios, we assume that the 2020 RET is met, and that new rooftop PV continues to be deployed after 2020 at a rate of 1 GW per year. The cost and benefit of rooftop PV systems accrues

to the building owner and appears as an apparent drop in electricity demand. However, the cost of hourly balancing of rooftop PV is included in our modelling.

- High voltage transmission: Optimisation of renewable energy deployment requires additional high voltage transmission to allow movement of wind and PV energy between states depending upon weather and demand. We utilise high voltage AC transmission for this purpose, at a cost of $1000 per MW-km (and lifetime of 50 years). Distances amongst the major cities, Brisbane, Sydney, Melbourne, Adelaide and Hobart, are used to estimate the length of new high voltage AC transmission lines. The new transmission lines comprise Qld-NSW (5.2 GW), NSW-Vic (5.4 GW), SA-Vic (1.4 GW) and Vic-Tas (1.5 GW). A second (undersea) Basslink costs $4000/MW-km.
- Gas prices have increased in recent years due to exposure of Australian gas consumers to world pricing via the construction of large LNG export facilities. A recent report to Government noted *"The opaque nature of Australia's wholesale natural gas markets and the deregulation of natural gas retail markets in most states and territories mean there is limited information in the public domain about the gas prices paid by industrial and residential customers"* [15]. This report estimates the wholesale price of gas to be $7-11/GJ. The Renewables scenario does not require an increase in gas consumption for electricity generation, thus reducing pressure on gas prices.
- Electricity demand in Australia has been static or falling since 2008, caused by improving energy efficiency, reduced demand from heavy industry, and increased price of electricity. We assume that this trend continues until 2030. Demand in the NEM remains at 205 TWh per year (including rooftop PV). Thus, improved energy efficiency is offset by rising population.
- Existing hydro and bio energy: We include existing hydroelectricity generation and pumped hydro stations but exclude additional river-based hydroelectric deployment due to lack of significant further rivers to dam in Australia. We also include existing biomass generation (based on agricultural waste), but exclude additional deployment of biomass because utilization competes with food, timber and ecosystem values for the provision of land, water, fertilisers and pesticides. Wind and PV (including rooftop PV) contributed about 21 TWh in Australia in 2016 compared with hydroelectricity (18 TWh) and biomass electricity (4 TWh).
- Modelling: For ease of modelling we make all of the required emission reductions in the NEM. Electricity emissions in Western Australia, the Northern Territory and remote areas is about 13% of total emissions. We divide the NEM geographical region into 43 cells and utilise historical hourly data for wind and PV in each cell throughout the years 2006-10, which comes from the AEMO 100% renewables study in 2012-13 [16,17]. We use historical NEM demand data for every hour of the years 2006-10. Existing bio and hydroelectricity (less than 10% of annual electricity demand) is assumed to be dispatchable. The existing river-based PHES is utilized.
- PHES: A private cost model is used, developed by an experienced hydro engineer based upon existing models. The model has been tested for consistency with publicly available PHES systems costs. The unit off-river PHES system is assumed to have a power of 200 MW, a head of 580 m, twin 20 m deep 5-hectare "turkey nest" ponds with earth walls built on flat land, penstock slope of 13 degrees, easy access, minimal flood control measures and a round trip efficiency of 80%. The estimated cost is $800 per kW (for penstocks, machinery and power conversion) and $70 per kWh (for pond excavation and construction), with scaling factors applied for different head and pond size.

Head is a strong inverse driver of cost of storage. Transmission to a high voltage node is an additional cost and calculated separately.

- Discount rate: We calculate the levelised cost of electricity (LCOE) using a real (i.e. inflation-free) discount rate of 5% per year. This includes bank finance for 70% of capital expenditure at a nominal rate of 5% per year, a return on investment of 10% (nominal) on equity (30% of capital expenditure) and an inflation rate of 1.5% per year. The Reserve Bank of Australia cash rate is currently 1.5% per year. We use Australian dollars and an exchange rate of AU$1.00 = US$0.75.
- The price of wind and PV continues to fall rapidly. Our estimate for current (2017) prices in Australia is <$60/MWh and <$70/MWh for wind and PV respectively [5-9,18]. This takes account of a 20% reduction of the international market price for PV modules over the past 18 months, and the rapidly growing scale of the PV industry in Australia. Whereas the ARENA LSS program funded systems of typically a few tens of Megawatts, today there are frequent announcements of PV systems in the hundred-megawatt range. Wind energy technology also continues to improve in every aspect, including the size of turbines and the ability to achieve capacity factors above 40%.

Three scenarios summary

Table 1 shows details of the modelling of the Renewables, Gas and Status Quo scenarios.

Scenario	**Renewables**	**Gas**	**Status Quo**
Emissions (MT); NEM target = 66 MT	66	66	113
Emission reduction **shortfall** (MT)	0	0	**47**
Coal capacity (GW)	9	3	19
Coal generation (TWh)	58	20	107
Gas capacity (GW)	5	16	9
Gas generation (TWh)	10	106	20
Wind capacity (GW)	24	8	8
Wind generation (TWh)	88	28	28
PV capacity (incl. rooftop PV) (GW)	26	23	23
PV generation (TWh)	40	33	33
Existing hydro and bio capacity (GW)	8	8	8
Existing hydro and bio generation (TWh)	13	18	18
Pumped hydro capacity (GW)	5.3	1.3	1.3

Table 2: optimised capacity and electricity production for each scenario

- Storage: Snowy 2.0 (2 GW power, 350 GWh energy) plus additional pumped hydro (2 GW, 12 GWh) + existing pumped hydro of 1.3 GW and 26 GWh.
- Average capacity factors in the Renewables scenario: rooftop PV (15%), 1-axis tracking PV (23%), wind (41%), coal average (74%), CCGT (34%), OCGT (23%).
- LCOE: wind ($50/MWh), PV ($50/MWh), existing coal (brown $20/MWh, black $40/MWh)

Costs

Operational and financial parameters are tabulated in Table 3 and 4, taken from the CO2CRC report [19].

Technology	Capital cost ($/kW)	Fixed O&M ($/kW/year)	Variable O&M ($/MWh)	Fuel cost ($/GJ)	Thermal efficiency (%)	Emission intensity (t/MWh)	Technical lifetime (years)
Brown coal	0	111	1.1	0.4	27	1.22	50
Subcritical black coal	0	47	2.0	3.1[a]	35.6	0.918	50
Supercritical black coal	0	45	1.9	3.1[a]	37.6	0.895	50
CCGT	0	30	1.1	8, 11	47.5	0.389	30
OCGT	0	12	8.3	8, 11	30	0.620	30
Hydro	0	49	6.6				150
Bio[b]	0	109	7	0.6	22		30

Note. Cost estimates for 2016. Data for legacy assets is derived from the ACIL Allan report 2013 & 2014.
[a] 2015-16 average prices for Australian thermal coal
[b] Source: AEMO 100% renewables study 2013

Table 3. Cost assumptions for power generation technologies (legacy assets)

Technology	Capital cost ($/kW)	Fixed O&M ($/kW/year)	Variable O&M ($/MWh)	Fuel cost ($/GJ)	Thermal efficiency (%)	Emission intensity (t/MWh)	Technical lifetime (years)
Supercritical black coal	3000	45	2.5	3.1	40	0.792	40
CCGT	1450	20	1.5	8, 11	50	0.373	30
OCGT	1000	8	12	8, 11	34	0.548	30
1-axis tracking PV	1100 DC	0	15	0			25
Wind turbines	1800	30	10	0			25
Pumped hydro	800 / 70[a]	20	0	0			50

Note. Cost estimates for 2020s. Data for new-build coal and gas power plants is derived from the CO2CRC report 2015 [19]
[a] $800/kW for power components including turbines, generators, pipes and transformers; $70/kWh for storage components such as dams, reservoirs and water. Sources: private model

Table 4. Cost assumptions for power generation technologies (new-build plants)

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References

1. Emissions: http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/publications
2. Paris target: http://www.environment.gov.au/climate-change/publications/factsheet-australias-2030-climate-change-target

3. Snowy 2.0: http://www.snowyhydro.com.au/our-scheme/snowy20/
4. Snowy 3.0: https://www.snowyhydro.com.au/our-scheme/snowy20/frequently-asked-questions/
5. Andrew Blakers, Bin Lu, Matthew Stocks "100% renewable electricity in Australia", Energy, Volume 133, August 2017, pp 471–482, http://www.sciencedirect.com/science/article/pii/S0360544217309568
6. Fortune. A jaw-dropping world record solar price was just bid in Abu Dhabi (2016) Available from: http://fortune.com/2016/09/19/world-record-solar-price-abu-dhabi/
7. Mexico signs lowest-price solar contracts to date, PV Mag Int (2017) Available from: https://www.pv-magazine.com/2017/02/06/mexico-signs-lowest-price-solar-contracts-in-the-world-to-date/
8. India's Madhya Pradesh auctions nation's lowest-priced solar, PV Mag Int (2017) Available from: https://www.pv-magazine.com/2017/02/09/indias-madhya-pradesh-auctions-nations-lowest-priced-solar/
9. http://reneweconomy.com.au/chile-solar-auction-sets-new-record-low-for-solar-pv-85114/
10. REN21, *Renewables 2016 global status report*. 2016, Paris: REN21 Secretariat. http://www.ren21.net/status-of-renewables/global-status-report/
11. Frankfurt School-UNEP Centre/BNEF, *Global trends in renewable energy investment 2015*. 2015. http://fs-unep-centre.org/publications/global-trends-renewable-energy-investment-2015
12. International Renewable Energy Agency, *Renewable capacity statistics 2016*. 2016. http://www.irena.org/DocumentDownloads/Publications/IRENA_RE_Capacity_Statistics_2016.pdf
13. ACIL Allen, "Electricity sector emissions - modelling of the Australian electricity generation sector", Report to the Department of Innovation, Industry, Climate change, Science, Research and Tertiary Education, September 2013 https://www.environment.gov.au/system/files/resources/65462f51-a20a-4f35-bdd0-d88d6ee5ac4e/files/electricty-sector-emissions.pdf
14. http://www.cleanenergycouncil.org.au/news/2017/May/2billion-renewable-energy-investment-2017-unprecedented.html
15. Gas Price Trends Review Report, commissioned by the Commonwealth of Australia as represented by the Department of Industry, Innovation and Science, and prepared by Oakley Greenwood, EMS and MDQ Consulting https://industry.gov.au/Energy/Energy-information/Documents/Gas-Price-Trends-Report.pdf, updated February 2016
16. Australian Energy Market Operator, *100 per cent renewables study - Modelling assumptions and input*. 2012.
17. Australian Energy Market Operator, *100 per cent renewables study - Modelling outcomes*. 2013. https://www.environment.gov.au/system/files/resources/d67797b7-d563-427f-84eb-c3bb69e34073/files/100-percent-renewables-study-modelling-outcomes-report.pdf
18. http://reneweconomy.com.au/video-wind-solar-cheaper-than-coal-and-gas-so-lets-get-on-with-it-67093/ | https://www.originenergy.com.au/about/investors-media/media-centre/origin-adds-530mw-of-renewable-energy-to-its-portfolio.html
19. CO2CRC Limited, Australian Power Generation Technology Report. 2015. http://www.co2crc.com.au/wp-content/uploads/2016/04/LCOE_Report_final_web.pdf