Towards a Sustainable, Economic and Reliable Power Grid for Australia

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***Abstract*—The Electricity Network needs to eliminate the CO2 it produces by 2050. The price of solar PV and batteries is falling at more than 20% per year. Over the next few years, many consumers will install solar PV and batteries and thus become both producers and consumers (prosumers) of electricity. Ageing coal-fired generators will be replaced with grid size renewable power plants, making power generation more variable. This will require large-scale electricity storage and new network stability mechanisms. Distributed energy management, using suitable communication networks will be required for a stable low cost power system. This paper gives an overview of these issues.**

Index Terms*—Renewable energy sources; Power system stability; Energy storage; Energy management; Power generation.

I. INTRODUCTION

Global warming requires the reduction of CO_2 emissions from the Power supply. Australia is one of the 144 that ratified the 2015 Paris Agreement of the UNFCCC, (Paris COP21) [1], which stated that: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;". In April 2017, the temperature rise is already 0.99°C [2], so that rapid action is needed. However, such action may increase the cost of electricity to consumers. How do we balance the short-term economic benefits, with any resulting long-term economic consequences?

In Australia three quarters of the coal-fired generators are already beyond their designed life [3]. Many of these coal fired power stations will need to be replaced in the near future. The levelised cost of electricity (LCOE) of wind farms and large scale solar are already lower than the LCOE of gas and coal. However replacing coal with renewables reduces inertia and the certainty of available power.

The cost of electricity to consumers is rising and the cost of rooftop PV and battery storage is falling, resulting in an increasing number of consumers installing rooftop PV and battery storage, thus becoming prosumers instead of just consumers. Having a significant proportion of the power generation produced by an uncontrolled supply system may cause network stability problems, but with the appropriate techniques, these distributed generation systems may also assist in keeping the power system stable.

II. A SUSTAINABLE POWER NETWORK

For 400 000 years before 1950, CO_2 levels were below 300 ppm [2]. In August 2017, the seasonally corrected level of CO_2 at Muana Loa, Hawaii, was 406.9 ppm and is rising at >3ppm per year, as shown by the blue curve in fig. 1. The red curves in fig. 1 shows the mean global temperature relative to the 1951 - 1980 global average [2]. At present more than 75% of the world's and 84% of Australia's electricity is produced by burning fossil fuels.

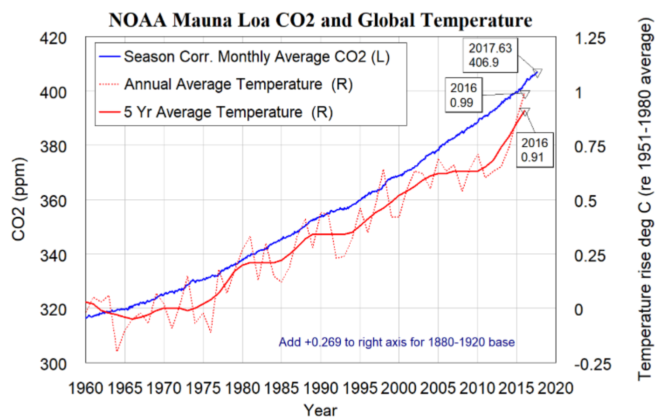

Figure 1. Atmospheric CO_2 and Temperature rise over time.

To comply with the Paris COP21 and limit global warming all fossil fuels generators will need to be replaced by renewable power by 2050. The Electricity Network Transformation Roadmap, final report by Energy Networks Australia & CSIRO [4], shows how this can be achieved and fig. 2 shows the expected transition over time, using the lowest cost transition path. Ignoring climate change is like ignoring the oil warning light in a car, that results in a lower short term cost but will result in a much larger long term cost.

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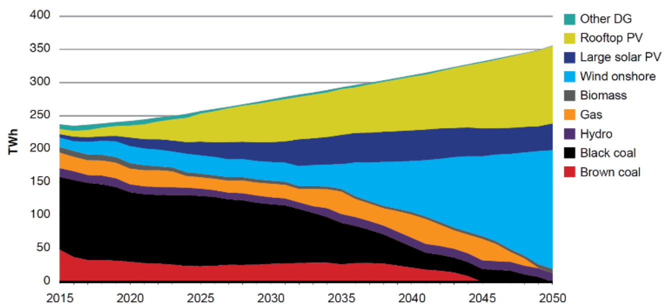

Figure 2. Electricity generation fuel mix road map. [4]

III. An Economic Power Network

A. LCOE of generator types

Many of the aging coal fired generators need to be replaced during the next decade. It is important that any replacement generators do not increase the cost of electricity to the consumer. Table 1 shows the best estimate of the current cost of different generation sources, based on [5] – [8].

TABLE I. LCOE Comparison

Technology	Utility Factor	CO_2 (kg/MWh)	LCOE ($/MWh)	Comment
Brown Coal	83	1213	121	1, [5]
with CCS	83	175	173	
Black Coal	83	827	93	1, [5]
with CCS	83	134	143	
Gas OCGT	10	699	222	1, 2, [5]
	83	699	97	1, 2, [5]
Gas CCGT	83	478	85	1, 2, [5]
with CCS	83	97	117	1, 2, [5]
Wind	43	0	<60	3, [6]
Solar PV (FFP)	21	0	80	4, [5]
Solar Thermal	42	0	78	5, [7]
Nuclear	95	0	181	6
Pumped Hydro	20	0	161	1, [5]
Battery	20	0	106	7, [8]

Table 1 comments: **1)** This data is contained in the AEMO SA fuel and technology report [5], with a $25/t CO_2 carbon cost added, if an Emission Trading Scheme (ETS) is introduced, the effect is likely to be similar. Carbon Capture and Storage (CCS) can be applied to fossil fuel power stations but no large-scale demonstrations have been achieved to date and applying CCS will reduce the thermal efficiency by about 8% [5]. The cost of CCS of $78/MWh for brown coal and 68$/MWh for black coal [5] is more than the LCOE for wind [6] and close to the LCOE for solar. **2)** The Gas price has more than doubled since 2016 so that the LCOE in [5] is far too low for current costs. **3)** AEMO [5] indicates $85/MWh, but Origin Energy signed an agreement for a long-term price, well below $60 MWh for the Stockyard Hill Wind farm in Victoria [6]. **4)** Flat Fixed Panel, Current tenders, AEMO [5] indicates $152/MWh in 2015 and $96/MWh in 2017. **5)** SA government contract price for the Solar Thermal plant at Port Augusta [7]. **6)** The "strike price" for Hinkley Point C £92.50 converted to $AU in 2017. Nuclear is baseload only and is a poor match for power systems with a large portion of renewable generation. **7)** Data from figure 4 of [8], AEMO [5] indicates $216 for 2017.

The cost of wind generation is dropping slowly. The cost of solar PV and batteries is dropping at about 24% per year [8]. The fuel costs of solar and wind are zero so that, solar and wind can outbid coal and gas in the electricity market, resulting in a reduced utility factor and an increased LCOE for coal and gas. In addition, coal plants are not very suitable as load following plants. As a result, it is likely that no new coal plants will be built in Australia. Gas plants can be used as load following plants and can provide the Frequency Control Ancillary Services (FCAS) presently needed to keep the network stable.

Replacing the ageing fossil fuel plants with wind and solar plants is thus an economic option if one considers LCOE alone. Fossil fuel, baseload plants operate at close to a 100% utility factor, while renewable plants have utility factors less than 50%, so that other power sources or energy storage must still be available. Leitch [8] indicates a price of Battery and renewable as $186/MWh in August 2017, that can provide dispatchable power and FCAS and is comparable in price with coal including CCS. The Electricity Network Transformation Roadmap report [4] shows that a 100% renewable energy mix is likely by 2050. The Blueprint for the future report by Finkel [9] suggests that new solar PV and wind generators must include storage or other dispatchable generation. Both reports indicate that massive energy storage is required to provide power all the time.

B. Storage options

There are different ways that energy can be stored:

1) **Batteries.** With the development of Electric Vehicles, the energy density and lifespan of batteries have been increasing while the cost has been decreasing. Larger than 10 MWh sized Li-ion grid batteries are now being installed [10, 11]. The cost of these batteries is falling rapidly.

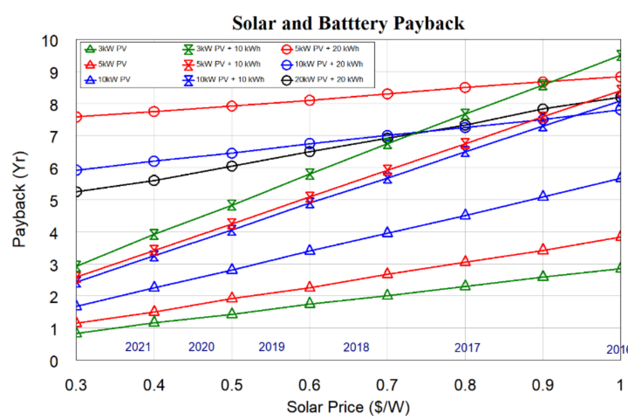

Figure 3. Rooftop solar PV and battery payback time.

Fig. 3 shows the estimated payback period for the author installing solar PV and storage batteries at his residence in Adelaide, South Australia (SA), using quoted prices, a 30 kWh average daily consumption and September 2017 electricity tariffs. Fig. 2 shows that at present the payback period for a 10 kW rooftop solar with a 10 kWh battery system is more than 6 years. At present trends, in 2 years' time, it will be about 4.5 years and in 4 years' time, it will be about 3 years. This implies that there will be a massive uptake in these systems and [4] estimates that by 2035, 70% of residences will have rooftop solar and 50% will have storage batteries. In Queensland, the general supply tariff is lower and the feed-in tariff is higher than in SA. As a result, in Queensland batteries have a payback period larger than their warranty period. The present Australian demand is about 500 GW/day. The Tesla Gigafactory will produce 35 GWh of batteries in 2018 [12]. One-day Australian storage would require 14.5 years of production, which clearly is not realistic, so that other storage capabilities are also needed.

2) **Solar Thermal.** One technique uses parabolic troughs to heat oil to about 400 °C, which then produces steam for a conventional steam turbine. However, many of these systems are plagued by problems and the parabolic trough Solana Generating [13] station has been producing 30% less energy than expected. A simpler technique uses mirrors to focus sunlight on a heat exchanger on a solar power tower. Often the heat is used to heat and store molten salt to 650 °C and use that to drive a conventional steam turbine. Solar Reserve is planning a 2GW / 20 GWh solar thermal power tower plant called Sandstone. They have also been contracted to build a 150 MW / 1 GWh solar thermal power tower plant [7] near Port Augusta, SA, to be completed by 2020. Sundrop tomato farm already has a 39 MW solar thermal power tower plant, at Port Augusta, providing electricity, heating for the glasshouses and power for desalinating water

3) **Pump Storage.** A pump-storage power station, pumps water uphill at time of low wholesale electricity prices and uses the resulting hydropower at times of high-energy prices. Worldwide installed capacity is 140 GW and about 1.4 TWh in storage. The Bath County Pump storage Station is the world's biggest battery [14] at 3GW / 30 GWh capacity. Australia has 1.3 GW pump storage installed in the Shoalhaven, Wivenhoe and Tumut3 stations. Pump storage can be developed using the sea as the lower level. This is being investigated for SA [4].

4) **Heat Storage**. Heat can be stored in water, rocks, molten salt, concrete, ice and so on. The Drake Landing Solar Community in Alberta, Canada [15], has achieved 100% year-round heating with solar thermal energy storage. At James Cook University, in tropical Queensland, a 12.5ML tank is used to cool water at night and then cool the buildings during the daytime. The heat storage is 200 MWh and is driven by a heat pump with a 700% efficiency, thus requiring only 18 MWh of electricity. A 2.5 kL tank raised by 20°C stores 58.5 kWh of energy, which is sufficient to heat the author's house. The power can be provided by a 10 kW solar panel and a heat pump. Heat storage can be used for both heating and cooling.

Endothermic and Exothermic chemical reactions can be used to store energy for very long periods at no loss and use stored summer heat for winter heating. Current trial systems dehydrate and hydrate salt [16], [17] with low losses.

5) **Hydrogen Storage.** Hydrogen has an energy density of 39.4 kWh/kg at 700 bar. When stored in a container in vehicles, this reduces to about 1.8 kWh/kg [18]. Excess renewable or baseload power can be used to produce hydrogen. This can be piped around the country using pipelines. Hydrogen can be converted back to electricity in fuel cells with up to 50% efficiency, or burned in gas power plants at up to 60% efficiency. Hydrogen can be also used for electric vehicles [19], but the resulting 30 - 40% round trip efficiency is much lower than that for batteries. Liquid Ammonia NH_4 is much easier to store and transport than hydrogen and can be used as an LNG replacement. Ammonia is toxic and corrosive. Despite this, it is suitable as a fuel replacement for gas turbines and can be converted to hydrogen for use in cars.

IV. A Reliable Power Network

A reliable power network is one that seldom has blackouts and has sufficient generating capacity on-line to meet the power demand. The present system copes with slow variations in demand by having sufficient "spinning reserve". The stored energy in the rotational inertia of the generators can accommodate sudden load changes. Conventional power generators can provide reactive power and absorb power by acting as a motor if needed. As fossil fuel fired power stations are replaced by solar and wind power, how can the system reliability be maintained?

A. Spinning reserve

"Spinning reserve" is the extra generating capacity that is available by increasing the power output of generators. Traditionally this has been provided by running the generators below their maximum capacity. The required power changes are controlled by the governors on the generators, which keep the output frequency at exactly 50 Hz. Wind generators, can vary the pitch of the blades to produce less power than what is available. The output frequency of the wind turbine is kept at exactly 50 Hz using power electronics. The difference between the available and the actual power is equivalent to the "spinning reserve". By varying the pitch of the blades, the wind turbines can respond to load changes faster than fossil fuel generators.

Advanced inverters can reduce the output from solar PV systems and then adjust the system output up or down as required, to provide "spinning reserve". Most storage systems described above can also be used to provide electrical power to compensate for the load variations. Inverters have ramp rates much faster than fossil fuel generators. Since Batteries and solar panels do not spin, the term "spinning reserve" should be replaced by another term such as "reserve power".

B. Inertia and Reactive Power

Generators have a large inertia. That kinetic energy is available to absorb very fast load changes and keep the system stable, while the governors of the generators compensate for the longer-term variations of those loads. As larger motors are replaced with variable speed drives and as fossil fuel generators are retired, the stored kinetic energy in the power system is reducing. Reactive power is required to control the voltage on the electrical network. Synchronous generators can provide the kinetic energy and reactive power to keep the network stable and operating at the correct voltages, AEMO provides extra payments to generators that can provide Frequency Control and Ancillary services (FCAS) [20]. How can renewable power supplies and storage provide inertia or reactive power?

Wind turbines have significant inertia in their rotating blades. Type 3, 4 and 5 wind turbines can provide reactive power and can use both their inertia and power electronics to vary their output power. They can thus provide FCAS [21]. A trial to demonstrate this is underway at Hornsdale 2 [22].

Many inverters can provide full 4-quadrant power control and thus provide reactive power. Q. C. Zhong [23] showed that, inverters can be designed as a "Synchroverter", to have exactly the same terminal properties as a conventional turbine. The "inertia" provided by inverters is also called "fast frequency response" (FFR) [23] and describes the required function rather than properties of rotating machinery. Such inverters can be placed at the output of any large scale renewable energy system. Solar PV systems can thus provide FACS and FFR. Batteries and inverters are ideal for providing FFR, since their ramp rate is 100% in 5mS [24], if needed, and they can both generate and absorb power. They can also satisfy all the 6 different FACS markets and all the bands up to the rating of the inverter [24].

The state of NSW typically more than 90% of its power provided by synchronous generators. Summers [26] shows that on 10 Feb 2017, a generator trip caused a 7 minute sustained frequency oscillation on the power system. Since the control system transient response on advanced inverters can be designed to have any desired response, having these inverters will be able to provide a better system stability than can be achieved at present.

The System Inertia for SA being below 4 GWs (67 MWh) is of concern of AEMO [24]. A rotating generator or motor has stored kinetic energy of:

$$E_{kinetic} = \frac{1}{2} I\omega^2 = HSb \quad (1)$$

$$P_{inertia} = I\omega \frac{\delta\omega}{\delta t} = \frac{2HSb}{f} \frac{\delta f}{\delta t} = \frac{2.RoCoF.SysInertia(MW.s)}{50Hz} \quad (2)$$

H is the inertia constant, which relates the inertia *I* to *Sb*, the nameplate rating of the generator, *HSb* is the System Inertia in MWs. ω is the rotational speed in rad/s. Differentiating (1) results in (2) which is the power that the generator can provide or absorb using the available kinetic energy. That power is limited by the maximum allowable RoCoF = δf/δt, which typically is 1Hz/s. In addition, it is limited to just above the nameplate power rating. For a typical generator H ranges from 2-10. For a 200 MW generator and H=6 gives a 1.2GWs System Inertia. For the minimum RoCoF=1 [24], applying (2) results in $P_{inertia}$=48 MW. This power can be obtained for 1 second, because then the generator will have reached 49 Hz and may trip under-frequency relays. Four 200 MW conventional generators will thus provide $P_{inertia}$=192 MW and 4.8 GWs System Inertia, which is more than the AEMO 4 GWs [24].

The SA government is installing a 100 MW/100 MWh battery to be operational by the end of 2017 [10]. The inverters of grid-size battery storage systems can provide full power within 5ms [24]. This battery can thus provide $P_{inertia}$=100 MW. Two of these battery systems will thus satisfy the 4 GWs system inertia requirements of AEMO at the 1 second RoCoF rate.

The power that system inertia can provide (2) depends on the RoCoF rate. At present, there is no standard for RoCoF [24]. Generation access requirements are 4 Hz/s for 0.25 s and 1 Hz/s for 1 s. Since the future electricity network [4] will have much more power produced by inverters than synchronous generators, network stability requirements should be specified using technology agnostic terms of fundamental control system parameters, such as damping factors, and resonant frequency. Maximum load or current changes due to faults also need to be specified. "Inertia" should not be used since that applies to a network with synchronous generators only. Inverters can supply a much more flexible transient performance to enhance network stability.

C. *Distributed Energy Resources (DER)*

The Electricity Transformation Roadmap [4] expects 45% of all electricity to be generated by customers in 2050. Those prosumers are likely to be willing to sell their power to the grid if suitable tariffs are in place. It may also be economic for prosumers to charge their batteries from the grid at time of low electricity prices and sell the electricity back at times of high prices, thereby keeping the supply & demand balance of the power network. Having controllable DER available should keep the electricity prices less volatile and improve the power network stability.

Smart meters have been rolled out in Victoria and any new meter installed in Australia after 1 Dec 2017 will be a smart meter as indicated in the Australian Energy Market Commission (AEMC) "Expanding competition in metering and related services rule change" [28]. Smart meters by definition "can transmit data, receive commands, monitor supply and communicate with appliances". This rule [28] requires each retailer to appoint a metering coordinator to provide metering services at a connection point. The minimum services specification for smart meters include: remote disconnection and connection, remote on-demand and scheduled meter reading and a metering installation inquiry. The ability to communicate with appliances for SmartGrid applications and provide controllable DER is not a minimum requirement for the meters being installed. In SA the meter specification includes the capability to provide the same functionality as existing meters, i.e. the timed switching of hot water services. In SA, the minimum daily demand often occurs near midday on sunny days and the water heaters turning on at 11.30 pm often cause the near maximum daily demand. It is more efficient to have DER control for discretionary loads such as water heaters, air conditioners, pool pumps and electric car charging, in order to balance the supply and demand in an optimal manner. The retailer appointing the metering coordinator shows that the prime purpose of the smart meter is only meter reading and not DER control.

The communication system used to read smart meters in Australia depends on what the metering coordinator decides. It is likely that different metering coordinators will use different communication systems. In the Victorian rollout, 2 different radio systems were used depending on the retailer. Having competition may not provide the lowest cost for a smart meter rollout. The average cost per meter in Victoria was $800. In Europe, using PLC, the cost is about $355 per meter. If different retailers have different meters, with different physical layer communications systems, then that may make it more difficult to: 1) implement effective DER control and 2) for customers to change retail providers.

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If 50% of households have battery storage [4], then DER control is essential for network stability [29]. DER control can provide economic benefit to both the prosumer and the network operators. Reposit and AGL's virtual power plant already have systems for this in place, using internet communications. Prosumers with DER control will thus need to have two physical communication systems, one for meter reading and one for DER control. That is inefficient and costly. One physical layer communication system should be used for both meter reading and demand management.

V. Conclusion

For both sustainability and economic reasons, the electricity power sources are changing rapidly from fossil fuel generators to renewable generation and storage. This will result in a lower cost, but more intermittent supply. Economic storage systems are available to overcome this intermittency. New technology agnostic regulations will need to be in place to ensure a smooth transition and not subsidize existing generators or prevent new lower cost generation and storage. DER control is more critical to power network stability and economics than remote meter reading. However, the current Australian smart meter requirements do not reflect that, so that prosumers will require two separate communication networks for their electricity supply.

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