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3 February 2017

Dr Patrick Hodder
Electricity Infrastructure Senate Committee Secretary
PO Box 6100
Parliament House
Canberra ACT 2600
Via email: electricity.infrastructure.sen@aph.gov.au

Dear Dr Hodder,

Submission to The Senate Select Committee into the Resilience of Electricity Infrastructure in a Warming World

Please find enclosed a submission by the Australian National University Energy Change Institute to The Senate Select Committee into the Resilience of Electricity Infrastructure in a Warming World.

The ANU Energy Change Institute combines leading research and teaching on the science, engineering, policy, law, sociology and economics of moving to a sustainable and dominantly renewable energy future. The Institute comprises more than 200 staff and PhD students from all 7 Colleges of the University, and over $100 Million in infrastructure and facilities, supported by a major portfolio of external grant funding.

We hope that this submission is useful in informing your inquiry into the future role of storage technologies in the Australian electricity grid, along with measures to effectively incorporate those technologies into the Australian energy market.

We would welcome to opportunity to meet with members of the committee to discuss our submission further. Please contact Professor Ken Baldwin or Dr Evan Franklin for any queries regarding this submission.

Yours sincerely,

Professor Ken Baldwin,
Energy Change Institute Director

Dr Evan Franklin,
Research School of Engineering
Energy Change Institute

SUBMISSION TO THE SENATE SELECT COMMITTEE INTO THE RESILIENCE OF ELECTRICITY INFRASTRUCTURE IN A WARMING WORLD
BY THE AUSTRALIAN NATIONAL UNIVERSITY ENERGY CHANGE INSTITUTE (ANU ECI)

3 FEBRUARY 2017

Executive Summary

Storage technologies, along with localised, distributed generation, can play a very important role in strengthening the resilience of electricity grids against disturbances occurring as a result of extreme weather events. Resilience, as it relates to interconnected electrical power systems, describes the ability to deliver to customers safe, stable and uninterrupted supply of power in the face of significant external disturbances or perturbations. We consider various different aspects of resilience, and conclude that various storage technologies are able in differing degrees to meet these resilience aspects, provided that they are operated with these objectives in mind.

In our assessment, and based on the status and availability of storage technologies today, we expect a mix of distributed battery storage, pumped hydro and possibly concentrating solar thermal with storage, to contribute significantly to the resilience of electricity infrastructure in Australia in the long term as we make the transition to an electricity system based largely on variable renewable generation:

- Battery storage will provide very fast dynamic primary frequency response, secondary response (or spinning reserve) services, as well as local demand smoothing, and can also facilitate islanded or microgrid operation.
- Pumped hydro technology will be used for provision of inertia, primary frequency response and secondary spinning reserve, medium term (in the order of days) energy balancing, voltage stability and black-start capabilities.
- Concentrating solar power with thermal storage can provide inertia, voltage stability, short to medium term (hours to overnight) energy balancing, as well as some spinning reserve capability and black-start capabilities.

To facilitate the rollout of storage technologies in the Australian market, and in particular to ensure that such technologies are operated in a way that ensures the objective of improved electricity grid resilience, on the basis of the evidence we present, a number of approaches can be considered:

- a market approach to ensure the realisation of the full value proposition of these technologies, including their capability for provision of resilience services
- exposure of both utility-scale and localised distributed storage, to wholesale energy prices so as to provide incentives for servicing peak demand
- moving from 30-minute settlement periods to 5-minute settlement periods to better reflect the real demand peaks and recognise the flexibility and responsiveness that storage technologies are capable of delivering.

We note that centralised utility-scale storage will probably require different treatment compared to distributed storage, owing to the different markets in which they operate. At this early stage of development there is merit in considering demonstration or trial projects for utility-scale storage in Australia to help drive down local costs through learning / experience.

Finally, we recognise the unique position Australia is in when it comes to the challenges associated with high penetration renewables. It is therefore timely to consider making energy storage research a funding priority which would also provide Australia with the opportunity to lead global innovation in renewables integration.

Contents

1 Context and structure of submission

Australia has the potential to be a world leader in the integration of high renewable energy penetration in a large interconnected electricity network. Australia has some of the best wind and solar resources in the world, without the space constraints of many other countries. Australia does not have international electricity connections so will depend on balancing supply and demand locally. The incorporation of considerable amounts of energy storage technologies into the system will thus be critical in allowing this energy balancing to be achieved on all time scales and under conditions of high content of variable renewable energy generation. Wind and solar PV are fast becoming the dominant technologies for new power generation globally (Figure 1 shows global additions of new generation capacity in 2014 and 2015)[1,2,3], and thus any deployed storage technologies will need to operate in the context of high solar PV and wind generation.

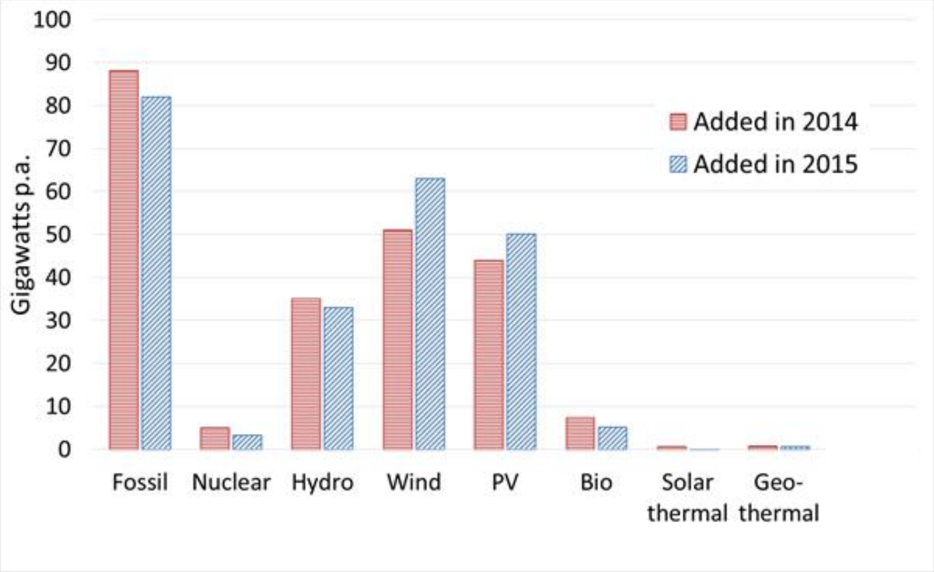

Figure 1. Worldwide power generation capacity additions, 2014 & 2015

Australia's southern and eastern electricity grid, on which the NEM operates, is geographically one of the largest interconnected power grids in the world, stretching from northern Queensland along the eastern seaboard through to South Australia. However, it is a long and skinny grid, with relatively low level of meshing and with only weak interconnects linking each of the five distinct operating regions. As a result, the security and stability of the grid may be considered to be quite weak when compared to many other large interconnected power systems.

The knowledge and skills developed during the transformation towards a high renewable energy power system can position Australia to lead the world in managing variable renewable energy generation and in tackling the challenges associated with ensuring electricity infrastructure resilience in the face of increased extreme weather related events.

Our submission structure follows the terms of reference provided in the invitation to provide a submission.

In Section 2 we provide information on each of the relevant energy storage technologies and localised, distributed generation technologies. For each technology we follow the same structure, first providing a summary of the state-of-the-art, then describing key characteristics of how the

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[1] International Renewable Energy Agency, Renewable capacity statistics 2016. 2016

[2] REN21, Renewables 2016 global status report. 2016, Paris: REN21 Secretariat.

[3] Frankfurt School-UNEP Centre/BNEF, Global trends in renewable energy investment 2015. 2015.

technology interacts with the electricity infrastructure, before providing a 'report card' on how effectively it can address resilience, which for the purpose of this submission we define later in this section.

In Section 3 we respond to the question of what measures might be taken by government to effectively allow the advantages of storage in terms of grid resilience to be realised. This includes a description of the limitations of current market and regulatory settings, discussion of changes that could affect better utilisation of storage technologies for enhancing grid resilience. We comment in particular on how such measures might stimulate demand, create jobs and in which ways this might help position Australia as a leading authority on storage technology deployment.

In Section 4 we discuss briefly some other matters that are related to this inquiry but which do not necessarily fall within the defined scope or terms of reference. This includes a brief outlook on the potential impacts that demand response technologies, increasing electrification of thermal energy services, and electric vehicles may have in future on the resilience of electricity grids.

Finally, we make use of a specific case study in Section 5 to demonstrate the potential benefits of storage in providing resilience. We focus on one aspect of resilience only, and on one aspect only of the system separation event which occurred in South Australia on 28 September 2016.

1.1 Definition of resilience

Central to the committee's inquiry is the concept of *resilience*. Resilience can be taken very broadly to refer to a variety of aspects. However, in framing arguments for the role that storage technologies may play in providing that resilience, a more specific definition is required. In the context of this inquiry, resilience refers to the ability of the electricity infrastructure (generation, transmission, and distribution systems) to maintain uninterrupted supply of power to customers, in the face of inputs or external factors that are changing significantly on either very short to long time scales, and/or to restore that supply in the event of an interruption.

This inquiry requests information about resilience specifically in the scenario of a warming world, and thus we seek where appropriate to consider those changing inputs or external factors related to weather events that have been cited as having association with a changing climate.

For the purposes of our submission we further define resilience to refer to six (6) key aspects of the electricity infrastructure and how it is utilised / operated:

1. **Physical infrastructure asset integrity**
    - Refers to the ability of the physical electricity grid infrastructure, consisting chiefly of power generating plant, transmission and distribution lines (towers and conductors), transmission and distribution cables, substations and transformers, and customer connection hardware, to remain intact and available for operation at all times.

2. **Islanded infrastructure autonomy**
    - Refers to the ability of an 'islanded' section of electricity grid of any nominal size, in the event it becomes isolated from the remainder of the electricity grid, to continue to operate within appropriate power quality standards for an extended period of time until re-connection is achieved (if at all).

3. **Power system dynamic stability**
    - Refers to the ability of the overall power system to stay within bounds of normal stable operation, or otherwise return to operate within these bounds in a specified timeframe, in the face of any feasible or credible change or perturbation in power system conditions. Dynamic stability is typically characterised by system operating

frequency and system voltage angles (and generator rotor angles) being maintained within acceptable bounds and not exhibiting fluctuations in time, and is often referred to as generator stability. In the context of this submission, a system perturbation could occur for example because of the failure of a large transmission system asset or generator or the loss of a large section of customer load as a result of an extreme weather event.

4. **Electricity network (transmission) voltage stability**
    - Refers to the ability of the electricity transmission system to maintain non-fluctuating voltage within acceptable operating limits in the face of any feasible or credible changes to power system conditions. While voltage stability and frequency stability are often linked (and occur together), voltage stability is often referred to as load stability and is chiefly related to changes in load conditions and the subsequent response of voltage management devices and of loads to that changing voltage. In the context of this submission, a perturbation effecting voltage stability might typically be the loss of a large section of load due to failure of critical distribution lines, substation or large customer connection hardware as a result of an extreme weather event.

5. **Electricity network (distribution) voltage and power quality**
    - Refers to the ability of the system to maintain power supply to end customers within the guidelines of the national electricity rules – voltage within limits, and power supplied without excessive harmonic content, power surges or voltage spikes or sags. In the context of this submission this refers primarily to changes brought about by alterations in network configuration due to loss of assets through extreme weather events or for example more directly via transient behaviours occurring because of lightning strikes or flashover associated with distribution network infrastructure.

6. **Power system restoration capability**
    - Refers to the ability of the power system, or a major part of the system, to re-start after a major black event has occurred. Power system restoration, though rarely required, is a complex process since most generators require auxiliary power to re-start, because load and generator behaviour after restoration is not easily predictable and because a number of precise operating conditions must be met prior to reconnection / synchronisation of large regions. We exclude here the far more common scenario where a relatively small load-containing distribution network segment is gradually re-connected with little or no impact on operation of the remainder of the system.

1.2 Other definitions

For the purposes of our submission it is useful and necessary to make a few additional key definitions.

Storage technologies: those technologies capable of storing energy on time-scales from milliseconds up to days, and able to deliver that energy in the form of 50 Hz AC electricity which may be used locally at point of delivery or otherwise may be sent to other users via the electricity infrastructure. We do not for example refer to storage technologies which have local storage for specific purpose loads (e.g. batteries for appliances like laptops, one-directional UPS) or to thermal storage designed for direct local use only and incapable of being transformed into electrical energy.

Localised, distributed generation: we define this to include any generation technology which is connected to the low voltage (LV) or medium voltage (MV) distribution network (typically 415 V, or

11 kV to 33 kV) and which is located in close proximity to load connection points. We make no size or technology definitions, since this is highly dependent upon local conditions, but note that the vast majority of local, distributed generators in Australia now and in future will be small photovoltaic systems (up to for example 10 kW) connected at households and small businesses, small-to-medium sized photovoltaic systems (typically up to 1 MW) connected at commercial and industrial sites, and medium sized photovoltaic systems (for example up to around 20 MW) connected at dedicated stand-alone sites within the distribution networks. Since assessment of resilience is dependent upon technology type, we simplify that assessment by choosing to consider PV systems only, recognising meanwhile that other distributed generation technologies would be assessed differently. We exclude for our purposes those large utility-scale solar and wind generators connected to the transmission or sub-transmission networks.

Electricity networks: this could include the NEM, but also the SWIS, the NWIS and numerous other isolated networks around Australia. Resilience in each case is equally as important and may be as vulnerable to weather events in any case. However, much of the focus of our submission is on the NEM and the SWIS, being large and complex interconnected systems serving a very large customer base. Small grids in contrast often have different design and operational considerations and may also have somewhat different (for example more demanding) requirements for storage. We also do not refer to electricity infrastructure owned by electricity customers or embedded within customer sites beyond the meter point.

1.3 Exclusions from this submission

We feel that it is important to clarify what our submission does not aim to address, but which may indirectly be referred to in the terms of reference or which may otherwise be assumed to be addressed.

An increasing severity and frequency of extreme weather events driven by global warming: Most electricity infrastructure outages, small or large, that are unplanned are a result of weather events, typically high temperatures, bushfires, strong winds, thunderstorms and lightning strikes. We recognise the body of evidence suggesting that we are now experiencing an increase in weather-related outages (see for example Figure 2, which uses data collected from the US Department of Energy[4]) and observe that resilience to such events is likely to become increasingly important. However, for the purpose of this submission alone we do not attempt to comment on whether the need for resilience is increasing as a direct result of global warming itself. Security of supply has always been and remains central to the planning and operation of electric power systems, and storage can play a role in meeting those needs regardless of changes in the severity and frequency.

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[4] US Department of Energy & President's Council of Economic Advisors, Economic benefits of increasing electric grid resilience to weather outages, Executive Office of the President, 2013

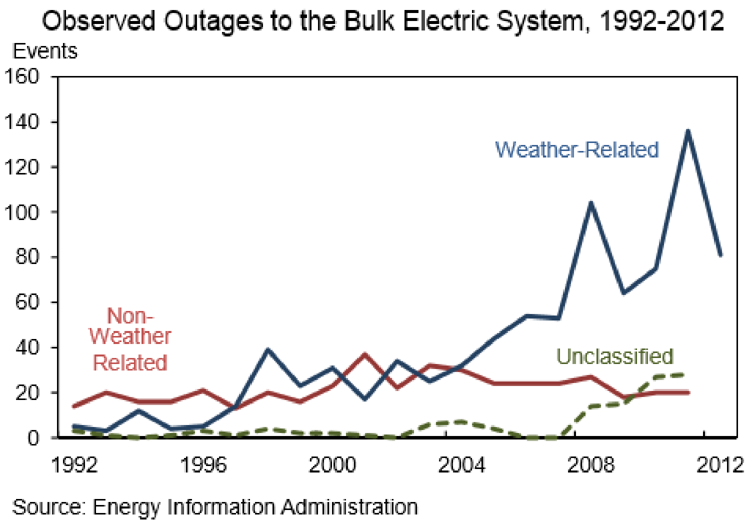

Figure 2. Reported cause of outages in the USA, 1992 – 2012 (source: US DoE)

Infrastructure reinforcement: We do not consider directly in this submission the likelihood that existing or new electricity infrastructure may be built, upgraded or replaced in the face of changing standards and codes that relate to weather conditions (increased wind-loading requirements for example). This is perhaps the most obvious and primary measure that might be considered, and indeed we have listed it as one of the key aspects under our definition of resilience. However, it may be one of the least cost-effective and impractical means for achieving improved resilience in a short timeframe. An extreme example of this may be where infrastructure owners are required in a particular region to replace overhead lines with far more expensive underground cables in order to avoid most or all weather-related outages. Under such a scenario, the advantages of storage in providing resilience in that region will be largely eroded. For the purpose of this submission we do not consider significant physical system strengthening (related to weather events) to be likely to take place, and we therefore frame the advantages of storage in providing resilience in terms of the existing infrastructure.

Infrastructure investment planning process: We also do not attempt to assess the impact that storage and distributed generation technologies may have on the resilience of the infrastructure investment planning and decision-making process itself. However, we recognise that the introduction of a range of storage or distributed generation technologies operated in part for the purposes of providing system resilience would change the norms used to assess infrastructure needs and could thus complicate investment planning, either strengthening or weakening the resilience of that planning process.

Electricity network protection settings: We do not consider in any great detail in this submission the impact that distributed generation and storage resources may have on electricity network protection settings. We do however recognise the complexities that can be associated with incorporation of high penetration of such resources into existing networks, and in turn recognise the relationship between fault detection, fault clearing and ‘resilience’. The addition of distributed energy resources changes the way protection settings may operate and be coordinated. On the one hand, the addition of distributed sources of generation may provide fault current directly to a fault on a distribution networks, thus partially bypassing the protection equipment which would normally be co-ordinated to activate if fault current was supplied only via the transmission network. On the other hand, most types of power electronics interfaced energy and storage systems (PV systems and battery systems for example) are not capable of providing the same level of fault current for the same length of time as traditional generators are, and hence replacement of conventional generators with such devices may limit the ability to act quickly to isolate faults when the occur. We anticipate therefore that power system designers will need to alter protection settings and hardware as the level of distributed energy and storage resources increases, so as to ensure the same level or better of fault detection and clearing.

2 Response to Senate Select Committee Terms of Reference item (a): ‘the role of storage technologies and localised, distributed generation’

Storage technologies, along with localised, distributed generation, can play a very important role in strengthening the resilience of electricity grids against disturbances occurring as a result of extreme weather events. We envisage that a range of different storage technologies, including battery systems, pumped hydro energy storage, concentrating solar power with thermal storage, could each, to differing degrees, address the various aspects of resilience which we have identified. We note that some technologies are able to address certain aspects better than others and we also note that the availability of some technologies to rapidly reach the market also differs.

We summarise briefly the status and state-of-the-art of the each of these technologies, those important features defining their interface with the electricity infrastructure, along with an assessment of their ability to provide resilience against each of the criteria we have defined. Very importantly, we note that many of the resilience support services that these technologies can provide will not be provided by them under current arrangements: each storage system owner will operate in their best interest given the economic and regulatory frameworks in place and as such technologies will not act in the interest of electricity grid resilience unless there is an economic incentive or other requirement to do so.

2.1 Localised, distributed generation

Technology overview and status: Local distributed generation may consist of technologies such as small wind turbines, small concentrating solar thermal plants, diesel or bio-diesel generators, co-generation or tri-generation or fuel cells, but for ease of discussion we largely restrict this section to photovoltaic systems. According to our definition, PV systems dominate all forms of local distributed generation and can be expected to continue to do so into the foreseeable future. Some aspects of PV technology and its interaction with electricity infrastructure will be common for other technologies, although certainly not all. For the remainder of this assessment of localised, distributed generation we consider distributed PV systems, noting that other distributed generation technologies might be assessed differently under some criteria.

Photovoltaic technology is now very well advanced, with energy generation costs being competitive or well below most other forms of electricity generation. PV technology is based on solid-state semiconductor technology, with numerous combinations of solar cell materials still at research and development but with silicon technology being the dominant technology in the market and at the heart of the well-established global PV manufacturing industry. Annual deployment of PV generation now represents over 20% of all new power generation capacity globally[5], with this fraction anticipated to increase for years to come. In Australia much of the uptake to date has been in small, distributed rooftop systems and, despite the sharp increase expected over coming years in utility-scale PV systems, this will continue to be the major PV generation source for some time.

Key Grid Interface Characteristics: The vast majority of localised, distributed generators (all PV systems for example) interface with the electricity grid via power electronics hardware and associated software. The most common example of this is a photovoltaic system, which connects typically to the low voltage or medium voltage distribution network via a DC/AC ‘inverter’. Inverters contain fast switching power electronics circuits, with switching managed by software to control the amount of power flow at each instant in time. The amount of output power is generally determined

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[5] International Renewable Energy Agency, Renewable capacity statistics 2016. 2016

by the input power alone, for example for a PV system the amount of incident solar irradiance, rather than being controlled to any pre-determined or requested output set-point or being altered automatically depending upon electrical power system conditions.

PV generators are capable of outputting both real and reactive power (although reactive power is usually only able to be provided over a limited range, dependent upon inverter type and rating), and the power electronics control software gives them the capability to ramp power output up and down with a response time of milliseconds. There is no reason that PV inverters or other distributed generators could not output less power than the input supplies at a given instant in time, if this was required (Indeed this will become standard procedure under AS4777 for grid-connected PV inverters when very high system frequency indicates excess generation in the system)[6].

Increasingly, PV inverters (and other distributed small generators) are able to communicate with the outside world, usually via some existing, non-dedicated internet communications facility, and thus are in theory able to make decisions based on a number of external factors. Nonetheless, these generators still do not typically alter their output in the face of changing externalities (they just output as much power as the input energy source provides) or sensed conditions.

Resilience Report Card: The table below shows our assessment of the potential impact of localised, distributed generators on electricity infrastructure resilience, according to the six key aspects identified. A commentary on some of these resilience aspects is included below the table.

This assessment is based on the potential for PV systems, and it must be noted that PV systems installed without appropriate technology or operating configuration will or may not be able to deliver on these. It should also be noted that to achieve some of the outlined improvements in resilience will come at a cost to the PV system owner and would require appropriate incentives that currently do not exist.

Resilience Criteria	**Impact of Technology**	**Comments**
Infrastructure Asset Integrity	Neutral	
Islanded Infrastructure Autonomy	Neutral / Positive	Not possible without some battery support, but can support microgrid
Power System Dynamic Stability	Neutral / Positive	Could provide fast frequency response, but with some lost generation; less system inertia req'd.
Transmission Network Voltage Stability	Negative / Neutral	Little scope for voltage response, larger net demand changes.
Distribution Network Voltage & Power Quality	Neutral / Positive	Able to help manage changes on network; but some lost generation
Black-start / Restoration Capability	Negative / Neutral	Not able to; may have displaced other generation capable of doing so.

Localised distributed generators are unable to prevent electricity grid infrastructure damage due to extreme weather events. However, local generation that is naturally located near to loads of similar size will reduce the power flow requirements on large transmission assets, thus rendering the system less vulnerable to the loss of those major assets at times when there is considerable local generation.

Most distributed generators, PV systems for example, are unable to provide any islanded operation or local back-up unless supported by co-located battery system. In an islanded microgrid situation

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[6] Standards Australia, AS4777.2:2015 – Grid connection of energy systems via inverters, 2015

where an alternative generator or a large battery system manages the microgrid, PV systems can however support and contribute to its operation.

Most localised distributed generators such as PV systems have no inertia associated with them and hence if they displace conventional synchronous generators they generally impact negatively on power system dynamic stability because of the consequence of higher rates of change of system frequency after a disturbance. However, since they are connected via a responsive power electronics interface, they could potentially contribute to stability by offering very fast response to changes in frequency. Inverter power output could be rapidly reduced (below the solar input power) to arrest rising system frequency, and similarly in some situations power output could be rapidly increased to arrest falling system frequency. In the latter case of course this would only be possible if the PV inverter output were already curtailed below what it would have been at full output. With appropriate incentives in place, systems could consistently operate at only a few percent below maximum available output and provide sufficient reserve capacity to handle a major power system disturbance.

Localised, distributed generation is generally unable to respond to voltage changes in the transmission network, and local generators such as PV systems, without significant storage are unable to shape net demand. Some studies of voltage stability on the NEM have suggested that reduced stability is likely under a scenario with very high penetration of distributed, uncoordinated PV systems[7].

Localised generators on distribution networks do have the capacity to manage voltage and constraints on that network (though with potentially some loss of generation under some circumstances requiring power curtailment) and should have no major negative consequences for power quality. However, local generators themselves generally will provide no resilience against surges or spikes that may originate at other locations on the network.

2.2 Battery storage

Technology overview and status: Battery storage is based upon the storage of energy in chemical bonds which can be released via chemical reaction and directly converted to electrical energy in a reversible process. The process is enabled by electrochemical ‘cells’ which facilitate the reversible electrochemical reactions to take place at electrodes via an external electrical circuit. All batteries are based upon the same principle, but the electrode materials, electrolyte type and electrochemical cell construction differ markedly.

Formerly the dominant battery technology for energy storage was based on lead-acid technology, while the market is now fast becoming dominated by various lithium-ion chemistries. Lithium cells use lithium ions to transfer energy into and out of electrodes and through the ‘solid’ electrolyte in each half of the electrochemical cell. There are many different lithium-ion battery types, each making use of different electrode materials and electrolyte chemistries and having different characteristics. A few other notable battery types, each at various earlier stage of development or commercialisation, include lithium-sulphur batteries, sodium-ion batteries and flow batteries.

Complete grid-connected battery systems consist of a large number of individual electrochemical cells, packaged into two terminal devices which are then controlled or managed via DC power electronics (the battery management system), before finally being interfaced with the AC electricity grid via an AC/DC power electronics ‘inverter’. The capacity of the battery system to store energy and the maximum rate of charge or discharge depends upon many factors: battery type and chemistry, cell construction and surface technology, and configuration and packaging of the individual cells. These factors in turn influence the ability of the system to be operated to suit the various potential uses.

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[7] Marzooghi et al., Generic Demand Model Considering the Impact of Prosumers for Future Grid Scenario Analysis, Submitted to IEEE, 2016

Battery storage technology is rapidly advancing and costs are declining fast as production increases to meet growing demand from electric vehicles and stationary energy storage applications. However, the cost of batteries for bulk energy storage is still relatively high (compared to both wholesale costs of energy and compared to other forms of bulk energy storage – thermal and hydro in particular). This means that small, behind-the-meter battery systems, the market being driven by retail tariff margins, will dominate over utility-scale battery systems for some time to come.

Key Grid Interface Characteristics: Battery storage systems, regardless of size and technology, are connected to the electricity grid via a similar modern, fast power electronics interface. The power electronics and associated control software determines the direction and amount of power flow at each instant in time, ensuring operation within the limits of the battery hardware itself. The key defining parameters for battery systems, as far as grid interaction is concerned, are the usable stored energy capacity (kWh, MWh), the battery charge or discharge power capacity (kW, MW), the total available system apparent power output (kVA, MVA) and during operation the state of charge of the battery. Battery systems are capable of being dispatched by the power system operator (feasible even for behind-the-meter systems via intermediaries / aggregators) and can be operated as both source and sink of power up to the power rating of the system.

In most instances the power electronics also incorporates other functionality or decision-making such as that associated with co-located PV generation and local load monitoring and decision making such, and can often be referred to as for example a building or home energy management system. Invariably the battery control hardware also contains fast communications with the outside world via a cloud-based interface and usually using some existing internet communications facility. Battery systems are mostly or all capable of interacting with an external aggregator or electricity network operator, at the very least providing information, with most able to receive information and/or settings, requests or even commands that can influence their operation directly or indirectly. Some battery systems, such as those utility-scale systems, are connected with the express purpose of responding to external commands. Others, such as behind-the-meter household or small commercial systems, operate to suit primarily local needs but can sometimes be deployed for wider purposes if incentives them to or if regulations / rules force them to.

Battery systems are capable of outputting both real and reactive power (although reactive power cannot always be provided over the same range as for example a synchronous generator), and are capable of ramping power up and down or reversing power flow with a response time of milliseconds. Communications between an external party and a battery system will in most cases be the limiting factor in terms of response time, and so very fast or automatic response needs to be configured internally in battery system control hardware. Response to changing system frequency or voltage is for example able to be done automatically by sensing these parameters at the terminals of the hardware and by responding accordingly from pre-set or externally controlled set-points.

Resilience Report Card: The table below shows our assessment of the potential impact of battery storage on electricity infrastructure resilience, according to the six key aspects we have identified. A commentary on some of these resilience aspects is included below the table.

The assessment is based on the potential for battery storage to address these aspects, and it must be noted that battery systems installed without appropriate technology or operating configuration will not or may not be able to deliver on these. It should also be noted that to achieve simultaneously each of the outlined improvements in resilience, while also meeting the battery owner's other key criteria (such as PV self-consumption, tariff optimisation), may be difficult to achieve and almost certainly will require appropriate incentives that otherwise do not exist.

Resilience Criteria	Impact of Technology	Comments
Infrastructure Asset Integrity	Neutral	But may be used to remove some or all load from strategic assets before weather event
Islanded Infrastructure Autonomy	Positive	May supply local loads, or support microgrid networks in islanded mode if configured and coordinated
Power System Dynamic Stability	Positive	Provide fast frequency response, still requiring some system inertia. In future may provide virtual inertia.
Transmission Network Voltage Stability	Neutral / Positive	Rapid response to mitigate large changes in load. Some scope to supply reactive dynamic support.
Distribution Network Voltage & Power Quality	Positive	Able to actively manage changes on network; some may be able to provide surge protection for local loads
Black-start / Restoration Capability	Neutral / Positive	Able to initiate start-up without auxiliary power, but more complex owing to widely distributed nature.

Distributed battery systems are of course unable to prevent electricity grid infrastructure damage due to extreme weather events. However, the immediate impact and flow-on effect of major asset failure may be able to be reduced by appropriate deployment of battery resources ahead of time. For example, a major transmission line which is soon expected to be exposed to potentially damaging weather may be able to be partially or fully unloaded by utilising power capacity of distributed battery resources at strategic locations in the network.

Distributed battery systems on distribution networks certainly can provide some robustness in the face of network outages, by sensing loss of grid and then operating in islanded mode. This may take the form of servicing some local loads only (back-up power), or in the case of a coordinated microgrid approach by maintaining supply (usually along with other resources on the same microgrid) to a number of loads on the islanded part of the network.

Owing to the fact that battery systems are connected via a power electronics interface, they contribute no natural inertia to the power system. Thus in the event of a system disturbance the rate of change of frequency, a key driver of dynamic stability, will be larger if power is currently being supplied to the system by battery system. However, battery systems can be made to operate in a frequency response manner (although this is not usually the case) and are also able to respond very quickly (on the millisecond time scale), and thus even in a scenario with far less system inertia they can have a positive impact on dynamic stability. It should be noted that such a response can be achieved by calling upon only a small fraction of a battery system fleet's total capacity. Using for example an estimate of 10 GW / 20 GWh of installed battery storage in the NEM by 2035, a typical major disturbance such as the loss of a 500 MW generating unit or load centre would require just 5% and 0.2% of total power and energy capability to immediately balance the power system while allowing 5 minutes for other, more conventional, balancing solutions to contribute. Although no such technology exists at present it may be possible in future for battery systems to be configured to operate in such a way that they provide 'virtual inertia' and thus can replace the more conventional providers of inertia. However, until such time, battery systems are capable of providing fast dynamic response to system disturbances but there still needs to be present some inertia provided by conventional generators or other inertia providers (pumped hydro or flywheel inertia for example).

Voltage stability on transmission system is a major issue and is mostly related to changes in load and the subsequent response of voltage management devices and of loads to changing voltage. Battery storage can provide fast reactive power support or active power support to assist with voltage stability and has been shown to improve stability in scenarios with high renewables penetration[8]. Reactive power support for voltage stability is less effective for distributed battery systems residing in the low voltage distribution network (i.e. at household level).

2.3 Pumped hydro storage

Technology overview and status: Pumped hydro energy storage is the dominant form of world-wide energy storage because it is an established technology, is cheap and provides a broad range of support services for the electrical grid. Water is pumped up a height difference when there is excess energy generating capacity available (i.e. when it is low cost) and the water is released to generate power when demand (and hence cost) is high. Owing to its comparatively low cost, over 96% of all energy storage installed in global electrical power systems to date have used pumped hydro technology[9].

Australia already has several pumped hydro energy storage facilities in Australia (Tumut 3, Shoalhaven, Wivenhoe) totalling 1500MW. These systems are all small parts of larger systems based on-river. Recent research, meanwhile, has shown that there are numerous excellent sites in Australia for systems which are off-river, requiring relatively small reservoirs (oversize farm dams) at the top and bottom of hills with the water cycling between as supply and demand varies[10]. Abandoned mines may also be used as reservoirs, as per the proposed Kidston mine being developed by Genex.

Pumped hydro plants can be configured in a number of different ways: most plants use a single turbine/pump set and a single electric machine (generator/motor), but some may use a separate turbine and pump with a single machine, or for greatest flexibility but highest cost a separate turbine-generator and pump-motor configuration. Configuration and electric machine type together determine the ability of the plant to offer flexibility in terms of power system operation.

Key Grid Interface Characteristics: The electrical power system interface for a pumped hydro plant is either a direct electro-mechanical coupling using a synchronous machine, or alternatively via a full or partial power electronics interface. A pumped hydro plant would typically be quite large and connected to the transmission system. Pumped hydro plants can typically be dispatched by the power system operator and can be operated as both source and sink of power up to the power rating of the plant.

For direct-coupling approach a synchronous machine operates in the same way (while generating) as does a conventional hydro power generator, and provides a large degree of flexibility. The plant contributes power system inertia and is able to ramp power output up and down quickly (in the order of 1% per second) over the full range. In pumping mode, the plant similarly provides system inertia but is essentially limited to operation at near to full power and hence loses the ability to ramp up and down according to external power system requirements. In either mode of operation, the plant is able to responsively provide reactive power over a wide range in order to regulate transmission system voltage.

For the power electronics interface approach either a synchronous machine or asynchronous machine may be used. The machine in either case is not synchronised with the electrical power system, relying upon power electronics to transfer power between the machine and the electricity grid. With this approach, the plant is not able to provide any inertia to the power system but is able

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[8] Marzooghi et al., Generic Demand Model Considering the Impact of Prosumers for Future Grid Scenario Analysis, Submitted to IEEE, 2016

[9] US Department of Energy, Global Energy Storage Database, 2017

[10] B. Lu et al., 100% Renewable Electricity in Australia, [Submitted], 2017

to quickly ramp the power input/output up or down over the full range in both generating and pumping modes. Reactive power for voltage regulation is possible of a wide or partial range, depending upon the power electronic converter.

A pumped hydro plant with completely separate turbine and pump may use a synchronous generator and an asynchronous motor, thus providing power system inertia, full reactive power capabilities for voltage control, and rapid ramp up and ramp down in either operating mode.

Resilience Report Card: The table below shows our assessment of the potential impact of localised, distributed generators on electricity infrastructure resilience, according to the six key aspects we have identified. A commentary on some of these resilience aspects is included below the table.

The assessment is based largely on the potential for PV systems, and it must be noted that PV systems installed without appropriate technology or operating configuration will or may not be able to deliver on these. It should also be noted that to achieve some of the outlined improvements in resilience will come at a cost to the PV system owner and would require appropriate incentives that otherwise do not exist.

Resilience Criteria	Impact of Technology	Comments
Infrastructure Asset Integrity	Neutral	
Islanded Infrastructure Autonomy	Neutral / Positive	Generator can support islanded section (large size) of grid
Power System Dynamic Stability	Positive	Can provide fast frequency response in both modes of operation; can provide system inertia if synchronous technology, even when idle.
Transmission Network Voltage Stability	Positive	Independent reactive power support and voltage control.
Distribution Network Voltage & Power Quality	Neutral	Does not operate at distribution level
Black-start / Restoration Capability	Positive	First choice candidate if synchronous

Pumped hydro plants are suitable for managing islanded networks, although since plants will typically be quite large this doesn’t provide resilience against islanding of small parts of distribution networks.

Dynamic stability via managing and responding to power system frequency can be suitably provided by pumped hydro plants. Synchronous pumped hydro units have the same generation technology (turbine connected to motor/generator) as conventional synchronous generators (coal, gas and hydro) and provide inertia in both generating and pumping modes (or in synchronous condenser mode when neither is required), thus providing frequency support by reducing the rate of change of frequency after system disturbances. Power can be rapidly ramped for most pumped hydro plant configurations in both modes of operation, with a change from 0-100% power input/output possible in ~1min in generating mode and also in pumping mode for asynchronous units, to provide primary response to frequency deviations and to subsequently restore stable operation.

Synchronous pumped hydro plants provide the full range of reactive power injection for voltage control and stability in an identical manner as conventional generators do. In asynchronous configuration, pumped hydro plants can also provide similar levels of responsive voltage control.

Synchronous pumped hydro systems can provide black start capabilities without requiring additional power generation support. Such systems are thus well-suited to rapid recovery after region-wide black events (such as occurred in the South Australian system in September 2016) with conventional hydro plants typically considered be the generator of choice for initiating system black starts.

2.4 Concentrating solar thermal power with thermal storage

Technology overview and status: Concentrating solar thermal power (CST or CSP) plants with thermal storage involve the use of a large array of mirrors to concentrate sunlight onto a 'receiver' where the energy is collected by heating a fluid; the fluid can be stored and then later, when needed, used to make steam and run a turbine/generator to produce electricity. The particular benefit of CST is that its configuration allows energy storage as an easily and cost-effectively integrated part of the system. Systems with as much as 15 h of storage capacity have been installed (e.g. Gemasolar, Spain and Crescent Dunes, USA), achieving commercial supply of 24-h solar energy for the first time[11].

CST systems can also be hybridised with small amounts fossil or biomass fuels, for higher levels of reliability with minimal redundant equipment, a configuration which may assistant in a reliable migration towards 100% renewables in coming years. CST systems can also be beneficially hybridised with other renewables such as PV[12].

CST with thermal storage systems are distinct from other renewable energy technologies in that, in most cases, they can incorporate storage cost-effectively as an integral part of the plant. Conversely, the integrated nature of thermal storage means that is not able to be easily deployed as standalone storage, without the CST generation component. When storage is added within a CST power plant, the annualised cost of electricity from that system generally decreases rather than increases, as is the case with all other renewable energy generation technologies. We do note however that CST is currently more expensive than PV and wind, and hence the major focus of R&D in this technology is to improve efficiency and reduce cost, while also maximising the value that the integrated storage can provide.

CST plus storage plants are typically utility-scale (100MW+), will mostly be connected to the transmission network, and will usually be located in semi-arid or arid regions typically away from heavily populated coastal centres but able to very effectively serve local, regional loads. We do note, however, that smaller and more distributed CST plants may in future become cost-effective. The dry, sunny Australian environment is highly appropriate for CST technology, having one of the highest average levels of direct (focusable) sunlight in the world.

Key Grid Interface Characteristics: CST plants now primarily use synchronous generators to interface directly to the electrical power system. Since they operate a thermal cycle in much the same way that a modern, conventional thermal power plant does, a CST plant's output operating characteristics (minimum output, start time and ramp rates) are also quite similar. CST plants with storage are typically connected at transmission system level and can be dispatched by the power system operator as a power source only and within ramp constraints.

The use of a synchronous generator means that CST plants automatically provide power system inertia, primary frequency response can be an integral part of operation, and integrated thermal storage facilitates secondary 'spinning reserve' functionality in the same manner as for conventional thermal power plants. Appropriately sized and operated synchronous generator ensures that reactive power can be supplied independently of real power output to regulate voltage.

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[11] E Fitzpatrick, Oct 2013. 'Solar storage plant Gemasolar sets 36-day record for 24/7 output', *RenewEconomy*

[12] Green et al., High capacity factor CSP-PV hybrid systems. *Energy Procedia* **69**:2049–2059, 2015. doi:10.1016/j.egypro.2015.03.218.

Resilience Report Card: The table below shows our assessment of the potential impact of CST storage and generation on electricity infrastructure resilience, according to the six key aspects we have identified. A commentary on some of these resilience aspects is included below the table.

The assessment is based largely on the potential for large utility-scale plants with several hours or thermal storage, but it should be noted that CST plant systems installed without appropriate technology or operating configuration will or may not be able to deliver on these.

Resilience Criteria	**Impact of Technology**	**Comments**
Infrastructure Asset Integrity	Neutral	
Islanded Infrastructure Autonomy	Positive	Generator can support islanded section (large size) of grid
Power System Dynamic Stability	Neutral / Positive	Provides system inertia and can provide moderate speed frequency response.
Transmission Network Voltage Stability	Positive	Independent reactive power support.
Distribution Network Voltage & Power Quality	Neutral	Not connected at distribution level
Black-start / Restoration Capability	Neutral / Positive	Auxiliary power required; may be configured to be suitable

CST plants with storage can manage islanded networks, although plants will be quite large and so no resilience against islanding of small parts of distribution networks can be provided.

Power system stability is positively contributed to by CST plants, with system inertia being provided during operation, automatic governor control for primary response to frequency deviations, and medium to fast ramp and ramp down possible during all times of operation (subject to thermal storage being appropriately managed) to provide secondary response to restore frequency.

Synchronous generators of CST plants with storage can independently control reactive power over a wide range, thus contributing to voltage stability in the same manner as conventional generators.

CST plants with storage could provide the controlled power output that is needed for black start, likely requiring lower levels of auxiliary power when compared to conventional thermal plants and generally being capable of supplying stable, load-matching output during re-energisation.

3 Response to Senate Select Committee Terms of Reference item (b): ‘recommended measures that should be taken by governments’

In our assessment, storage technologies can indeed provide Australia’s electricity infrastructure with improved resilience to withstand extreme weather events, variously addressing many of the key aspects that we have defined. The rollout of these technologies should certainly be encouraged, and done in such a way that allows investors and consumers to choose the technology to best suit their application and needs. However, we wish to point out again here that the take-up of these storage technologies, while addressing automatically some aspects of resilience, will not necessarily guarantee increased resilience where it is required most. This is simply because the details of operation of a given storage system or localised, distributed generator determines whether or not it is able to provide a certain resilience service, and the details of operation are in turn driven primarily by the regulatory and economic environment in which the system operates. A particular storage system for example may be capable of providing system frequency stabilisation, yet without appropriate financial incentive or regulations it will not operate in such a way. Therefore, we recommend not only that rollout of these technologies is encouraged through government actions, but also that appropriate markets and rules are modified or created in order to ensure the necessary resilience capabilities are realised.

3.1 (i) Creating jobs

Developing a new energy system as we transition from centralised fossil fuel generators to renewable will result in billions of dollars of private investment with associated employment opportunities. According to the ABS, annual direct FTE employment in renewable energy activities in Australia stood at 14,020 in 2014-15. This is already higher than the numbers employed in the conventional electricity industry[13]. Continued growth in renewable energy generation, in combination with storage, will be a significant net employer.

We note that some storage technologies are more likely to create more local jobs than others. Of those three resilience-enhancing storage technologies that we have detailed in this submission, we anticipate pumped hydro and CST plus storage to create greater number of local jobs per GW installed, owing chiefly to the fact that battery and power electronics hardware will be predominantly manufactured overseas and imported into Australia for battery systems, although we do note that multiple installations of distributed battery systems will likely create a higher number of jobs than a smaller number of utility-scale battery installations .

While jobs may be created in the energy storage sector in Australia over the coming decades as we transition to a high renewable electricity system, there does not appear to be a macroeconomic driver to focus specifically on job creation in this sector. Job creation is a macroeconomic issue, and may follow naturally from increased sector activity that occurs through other drivers.

We feel it is important to note that Australia is in a unique position to capitalise on our research expertise in renewable energy research and renewables integration. Research and development activities around energy storage are critical, so considering making energy storage research a funding priority area for our research agencies could create opportunities for the development of storage technologies and related industries in Australia, while also providing export opportunities.

3.2 (ii) Stimulating demand

We point out first that stimulating demand for storage technologies is not an end in its own right. Demand for storage should be driven by economic need for the technology, and we see the ***role of***

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[13] Australian Bureau of Statistics, Employment in Renewable Energy Activities, Australia, 2014-15

government in this respect being to ensure that markets appropriately recognize the full value proposition for storage (by, for example, ensuring that the potential role in strengthening electricity infrastructure resilience is able to be ‘priced’ appropriately). Further, NEM regulations should be technology neutral and should not hinder the deployment of storage systems as alternative sources of electricity provision. We recognise that, particularly under current arrangements, policies for centralised, utility-scale storage compared to localised, distributed storage require very different responses.

In this context we do note that the current market frameworks are such that small-scale, behind-the-meter battery systems are an apparently more attractive investment option for householders than other storage technologies. Hence we expect this to be the dominant domestic storage market over the coming years, despite the likelihood that it may not be the most cost-effective or even easiest means of achieving energy and power balancing at a system-wide level with high penetration of renewable generation. This is an example of individual consumer decisions acting independently not necessarily being aligned with the best economic outcome for the public good.

We note also that while battery systems currently being installed in Australia may address some of the resiliency aspects that we have identified, it is highly unlikely (owing largely to lack of clear incentives) that they will address some of the more significant resilience aspects. At the same time we recognise the significant barriers and higher costs for early-entrants into the utility-scale storage market. This is an argument, under appropriate conditions, for government incentives for the initial deployment of large-scale storage in Australia to expedite driving down the cost curve by diminishing the first-mover barrier.

There is also an argument for ***strengthening markets other than energy-only markets so that appropriate price signals can drive investment*** in storage systems that provide the additional services required. This might include allowing the market to determine a price for system inertia and primary governor response (currently provided for free by conventional generators), and for voltage stability services (also provided for free). This could be achieved, for example, in a similar way to the FCAS secondary response / spinning reserve markets, and by allowing markets to operate at the distribution network level.

For decentralised behind-the-meter storage, which amongst the storage technologies plays a unique role at distribution level, policies to increase uptake could parallel policies to enhance rooftop solar, beyond the up-front rebates and enhanced feed-in tariffs which have been used in the past. Examples might include income contingent loans (similar to the successful HECS-HELP scheme for higher education), feed-in tariffs for peak demand periods, establishment of distribution network level markets, and arrangements to encourage rental property participation. Any such measures should be designed to be cost-effective, delivering net value in the overall context (for example, grid security & reliability, investment in renewable generation or avoided grid expansion).

For centralised energy storage, it is likely that the strong learning/experience effects that have been observed in large-scale solar photovoltaics, specific to deployment in Australia, could be replicated for large-scale projects in pumped hydro, solar thermal and (to a lesser extent perhaps) utility-scale battery storage. Consideration could therefore be given to ***funding mechanisms that support early stage trials and pilots of utility-scale storage in the Australian context*** (for example, via ARENA or the CEFC). For any such funding scheme, it would be very important to learn from and avoid the problems experienced under the past Solar Flagships program and to ensure that project completion is assured.

Finally, policy stability and market certainty are key requirements for any large-scale investment in the electricity system in Australia, and long-term, large-scale investment in storage is no exception. It is important therefore that governments act to provide clarity and about future market and policy settings as they relate to the NEM, renewable generation and storage technologies. Current policy uncertainty, and uncertainty about possible future changes to NEM rules, is a strong deterrent to investment, and “waiting” is consequently the dominant investment strategy.

3.3 (iii) Market rule changes

We note at the outset that the terms of reference refer to market rule changes as they relate to deployment of localised distributed generation; the issue of market rules as they relate to storage technologies is broader than this, and likely should include consideration of deployment of large-scale renewable generation in addition to localised generation.

Generally speaking, ***markets should reflect the value of both energy and non-energy ‘services’ via price signals which drive operational behaviour*** and, in turn, investment decisions.

Some non-energy services, such as system inertia or primary frequency response, will likely have quite low real value with the current NEM generation mix, but as scarcity of these service increases (with removal of conventional generators) the value will increase. ***Creating a market structure early during the transition will ensure that generation and storage technologies are able to deliver the service once it is needed***, thus ensuring ongoing stability.

If storage technologies are not able to provide the service at low enough a cost (or, rather, if the value of the required stored energy can achieve a higher price elsewhere), such markets may even support the retention of some conventional generators in the system simply to provide those stability services. The alternative to a market approach, being prescriptive in what stability services must be provided by new entrants, would likely to lead to sub-optimal use of resources.

Stronger links between the wholesale market and retail market need to be made, so that local distributed generation and storage systems are rewarded for providing energy when energy prices are high and incentives are given to storage systems to use energy when prices are low. Additionally, ***NEM settlement periods could be reduced, for example to five minutes, to reward fast response systems*** such as pumped hydro storage or battery systems. The current thirty minute settlement periods results in market participants benefitting from the high prices in one or the six five minute periods while those who contribute to the ‘critical’ five minute period where additional supply is needed (and hence high prices) only receive the lower average price. This reduces the viability of storage to economically meet rapidly changing demand while rewarding incumbent generators which did not respond.

Network costs need to be reflected more appropriately in end-user price structures used for decision making. This would allow distribution level storage or generation systems to operate to address network requirements as well as have consideration for energy market prices and local needs, and would encourage investment in storage in locations where it has highest value.

3.4 (iv) Cost reductions via economies of scale

Cost reductions through economies of scale for storage technologies will not, generally speaking, be driven by any measures specific to Australia. Australia is a very small player in the world energy market and is largely a price-taker when it comes to the key components of storage technologies, such as batteries. Economies of scale benefits will accrue in the Australian context as the global demand for storage technologies increases and the global manufacturing volumes grow accordingly.

However, this is not to say that there are not some local cost reductions that will be come out of increased activity in Australia. For battery storage for example, similar to the situation observed for the PV industry, increased volumes should see improved buying power for imported components, reduced local installation and financing costs. In this respect, ***measures which see the continued growth of battery storage market in Australia will help to build critical mass, experience and increased competition in the supply and installation***, and this should continue to result in local cost reductions.

Likely the most significant cost reductions available for utility-scale storage in Australia, which might be driven by government measures, could be expected to occur as a result of ***support for demonstration and trial utility-scale storage projects***. Successful projects completed on Australian soil result in better understanding of the technology and its performance, better understanding of the local costs, and hence better understanding by banks and investors of the financial risks involved, typically resulting then in internationally more competitive pricing for subsequent projects in Australia of a similar type. Measures for supporting large-scale storage projects, described in our response to ‘stimulating demand’ could, amongst other things, achieve this outcome.

3.5 (v) Global leadership opportunities for Australia

Australia’s long and weakly-interconnected electricity grid, outstanding renewable resources, incumbent energy generation technology mix, and recent rapid deployment of renewable technologies presents as both a significant challenge and also as a major opportunity. The entire world will transition over the coming decades to a renewables-based electrical power system. Australia will experience many of the challenges of high penetration renewables before most electrical power systems and markets around the world do. The opportunity to solve these challenges first in Australia and then export those solutions to other markets is therefore significant.

Australia has been investing significantly to build up a world-class capacity in research and development of distributed photovoltaic generation, concentrating solar thermal power with storage, and more recently in battery storage and renewables integration, largely through project and program funding from ARENA. Australia is well-positioned to lead in these areas and play a major role in the global transition. Meanwhile, numerous companies with world-leading technology are based in Australia because of the opportunities here in storage and integration.

Australia should ***consider supporting R&D and innovation in development of policies, markets and technologies*** which enable storage and distributed generation technologies to address the challenges that will come with high renewables penetration.

4 Response to Senate Select Committee Terms of Reference item (c): 'any other relevant matters'

We mention briefly a few other relevant matters, not directly associated with storage or generation as we have defined it in our submission, but which are nonetheless relevant when it comes to considering how future electrical power systems may operate and how these factors may relate to resilience in the face of extreme weather events. While listed here separately, each of these technologies (which we expect to see taken up significantly in Australia over the coming decades) can essentially be used in a similar manner to provide improved resilience by presenting as a controllable, somewhat schedulable, flexible and responsive load. At local customer level most of these technologies, along with any local battery storage and local generation, will be managed by an integrated energy management system which will in turn interact with the wider electricity system and associated markets.

4.1 Demand response technologies

Loads which can be controlled remotely or locally according to sensed system conditions, potentially with very fast response, may play a similar role to distributed battery storage in addressing some of the resilience factors. Demand response loads may be, depending upon how they are operated and under what incentives or rules they operate, almost as effective at ramping up and ramping down their power input (hence appearing as a net source or sink). They can potentially balance highly-variable generation or other loads, can help to manage distribution network constraints and can also contribute to power system level stability by supplying primary and/or secondary frequency response.

4.2 Electrification of thermal energy services

Increased electrification of thermal loads such as water and space heating will increase the total power system generation requirements. They also represent a form of stored energy which will be used 'later' by the end consumer, and thus are another easily controlled load that can be used to respond to system disturbances in the same way as electricity storage.

4.3 Electric vehicles

The proliferation of electrical vehicles, likely in Australia over the next few decades, will also place additional requirement on the electrical power system (more total energy generation required, and in this case potentially considerably higher peak demand requirements). Electric vehicles will be integrated into the power system en masse as highly-controllable loads, being able to provide many of the same responses as battery systems (in fact the hardware, software and response times and limitations will be very similar to a distributed battery storage system).

5 A “What if?” scenario for South Australian separation event, 28 September 2016

In this section we aim simply to illustrate the potential for storage to provide valuable resilience, by way of a practical case-study exercise. In doing so we gain some quantitative feeling for the impact that certain storage systems and sizes may have in addressing some of the challenges that the power systems may face. We choose as an example the immediate events after the loss of synchronisation, or separation, of the South Australian power system that occurred on 28 September 2016. Note that in this analysis we only look at one single aspect of the system (that is, frequency stability) and we restrict ourselves to the reaction of the system after separation itself. It is not our intention to make any comments related to the events leading up to the separation, or about other aspects of system behaviour. Full details on the black event, as they are reported so far, are contained in AEMO’s third preliminary report[14], which we use as the basis for our analysis.

System separation can occur for a number of reasons, with the inevitable result that one islanded region of the system then contains an excess of generation (supply) over demand and the other contains a deficit. Power system frequency then increases or decreases respectively in each region, with corrective action required within seconds to prevent an entire region blacking out. The rate at which frequency rises or falls depends upon the amount of the supply/demand imbalance and on the amount of rotational inertia (provided by synchronous machines) in each islanded region.

In South Australia immediately after separation on 28 September, total demand (1826 MW) was well in excess of available supply (approximately 829 MW, consisting of 330 MW Gas, 114 MW Murraylink DC interconnect and 385 MW residual wind not lost prior to separation). An exact value for power system inertia in South Australian at the time of separation is not readily available, though it is reasonable to assume that inertia would be close minimum values previously reported (also occurring on days with very high levels of wind generation). We assume a value of 4000 MW.s for system inertia at time of separation, which is the minimum value observed in South Australia between 2012 and 2015[15]. This allows us to calculate a South Australian system-wide initial rate of change of frequency (RoCoF) immediately after separation of 6.2 Hz/sec. We observe that this is consistent with the average value (6.25 Hz/sec) measured across South Australia’s network and reported by AEMO. With no prospect of conventional generators being able to respond adequately (large enough increase in very short time) to appreciably increase supply, the system is reliant on under-frequency load shedding (UFLS) to remove demand before frequency drops below critical values, thereby avoiding a total black event. Limitations of the South Australian ULFS scheme (ULFS schemes in general) mean that it is generally incapable of responding to a RoCoF of greater than 3 Hz/sec, and thus a black event occurred.

We now consider the events under a single scenario, with no changes other than the inclusion of pumped hydro storage and distributed battery system storage. We explicitly assume a mode of operation of these storage systems which acts in the best interest of system resilience, noting again that this is possible but unlikely under the current frameworks (markets, incentives, regulations etc.). We consider a scenario which includes a pumped hydro storage plant with capacity of 150 MW, located in South Australia and operating using synchronous machines, and we assume that it remains connected to the system during the events leading to separation. We also consider 30,000 distributed battery systems installed in households and business around South Australia, with an average power capacity of 5 kW each. We assume, given the very high level of wind generation in the system, that the pumped hydro plant would have been operating to actively store energy, thus creating an additional 150 MW of required supply which we logically assign to additional conventional generators located in South Australia. We make no assumption about the battery systems prior to separation other than that they are neither empty or fully charged and hence are capable of discharging or charging as required. Subsequent to separation,

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[14] AEMO, Black System South Australia 28 September 2016 - Third Preliminary Report, December 2016

[15] ElectraNet and AEMO, Update to renewable energy integration in South Australia, February 2016

we assume the pumped hydro plant remains as a 150 MW load (it is unable to ramp quickly enough for significant change) but that the battery systems are able to respond very quickly to high frequency roll-off and soon after start supplying maximum output. The new conditions after separation consist of the same total net demand (1826 MW) but an increased supply (979 MW, consisting of 330 MW + 150 MW Gas, -150 MW Pumped Hydro, 114 MW Murraylink, 385 MW wind, and 150 MW batteries) and an increased inertia (7600 MW.s, with necessary assumptions on generator type and size). This leads us to calculate a new initial South Australian system-wide frequency drop-off (RoCoF) of 2.8 Hz/sec, now at least within the limits of the UFLS scheme.

We do not wish to assert here that 150 MW of pumped hydro plus 30,000 distributed battery systems would necessarily have prevented the ultimate system black event in South Australia on 28 September 2016. However, we do think it is of value to consider critically the role that a given amount and type of storage might play during such a major system events, provided that the right technologies and operating regimes are encourage and adopted. It is evident that storage, even at relatively modest levels, has the potential at least to improve the resilience of our electricity infrastructure.