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Short-Term Off-River Energy Storage to facilitate a 100% wind & photovoltaics scenario for the South West Interconnected System in Western Australia

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Abstract

In Australia, as renewable energy penetration in electricity markets increases along with closure of fossil fuel power stations at the end of their lives, the need for grid-scale, commercially available energy storage systems intensifies. To ensure a secure and reliable renewable power system, it is critical to deploy sufficient energy storage facilities in a cost-effective way, balancing intermittent energy production from wind & solar PV farms with the varying demand for electricity in real-time.

Short-Term Off-River Energy Storage (STORES) is a new breed of pumped hydro energy storage designed to assimilate short-term fluctuations in power system. Compared with conventional on-river pumped hydro energy storage (PHES) which requires the construction of dams on existing major water systems, no existing natural water body is required for the paired reservoirs for pumping/generation operation, and hence there is no flood control issues and no interaction with the ecology of river system. Moderately-sized pondage (1-10 ha) means low water consumption for initiating and operating the facilities, as well as low land use requirements.

A GIS-based screening study for prospective STORES sites was conducted over the southwest of Western Australia (WA) on the basis of pre-defined search criteria (Table 1). Isolated from the National Electricity Market (NEM), the self-contained South West Interconnected System (SWIS) is a network where STORES systems can be of great value. The GIS searching process was designed as three sequential procedures: sites location, reservoir identification, and potential quantifying (Figure 1). GIS algorithms applied in the screening study showed improvements in productivity in searching process and yielded satisfactory results as required.

The study proceeded to chronological dispatch modelling based on analysing half-hourly wind speed and direction data, gridded hourly solar DNI & GHI data, and half-hourly SWIS electricity demand, together with the results of searching process from the GIS screening study. The research showed STORES has a great potential to be deployed in the southwest of WA especially in the Darling Range area. A dozen prospective sites (Head ≥ 200m) with a total energy potential of 10 GWh were identified (Figure 2). This can provide sufficient storage to smooth short-term fluctuations and support a 100% wind & solar PV scenario for the SWIS network.

1. Introduction

Growing wind and PV generation in Australia leads to a sustained increase in the penetrations of renewable energy in the electricity grids, with 13.47 % of the country's electricity produced from renewable sources in 2014 and over 46% of them coming from intermittent wind and PV generation (Clean Energy Council, 2014). By 2020, this level is expected to be doubled by the reformed Renewable Energy Target (RET) reaching 33 TWh which is about 23.5 % of Australia's annual electricity production (Hunt & Macfarlane, 2015). In fact, all of the proposed new power generation up to 2020 is expected to be renewable power plants amongst which wind energy and large-scale solar PV comprising 84% and 13% respectively (AEMO, 2013b).

At the same time, conventional fossil fuel power stations become progressively de-commissioned at the end of their lives, such as the Delta's 1400 MW Munmorah coal power station which was constructed in the 1960s and closed in July 2012 (Delta electricity, 2012) and more recently, the closure of the Alcoa's 150 MW Anglesea coal plant in August 2015 after 46 years of operation (Alcoa, 2015).

These intensify the need for large-scale, commercially available energy storage systems to be deployed in the electricity grids in a cost-effective way, balancing intermittent energy production from wind & PV farms with the varying demand for electricity in real-time. Indeed, it is expected that the potential commercial market for energy storage devices in Australia could be 3 GW by 2030 (Clean Energy Council, 2014).

With a complete dominance in the energy storage markets around the world, PHES is regarded as the only well-developed, widespread-adopted centralised bulk energy storage technology that is capable of large-scale peak shaving and load shifting, while other technologies such as compressed air energy storage (CAES) remain to be at their early stages of development (Kaplan, 2009). As a matter of fact, in the context of the globally increasing penetrations of intermittent renewable energy sources in power systems, the markets for PHES are witnessing a worldwide resurgence wherever in the U.S. (Federal Energy Regulatory Commission, 2014), Europe (Zuber, 2011), China (Zeng et al., 2013) or India (Sivakumar et al., 2013).

2. PHES studies in Australia

In Australia, nearly all the existing PHES plants were constructed and commissioned in the 1970s and 80s, including the largest three: Tumut 3, 600 MW, 1972; Wivenhoe, 500 MW, 1982; and Shoalhaven, 240 MW, 1977 (Hearps et al., 2014). Opportunities for the construction of new conventional on-river PHES projects are regarded to be extremely limited in Australia. For example in the NEM region, while dozens of potential PHES sites including those retrofits to existing dams were located, all of these sites were not considered to be included in the AEMO 100% renewable modelling due to environmental concerns and the high capital expenditure to build dams on the existing main-stem rivers (AEMO, 2013a).

Instead, seawater PHES located in the mountainous coastal regions utilising oceans as one of the coupled reservoirs is deemed to be an attractive alternative to the conventional PHES. A range of potential coastal regions suitable to build seawater PHES were identified in previous studies, including the coasts along the Eyre and Yorke Peninsulas and the Spencer Gulf region in South Australia (Hearps et al., 2014), the Illawarra Escarpment region in the north of Wollongong (Phillips et al., 2013), the hilly east coasts of Queensland (Winch et al., 2012), the areas adjacent to the Portland Wind Farm in Victoria (Hessami & Bowly, 2011), and the north of Geraldton and east of Albany in WA (Sustainable Energy Now, 2013) etc.

The challenges associated with the deployment of seawater PHES systems in Australia include,

1. The majority of identified prospective coastal cliffs are located in the land use classes of nature conservation or other protected areas (ABARES, 2014);
2. High construction costs related to corrosion resistance against saltwater and environment protection measures (J-Power, 2006) and current Australia-specific costs of seawater PHES projects remain to be uncertain;
3. The lack of adequate cliff-top elevation differences leads to relatively low water heads, which means large volume of reservoirs and substantial land uses will be needed to store sufficient electrical energy as gravitational potential energy of water.

A conceptual model for the short-term off-river pumped hydro energy storage for Australia was built at the Australian National University along with a series of preliminary studies being undertaken since 2010. The greater Canberra and central Tasmania were investigated in 2010 where dozens of potential sites suitable for building Turkey's nest-type PHES reservoirs on large flat lands were identified such as the Araluen Valley (Blakers et al., 2010). Subsequent searching works progressively recognised several prospective locations in the Australian Capital Territory (Piekalns, 2014), Northern Territory (Blakers et al., 2012) and South Australia etc.

It is noted that due to long time prosperity of mining activities in Australia, there are a number of closed or about-to-be-closed mines that are possible to be transformed into PHES systems. A typical example of this is the Genex Power's Kidston PHES project with 330 MW/1.65 GWh which is located in Northern Queensland on the site of the historical Kidston Gold Mine.

3. Short-term off-river pumped hydro energy storage

STORES is a new breed of pumped hydro energy storage designed to assimilate short-term fluctuations in power system (Blakers et al., 2010). It features,

1. Large heads, with storage of only hours or days of turbine capacity with minimum water requirements;
2. Off-river, thus no flood control and potentially little environmental constraints;
3. Proximity to transmission lines being located not far from electricity loads;
4. Relatively low cost compared to the conventional pumped storage with large dams & lakes.

Significantly, STORES can be strategically inserted into electricity grids at a particular geographical location. For example, to directly link it attached to wind & PV farms allows mitigating the curtailment of fluctuating electricity generation and sharing of switchyard, transformer and transmission costs with renewable energy(Bueno & Carta, 2006; WorleyParsons & SKM-MMA, 2011).

Isolated from the National Electricity Market, the self-contained SWIS is a network where STORES systems can be of great value. A large-scale undulating topography in the Darling Range area lying in the east edge of the Swan Coastal Plain creates a wide range of large vertical separations for pumped storage. And remarkably, it coincides with the outstanding wind resources spreading along the coastal regions, and the populated areas of WA, as well as the existing transmission infrastructure in the SWIS network which extends from Kalbarri in the north to Albany in the south and to Kalgoorlie in the east (Australian Energy Regulator, 2009; Geoscience Australia, 2014; The Bureau of Resources and Energy Economics, 2014).

Due to orographic precipitation, the average annual rainfall around the Darling Range exceeds 1000 mm (The Bureau of Meteorology, 2010) and its average annual pan evaporation ranges from 1200 to 1600 mm (The Bureau of Meteorology, 2006). Far more important is its volatile electricity prices with a huge difference between on-peak and off-peak periods such as 5.4583 cents per kWh effective from 1 July 2015 which is more than half of the off-peak electricity charge (Synergy, 2015). This creates a golden opportunity for energy arbitrage of the storage technology.

4. GIS-based searching process

A GIS-based screening study for prospective STORES sites was conducted over the southwest of WA on the basis of pre-defined search criteria (Table 1). The GIS-based searching process was designed as three sequential procedures: sites location (SL), reservoir identification (RI), and potential quantifying (PQ) (Figure 1).

Table 1. Search criteria for locating prospective STORES sites

Criterion	Abbreviation	Threshold/Range
Min electrical energy stored in an individual site, MWh	$E_{p.min}$	100
Min elevation difference between paired reservoirs, m	$D_{v.min}$	200
Max horizontal distance between paired reservoirs, km	$D_{h.max}$	10
Min slope for water pipelines connecting reservoirs, %	$S_{c.min}$	10
Surface area of an individual reservoir or land use, ha	A_s	1 – 10
Dam wall height of Turkey-nest reservoirs, m	H_d	10 – 30
Max Euclidean distance to transmission infrastructure, km	$D_{t.max}$	100
Max Euclidean distance to water source of availability, km	$D_{w.max}$	100
Max Euclidean distance to road transport systems, km	$D_{r.max}$	100

The SL procedure eliminated sites that compete with intensive land uses or conflict with nature conservation and those without considerably undulating terrain to separate pairs of closely-spaced connected reservoirs at a substantially different altitude.

Within this procedure, land use classes related to conservation and natural environments, intensive land uses, irrigated agriculture and plantations were excluded, which means 9 sub-classes were not included in the GIS-based searches: nature conservation, other protected areas, minimal use, urban intensive uses, intensive animal and plant production, rural residential and farm infrastructure, irrigated pastures, irrigated cropping, irrigated horticulture.

Moreover, the regions in close proximity to the high-voltage (HV) transmission network, water availability and existing arterial roads were assigned more priority in order to avoid a large amount of times spent on analysing massive areas of land. Instead of applying the crispy Boolean buffers, the Fuzzy logic was used at this stage to buffer the search criteria $D_{t.max}$,

$D_{w.max}$ and $D_{r.max}$ to the above features, which allowed those potential sites located at the edge not to be overlooked.

The topography undulation test was conducted on the basis of pre-defined search criteria $D_{v.min}$, $D_{h.max}$ and $S_{c.min}$ by the cell-by-cell analysis.

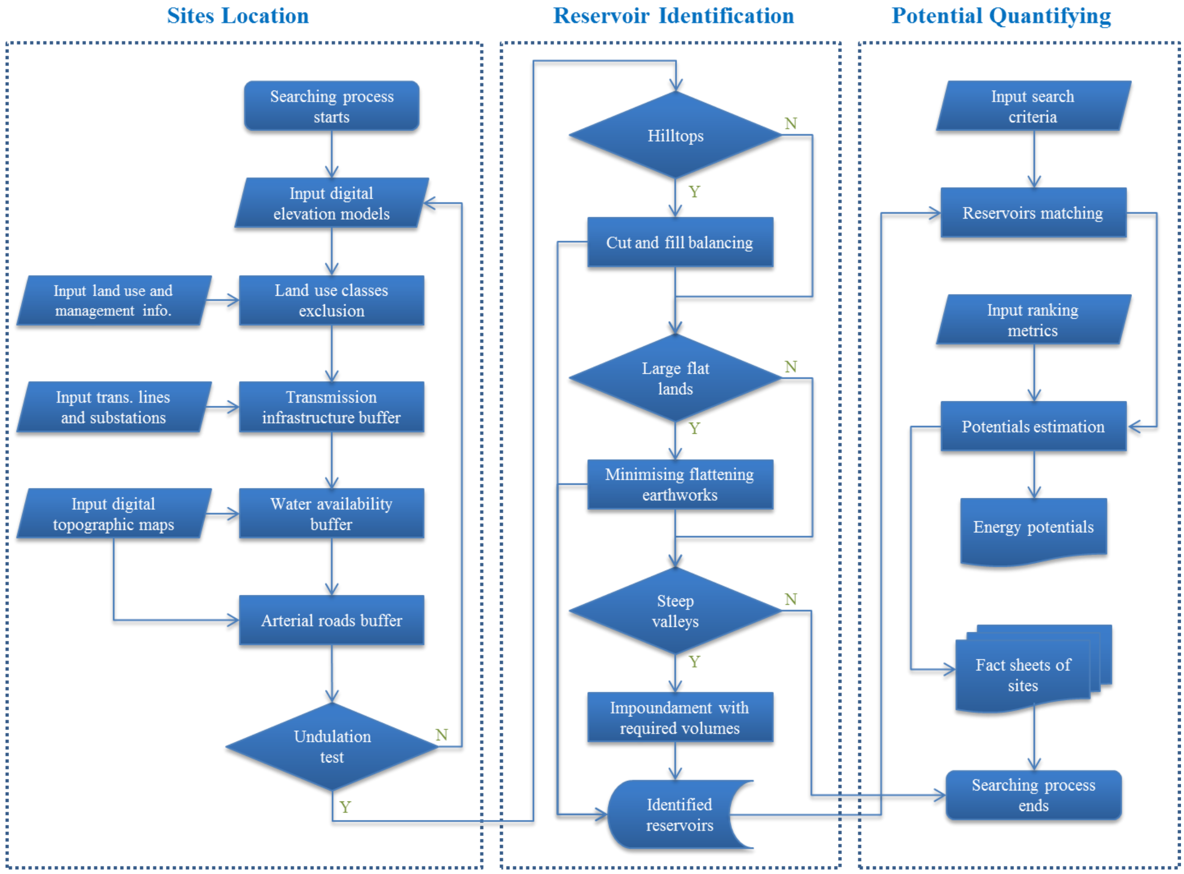

Figure 1. A diagram for the GIS-based searching process

The RI process was to identify specific topographic structures across the lands positioned in the preceding procedure to build prospective STORES reservoirs that can be formed by: a) balancing earthwork cut and fill on hill-tops; b) constructing Turkey-nest dams on large flatlands; and c) impoundments in steep valleys with required volumes. The processes of creating these 3 types of reservoirs were constrained by the pre-defined criteria A_s and H_d.

And finally, the identified prospective reservoirs were matched in the PQ procedure constrained by the pre-defined search criteria $E_{p.min}$, $D_{v.min}$, $D_{h.max}$ and $S_{c.min}$. This procedure was designed to deal with the issues related to estimating energy potentials stored in prospective STORES sites and figuring out the optimal configurations for identified reservoirs in the RI process.

The GIS-based screening study showed that STORES has a great potential to be deployed in the southwest of WA especially in the Darling Range area. A dozen prospective sites (Head ≥ 200m) with a total energy potential of 10 GWh were identified in the study (Figure 2). A typical example comes from the site located near the North Dandalup & Fairbridge boundaries, approximately 3.8 km south from the North Dandalup town and 5.0 km southwest from the North Dandalup Dam (Coordinates: 115.982491 E, 32.552447 S).

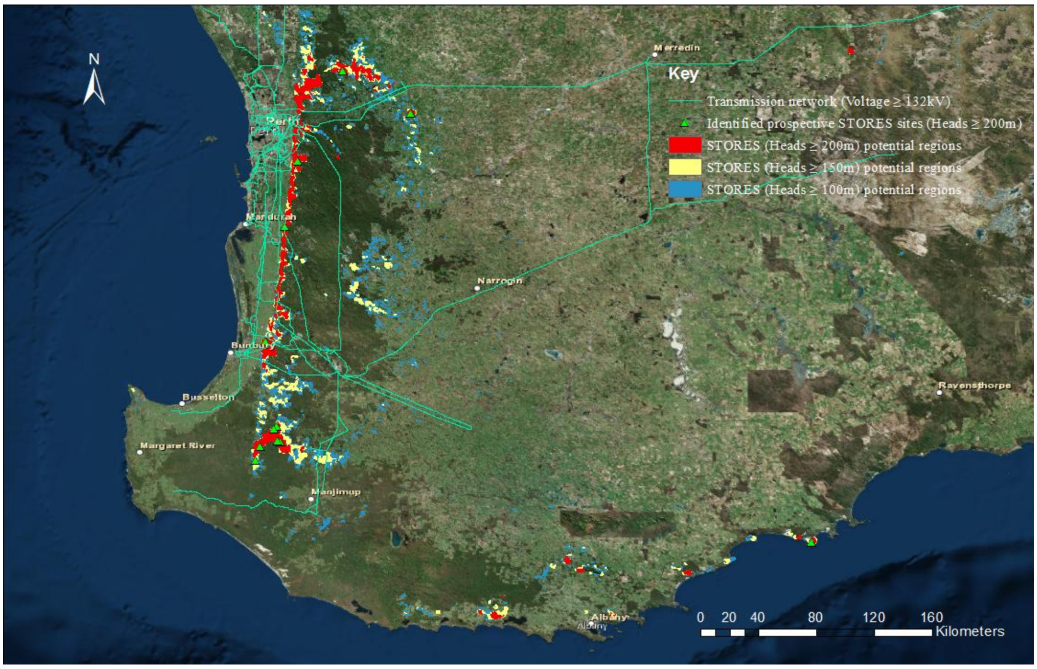

Figure 2. Potential areas for the deployment of STORES in the southwest of WA

5. Grid-integration modelling

Chronological dispatch modelling was to explore the benefits of the integration of STORES system into the hypothetical scenario for the SWIS network and to examine its performances on system reliability and security.

From the high-resolution meteorological data produced by the Bureau of Meteorology (BoM), the hourly 1 MW traces for wind and PV generation within each longitude/latitude grid cell were derived by using the System Advisor Model. As the hourly solar irradiance data DNI & GHI were gridded at a resolution of 0.05 degrees, the 90th percentile solar data was selected out of the 400 pixels (20 rows by 20 columns) within each longitude/latitude grid cell to reflect the exploitation of the best solar resources in that cell. Similarly, the 90th percentile wind data was utilised in the modelling based on the half-hourly wind speed and direction data measured in BoM's weather stations distributed in each cell.

The input and assumptions for the hypothetical scenario modelling are listed as below (Table 2). To test the sensitivity of each input parameter, these baseline figures were allowed to be varied from -20 % to +20 % at an interval of 5 % in the subsequent sensitivity study.

Table 2. Input and assumptions for the scenario modelling

Input parameters	Wind	PV	STORES	Transmission
Capital cost, $/kW	2,000	2,000	$800/kW $70/kWh	$4/kW/km
Operating & maintenance costs, %/year	2	0.7	0	0
Number of active longitude/latitude grid cells, North-Centre-East-South	2-2-0-2	4-2-4-0	0-2-0-1	–
Maximum installed capacity, %	25	25	–	–
Lifetime, years	25	25	50	50
Discount rate/inflation rate, %	10%/2.5%			

In terms of Perth, half of the residential houses including 492,962 separate houses and 74,518 semi-detached, rows or terrace houses, townhouses were assumed to be PV panels-mounted and hence there will be a total electric power of 2.8 GW contributed from their rooftops in the hypothetical scenario.

Based on the characteristics of wind and solar resources in the southwest of WA, together with the STORES sites identified in the GIS-based screening study, and in consideration of system security's requirements, 14 grid cells were decided to be activated for the deployment of wind energy and large-scale solar PV farms, STORES plants, as well as residential rooftop PV. And 3 transmission corridors for the construction of new HV powerlines connecting active cells located in the regions of North, East and South were proposed (Figure 3).

The modelling results showed that pumped storage played a significant role in balancing intermittent energy production from wind & PV farms with the varying demand for electricity in real-time. It assimilated short-term fluctuations in the hypothesized power system to help electrical demands be satisfied by the volatile wind and PV generation (Figure 4). Consequently, pumped storage has enormous potentials to facilitate a 100% wind & PV scenario or a WPS-dominated (wind, PV and STORES) scenario for the SWIS.

The critical weeks of the whole year occurred during the periods when PV generation reduced close to zero and wind power was not enough to support winter evening peaks and pumped storage has been exhausted (Figure 4). However, this can be backed up by using other sources of renewable energy during these critical periods.

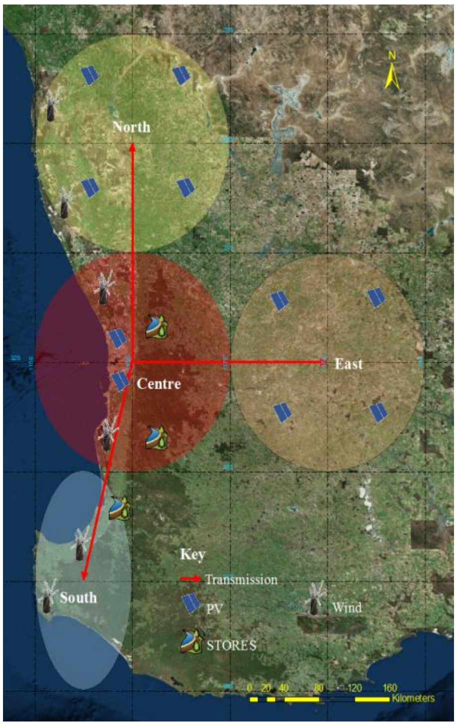

Figure 3. A hypothetical scenario for the SWIS network

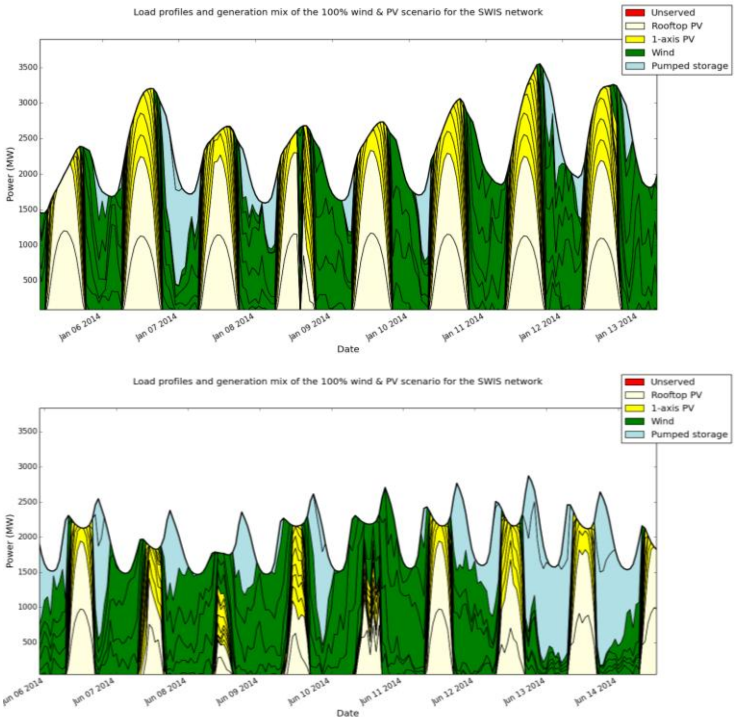

Figure 4. Load profiles and generation mix in two typical weeks of January and July

An alternative solution for these weeks is to use the electricity generation from additional large-scale pumped storage which can be transformed from prospective abandoned mines. A preliminary study on the Kalgoorlie Super Pit demonstrated that by assuming the water surface reaches 360 m of elevation, the Pit is able to impound nearly 200,000 ML of water that can produce tens of GWh-scale electrical energy.

As a further hypothesis, these challenging weeks can be supported by the biomass generation in WA where over 10 million tonnes of waste biomass on average are produced every year (Brooksbank et al., 2014). This can contribute up to 14.2 TWh/yr of electricity by assuming an energy content of 19 GJ/t and a conversion efficiency of 27% (Crawford et al., 2012).

In addition, demand-side participation such as urban thermal storage using rooftop PV and heat pumps is expected to contribute some supports to meet the residual peak demands in those winter evenings.

6. Limitations and suggested future work

Firstly, the study hypothesized a 100% wind & PV scenario by assuming that the wind & PV outputs will follow the trends of weather conditions in the last decade and the electrical loads will be leveling off in the scenario year due to constantly improved energy efficiency being offset by increasing electric vehicles. Consequently the future study needs to integrate long-term wind & PV outputs forecasting models into the system simulation, as well as to assume multiple scenarios of electrical demand for the SWIS network to be analysed.

Secondly, the longitude/latitude grid cells in the regions of North, Centre and South were activated to capture the best renewable energy resources in the southwest of WA and in close proximity to the loads centre. And the eastern 4 cells were exploited to make the deployment of PV farms as distributed in broader geographic locations as possible to mitigate the impacts of incidental weather events. This needs to be further investigated to enhance system security and reliability including the influence of accidental system faults.

Thirdly, more information on the HV transmission corridors and the availability of current transmission framework needs to be collected to generate more accurate models for the construction of new transmission infrastructure. Other suggested future work includes,

1. Broaden the study scope to the whole of Australia to undertake a national-scale analysis of STORES potentials in the populated areas of the country and its roles in facilitating 100% wind & PV powered or WPS-dominated power systems.
2. Integrate a costing model into the GIS-based screening study to allow ranking the prospective sites by cost-related metrics such as a least-cost portfolio or a maximum benefit/cost (B/C) ratio.
3. Investigate water supplement measures to offset the differences between rainfall and evaporation plus leakage within each prospective site such as by enlarging one of the paired reservoirs or by building a supplementary pond nearby to collect sufficient rainwater as a complement to the gaps.
4. Study the availability of other renewable energy resources such as biomass and the closed or about-to-be-closed mines like the Kalgoorlie Super Pit to provide adequate supports to the peak period of winter evenings in those most critical weeks.
5. Undertake a comprehensive analysis of the synergy of energy storage technologies to provide multiple ancillary services such as regulation, spinning and non-spinning reserves, voltage supports to the Australia’s electricity grids (Akhil et al., 2013).
6. Conduct a series of field works in the most promising STORES sites to collect more detailed information about those prospective sites.

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