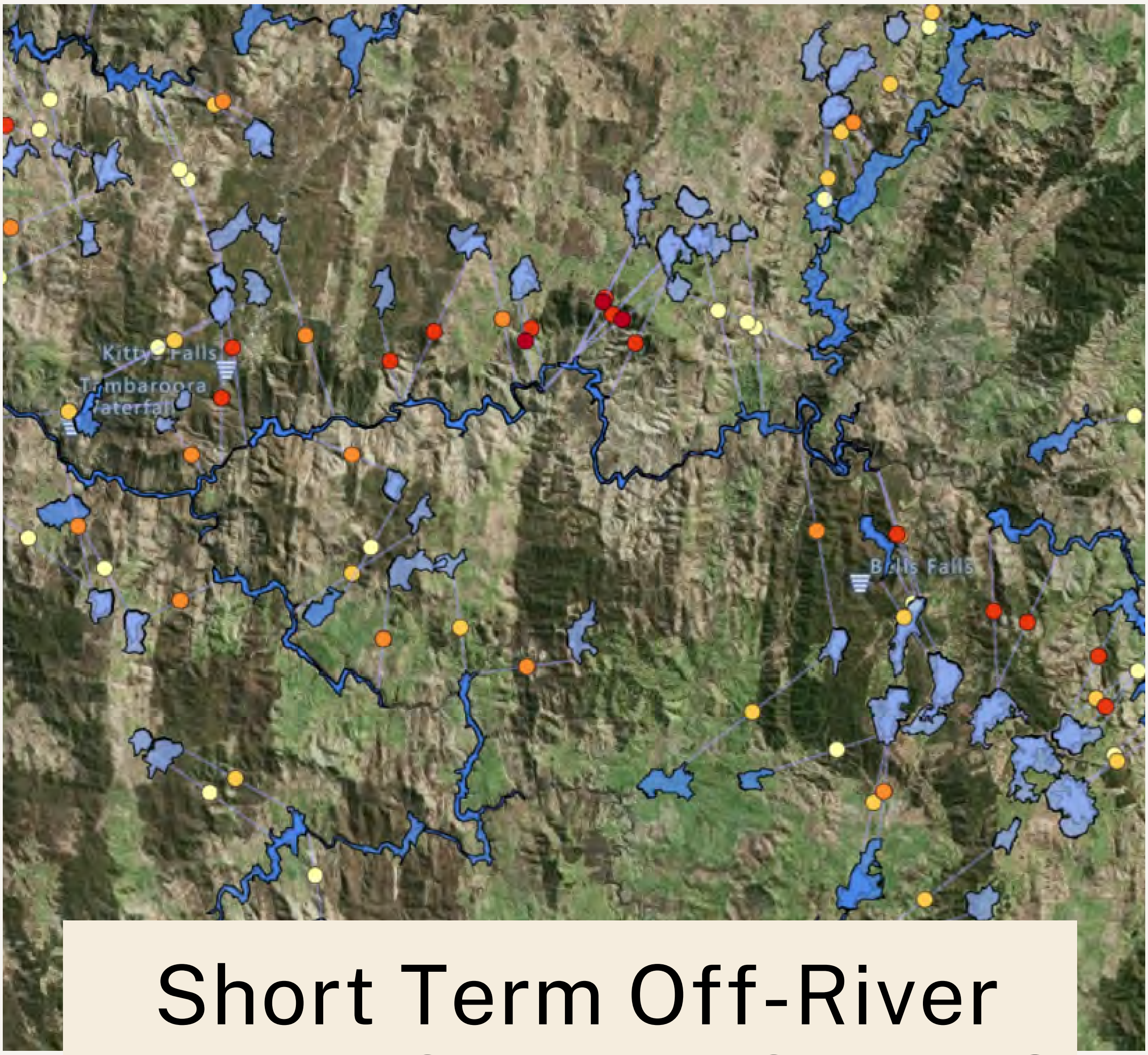

Short Term Off-River Energy Storage Stage 2

Final knowledge sharing report

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re100.eng.anu.edu.au

ABOUT THIS REPORT

Acknowledgements

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Disclaimer

About RE100

The RE100 research group explores renewable electricity and energy consumption, generation, and storage, and is based at the Australian National University.

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The cover image shows the STORES 2 greenfield sites in the area around Orange in NSW, from National Maps https://www.nationalmap.gov.au/#share=s-py9ofDCNEwqsrfGGkptS5dJ9wSq .

TABLE OF CONTENTS

GLOSSARY AND ACRONYMS

ANU	Australian National University
ARENA	Australian Renewable Energy Agency
GIS	Geographic information system
GW	Gigawatt
GWh	Gigawatt hour
Head	The altitudinal difference between the two reservoirs, which determines the energy and power capacity
NEM	National Electricity Market
RE100	100% Renewable Energy group at ANU
PV	Photovoltaics
STORES	Short Term Off-River Energy Storage

EXECUTIVE SUMMARY

Solar and wind have won the race, with global installation rates higher than all other forms of electricity generation combined. These variable technologies need mature, low cost, and safe balancing technology—short time off river energy storage is the perfect match.

Pumped hydro, batteries and demand management are leading the way to balance solar and wind electricity as Australia heads towards 80-90% renewables in 2030.

Pumped hydro energy storage has provided more than 95% of energy storage globally and is particularly well suited to longer periods of energy storage than batteries (e.g., more than eight hours). Australia currently has 1.4 Gigawatts of existing pumped hydro [1–3], and a further ca. 13 Gigawatts of pumped hydro either under construction or announced by Government, including Tumut 3, Wivenhoe, Kangaroo Valley, Snowy 2.0, Kidston, Pioneer-Burdekin, Borumba, Tasmania Battery of the Nation, and announcements by the NSW and Queensland Governments. However, none of them include new dams on rivers [4–10].

Short Term Off-River Energy Storage (STORES) sites are especially well-suited to providing energy balancing for the renewable energy transition, as they can be carefully and conveniently sited with existing electricity infrastructure and away from endangered ecological sites, and are not nearly so large as conventional hydroelectric projects [11].

The purpose of the STORES project was to provide comprehensive details of pumped hydro storage opportunities in Australia.

We found ca. 5,500 good sites, including ca. 4,000 Greenfield sites (requiring two new reservoirs) and ca. 1,500 Bluefield sites (where one of the reservoirs already exists). Each site has 16 metrics including location, cost class, head, and reservoir area.

All the sites are publicly available on the Greenfield and Bluefield atlases, which are accessible via https://re100.anu.edu.au/. These maps can be panned and zoomed to a resolution of 30 metres.

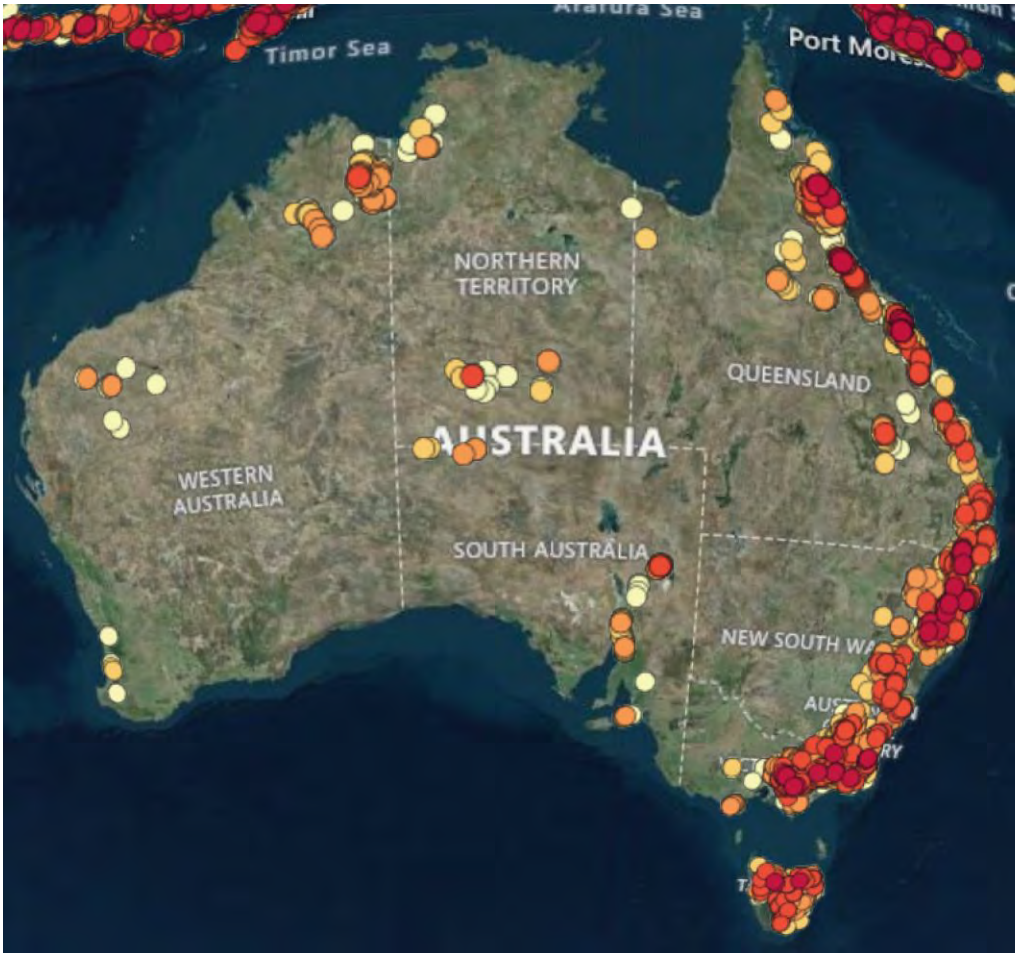

Figure 1: *Thousands of greenfield sites around Australia:* https://re100.anu.edu.au/

The STORES project helps people find potential pumped hydro sites, and reduces the time and cost of pre-feasibility evaluation:

1. Site-search: find thousands of potential pumped hydro energy storage sites in Australia; and
2. Grid balancing: hour-by-hour balancing and cost modelling of the National Electricity Market (NEM) and other regions with high renewable electricity penetration supported by storage. Grid balancing integrates site searching and the cost model with solar, wind and demand data.

The STORES project had a substantial impact on Australian energy policy. While previously there was little appreciation of the great potential of off-river pumped hydro energy storage to support high penetration of variable wind and solar, this is now common knowledge, largely because of our work.

INTRODUCTION

Increases in the cost of energy, the ageing coal generation fleet, and the need to decarbonize our electricity supply whilst scaling up generation for future all-electric homes and industry have led to a huge increase in solar and wind installed in the NEM. STORES is well-suited to providing energy balancing for this generation [12].

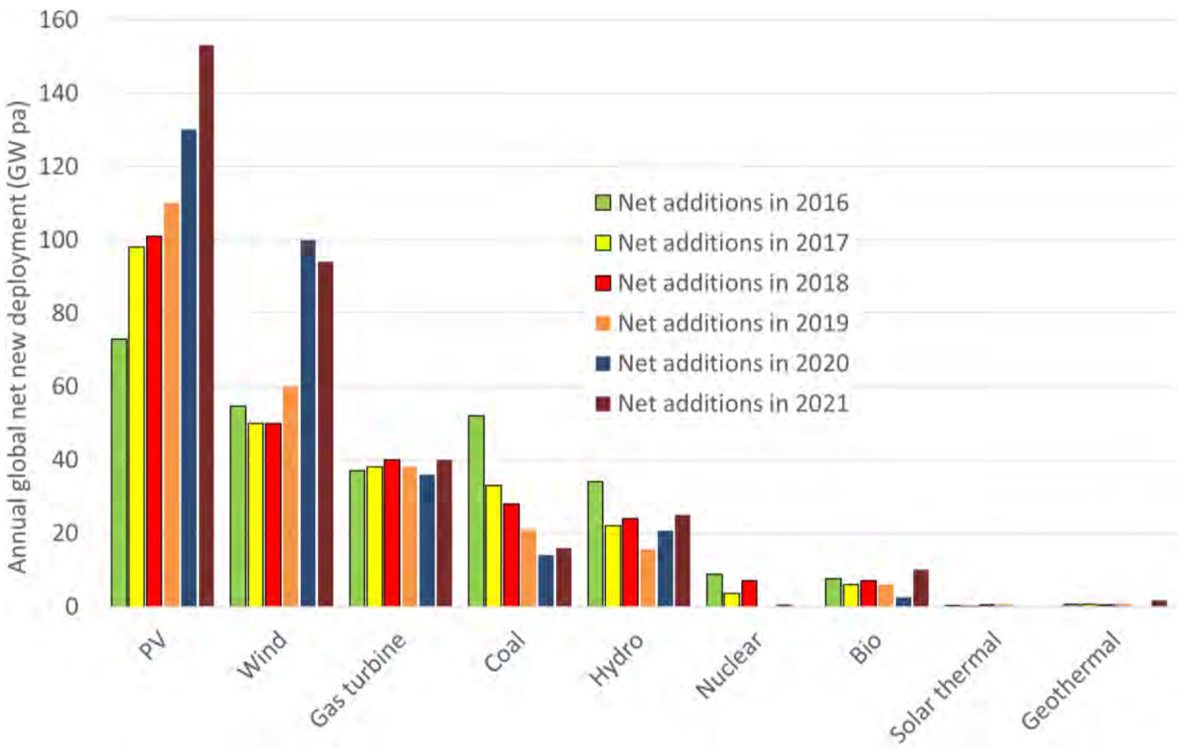

Figure 2: Net global capacity additions by technology for 2016-21[1]

The majority of the global population lives within the sunbelt, where winters are relatively mild, and the solar resource is particularly good. In these conditions, longer term, seasonal electricity storage is not generally needed. Storage with durations of 24 hours is typically sufficient to balance electricity generation and demand within these countries. This can be provided cost effectively through STORES [12].

[1] Sources:
IRENA Capacity Statistics 2020 http://www.irena.org/home/index.aspx?PriMenuID=12&mnu=Pri
Nuclear: http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx
Coal: https://endcoal.org/
Hydropower Status Report: https://www.hydropower.org/
Gas turbines: https://www.turbomachinerymag.com/worldwide-gas-turbine-forecast-2/

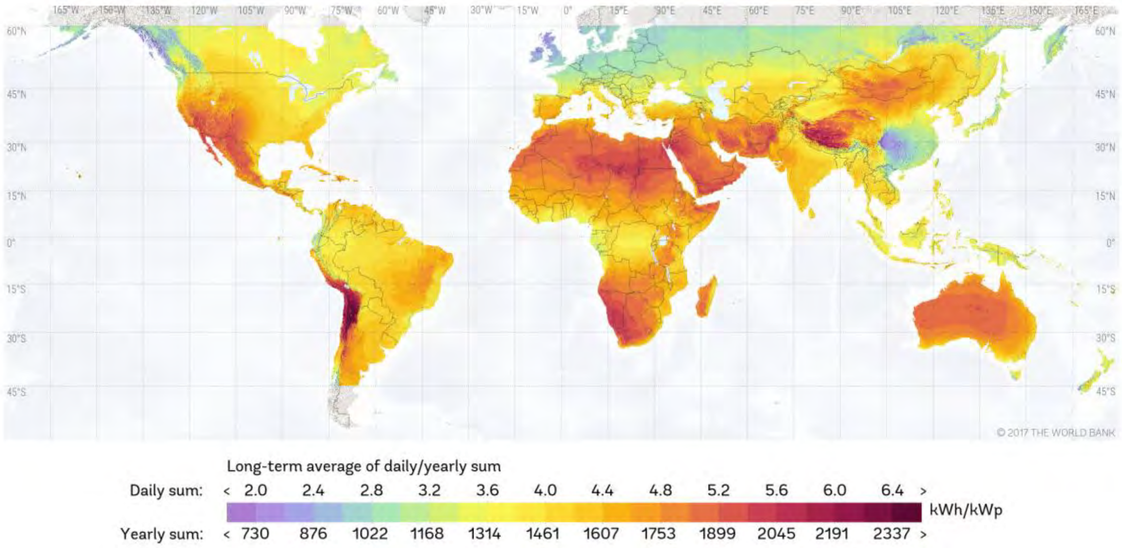

Figure 3: Solar resource is abundant for locations within ±35 degrees. Most of the global population lives within these latitudes. Map from https://globalsolaratlas.info/

A STORES facility consists of two reservoirs that are at different altitudes and connected by pipes or tunnels. Turbines can be used to either generate electricity or pump water back into the upper reservoir. The head, i.e., the altitudinal difference between the reservoirs, is very important as it determines the energy and power cost [11]

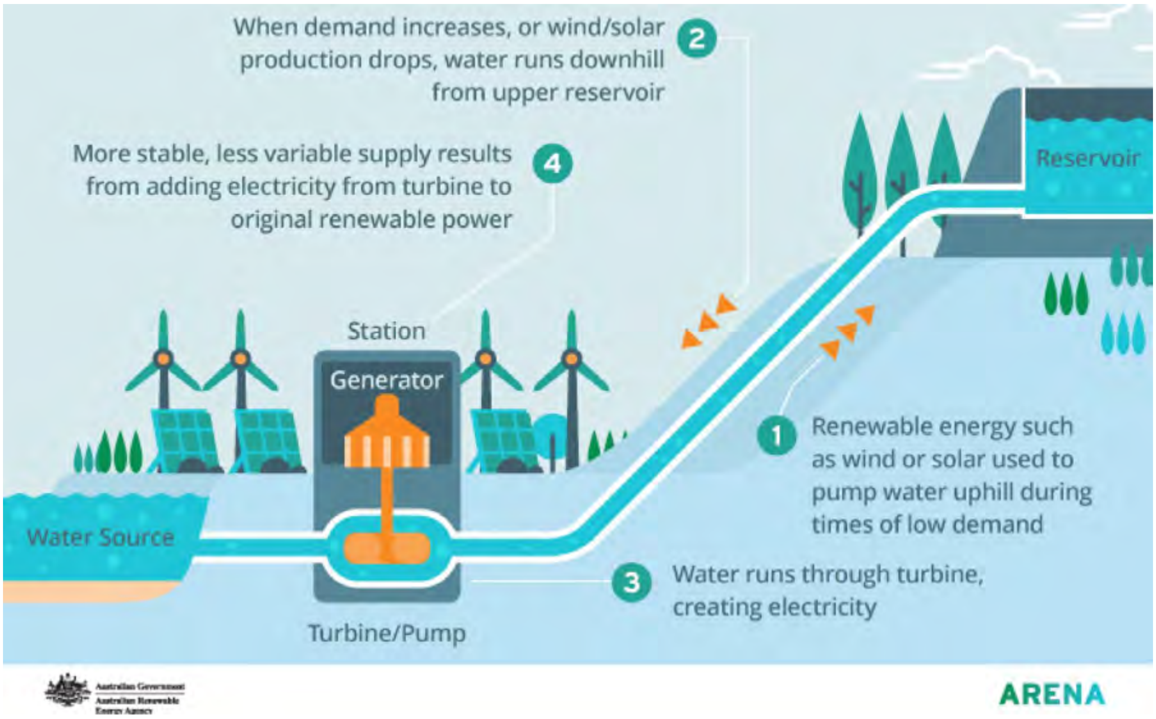

Figure 4: Schematic showing a pumped hydro energy storage system. For this to be a STORES site, the lower reservoir would need to be off-river [13].

STORES sites are distinct from conventional hydroelectric plants in several important aspects. The latter often involve the damming of river valleys, the alienation of huge swathes of land, and movement of people and animals living on this land. Conventional hydroelectric plants can also have lower head than would be possible with a STORES system, e.g., Figure 5 shows the Tumut 3 river-based pumped hydro installation with 151m head, which is located beneath a hilly landscape that could offer heads of more than 600m [11]. Some of these alternatives from the Greenfield Atlas can be seen in Figure 6 below.

The reduced size and increased flexibility in siting STORES sites mean there are many hundreds of thousands of possible locations for these around the world. In contrast, sites for new on-river hydroelectric installations are scarce, and their large environmental impact often precludes their construction [11].

Figure 5: Tumut 3 Power Station, which is within an on-river hydroelectric scheme, image from [11]

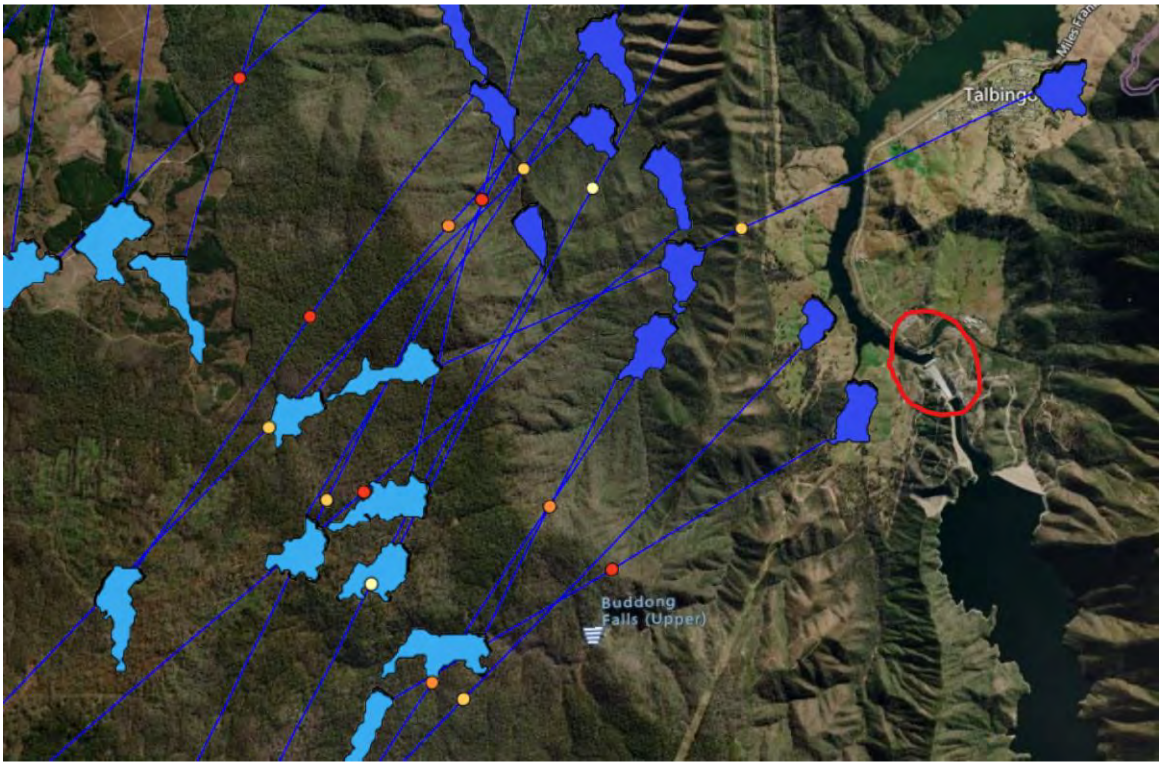

Figure 6: Possible 5GWh 18h sites from the Greenfield Atlas close to Tumut 3 Power station, which is circled in red on the right side of the image. More details can be found here: https://re100.anu.edu.au/#share=g-78ec3497f8d761b8b5a514632f026950

Batteries and longer-term storage options such as STORES facilities play complementary roles in supporting the electricity grid, and it is expected that a fleet of each will be needed to ensure a reliable electricity supply. Batteries provide support for microsecond to minute or hour durations, whereas STORES provide support for hours or days.

However, STORES and the related opportunities are generally poorly understood, because STORES is often associated with conventional hydroelectricity or thought to be scarce. As an example, the *Climate Change 2022: Mitigation of Climate Change* report, published by the Intergovernmental Panel on Climate Change in 2022, stated: "locations for large-scale [pumped hydroelectric storage] plants are limited", which is at odds with the findings in this project [14].

The key objective of the STORES project was therefore to raise awareness of the opportunities of pumped hydro storage and to identify suitable locations for the potential development of STORES sites.

Preparing and publishing the STORES 2 atlases has been an important counter to the idea that opportunities for off-river energy storage have been exhausted. STORES 2 was an extension from the original STORES project, in which the initial site searching algorithm was developed and deployed to find unmatched reservoirs with dam wall heights of 40m.

RESULTS AND DISCUSSION

Methodology

Locations for potential Greenfield STORES sites were discovered by using geographic information system (GIS) techniques to simulate reservoirs in the landscape. Once this initial set of reservoirs was complete, the possible sites were paired by distance and head. The algorithms were improved by moving to a machine compiled language, which sped up the process significantly. Further details of the methodology can be found within *Global atlas of closed-loop pumped hydro energy storage*, which was published to detail the process of creating the Greenfield Atlas [15] The capital cost range is described and quantified in our published paper at https://doi.org/10.1016/j.joule.2020.11.015

The Bluefield Atlas was created by collecting details of existing water bodies, e.g., for Australia the sources included: the Australian Water Resources Information System which is managed by the Bureau of Meteorology, the Australia's Water Storage Information, the ANCOLD Register of Large Dams, the Surface Hydrology dataset from Geoscience Australia, and information from Tasmania Irrigation [16].

The STORES 2 project expanded upon the work completed within the STORES 1 project. In this initial project, 22,000 favourable upper reservoir sites were found using GIS mapping techniques. These were unpaired and limited to heads of 300m and dam wall heights of 40m. Improvements from completing STORES 1 can be seen in the table below.

Table 1: Improvements to features from STORES-1 to STORES-2

Feature	LOW-RES STORES 1	HIGH RESOLUTION (STORES 2)
Search algorithms	Basic	Greatly improved and speeded up
Sites	Upper reservoirs only	Pairing, with matched water volumes
Minimum head	300 metres	100 metres
Brownfield sites	No	Yes: mine pits + existing reservoirs
Dam wall height	40 m (fixed)	Continuous in the range 10-100 m

Water conveyance, transmission, roads	Not considered	GIS calculation of optimum routes
System sizing		Small to large e.g. 2GWh/6h storage to 150GWh/18h
Ranking	A “beta” cost model was developed	Detailed figure of merit based on the beta cost model
Database	-	Searchable database
Visualisation	Google earth	Online access to visualization

The information included for each reservoir pair in the STORES 2 Atlas is listed below.

1. Longitude
2. Latitude
3. Elevation
4. Head
5. Energy storage
6. Water area
7. Average water depth
8. Water volume
9. Approximate conveyance route
10. Shape of the reservoir and dam wall
11. Amount of rock needed for the dam wall
12. Dam length
13. Water-rock ratio
14. Visual aids, such as shape, KML and map files
15. Site estimated capital cost class, i.e. whether the site is class A – E

Key Results

As a result of the STORES project, the following maps have been developed:

- Greenfield atlas – global between 60°N and 56°S
- Bluefield atlas - Australia, Malaysia, Indonesia, the Philippines, Timor-Leste, Nepal, Sikkim, and Bhutan

Hundreds of thousands of possible paired sites around the world with millions of GWh of potential combined storage have been identified. A total of 3996 Greenfield and 1479 Bluefield sites with 215 Terawatt-hours of storage were identified in Australia and can be freely visualised on National Map and the ANU RE100 website.

The Greenfield Atlas (i.e., made up of STORES sites which would require two new reservoirs) has been completed globally. The original release included pairs with the sizes listed in the table below for head up to 800m.

Table 2 The Greenfield Atlas energy storage configurations and the approximate population that these would serve, more details: https://re100.eng.anu.edu.au/global/

	2 GWh	5 GWh	15 GWh	50 GWh	150 GWh	500 GWh	1500 GWh
6 hours	✓	-	-	-	-	-	-
18 hours	-	✓	✓	-	-	-	-
50 hours	-	-	-	✓	✓	-	-
168 hours	-	-	-	-	-	✓	-
504 hours	-	-	-	-	-	-	✓
Millions of people	0.1	0.25	0.75	2.5	7.5	25	75

The Atlas has been further improved, and now contains options with head up to 1600m. This new iteration also expands the energy storage levels to 500 and 1500 GWh.

The Greenfield survey is mounted on the RE100 dedicated mapping server at https://re100.anu.edu.au/#share=g-c25a63fc5df4c61b31e791a445853bcc

The Greenfield survey ignores existing reservoirs since satellite data on the shape of the land cannot see through water. To remedy this, a Bluefield site survey was undertaken, in which one existing reservoir is used and the second reservoir is constructed. Details and the shape of all existing reservoirs in Australia with water capacity over 1 Gigalitre were collected to inform a regional survey (10-20 km around each reservoir) to find possible locations of matching upper or lower reservoir sites (whether existing or potential reservoirs). This Bluefield survey required us to identify the location, shape and useable water volume of each reservoir from public databases. Useable water volume could be much smaller than actual volume.

In total, 1479 possible pairs with a cumulative 37.6 TWh of energy storage were found. Even accounting for overlaps, this represents a large multiple of the required energy storage for a

100% renewable Australian electricity grid. When combined with the greenfield survey, there are many prospective sites at low cost.

The Australian Bluefield survey is mounted on the ANURE100 website at https://re100.eng.anu.edu.au/index.html

A detailed state-by-state report on the Bluefield survey is located at [16].

To date, the Bluefield Atlas has been published for Australia, Malaysia, Indonesia, the Philippines, Timor-Leste, Nepal, Sikkim, and Bhutan, and datasets for other countries are being prepared and will be published soon. This includes all seawater pumped hydro sites, which would use the ocean as a lower reservoir, and required a different cost model due to the harsh saline conditions.

The Atlases have been carefully configured to ensure that protected land, urban sites, and other inappropriate areas have been excluded (although it should be noted that land use information in the datasets that we rely upon is not always accurate nor up to date).

Examples of Bluefield and Greenfield sites can be seen in the images below.

Figure 7: *Bluefield site: Eungella Dam*

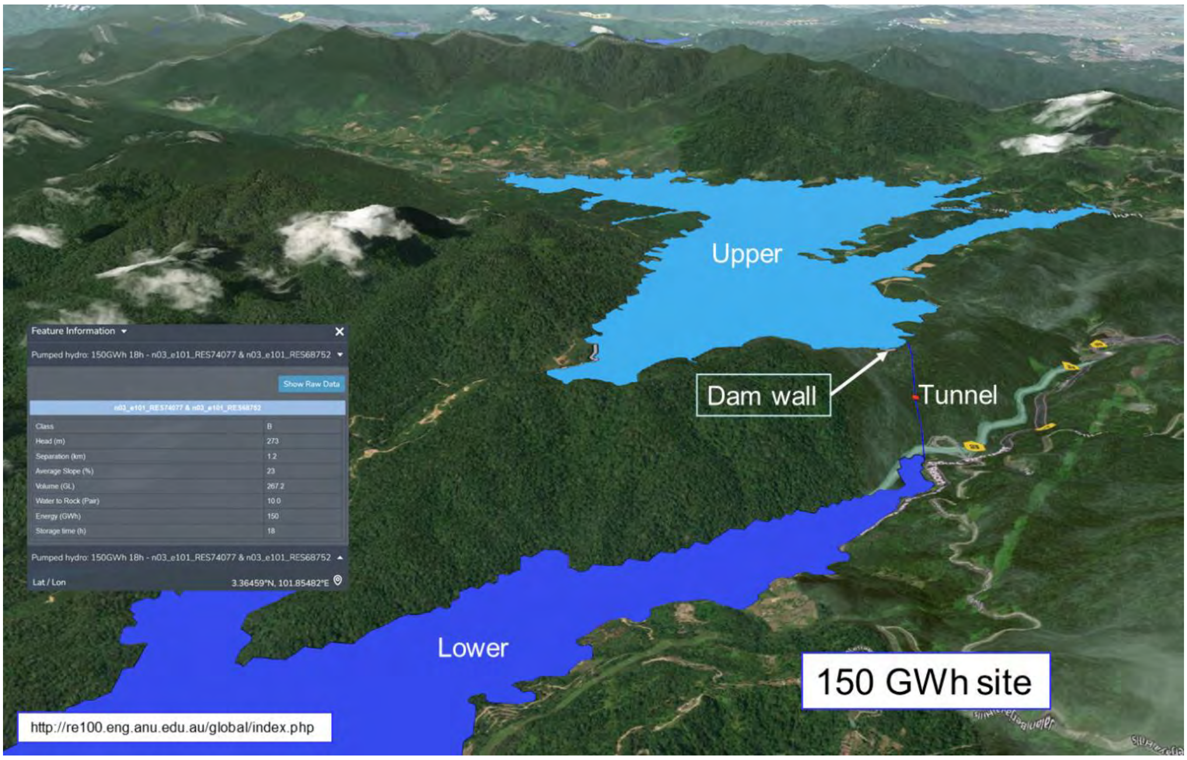

Figure 8: *Greenfield – detail of one of the 616,000 STORES sites we found worldwide including information popup.*

Outcomes and impact on the broader industry

We were very successful in translating outputs from the project into the public arena. Prior to STORES there was little appreciation of the great potential of off-river pumped hydro energy storage to support high penetration of variable wind and solar. Largely because of our work, this is now common knowledge. We created impact and shifted the national energy discourse. Before the atlases were published, it was completely unknown that Australia has 5,500 good sites for pumped hydro that do not require any new dams on rivers. This is about 300 times more than Australia needs to support 100% renewable energy.

The outcomes of the STORES 2 project are expected to strongly contribute to some of the key objectives of the broader energy industry in Australia and around the world.

The STORES 2 project has led to several meetings with Government and business figures to discuss the potential for STORES sites to be built and support the grid as more solar and wind are deployed.

Table 3: Objectives and impact of the STORES 2 project

Objective	Impact of STORES 2 project
Delivering secure and reliable electricity	Substantially reduce barriers to pumped hydro energy storage and thereby support increased deployment of variable wind and solar energy
Exporting renewable energy	Facilitate export of energy-rich materials and the linking of Australia and Indonesia via an HVDC cable by detailed analysis of pumped storage in northern Australia
Reduce the cost of renewable energy	Detailed information about pumped hydro storage to support variable wind and solar PV
Increase in the value of renewable energy	Reduce the effect of variability of wind and PV and support renewable energy zones
Reduction in barriers to renewable energy uptake	Provide comprehensive, ranked, searchable information about storage

CONCLUSION AND NEXT STEPS

The STORES 2 project has been extremely successful. All of the project goals have been completed, and knowledge of the widespread opportunities for new STORES sites has percolated to Government and industry.

The project team have developed their skills with GIS based processes, and have not only further expanded the capabilities of the STORES Atlases, but have also developed a new product – solar photovoltaics and wind heat maps for Australia. These maps incorporate GIS data to determine an approximate cost for a new solar or wind farm within each 1000m by 1000m or 250m by 250m pixel of Australia. All protected and urban areas and native forest remnants are excluded from this search. This information has been welcomed by Government and landholders. More details can be found here: https://re100.eng.anu.edu.au/heatmaps/

The further improvements to the Greenfield Atlas that have now been implemented include increasing the head to 1600m for future iterations of the project, and increasing the energy storage to 500 GWh and 1500 GWh. Further work includes investigating the implementation of aqueducts and longer distances for tunnels.

The global Bluefield Atlas is being prepared and published, as is the global Brownfield Atlas, which would utilise retired mining and other appropriate industrial sites.

Finally, this work has also led to a project in partnership with the Department of Foreign Affairs and EY Singapore, which has centred on knowledge-sharing and upskilling of employees of the largest electricity utility in Malaysia, TNB. This has included information on STORES sites within the country, their integration into the electricity grid, and the use of our Grid Balancing FIRM software to understand the resource availability of solar PV and wind supported by STORES in Malaysia.

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