A GLOBAL ATLAS OF 616,000 PUMPED HYDRO ENERGY STORAGE SITES

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Abstract

As the proportion of wind and solar photovoltaics (PV) in an electrical grid extends into the 30-100% range a combination of additional long-distance high voltage transmission, demand management and storage is required for stability. Pumped Hydro Energy Storage (PHES) constitutes 99% of electrical energy storage worldwide because of its low cost compared with alternatives. We have conducted a comprehensive global search for prospective PHES sites. We found 616,000 potentially feasible PHES sites with storage potential of about 23 million Gigawatt-hours (GWh) by using geographic information system (GIS) analysis. This is around 100 times more than required to support a 100% global renewable electricity system.

Keywords: pumped hydro energy storage, solar, wind energy

1. Introduction

This paper describes a global Atlas of pumped hydro energy storage [ANU, 2019].

Solar photovoltaics (PV) and wind constitute about two thirds of global annual net new capacity additions. Sustained price reductions mean that the PV and wind are competitive with fossil fuel generation in most countries. Thus, the PV/wind share of global generation could rapidly increase. Balancing an electricity system with 30-100% variable PV and wind is straightforward using off-the-shelf techniques comprising stronger interconnection over large areas to smooth out local weather; storage mostly in the form of pumped hydro and batteries; demand management; and occasional spillage of renewable electricity.

By far the leading energy storage technology is pumped hydro energy storage (PHES) [Hydropower 2019; Energy Storage Exchange 2019], which represents about 97% of global storage power (160 GW) and 99% of stored energy. Batteries are rapidly increasing in importance for short term storage (sub-seconds to an hour) and for electric vehicles. A world-scale battery [Liebman et al, 2019] has storage capacity of 0.13 Gigawatt-hours (GWh). As a comparison, the Snowy 2.0 pumped hydro project [Snowy Hydro, 2019] has storage capacity of 350 GWh. The batteries in an electric vehicle fleet represent a very large potential storage.

Most existing PHES is associated with hydroelectric projects on rivers. Vigorous social and environmental opposition is sometimes encountered for new hydroelectric projects, and the number of remaining potential sites is reducing as more hydro is built. However, PHES systems can be closed loop and located away from rivers. Since most of the land surface of Earth is not adjacent to a river, a vastly larger number of potential sites are available for off-river PHES compared with river-based PHES.

Off-river PHES typically comprises a pair of artificial reservoirs (each a few square kilometres in area), located close to each other (separated by a few km) but at different altitudes (200-1200 m altitude difference or “head”) and connected by a pipe or tunnel. Water is pumped uphill on sunny/windy days, and energy is recovered by allowing the stored water to flow back through the turbine. The round-trip efficiency (after accounting for pumping, generation, friction and other losses) is typically 80%. The water oscillates indefinitely between the two reservoirs, with occasional top-ups (to replace evaporation) from rainwater or by artificial means. Evaporation suppressors can be used. A significant advantage of off-river PHES is that minimal provision has to be made for flood control.

An example of an existing off-river pumped hydro energy system is shown in Figure 1.

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Fig. 1: Example off-river pumped hydro energy storage system at Presenzano, Italy. The upper and lower reservoirs are visible and they are connected via a tunnel. The head is 500 m, the water volume is 6 Gigalitres, the power rating is 1000 Megawatts and the combined reservoir area is about 100 hectares. Image: Google Earth.

2. A global Atlas

A recent study by the authors found 616,000 potentially feasible PHES sites with storage potential of about 23 million GWh by using geographic information system (GIS) analysis (Figure 2). Identified sites have energy storage potential in the range 2-150 GWh. The latitude range covered in the survey is between 60 degrees North and 56 degrees South.

Fig. 2: 616,000 potential off-river PHES sites. Detailed zoomable maps and spreadsheets are available [ANU, 2019]. Background: Bing Maps

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Most regions of the world have large numbers of potential pumped hydro energy storage sites nearby (Figure 3). PHES is mature off-the-shelf technology and is much cheaper than alternatives for large-scale energy storage.

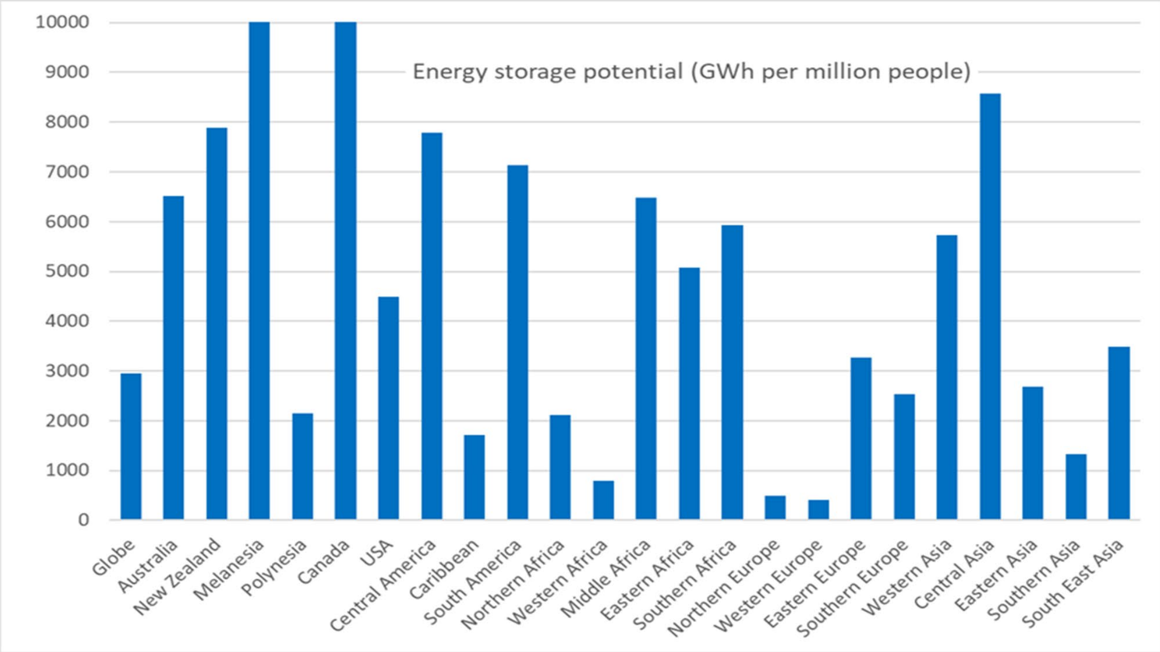

Fig. 3: Energy storage potential (GWh per million people) for global geo region. As a guide, the amount of storage required to support 100% renewable electricity in Australia is about 20 GWh per million people [Blakers et al, 2017]. Most regions have hundreds of times more storage than required to support high levels of variable wind and solar PV.

Potential sites for off-river PHES were identified using GIS algorithms [Lu, 2018] with defined search criteria. The surveyed latitude range is up to 60 degrees north and 56 degrees south. For each reservoir the following attributes are identified:

- Latitude
- Longitude
- Elevation
- Area (hectares)
- Water volume (Gigalitres)
- Length of the dam (in meters)
- Dam wall height (meters) – the maximum height of earth and rock wall; different wall heights will produce different dam and reservoir shapes and volumes
- Volume of rock in the dam wall (Gigalitres) based on a 3:1 upstream and downstream slopes
- Water-to-rock (W/R) ratio: ratio between volume of the stored water and volume of rock in the dam wall; reservoirs with higher water-to-rock ratio are economically more competitive.

For each pair of upper and lower reservoirs the following attributes are identified:

- Head (meters): minimum altitude difference between potential upper and lower reservoirs
- Distance (kms): minimum horizontal distance between potential upper and lower reservoirs
- Slope: ratio between the head and the distance
- The specifications for promising pairs of upper and lower reservoirs are: minimum head is 100m; maximum head is 800m; minimum W/R ratio = 3; minimum reservoir volume = 1 GL (corresponding approximately to 1 GWh of energy storage for 400m head); minimum slope between upper/lower reservoir pairs = 1:20. In this work the identified sites assume earth and rock walls with a maximum height in the range 5-100 m.

Wall heights are adjusted for each reservoir in a pair to yield equal water volumes to achieve the targeted energy storage. Energy (= head * volume *density*g * efficiency) and storage-length combinations are provided in Table 1. The last line is the approximate number of people that the reservoirs could service for a 100% renewable electricity grid [Blakers, 2017].

Tab. 1: Ten energy and storage length combinations are marked with an "x"

	2 GWh	5 GWh	15 GWh	60 GWh	150 GWh
6 hours	x	x	x	x	
18 hours		x	x	x	x
Millions of people	0.1	0.25	0.75	2.5	7.5

Each reservoir pair is ranked A, B, C, D or E according to an approximate cost model. More expensive schemes than rank E are not included. Rank A reservoir pairs would be expected to cost around half that of rank E. Larger systems are generally more cost-effective than smaller systems. The main cost components are:

- Water-to-rock ratio (how much rock must be moved to dam a given volume of water)
- Head (a doubled head for a reservoir pair compared with another similar pair provides doubled stored energy and the power component costs also reduce due to smaller water volumes)
- Slope between the reservoirs: the steeper the slope the shorter is the high-pressure tunnel/pipe. Water conveyances in a pair are the shortest distances between the reservoirs.
- Power: lower power systems are less expensive for a given energy storage volume

The algorithm considers all possible pairs within a region, calculates the best pair according to a cost model, and works downwards in ranking. Each upper reservoir is paired with the best available lower reservoir. This explains why some water conveyances (e.g. a B-class pair) bypass a close reservoir and go to a more distant reservoir (e.g. because the "nearby" reservoir forms part of an A-class pair). Virtually all upper reservoirs are away from rivers ("off-river", closed loop), and none intrude on the national parks or urban areas listed in the databases that we use. However, many of these databases are incomplete.

Visualisation of a site is shown in Figure 4.

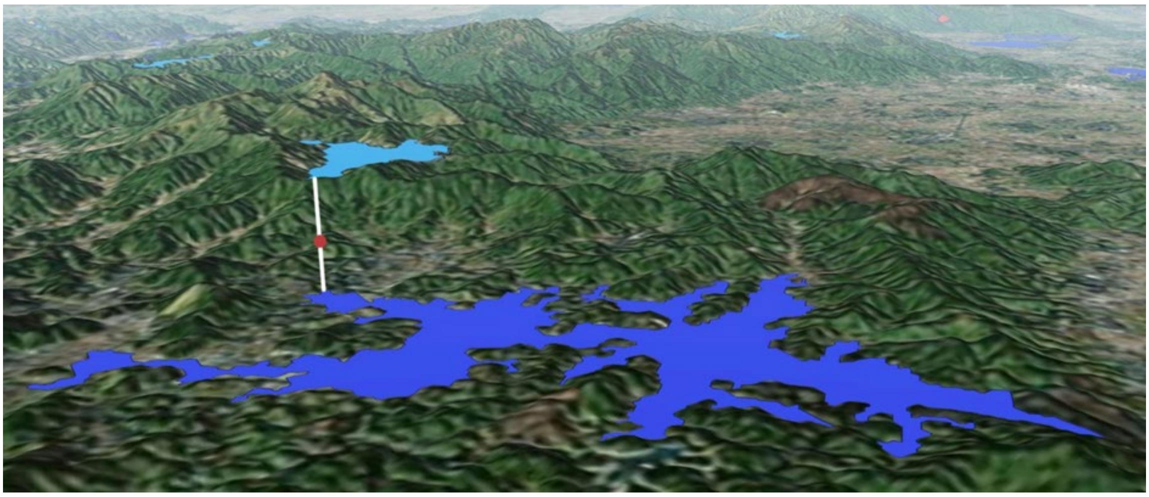

Fig. 4: 3D visualisation of a Class A off-river pumped hydro site in Southern China. Image credit: Data61 hosting and Bing Map background.

3. Land and water use

Legacy fossil fuels coupled with demand management can support and balance an electrical grid with a large proportion of variable renewable energy (solar PV and wind). However, as the renewable fraction approaches

100% then substantial storage is needed. Analysis of Australia showed that about 500 GWh of storage is needed to balance a 100% renewable electricity grid for 25 million people that includes strong interconnection over large areas (to smooth-out local weather) [Blakers et al, 2017]. If the storage is mostly in the form of pumped hydro, then 2-5 km^2 is required per million people for the upper + lower reservoirs. This is much smaller than the area of land required for the corresponding solar and wind energy systems that the storage supports. Most of the identified sites are not near significant rivers. Larger reservoirs (50-150 GWh) are more economical with land than smaller reservoirs.

The water requirements of a renewable electricity system relying on PV, wind, pumped hydro storage and wide-area transmission is far less than for a corresponding coal-based system because cooling towers are not needed for renewables. An initial fill of a pumped hydro system is required, of about 20 Gigalitres per million people (based on analysis for Australia). This water is retained indefinitely in an off-river (closed-loop) pumped hydro system. In some areas annual evaporation exceeds rainfall and the water will need topping-up. Evaporation suppressors can be used. The volume of water required to replace evaporation is a small fraction of agricultural water use and is far less than used in an electricity system based on coal. Pumped hydro can help make better use of existing transmission. For example, if a solar farm is in a region where building more transmission is difficult then it can make the existing transmission work 3-4 times harder by making sure that it is operating at its load limit most of the time (including at night). Many or even most potential pumped hydro sites may prove to be unsuitable. However, fewer than 1% of the identified sites are required to support a 100% renewable electricity grid. Developers and approval authorities can afford to be choosy.

4. Acknowledgments

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5. References

ANU, 2019: http://re100.eng.anu.edu.au/global/index.php

Blakers, A, Lu, B and Stocks, M, 100% renewable electricity in Australia, Energy, Volume 133, 15 August 2017, Pages 471-482, https://www.sciencedirect.com/science/article/pii/S0360544217309568

Hydropower (accessed June 2019) https://www.hydropower.org/status2019

Energy Storage Exchange (accessed June 2019) https://www.energystorageexchange.org/projects/data_visualization

Liebman, A and Khalilpour, KR, https://theconversation.com/explainer-what-can-teslas-giant-south-australian-battery-achieve-80738, 2019

Lu, B, Stocks, M, Blakers, A and Anderson, K, Geographic information system algorithms to locate prospective sites for pumped hydro energy storage, Applied Energy, Volume 222, 15 July 2018, Pages 300-312, https://www.sciencedirect.com/science/article/pii/S0306261918305270

Snowy Hydro, accessed June 2019, https://www.snowyhydro.com.au/our-scheme/snowy20/