An atlas of pumped hydro energy storage

South Australia, Queensland, Tasmania and the Canberra district

Andrew Blakers, Matthew Stocks, Bin Lu, Kirsten Anderson and Anna Nadolny

Australian National University

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Andrew.blakers@anu.edu.au | ph 61 2 6125 5905

matthew.stocks@anu.edu.au | ph 61 2 6125 9876

Australia has many potential sites for pumped hydro energy storage (PHES). In our initial survey of South Australia, Queensland, Tasmania and the Canberra district we have identified about 5,000 potential sites. Each site has an energy storage potential of at least 0.9 Gigawatt hours (GWh), and some have storage potential above 100 GWh.

The sites identified so far have a combined energy storage potential of more than 15,000 GWh, which is 35 times larger than required to support a 100 per cent renewable electricity grid in Australia. Further site searching is underway in NSW, Victoria, Western Australia and the Northern Territory, and will add greatly to this total. We expect eventually to find 70-100 times more sites than needed.

For comparison, the proposed Snowy 2.0 pumped hydro system would have a storage capacity of about 360 GWh. The Tesla battery to be installed in South Australia has a storage capacity of 0.13 GWh. Pumped hydro has a lifetime of 50 years compared with 8-15 years for batteries. About 36 km^2 of lake is required to support a 100% renewable electricity system, which is a small fraction of existing artificial reservoirs.

Virtually all sites are away from rivers, and none intrude on national parks or urban areas. The large number of potential sites provides some confidence that there will be a good number of technically feasible PHES sites. Site searching and development of a PHES cost model are being explored as part of an ARENA funded project.

Website

Data is regularly updated at http://re100.eng.anu.edu.au/research/phes/

Disclaimer

None of the PHES sites discussed in this study have been the subject of geological, hydrological, environmental and other studies, and it is not known whether any particular site would be suitable.

There has been no investigation of land tenure apart from exclusion of national parks and urban areas, and no discussions with land owners and managers. Nothing in this list of potential site locations implies any rights for development of these locations.

The commercial feasibility of developing these sites is unknown. As with all major engineering projects, diligent attention to quality assurance would be required for safety and efficacy.

Background

As the proportion of wind and solar photovoltaics (PV) extends into the 50-100% range over the next decade, a combination of additional interstate high voltage transmission, demand management and local storage is required to stabilise the grid [1]. Pumped Hydro Energy Storage (PHES) constitutes 97% of electricity storage worldwide and is the subject of this report. Batteries are also likely to contribute substantially to local storage.

PHES entails using surplus electricity (for example, on windy/sunny days or during off-peak periods) to pump water from a lower reservoir to an upper reservoir through a pipe or tunnel. Later, the stored water can be released through a turbine to recover most of the stored energy. Australia already has three river-based PHES facilities at Wivenhoe in Queensland, at Kangaroo Valley in NSW and Tumut 3 in the Snowy Mountains (the site of the proposed Snowy 2.0 PHES scheme).

Off-river PHES opportunities are far more prevalent than river-based sites because most of the Australian landmass is not near a river. Unlike conventional "on-river" hydro power, off-river (closed loop) PHES requires pairs of reservoirs that are generally 10-100 hectares in size, rather like oversized farm dams, located away from rivers, urban areas and national parks in hilly country. These sites are separated by an altitude difference (head) of 200-900 metres. Water cycles in a closed loop between the upper and lower reservoirs. Energy storage volume (i.e. reservoir size) is typically sufficient for 5-20 hours at maximum power.

The sites identified in this study are at least 300 m above nearby lower elevations where the lower reservoirs would be located (i.e. minimum "head" of 300 m). Most are dry gullies near mountain tops. "Turkey nest" reservoirs on flat land and deep open cut mining pits are also identified.

Most of the sites are conveniently located near the coastal backbone transmission system that spans Queensland, NSW, Victoria and South Australia (with connection to Tasmania by undersea cable).

The large number of upper storage sites identified provides some confidence that there will be a sufficient number of feasible PHES for very large-scale storage. Each site requires extensive investigation to determine its suitability. The occurrence of cyclones, storms and floods means that reservoirs must be constructed to a high standard. However, if a site is problematical then alternative sites are likely to be available nearby.

Summary spreadsheet

A spreadsheet is included listing characteristics of all of the sites identified in this work. This spreadsheet contains only basic information relating to each potential site.

Matched lower reservoirs are not included at this stage.

The head is assumed to be 400 m in most cases to allow a ballpark estimate of potential energy storage.

PHES sites by state

Site searching is in progress, with the following interim results. Details are located at http://re100.eng.anu.edu.au/research/phes/

South Australia

We have identified 185 potential sites with a combined energy storage capacity which is about 10 times more than required to support a 100% renewable electricity system in the state. South Australia is less hilly and has fewer opportunities than other regions.

Queensland

We have identified 2,213 potential sites with a combined energy storage capacity which is about 100 times more than required to support a 100% renewable electricity system in the state.

ACT and surrounding districts

We have identified 871 potential sites with a combined energy storage capacity which is about 200 times more than required to support a 100% renewable electricity system in the region.

Using Cotter Dam as a lower reservoir means that heads are small (~100 m), and may not be economically competitive. Naas offers heads of 300 m and is the most attractive region of the ACT for PHES. Corin Forest is another potential site, but will probably be unsuitable for several reasons.

Connection of Bendora and Cotter reservoirs offers a head of abut 240 m. A 14 km long tunnel/pipe would be required, and the volume of Bendora is a modest 12 Gigalitres (GL). For comparison, the Snowy 2.0 proposal entails a 25-30 km long tunnel between Tantangara and Talbingo reservoirs, and an attractive head of 650 m. Tantangera can store 254 GL (about 21 times more than Bendora).

Connection of Corin and Tantangara reservoirs entails a 25 km long tunnel and a head of 250 m, and is not attractive.

Nearby NSW has many more attractive greenfield PHES sites than does the ACT. Heads of 400-600 m are commonly available in nearby NSW. The Araluen Valley offers outstanding opportunities for off-river PHES: heads of up to 600 m, and a short steep pressure pipeline.

Tasmania

We have identified 2075 potential sites. Tasmania already has large water storages, several of which are suitable for pumped hydro energy storage. The large number of upper storage sites identified in this work provides confidence that there will be a sufficient number of feasible PHES for very large-scale storage.

Alice Springs district

We have identified 384 potential sites with a combined energy storage capacity which is about 1000 times more than required to support a 100% renewable electricity system in the region.

Finding PHES sites

Potential sites for off-river PHES can be identified from a geographic information system (GIS) platform such as ArcGIS based on algorithms with defined search criteria. Detailed information such as head, reservoir area, average dam depth and storage capacity is then derived from the search results for further analysis.

Many of the sites may turn out to be unsuitable.

A turkey nest reservoir entails a continuous earth wall around most of the impoundment. A head-of-gully reservoir entails a relatively short wall across a gully high in the catchment (to maximise head and minimise the flood risk).

In this work the identified sites assume earth and rock walls with a maximum height of 40 m. The average water depth of these sites is around 20 m and the minimum area is generally 10 hectares, giving a minimum water volume of 2 gigalitres in most cases. Dam walls have a slope of 1:1 (horizontal:vertical), yielding a calculated volume of rock.

Different wall heights will produce different dam shapes and volumes. At a later stage, we will extend the analysis by using different wall heights in the range 10-80 m. However, the most prospective regions are picked out by the sites we have identified using 40 m walls.

Good sites

Good PHES sites have the following characteristics:

- Large head: 300-600 m heads are desirable. Doubling the head doubles energy and power but often does not double the cost. For comparison, the existing Tumut 3 PHES system has a head of 150 m
- Gentle slopes behind the dam wall: so that a modest wall can impound a large amount of water
- Large water volumes: in our modelling we generally require a minimum of 1 GL, which roughly corresponds to 1 GWh of stored energy (for ~400 m head)
- Large volume of stored water compared with the volume of rock required for the dam. That is, a large water/rock ratio. A ratio above 10 is desirable, and preferably much higher
- Short and steep connecting pressure pipes/tunnels between upper and lower reservoirs to minimise length/cost
- Minimum conflicts with indigenous, environmental, social, heritage, urban, agricultural and land management aspects
- Appropriate geological characteristics
- Good access to roads and high voltage power lines
- Good access to water

Limitations

This work focuses on upper reservoir sites since there are far fewer potential upper reservoir sites than potential lower reservoir sites.

After identifying a suitable upper reservoir site, the remaining steps are to identify a lower reservoir site and a tunnel/pipe route connecting them. The sites identified typically have large areas of flat land at the base of the hills suitable for lower reservoirs (which are not included in this material).

A cost model is under development in this project that will allow optimisation of the pipe/tunnel route and lower reservoir site. Future releases of information will include this material.

Visualising potential sites for upper reservoirs

Google Earth is a free publicly available application that allows visualisation of potential PHES sites [2]. Google Earth used in 3-D mode with 3:1 vertical exaggeration provides good visualisation from any direction. Files with the right format (kml or kmz) can be loaded into the "Places" field to allow 3-D visualisation of potential reservoirs.

A kml file is available for download for each region. Opening this file with Google Earth allows visualisation of sites in 3D from any angle. Also shown is a representation of the dam walls. Clicking on a blue reservoir brings up data about that reservoir. Clicking on a dam wall brings up information about that dam wall, such as length, area and volume.

Figures

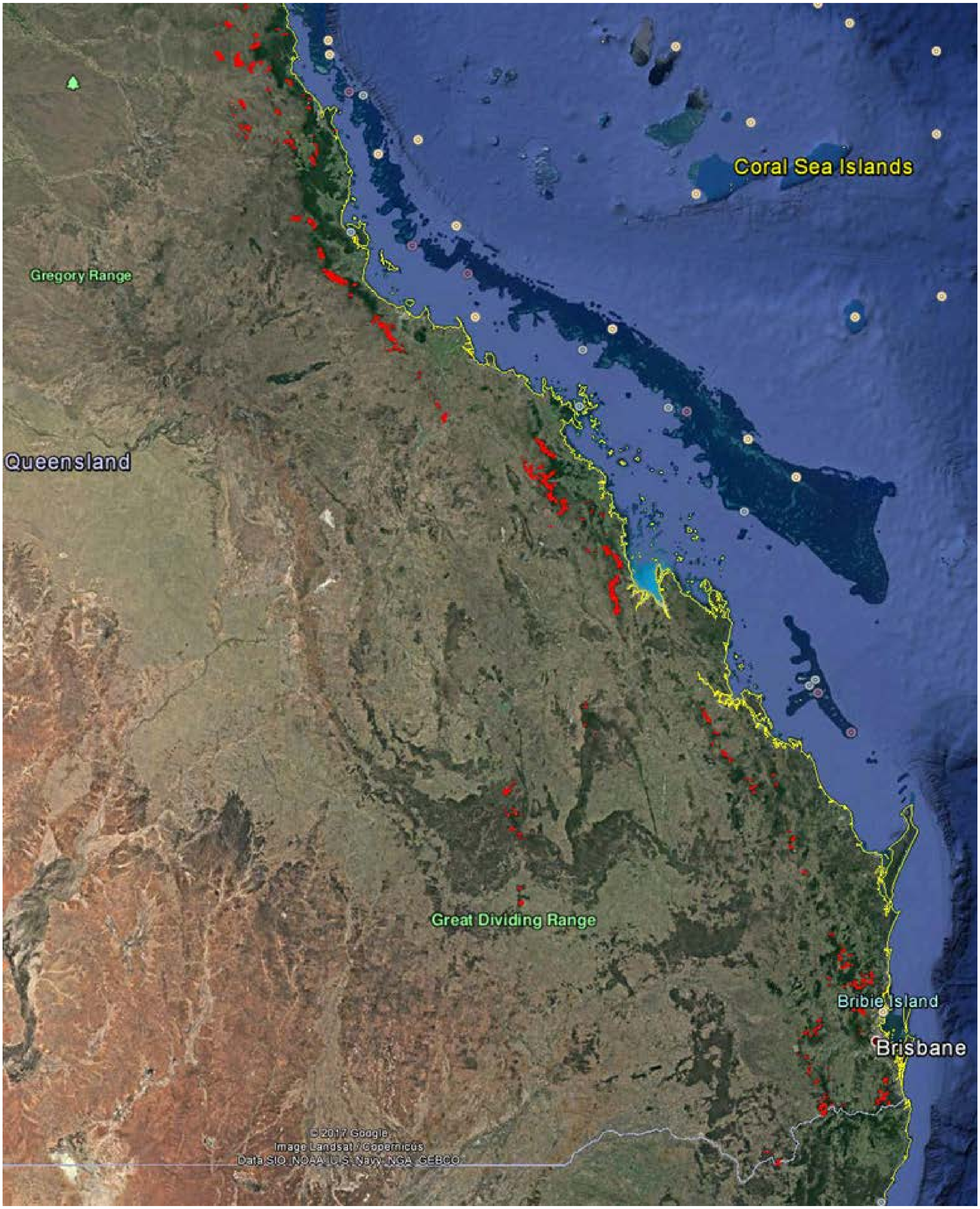

Figure 1: Potential PHES sites in Queensland are located near the Great Dividing Range (Google Earth).

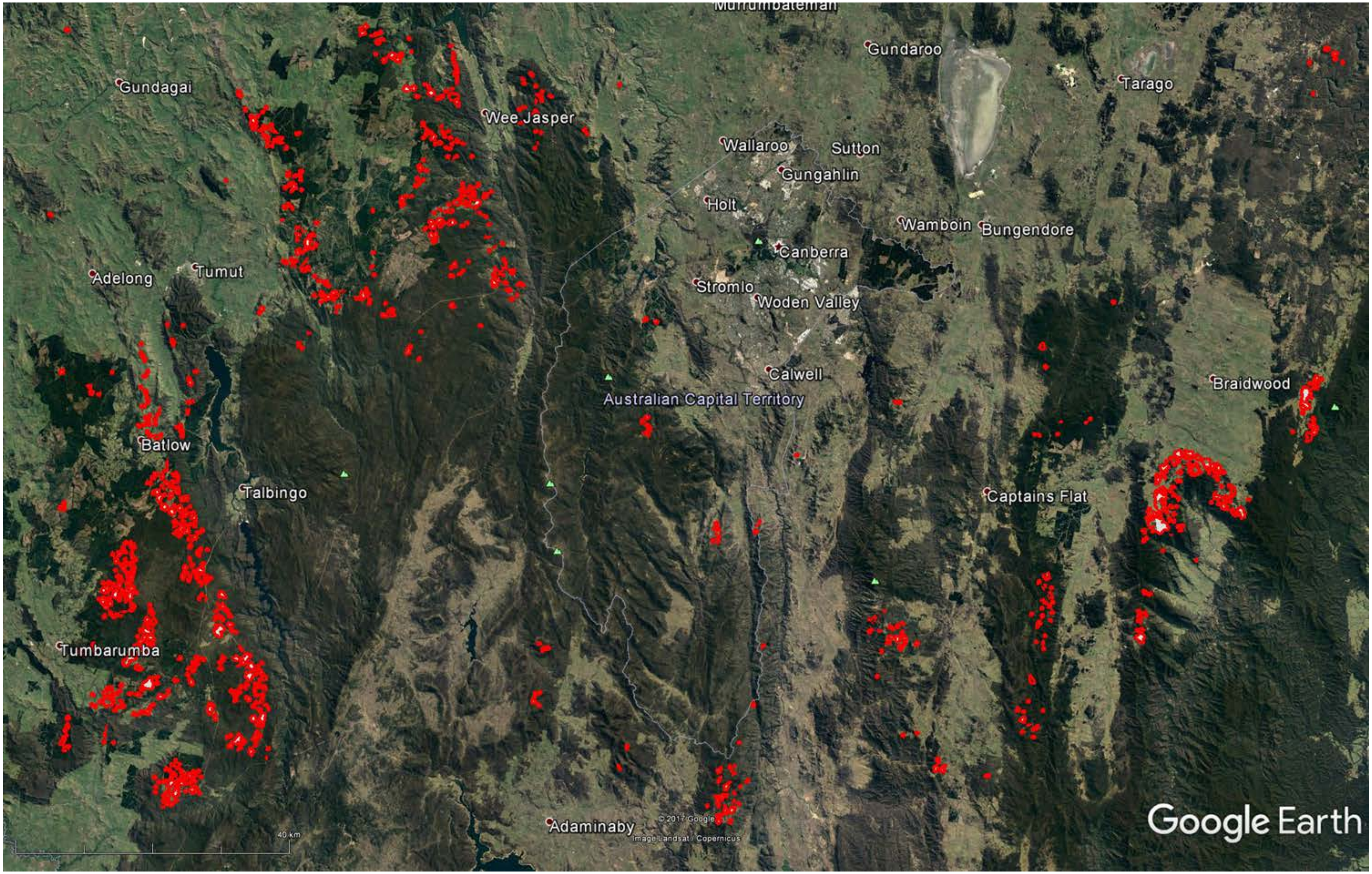

Figure 2: Potential PHES sites in the Canberra district.

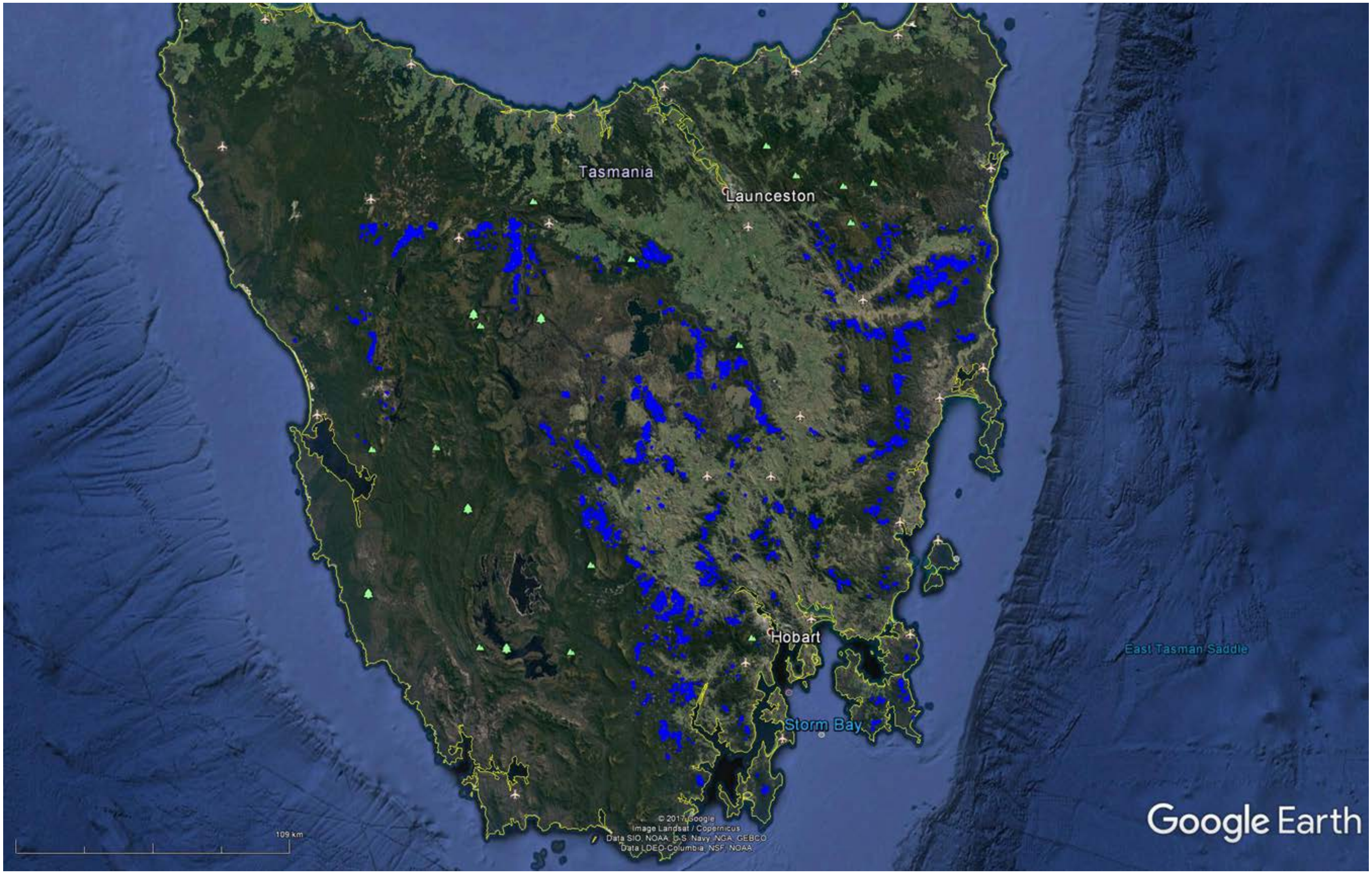

Figure 3: Potential PHES sites in Tasmania.

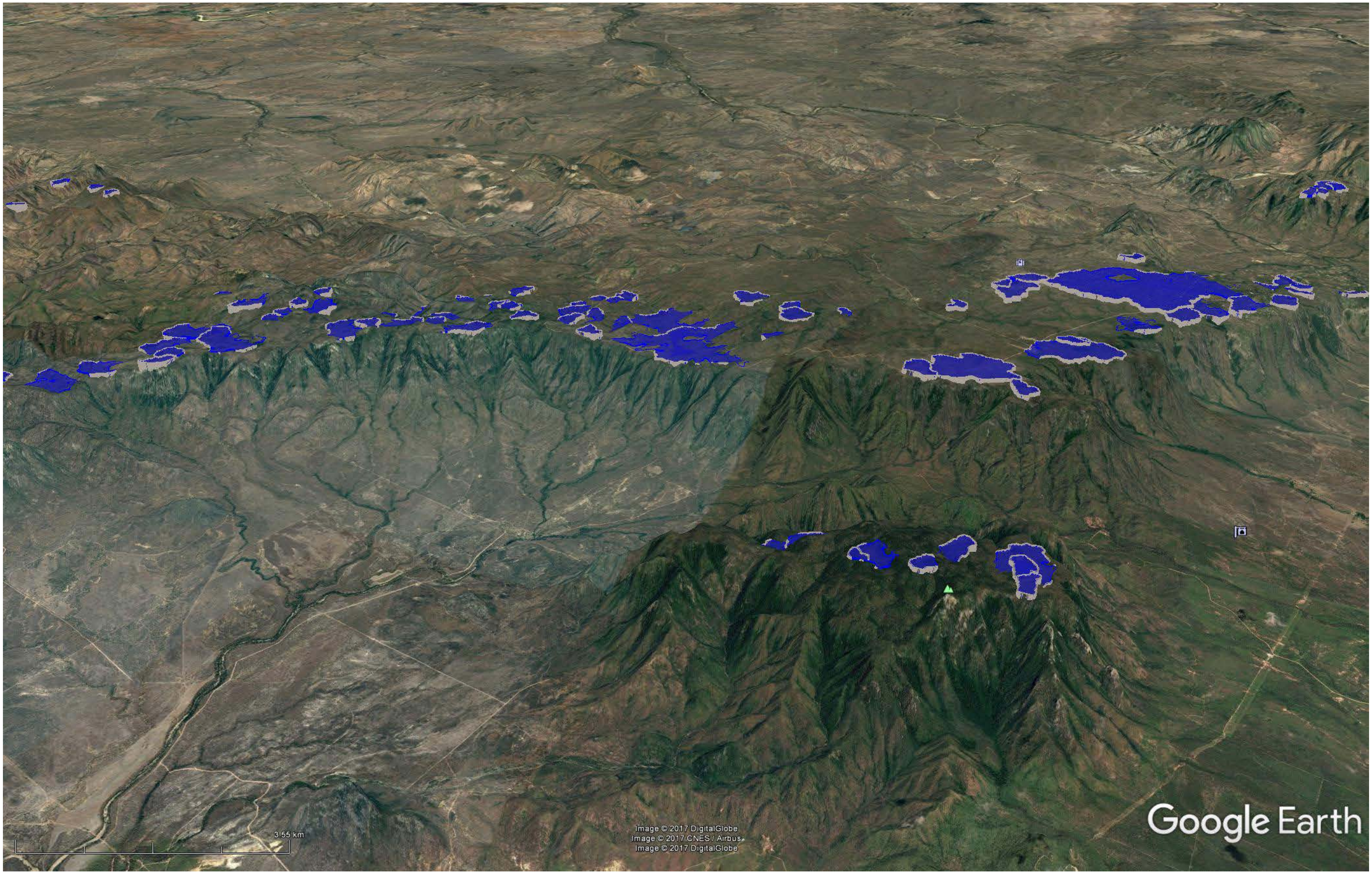

Figure 4: Potential PHES upper reservoir sites near Townsville (Qld). The lower reservoirs would be at the foot of the hills (bottom of the image).

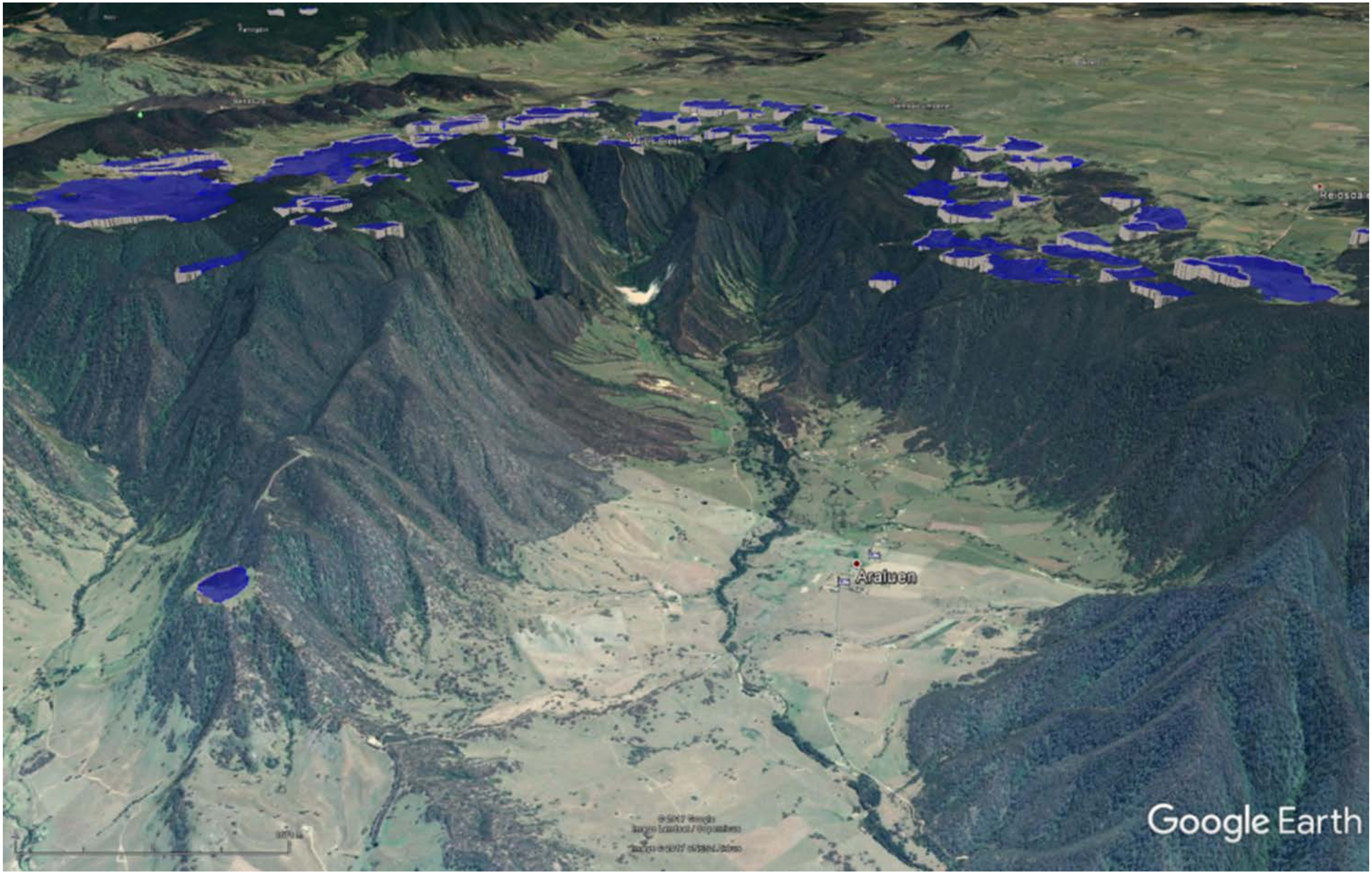

Figure 5: Potential PHES upper reservoir sites near Araluen (Canberra district). The lower reservoirs would be at the foot of the hills. Head is up to 600 m.

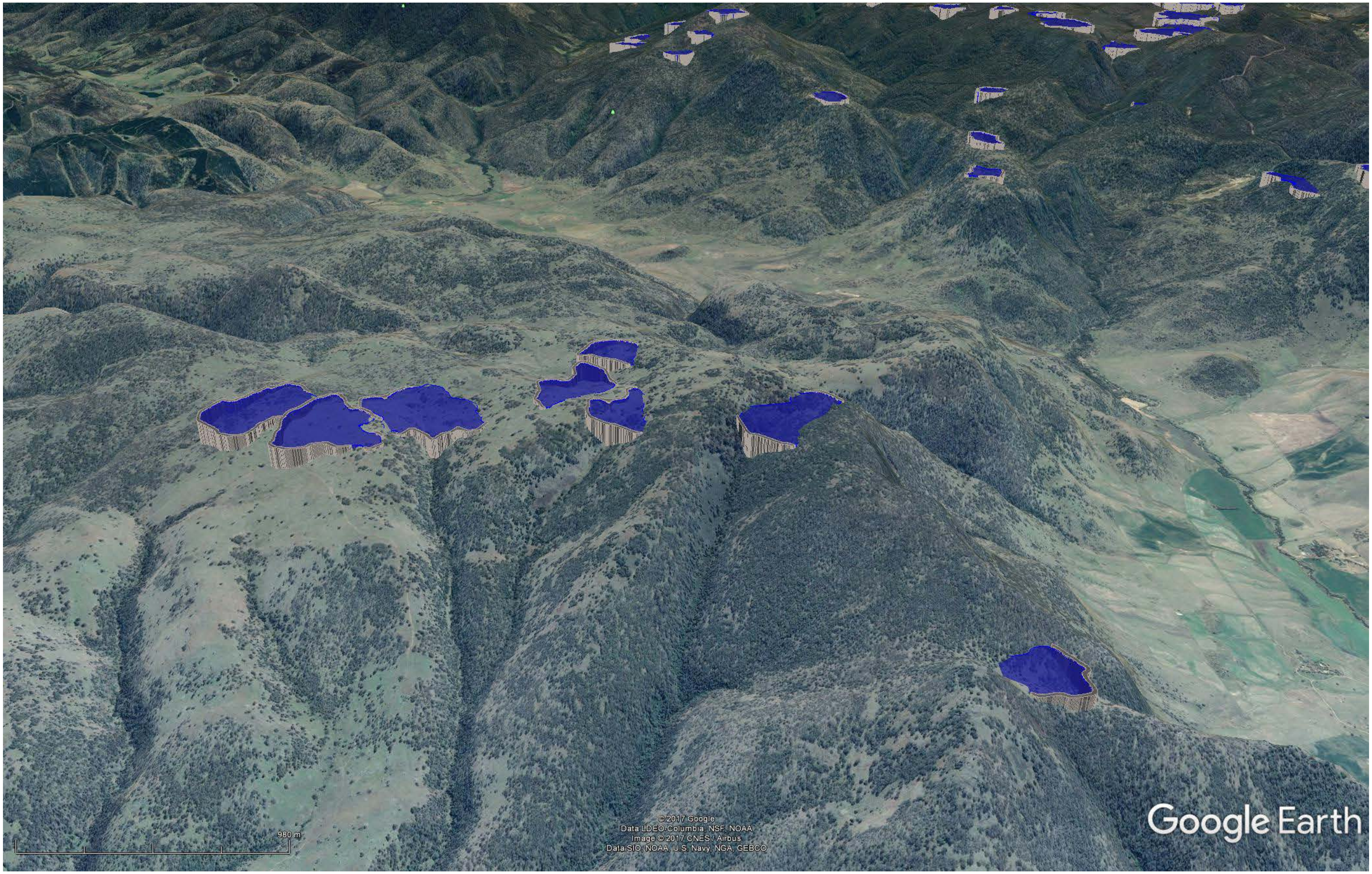

Figure 6: Potential PHES upper reservoir sites near Avoca (Tasmania).

Pumped hydro energy storage

Renewable electricity

As the proportion of wind and PV extends into the 50-100% range, a combination of additional interstate high voltage transmission, demand management and local storage is required to balance the electricity grid.

Local storage confers resilience in the event of transmission line failure. Additionally, it allows greater utilisation of expensive high voltage interconnectors to other states by storing excess wind and PV for transmission at a later time, thus increasing the average load in the powerlines (and reducing their required capacity and cost). PHES and batteries are both likely to be prominent in local storage.

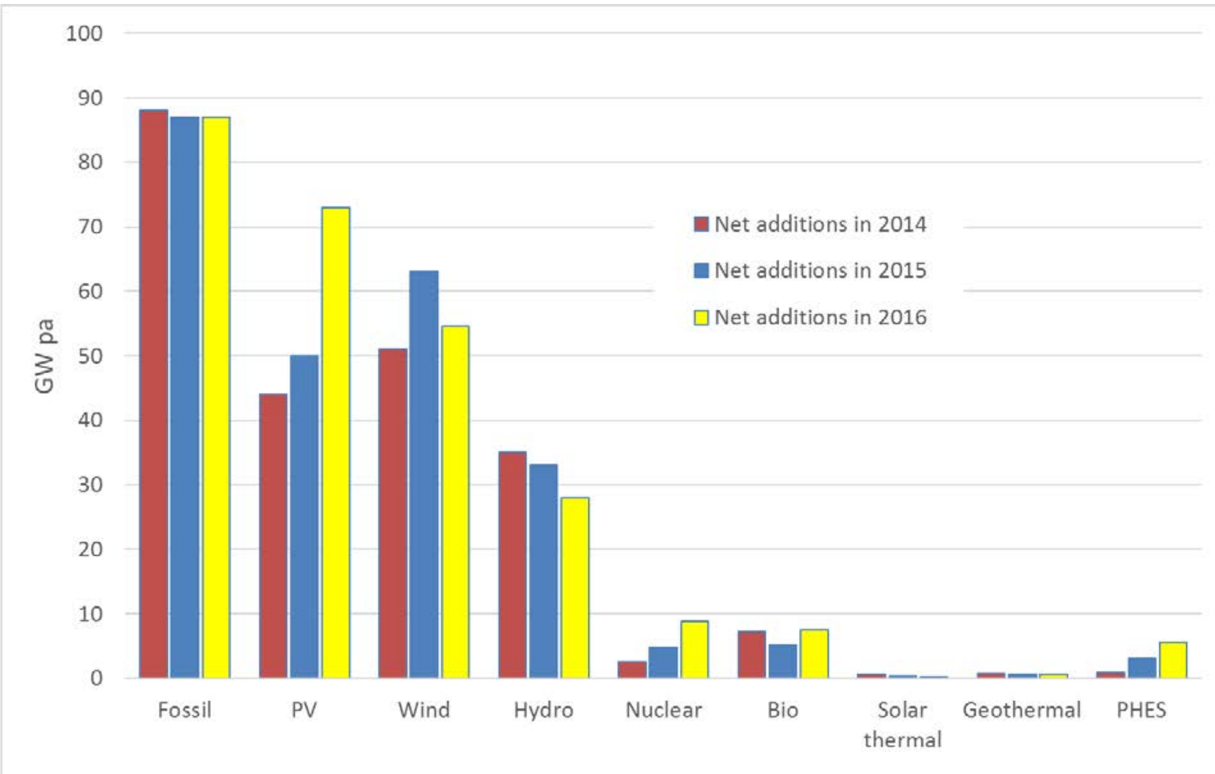

Figure 7: Net new capacity installed worldwide in 2016 [3,4,5]. PV and wind are the largest and second largest sources of new generation capacity, followed by coal.

PHES

Pumped hydro energy storage (PHES) entails using surplus energy to pump water uphill to a storage reservoir, which is later released through a turbine. About 20% of the stored energy is lost in the storage cycle. PHES constitutes 97% of electricity storage worldwide, 159 gigawatts (GW) [3].

In addition to storing energy, pumped hydro storage has additional capabilities that help support the electricity system. PHES can provide excellent inertial energy storage (the heavy rotating generator) which helps stabilise the system against disturbances, fast response time (idle to full capacity in one or two minutes) and black start capability (to restore a collapsed grid).

Australia already has river-based PHES facilities at Wivenhoe, Kangaroo Valley and Tumut 3. However, off-river PHES opportunities are far more prevalent than river-based sites. Unlike conventional "on-river" hydro power, off-river (closed loop) PHES requires pairs of reservoirs that are generally 10-100 hectares in size, rather like oversized farm dams, located away from rivers and national parks in hilly country. These sites are separated by an altitude difference (head) of 200-900 metres, and joined by a pipe or tunnel containing a pump and turbine.

In these systems, water cycles in a closed loop between the upper and lower reservoir. About 10% of the energy is lost in the pumping cycle and another 10% in the generation cycle, for a round trip efficiency of around 80%. They consume little water (evaporation minus rainfall) and have a much smaller environmental impact than river-based systems. Energy storage volume (i.e. reservoir size) is typically sufficient for 5-20 hours at maximum power.

Off-river PHES differs significantly from conventional river based hydro:

- The reservoirs are small (1-100 hectares rather than thousands of hectares)
- Minimal flood control measures are needed because the reservoirs are deliberately placed away from watercourses with sufficient catchment to cause serious flooding.
- The heads are 2-5 times larger because the upper reservoir can be on top of a hill rather than in a river valley. An increased head is advantageous because a doubled head allows doubling of energy stored and power developed, while the cost is generally less than doubled.
- Minimal environmental impacts as river flows are not disturbed

Alternatives to pumped hydro storage

PHES constitutes 97% of the world's energy storage markets and has about 159 GW of global deployment [3].

Batteries are currently expensive for long term storage (greater than a few hours), but are declining in cost. Small-scale residential batteries, electric vehicle batteries and low temperature thermal energy storage using heat pumps for space and water heating and cooling are becoming important, contributing substantial storage capacity and demand response capability to renewable energy systems. Importantly, these compete with high retail prices "behind the meter".

Storage methods other than those mentioned above are under development but have small scale of deployment hitherto, and it is difficult to obtain reliable cost estimates. Compressed air energy storage requires a special geologic structure such as a large underground cavern (hundreds of megalitres) to store high-pressure air, and there are two large commercialised facilities operated around the world. High temperature thermal energy storage such as molten salt has relatively low deployment of its primary technology (solar thermal energy).

Hydrogen storage has high round trip losses (typically 50% via electrolysis of water followed by fuel cell generation). Other energy storage technologies such as flywheels, superconducting magnetic and supercapacitors are either still at an early stage of development, or are not capable of grid-scale time shifting of energy use (GWh of electricity).

Energy storage in pumped hydro

The energy storage capability of a PHES system is the product of the mass of water stored in the upper reservoir (in kg), the usable fraction of that water, the gravitational constant ($g = 9.8\ ms^{-2}$), the head (in

metres), and the system efficiency. By way of example, a PHES system might comprise twin 20 hectare reservoirs, each 20 metres deep, with a usable fraction of 85%, separated by an altitude difference (head) of 400 metres, and operating with a round-trip efficiency of 81% (90% for each of the pumping and generating cycles).

The usable mass of stored water when the upper reservoir is full is 20 Ha * 10,000 m^2 per Ha * 85% usable faction * 20 metres depth * 1000 kg/m^3 (density of water) = 3.4 billion kg = 3.4 gigalitres (GL).

The effective energy storage capacity taking account of both pumping and generating losses is 3.4 billion kg * $9.8 m/s^{-2}$ (gravity) * 400 m head * 81% efficiency = 11 terajoules (TJ) = 3 GWh (gigawatt-hours). This much energy storage can generate 300 megawatts (MW) of power for 10 hours. Roughly speaking, 1 GWh of energy storage requires 1 GL of stored water for 400 m head.

Energy storage needs

The National Electricity Market (NEM) and grid covers eastern and southern Australia but excludes Western Australia, the Northern Territory and remote regions. Recent work shows that about 450 GWh of widely distributed storage is required to stabilise the NEM when renewable electricity reaches 100% (mostly wind and PV with some existing hydro and bio energy) [1].

Water use

The use of fresh water rather than salt water is preferred to reduce corrosion of turbines, pumps and pipes and to minimise the risk of salt contamination of the land environment. Typically, about 85% of the stored water is available for use in a PHES system.

Rainfall would be above 600 mm per year since most good sites are near the coast. Reservoirs would be lined if necessary to minimise seepage from the reservoirs.

Evaporation rates in reservoirs are relatively high at up to 2500 mm per year [6]. Evaporation suppressors in the form of coverings over the water reduce evaporation by reducing solar heating of the water, trapping water vapour and reducing wind flow across the water surface. High quality suppressors reduce evaporation by 90% [7]. This means that rainfall exceeds annual evaporation in most years, and top-up water requirements will be minimal. Harvesting of small amounts of water from micro gullies located near the reservoirs provides additional water at low cost. Whether or not evaporation suppressors were used would depend upon the cost of commercially supplied water or the availability of local water.

The initial water fill would be required over the next one to two decades as reservoirs are progressively constructed, and amounts to much less than 1% of the annual commercial water market.

Sites for off-river pumped hydro storage

An ideal PHES site has a large head because doubling the head doubles the power and energy available from the upper reservoir, and halves the water requirement for a given amount of storage, but usually does not double the capital cost.

Another important requirement is that the pipeline or tunnel connecting the upper and lower reservoirs be short and steep for a given head. A slope of steeper than 1:15 is preferred to minimise cost.

Preferably, the reservoirs are not located below any significant catchment to avoid the cost associated with coping with once-a-century floods.

Some potential sites will be unsuitable because of poor geology, restrictions on allowed land use or poor access.

The three common types of site are:

- Turkey nest: the upper reservoir is built at the top of a flat hill. Earth and rock is scooped from the interior to create a continuous earth wall perhaps 20 m high;
- Head of gully: an earth wall is placed across a small gully near the top of a mountain to impound water. This design has the advantage that the wall length and hence cost is reduced compared with a turkey nest reservoir;
- Old mine sites: the mining pit can form the lower reservoir, and the upper reservoir can be a turkey nest reservoir located near the edge of the pit. An example is the proposed 250 MW Kidston PHES project in an old gold mine in north Queensland [8].

Pipes, pumps, turbines, generators, substations and powerlines are standard equipment that is widely available from the hydroelectric power industry. Construction of reservoirs within Australia draws upon extensive experience in the construction of farm dams and tailings dams for mining operations.

Acknowledgements

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Some figures were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license.

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