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Continental-scale assessment of micro-pumped hydro energy storage using agricultural reservoirs

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HIGHLIGHTS

- Agricultural reservoirs reduce micro-pumped hydro construction costs.
- Identified 30,295 promising sites in arid and temperate climate zones.
- Average system has 52 kWh capacity, reservoirs within 132 m and 32 m of head.
- Estimated cost of 0.2 USD/kWh is comparable to home batteries at higher loads.
- Micro-pumped hydro supports uptake of solar in agricultural regions.

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ABSTRACT

The transition to low-carbon power systems necessitates cost-effective energy storage solutions. This study provides the first continental-scale assessment of micro-pumped hydro energy storage and proposes using agricultural reservoirs (farm dams) to significantly reduce construction costs. The continent of Australia is used as a representative case study for other arid and temperate regions internationally. From a new survey of its 1.7 million farm dams, we identified 30,295 promising pumped hydro sites in dam-to-dam and dam-to-river reservoir configurations. The average site had nearby reservoirs (132 m) with a high head height (32 m) and substantial discharge capacity (52 kWh). We then benchmarked a representative micro-pumped hydro site to a commercially available lithium-ion battery for a solar-powered irrigation system. Despite a low discharge efficiency (68%), pumped hydro storage was 30% less expensive (0.215 USD/kWh) for larger single-cycle loads (~41 kWh/day) due to its high storage capacity. By capitalising on existing farm dams, micro-pumped hydro energy storage may support the uptake of reliable, low-carbon power systems in agricultural communities.

1. Introduction

Wind and solar photovoltaics (PV) are leading the decarbonisation of electricity generation in numerous regions including China, Europe, and the United States [1]. However, as the share of these intermittent sources grows, so does the necessity of developing new energy storage solutions to ensure a reliable and affordable power supply. Decentralised energy systems will play a significant role in this transition, as distributed PV accounted for 22% of renewable capacity additions in 2022, while the number of household units is expected to quadruple from 25 to 100 million by 2030 [1,2]. For this burgeoning sector, distributed energy storage will be crucial.

By storing solar energy, residential and commercial prosumers can lower their electricity bills and decrease their carbon footprint through increased self-consumption. Depending on generation-demand profiles and storage capacity, battery energy storage systems can double the self-consumption of solar energy [3–7]. This self-consumption helps consumers avoid charges through peak shaving and load levelling, with

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Abbreviations: PV, Photovoltaics; Li-Ion, Lithium ion; LCOS, Levelised cost of storage.

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other arbitrage benefits dependent on local tariff structures and market regulations. In South Australia, for example, electricity retailers will charge general usage rates several times higher than solar feed-in tariffs: 0.35 AUD/kWh vs. 0.05 AUD/kWh [8,9].

Strong market demand for these distributed energy storage systems is demonstrated by battery attachment rates for new household solar installations, which range from 14% to 27% in the US, Europe and Australia [10–12] and are as high as 90% in Germany [13]. However, studies have shown battery cost savings can be marginal in certain cases [13,14]. Therefore, consumers' demand for batteries should also be attributed to non-financial benefits, including sustainability and security.

Energy security is an increasing concern for consumers whose trust in central providers may be undermined by volatile prices and grid instability. Energy Poverty in Europe provides a stark example of price impacts, which have been exacerbated by the COVID-19 pandemic and the invasion of Ukraine [15]. Extreme weather in America evidences the consumer responses to grid instability, with wildfires in California and deep freezes in Texas. A survey of 1500 representative U.S. households found those who had experienced an outage were 4 times as likely to have purchased a solar-storage system [16]. Here, batteries are the leading solution. However, battery backup power is generally limited to less than half a day, and fire risks and reliance on critical minerals persist [17]. Generators offer an alternative solution for backup power that can run for days to weeks. However, generators are dependent on affordable fuel supplies and produce harmful emissions. As such, there remains a gap for long-duration storage without fuel dependence. Micro-pumped hydro energy storage (Micro-PHES) presents an emerging opportunity to fill this gap.

Large-PHES is a mature technology that has mitigated daily and seasonal variations for national power grids over several decades [18]. Systems use the gravitational potential energy of water, pumped from a lower to high-elevation reservoir to store excess energy from the grid, before releasing it through a turbine to generate electricity when demand is high. Micro-PHES applies the same principles but services households and microgrids with a power output of <100 kW. Micro-PHES is an early-stage technology, at the pilot stage of development. However, development opportunities are growing with the rise of the distributed energy storage market.

Morabito and Hendrick [19] built and tested an advanced micro-PHES pilot at the Université libre de Bruxelles, approaching cost parity with battery technologies under certain conditions. The innovative system used an existing stormwater basin to reduce reservoir construction costs by 28% [19,20]. A single centrifugal pump-as-a-turbine (PaT) also limited hardware costs, with a variable speed drive used to optimise flow rate efficiencies and limit water hammer. Despite a low round-trip efficiency of 42%, the micro-PHES levelised cost of storage (LCOS) was superior to Li-ion and Lead-Acid batteries when used for 2–3 cycles per day. This early pilot suggests micro-PHES could become commercially viable for distributed long-duration applications, particularly if reservoir construction costs can be eliminated.

Capitalising on existing farm dams may enable these cost reductions. Farm dams (also known as agricultural reservoirs, ponds, impoundments or dugouts) are small constructed water reservoirs with a surface of around 0.01–0.1 ha also known as agricultural reservoirs, ponds, impoundments or dugouts [21,22]. Globally there are an estimated 0.5–3.2 billion farm dams [23], and these are advantageously dense in agricultural regions on the fringe of the network which may benefit from backup power. However, significant uncertainty surrounds previous farm dam estimates. As of yet, most global water surveys have overlooked smaller bodies, as demonstrated by a recent survey of China [24]. Some recent studies have surveyed these smaller water bodies in the US (7.8 million) [21] and Australia (1.7 million) [25,26]. However, these surveys only considered conservation purposes; there has been no assessment of their distributed energy storage potential through micro-PHES.

One study has conducted a global assessment of large-PHES potential, identifying 616,000 potential off-river sites. However, this study only considered large sites with a capacity above 2 GWh [27]. The gap left by this study is reasonable, given the lack of available data on small water bodies and the relative obscurity of micro-PHES compared to large-PHES. To the authors' best knowledge, micro-PHES using farm dams has only been proposed by Mousavi et al. [28,29] and García et al. [30,31].

Micro-PHES may offer economic and other advantages over battery storage systems for the agricultural sector [28,29]. Mousavi et al. analysed a solar-powered irrigation system with micro-PHES and found the payback period was four times faster than an equivalent battery system. In the study, micro-PHES benefited from the dual use of pumping hardware for irrigation. However, site-specific water availability should be considered for each new system, such as irrigation schedules, water management regulations, and drought restrictions. Additionally, the broader advantages of each storage technology should be considered.

Lithium-ion batteries are more expensive than lead-acid batteries but are generally preferred due to their superior lifespan, energy efficiency and energy density. Although, lead-acid batteries may be preferred if the storage is used infrequently. Micro-PHES offers a substantial storage capacity; however, batteries provide superior efficiency and response times. Therefore, batteries are generally preferred for applications that do not require a high storage capacity. However, other factors should be considered. For example, PHES offers lower life cycle impacts regarding global warming potential, mineral-metal demand, eutrophication and human health; the use of an existing dam limits the natural land transformation impacts faced by large PHES systems [32]. Micro-PHES may also offer a longer lifespan than batteries that suffer from degradation. However, proper maintenance would be required, and real-world validation is still required [19,29]. Lastly, micro-PHES avoid fire risk perceptions associated with lithium-ion battery technologies [33]. Besides batteries, generators are the other main method of distributed energy storage.

Garcia et al. [30,31] compared micro-PHES to diesel generators for solar power irrigation. The study found similar cost and environmental benefits due to reduced operational fuel consumption [31], and the potential to increase self-consumption to 90% through analysis of an irrigation network for grape crops with several reservoirs and pumping stations [30]. With Mousavi et al. [28,29], these studies present isolated micro-PHES works that analyse a single solar-storage irrigation system. Despite the growing opportunity for distributed energy storage solutions, there has been no broader assessment of small water bodies (farm dams) that could be used for micro-PHES, let alone at a continental scale.

Micro-PHES is a nascent storage technology for distributed energy systems powered by solar PV. System modelling and an early pilot suggest its long-duration storage could allow prosumers to decrease their electricity bills and carbon emissions while granting an increased sense of security. Unfortunately, the construction of reservoirs remains prohibitively expensive. Using existing farm dams as reservoirs could overcome this bottleneck, but there has been no assessment of potential sites for micro-PHES. This study bridges that gap by providing the first assessment of potential micro-PHES sites. This assessment is conducted on a continental scale, with Australia used as a representative case study for other arid, temperate, and tropical climate zones worldwide. This new assessment of potential micro-PHES represents a significant step in the commercialisation of an emerging distributed energy storage technology.

The paper is structured as follows. Unique combinations of proximate (<500 m) dam-to-dam and dam-to-river pairs are first identified, by analysing a new 2021 survey of 1.7 million farm dams in Australia [25]; the dams and rivers can be used as reservoirs for a new micro-PHES system to significantly reduce construction costs. We then filter commercially promising sites from this list of potential sites based on minimum capacity (24 kWh) and slope (17%). A large energy storage capacity allows increased solar self-consumption, while a steep slope decreases piping costs for a given power output. The cost and performance of an average site from this list of promising sites are then benchmarked against a commercially available home battery to indicate viability. This is the first assessment of micro-PHES storage potential, contributing a geospatial database of farm dams and rivers that could be used for future installations, and a method that can be replicated in other regions to affirm the distributed storage potential of micro-PHES.

2. Methods

2.1. Farm dam survey

The location and water volume of the 1,694,671 farm dams in Australia were sourced from Malerba et al. [25]. This new survey of small water bodies was created by training a deep-learning convolutional neural network on high-definition satellite imagery, with the final model achieving an accuracy of 94.8%. The study also developed a linear regression model (Eq. 1) to estimate the water volume of each farm dam, based on its visible surface area.

$$log_{10}(Water\ capacity; ML) = -3.593 + 1.237 log_{10}(Surface\ Area; m^2) \mid [R^2 = 0.91] \tag{1}$$

While the survey has some inaccuracies in the identification of dams and estimation of their volume, it provides the first large-scale assessment of these small water bodies. This new data is a necessary resource for estimating micro-PHES capacity using farm dams. However, given the inaccuracies, individual sites should be validated before progressing from this continental assessment of sites. The current study uses Australia as a case study. However, Malerba et al. have also surveyed farm dams in the U.S. [21], and future work may replicate the survey and assessment methods in other regions using satellite imagery.

2.2. Pairing dam-to-dam

The distance between dams was determined from their latitude and longitude data using the Python package `geopy', specifically the WGS-84 ellipsoid model [25]. The elevation above sea level at the centroid of each farm dam was calculated using Geoscience Australia's 3-s (ca. 90 m) SRTM Digital Elevation Model [34]. The centroid was used as this is typically the deeper part of a dam suitable for water pumping. A limitation of this approach is the direct path between the centroid of each dam may not represent the most suitable path, due to existing infrastructure, land use, topography, geology and so on. Therefore, each site should be manually inspected before creating a preliminary design. The micro-PHES concept in Section 2.4 demonstrates.

The Python package 'NetworkX' was then used to create and analyse the network of proximate (<500 m) dams. The 'max_weight_matching' algorithm was used to find the maximum energy storage capacity of unique dam-dam pairs, based on Edmonds' 'blossom' and 'primal-dual' methods [35,36], with the nominal capacity E (kWh) of each dam pair calculated by Eq. 2:

$$E_{PHES} = \frac{V \times g \times H \times \rho}{3.6 \times 10^6 \frac{J}{kWh}} \tag{2}$$

Where V (m^3) is the smallest of the two dam volumes, g (m/s^2) is the approximate constant of gravity in Australia, H (m) is the difference in elevation of the two dams, also known as the head height, and $\rho = 1000$ kg/m^3 is the approximate density of water. This nominal storage capacity does not account for efficiency losses and usable volume.

Importantly, each dam was paired with only one other dam, as adding a dam to the cluster does not always increase the system's energy storage capacity. An additional dam will only increase the energy storage capacity of a cluster if it increases the minimum dam volume or maximum head height. For example, if two large-volume dams lie at a low elevation, and one small-volume dam lies at a higher elevation, then the capacity of connecting both low-elevation dams to the high-elevation dam would be no greater than if only one were connected. Yet, if both pairs were included in the nominal energy storage capacity equations, it would lead to an overestimation of the dam's actual energy storage capacity. Therefore, each dam was paired with at most one other dam, providing a lower bound estimate of the total energy storage capacity of surveyed dams. However, future work should consider the potential benefits of larger networks. To further clarify this point, another dam cluster example is worked through in Fig. 1.

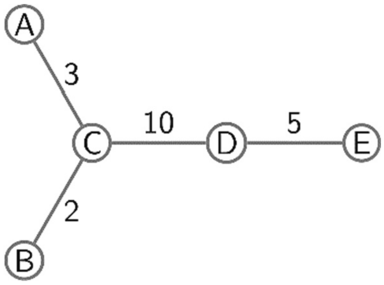


Fig. 1. Five dams labelled A to E are represented as the nodes of an edge-weighted network. Each edge in the network represents a pair of dams that lie within 500 m of each other, and the weight of the edge is the storage capacity of the dam pair that it represents. The sum of the four dam pair capacities is 20kWh, but this will only be possible for certain dam volumes and elevations. If allowing for only one unique pair, the capacity is 10 kWh, provided by the single dam pair (C, D). It is possible to choose more matched dam pairs here, such as (A, C) and (D, E). However, they only provide 8 kWh, less than the more heavily weighted single dam pair (C, D).

2.3. Pairing dam-to-river

The GIS dataset [37] was used to determine the geographical and geometric data for the rivers of Australia. The program QGIS was then used to determine the nearest river point to each dam. The elevation of the river points was determined using Geoscience Australia's 3-s (ca. 90 m) SRTM Digital Elevation Model [34]. The nominal capacity of each dam-river pair was also calculated using Eq. 2, except the volume of the dam was used. This capacity calculation assumes the river volume is larger than the dam volume. This assumption was made due to the lack of available data for the volumes of most rivers. This assumption might not be valid for many streams and other small rivers. As with dam-dam pairs, the shortest path between a dam-river may not represent the most suitable path, which would require local design studies to determine.

2.4. Micro-PHES concept design

2.4.1. Site selection

A dam-dam site was selected in South Australia due to the high penetration of variable solar and wind electricity generators. Possible sites in South Australia were manually inspected to minimise impacts, such as checking for environmental protection zones, sole property ownership, existing historical and indigenous heritage, land uses, site accessibility, and transmission lines. The selected site has a slope of 17% and a nominal capacity of 89 kWh. These performance metrics were lower than the average promising dam-dam site, which has a slope of 22% and a nominal capacity of 104 kWh. Therefore, the selected site provides a conservative example of the promising sites. However, the selected site incidentally benefits from an uninterrupted straight pipe path and the possible dam expansion to a third dam; features that may not be present for other pairs.

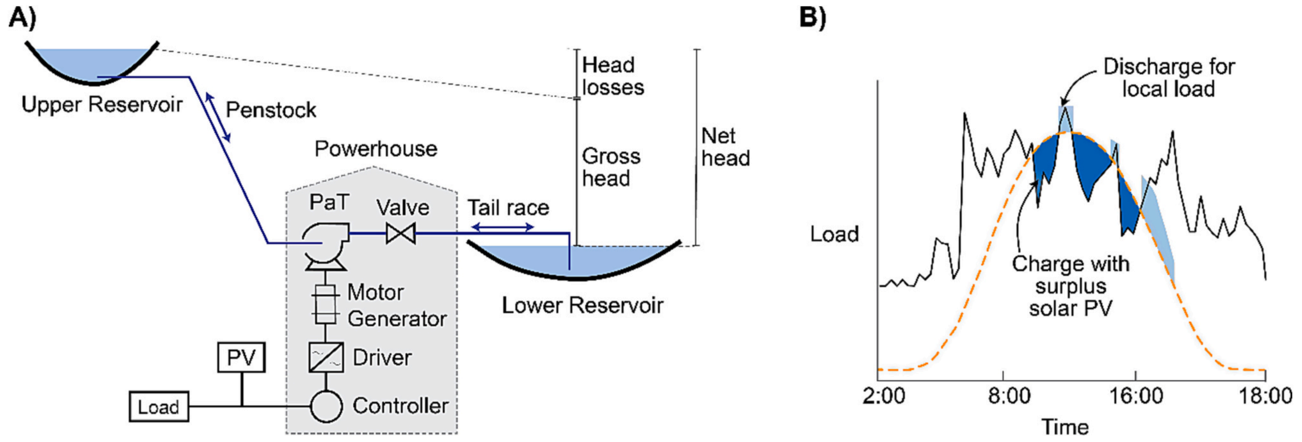


Fig. 2. A) Hardware configuration for micro-PHES B) Example charge-discharge operation for micro-PHES adapted Morabito and Hendrick [19] noting that solar generation capacity (kW), storage capacity (kW, kWh) and load will alter the charge and discharge profiles.

2.4.2. Hardware configuration

Following the design of the leading micro-PHES prototype system installed in Froyennes, Belgium [19], the concept applies a binary configuration with a pump as a turbine (PaT) [38]. A variable frequency drive and electromechanical valves are used to moderate the flow rate, allowing ramping to avoid issues such as water hammer or tuning flow rate for improved efficiency [19]. The system configuration is presented in Fig. 2A.

2.4.3. Microgrid configuration

Our study considers a solar-powered irrigation system. These irrigation systems often rely on grid power when solar generation fails to meet the load. However, in remote areas, the cost-effectiveness and reliability of grid power can be compromised due to the high maintenance costs of fringe network infrastructure, and vulnerability to weather events. Consequently, many solar-powered irrigation systems use generators for backup power. While generators offer a reliable solution with low upfront costs, their ongoing fuel costs and harmful emissions make them unsustainable in the long term. This is especially true for off-grid solar-powered irrigation systems, that routinely use generators to balance intermittent solar generation. Energy storage offers an alternative to the grid and generators [39,40].

Energy storage enables increased self-consumption of solar PV through peak shaving and load shifting. Storage is usually charged during the middle of the day when solar generation exceeds load, and then discharged in the evening as solar generation decreases but load continues; an example of this operation is depicted in Fig. 2B. Batteries are the prevailing distributed energy storage solution, although costs often limit storage duration to a few hours. For longer-duration storage, pumped hydro is an emerging energy storage solution for solar-powered irrigation systems.

Mousavi et al. analysed micro-PHES and battery energy storage systems for solar-powered irrigation [28,29,41]. Their approach involved complex simulation and optimisation of the energy management system, considering factors such as energy generation and demand, energy tariffs, water demand and systems losses to optimise cost-savings and feed-in income based on weather forecasts [28]. The data required for this approach is unavailable and exceeds the scope of this study, which seeks to assess energy storage capacity on a continental scale. Therefore, we consider a simpler solar-powered irrigation system.

For the solar-irrigation system, we assume that surplus solar energy provides all the charging power, and the local load utilises all the discharge power. This approach is in line with the operation of the micro-PHES by Morabito and Hendrick [19]. However, in practice, this assumption would have to be verified for each site. Furthermore, the optimisation of system capacities and operations based on local contexts - such as weather, tariff structures, and load requirements - would likely lead to a more cost-effective solution. Such detailed analysis and optimisation present opportunities for future studies.

2.4.4. Pump-turbine selection

During winter in South Australia, hourly electricity consumption peaks at around 2.16 kWh at 7 pm, and has a daily average of 20.0 kWh [42]. Home batteries typically have a discharge rate of 2.5 to 7.5 kW [43]. Therefore, a generator-turbine power output of 3 kW is targeted to meet average peak household demand and match existing distributed energy storage solutions. The turbine and pump efficiencies are defined as:

$$\eta_p = \frac{\rho g H_p Q_p}{P_m} \tag{3}$$

$$\eta_t = \frac{P_g}{\rho g H_t Q_t} \tag{4}$$

Where η is efficiency, ρ is density (kg/m^3), g is the gravitational acceleration constant (m/s^2), H is head (m), Q is the flow rate (m^3/s), P is motor-generator power (W). Initially, a turbine output of 3 kW and a discharge efficiency of 70% were assumed. These conditions would require a flow rate of 17.2 L/s. Given this flow rate and the head height of 31 m, the Lowara Centrifugal Pump (*E*-SHE 50–160/75) was selected. The pump had an efficiency of 74% at 17.2 L/s, a max head of 41 m, a max flow of 25 L/s, rated to 7.5 kW, weighed 67 kg and was 253x351x567 mm in size. A Hydrovar Variable Speed Pump Controller (HV 2.015–4110) was also selected, with a rated output of 11 kW.

2.4.5. Pipe selection

The micro-PHES requires approximately 181 m of piping length and has a nominal discharge rate of 17.2 L/s. Due to the long and mostly straight path, head losses from fittings are assumed to be negligible. The head loss through a straight pipe can be calculated through a straight pipe assuming polyvinyl chloride using the Hazem-Williams equation Eq. 5 [44]:

$$h_L = 10.67 \times L \times Q^{1.852} / C^{1.852} / d^{4.87} \tag{5}$$

Where L is the pipe length (m), Q is the discharge rate (m^3/s), C is the roughness constant (150), and d is the internal pipe diameter (m). A Vinidex high-pressure PVC-M pipe was selected to limit head losses to (0.11 m) and capital costs (USD 4756). The pipe has an internal diameter of 238.1 mm, and an outer diameter of 250 mm, and comes in 6 m lengths weighing 41 kg each.

Table 1
Estimated efficiency values for μ-PHES concept.

Piping	99.6% [44]
Turbine and generator-motor	70.0% [19,45]
Wiring and control	98.0%
Discharge efficiency	**68.4%**
Pipe efficiency	99.6% [44]
Pump-motor efficiency	74.0% [45]
Charge efficiency	**73.7%**
Round trip efficiency	**50.4%**

Table 2
Tesla Powerwall 2 capital cost includes Energy Gateway 2 and standard installation in South Australia. The micro-PHES 'rated' energy assumes 70% usable volume, and 'usable' energy also assumes a discharge efficiency of 68.4%. Micro-PHES maintenance covers filters, oil, and seals. Daily average household energy use is around 20 kWh [42], although irrigation systems can consume well above 50 kWh a day [48].

Variable	Micro-PHES	Tesla Powerwall 2
Capital cost	25,613 USD	11,753 USD [49]
Operational and maintenance costs	150 USD/Year [19,29]	0 USD/year
Operational cost growth rate	2.5 USD/year [50]	0 USD/year
Lifespan	20 [29] – 35 years [19]	10 [51] – 15 years
Discount rate	5% [27,52]	5% [27,52]
Rated energy	89.0 kWh	14.0 kWh
Usable energy	42.6 kWh	13.5 kWh [51]
Rated power	3.56 kW	5.00 kW [51]
Discharge efficiency	68.4%	94.9%
Round trip efficiency	50.4%	90.0% [51]
Efficiency annual degradation	−0.2%	−3.5% [53]
LCOS (*20 kWh/day*)	0.457 USD/kWh	0.208 USD/kWh
LCOS (*1 cycle/day, ~42 kWh/day*)	0.215 USD/kWh	0.308 USD/kWh [3× batteries]

2.4.6. *System efficiency*

Due to the lack of pump performance curves in reverse turbine mode and the prevailing challenge in reliably estimating them [38], the turbine and generator-motor efficiency is approximated at 70% [19]. Pump-motor efficiency is based on technical data sheets [45]. The remaining efficiency values are summarised in Table 1. The concept has a low round trip efficiency (50%), similar to previous prototypes (42%) [19]. However, this is only a preliminary estimate. Detailed design and construction are required to validate the real-world operational efficiency of the micro-PHES system.

2.4.7. *LCOS*

LCOS measures the average net present cost of electricity production of a system over its lifetime. It is used to compare electrical production and storage resources with different scales of operation and different periods of investment and operations:

$$LCOS = \frac{Net\,present\ value\ of\ costs}{Net\,present\ value\ of\ energy} = \frac{\sum \frac{(I_t+M_t+F_t)}{(1+r)^t}}{\sum \frac{E_t}{(1+r)^t}} \tag{6}$$

Where I_t is the yearly investment cost, M_t the yearly maintenance costs, r the discount rate, t the number of years, and E_t is the yearly energy output from the storage, and F_t is the yearly electricity cost for charging. Charging power is assumed to come from local solar PV, so charging costs are zero for the battery and micro-PHES. Additionally, the system does not trade with the power grid, with discharge power only used for local load.

The estimated capital costs for the pump-turbine (USD 3796.59 / 15% [46]) and variable controller (USD 4509.69 / 18% [47]) are based on commercial off-the-shelf parts. The cost of electrical work (USD 5122.62 / 20%), civil work (USD 5634.88 / 22% [19,20]), and other (USD 1792.92 / 7%) are approximated based on the average proportional costs in two previous micro-pumped hydro projects [19,20]. Civil works consider pipe trench digging, horizontal drilling and bedding material. Electrical works consider panel and control, electromechanical valves, data acquisitions system, connections and cabling. These capital costs are the best estimates for calculating LCOS in this study. However, local site studies and detailed design should be undertaken to reliably quote the system cost. Values used to estimate LCOS are summarised in Table 2.

3. Results and discussion

3.1. *Potential energy storage capacity*

Of the 1,694,675 identified dams [25], 823,370 were within 500 m of at least one other dam. These non-isolated dams formed 346,348 unique 'dam-dam' pairs with a nominal energy storage capacity of 14.0 GWh. Alternatively, these dams could be connected to a river, with 929,111 lying within 500 m of a river and having at least 1 m of elevation difference. These 'dam-river' sites have a nominal energy storage capacity of 35.2 GWh. In both cases, most high-capacity sites are in hilly rural areas and along the populated coastline away from the central deserts, as shown in Fig. 3. See 2.2 and 2.3 for relevant pairing methods.

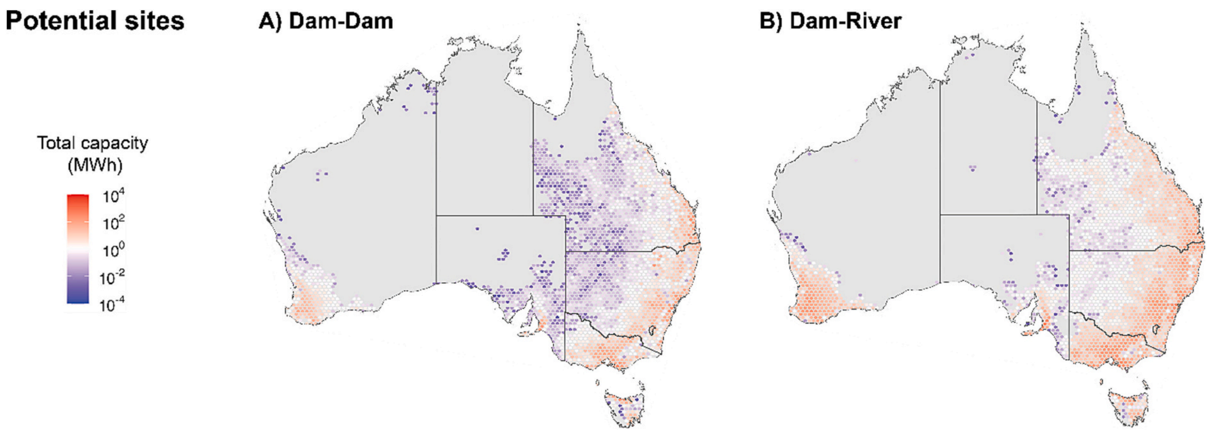


Fig. 3. Nominal energy storage capacity of A) dam-dam and B) dam-river sites in Australia. Nominal capacity includes unique pairs within 500 m. The nominal capacity does not account for efficiency losses or usable volume. Sites have also not been filtered for minimum slope or capacity.

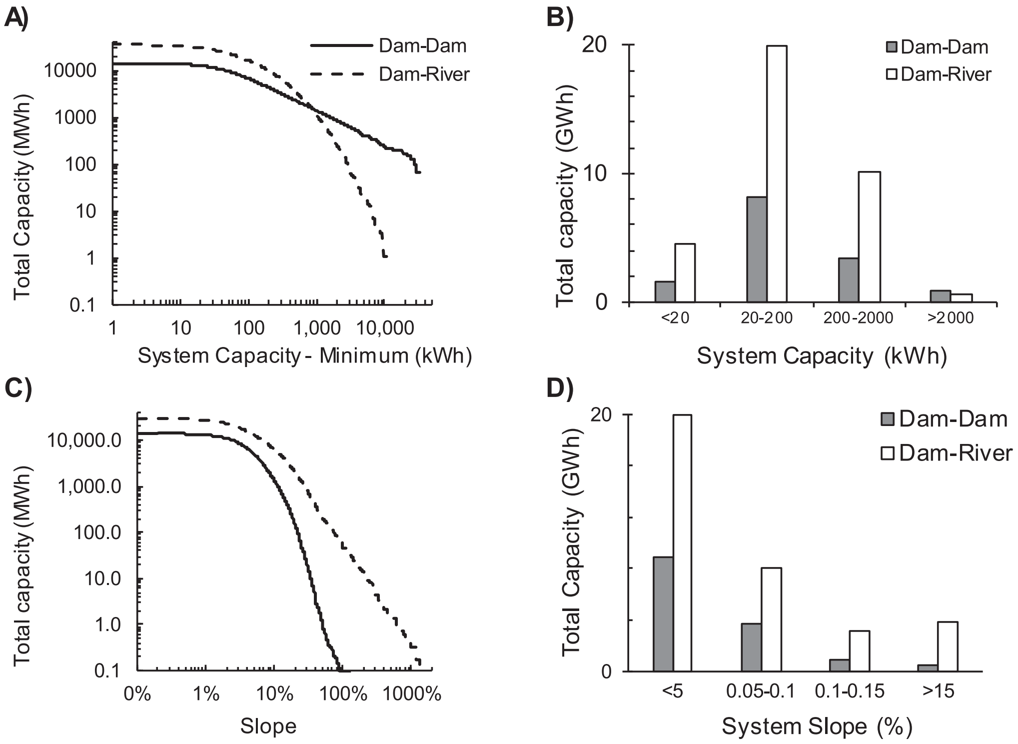
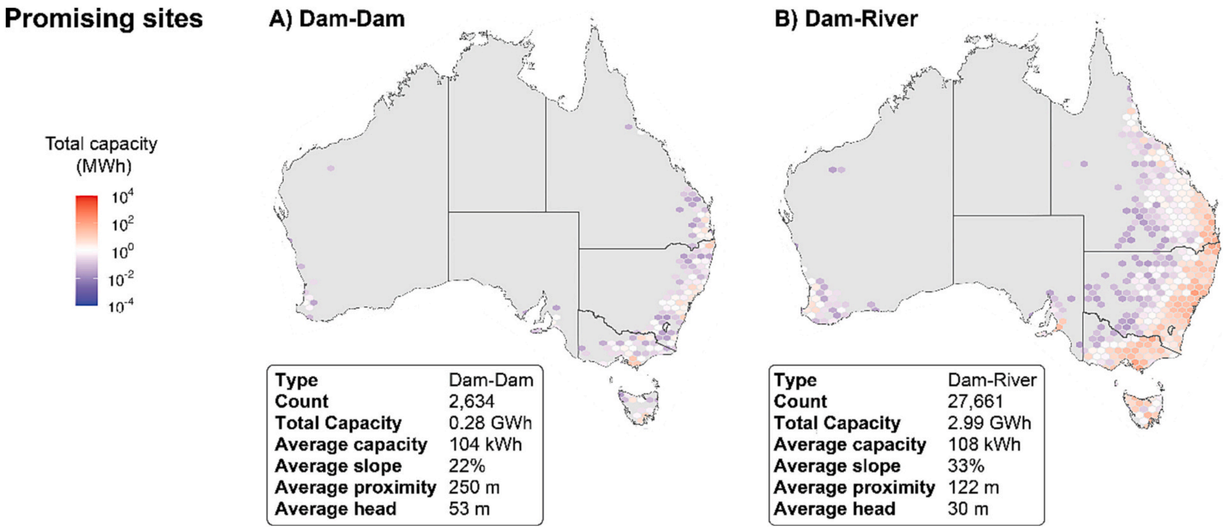


Fig. 4. A–B) Total energy storage capacity as a function of individual system capacity, for dam-dam and dam-river sites, most capacity exists in intermediate capacities between 20 and 2000 kWh. C–D) Total energy storage capacity as a function of individual system slope, for dam-dam and dam-river sites capacity drops off as slope increases. Although, dam-river sites have 11% of their total capacity above a slope of 15%, compared to 3% for dam-dam sites.



Type	Dam-Dam
Count	2,634
Total Capacity	0.28 GWh
Average capacity	104 kWh
Average slope	22%
Average proximity	250 m
Average head	53 m

Type	Dam-River
Count	27,661
Total Capacity	2.99 GWh
Average capacity	108 kWh
Average slope	33%
Average proximity	122 m
Average head	30 m

Fig. 5. Nominal energy storage capacity of promising A) dam-dam and B) dam-river sites in Australia. Includes sites with a nominal capacity above 23.82 kWh and a slope >17%. The nominal capacity does not account for efficiency losses or usable volume.

3.2. Promising energy storage capacity

The feasible energy storage capacity may be estimated by filtering sites below a minimum energy storage capacity and slope as in Fig. 4. For competitiveness, it is assumed that each site requires more storage capacity than a commercially available home battery (~13.5 kWh) while accounting for its low round-trip efficiency (50%), effectively filtering sites below a nominal energy storage capacity above 23.8 kWh. Sites with <17% slope are also filtered out to limit piping and civil work costs and provide sufficient power output. This slope value is based on the dam-dam concept slope analysed in Section 3.3.

After applying these filters, there remains significantly more promising dam-river (27,661) than dam-dam (2634) sites. Promising dam-river sites also have a higher total capacity (2.99 GWh) than dam-dam sites (0.28 GWh). Dam-river and dam-dam sites have an average capacity of around 106 kWh. However, dam-river sites have a higher slope (33% vs. 22%) and closer proximity (122 m vs. 250 m) on average, while dam-dam sites have a higher average head (53 m vs. 30 m). The geographic distribution and summary statistics for dam-dam and dam-river sites are shown in Fig. 5.

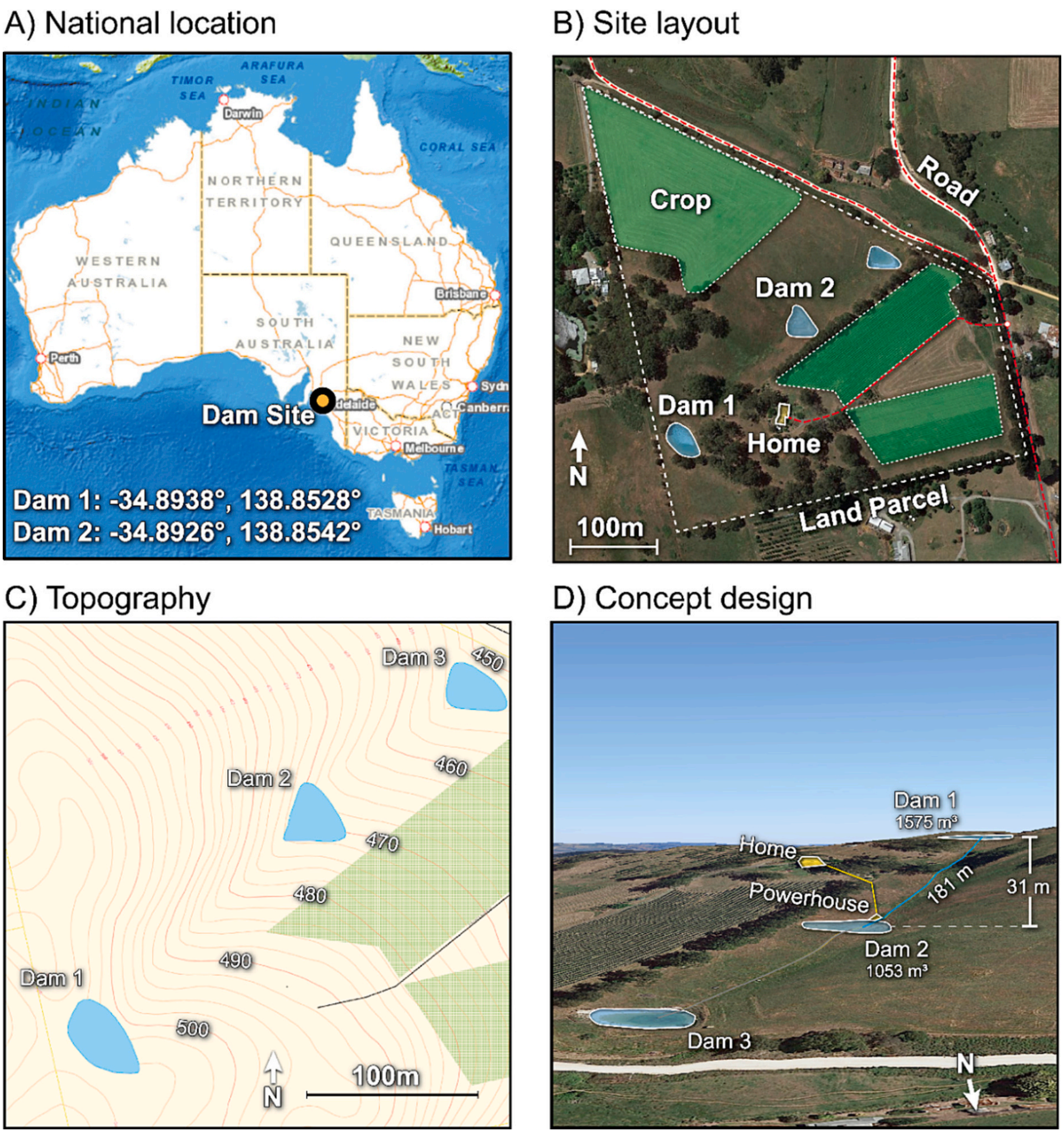


Fig. 6. A–D) The site has a nominal storage capacity of 89.0 kWh, which is reduced to 42.6 kWh when assuming a usable volume of 70% and discharge efficiency of 68.4%. The site is in South Australia in the Mount Lofty Ranges, within a Water Protection Area intended to protect water quality from contaminants such as wastewater, animal faeces and fertilisers. The most common soil type on the land is acidic sandy loam over brown or grey clay on rock [54–57]. This concept is based on publicly available information and commercial off-the-shelf parts; site-specific studies should be conducted before further development. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Micro-PHES performance, cost, and impacts

The micro-PHES concept is presented in Fig. 6 and is now compared to a Tesla Powerwall as an industry benchmark for small-scale energy storage; with section 2.4 relevant in the methodology. The micro-PHES had a lower power (3.6 kW vs. 5 kW) and slower response time than the battery. However, both are suitable for the solar-powered irrigation system considered by this study. The micro-PHES has a longer estimated service life (20 years vs. 10–15 years) and less annual efficiency degradation *(−0.2% vs. 3.5%) [19,29]*. However, the discount rate limits the net present value of these longer-term advantages. The micro-PHES has a significantly lower discharge efficiency *(67.6% vs. 94.9%) and higher capital costs (USD 25,613 vs. USD 11,753), so it must capitalise on its larger storage capacity (43 kWh vs. 13.5 kWh) to be viable. Although this margin may be reduced by future efficiency improvements, given the technological immaturity of* micro-PHES.

The micro-PHES and battery LCOS depend on daily load and cycles, as shown in Fig. 7. A Powerwall has the lowest LCOS across all loads assuming multiple cycles are feasible. For example, at a daily load of 20 kWh, the micro-PHES LCOS is *2.2× higher than the Powerwall: 0.457 USD/kWh vs. 0.208 USD/kWh.* However, higher loads (>13.5 kWh) require multiple battery charge/discharge cycles, which may not be possible given the limited hours of solar availability. For example, consider a 24/7 irrigation system that requires 2 kW and receives around 8 h of effective solar PV. A single Powerwall could sustain this system for about 7 h, unable to span the hours of unavailable solar PV overnight. In contrast, the micro-PHES sustain this system for up to 21 h. Of course, three Powerwalls could match this energy storage capacity. However, this would make the battery LCOS 1.43× more than the micro-PHES: *0.308 USD/kWh vs 0.215 USD/kWh.* The LCOS estimates suggest

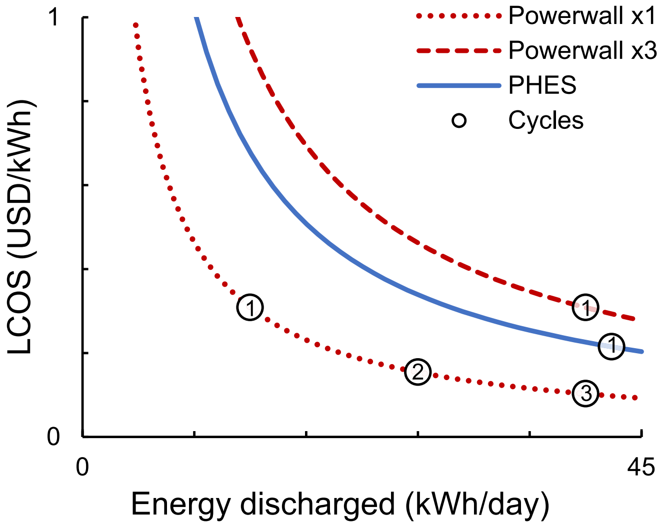


Fig. 7. LCOS for a micro-PHES, single Tesla Powerwall and three Tesla Powerwalls with respect to the load they are servicing. The circled numbers indicate the charge/discharge cycles required to meet the daily load. For reference, the average home in South Australia consumes around 20 kWh per day, although agricultural businesses are often much above this.

Table 3
Advantages of distributed storage for micro-PHES and lithium-ion batteries when coupled with rooftop solar PV.

Micro-PHES	Lithium-ion battery
Higher storage capacity Enables multi-day backup and extended load-shifting capabilities for residential prosumers. The increased capacity may also benefit high-demand commercial operators such as sugar, dairy and horticulture [48]	**More cost-effective for household loads** Lower capital costs and LCOS for typical household loads below 20 kWh
Long service life Potential for extended lifespan through periodic component replacement, such as the pump. Although, real-world validation is required.	**Low maintenance requirements** A more mature product with easy operation for customers, and no need to clear filters and maintain pump seals and oil.
Lower life-cycle impacts Reports of reduced impacts regarding global warming potential, mineral-metal use and human health (carcinogens) [32]	**Lower natural land transformation** Hardware may introduce visual and noise pollution [32], and operation may cause habitat loss through changes in water quality and disruption of river flow. Although, the use of existing reservoirs, rather than the construction of new ones, limits these impacts
Potential dual irrigation use Agricultural sites may benefit from increased irrigation capabilities. But this depends on irrigation schedules and water availability, with droughts and regulations presenting external risks [26]	**High round-trip efficiency** 90% efficiency benefits peak shaving and load shifting capabilities, as well as other arbitrage benefits depending on local tariff structures and market regulations.
Limits fire risks Avoid consumer perception of fire risks that are a persistent issue for lithium-ion batteries [33]	**Fast reaction speed** Suits fast response applications like frequency control ancillary services, or spot price arbitrage in a virtual power plant

micro-PHES could provide a competitive storage solution, aligning with the findings of earlier studies. However, the broader advantages and disadvantages should be considered in the context of the specific application. Furthermore, each technology's broader advantages and potential impacts should be considered; described in Table 3.

3.4. Generalisability of the Australian case study

The assessment of farm dam micro-PHES capacity was enabled by a new survey of these small water bodies by Malerba et al. [25]. The group trained a neural network on satellite imagery to identify 1.76 million farm dams in Australia, and 2.56 million in the U.S. [26]. The work significantly expanded the inventory of 0.01 ha to 0.1 ha water bodies in these nations, although significant uncertainty remains for other regions. However, some estimates suggest there may be around 3.2 billion worldwide [23]. These natural and constructed farm dams represent a significant opportunity for micro-PHES systems, although the distribution of this opportunity is uneven.

The distribution of farm dams has shown a consistent relationship with agricultural land area and precipitation. Based on a linear regression model of 13 regions in North America, Europe and India, the proportion of farm area covered by farm ponds (FP), increases with average annual precipitation (P) from around 0.1% to 6% following Eq. 6 from Downing et al. [58]:

$$FP = 0.019e^{0.0036P}\ \left[R^2 = 0.8, n = 13\right] \tag{7}$$

This relationship serves as a useful estimate when considering the generalisability of our Australian results to other regions. For example, regions with a high proportion of land area used for agriculture, and with high amounts of precipitation are likely to have a greater density of farm dams. Regions with higher levels than Australia include India, China, most of Europe, the United States, Mexico, Argentina, and parts of Western and Eastern Africa including Kenya and Nigeria. However, there are limitations to this approximation, some of which are clarified by mapping Köppen-Geiger climate zones and cropland areas as shown in Figs. 8 and 9.

Köppen-Geiger climate zones account for mean monthly temperatures and seasonality, as well as mean annual precipitation and patterns. Arid desert zones have sparse croplands due to difficulty collecting and conserving water [59]. As expected, the Australian case study also shows a limited number of farm dams in its central desert, with the majority along the eastern and south-western coastline in temperate agricultural regions. Notably, Australia does not have cold and polar zones. Freezing temperatures could significantly affect the performance and cost of a micro-PHES system. For example, the powerhouse and piping must be well-insulated and heated to prevent freezing. Partially frozen reservoirs may also affect storage capacity by reducing the available volume of water. Lastly, Australia has some isolated tropical zones, however, these do not provide a large representative sample for tropical regions in other regions internationally.

As a distributed energy storage solution, the demand for micro-PHES is bound to the demand for distributed energy generation from solar PV. Growth of distributed solar is strong in Europe, China, the U.S., Europe, Japan, and Australia. Australia provides a leading case, with panels already on 30% of homes [60,61]. Additionally, individual states provide broader cases with distributed solar contributing from 2.4% to 18.0% of annual electricity demand [62]. Uptake in these regions reflects different factors such as subsidies, homeownership rates and solar irradiance. Regions with limited uptake of distributed solar may find less demand for small-scale energy storage, such as micro-PHES.

A global assessment of micro-PHES from farm dams would be ideal, however, the data is not yet available. The survey method developed by Malerba et al. [25] can be replicated for other regions, to enable the accurate assessment of micro-PHES capacity using farm dams. In the interim, this first-of-its-kind continental case study provides a representative case study for many agricultural regions in arid, temperate, and tropical regions, with an uptake of distributed energy systems.

4. Conclusion

Energy storage is crucial for achieving an affordable, reliable, and

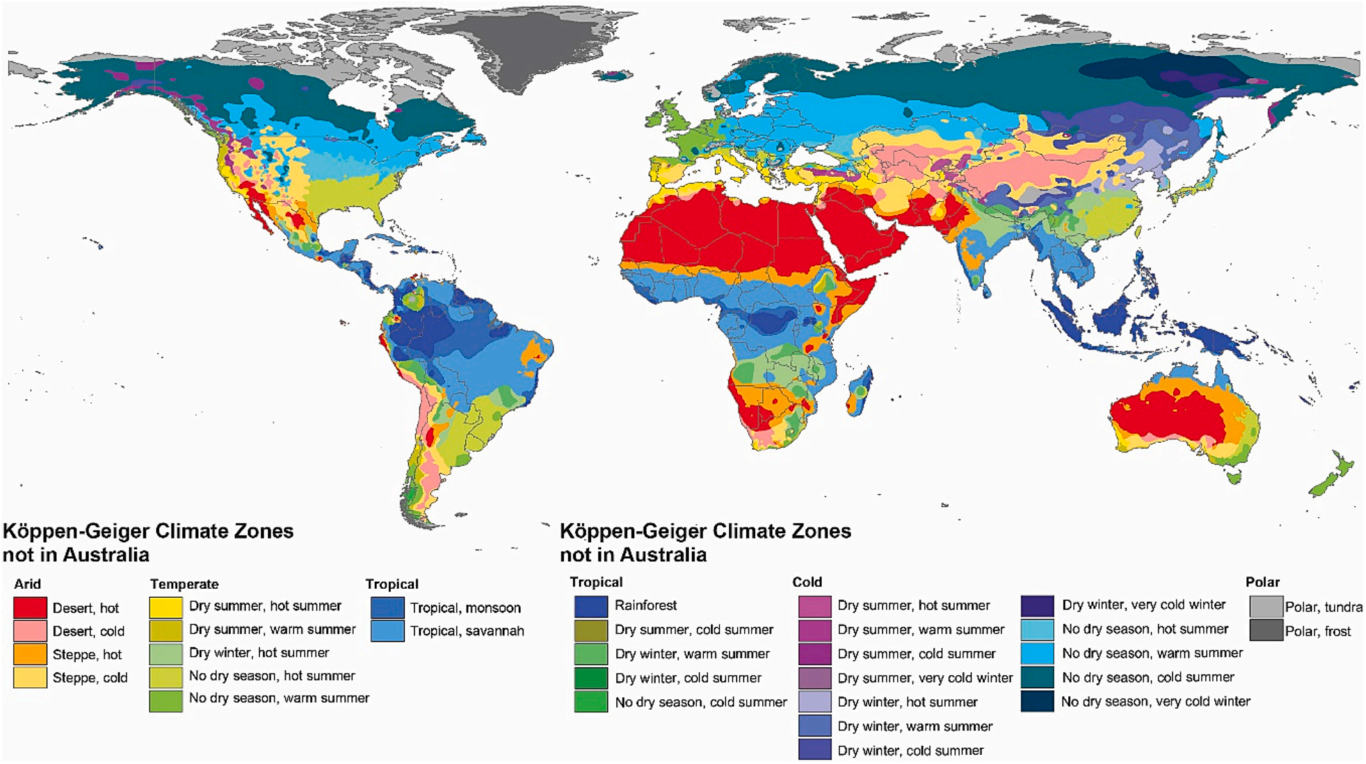


Fig. 8. A) Köppen Climate Zones with those present in Australia listed in the left legion, and those not listed in the right legend [59].

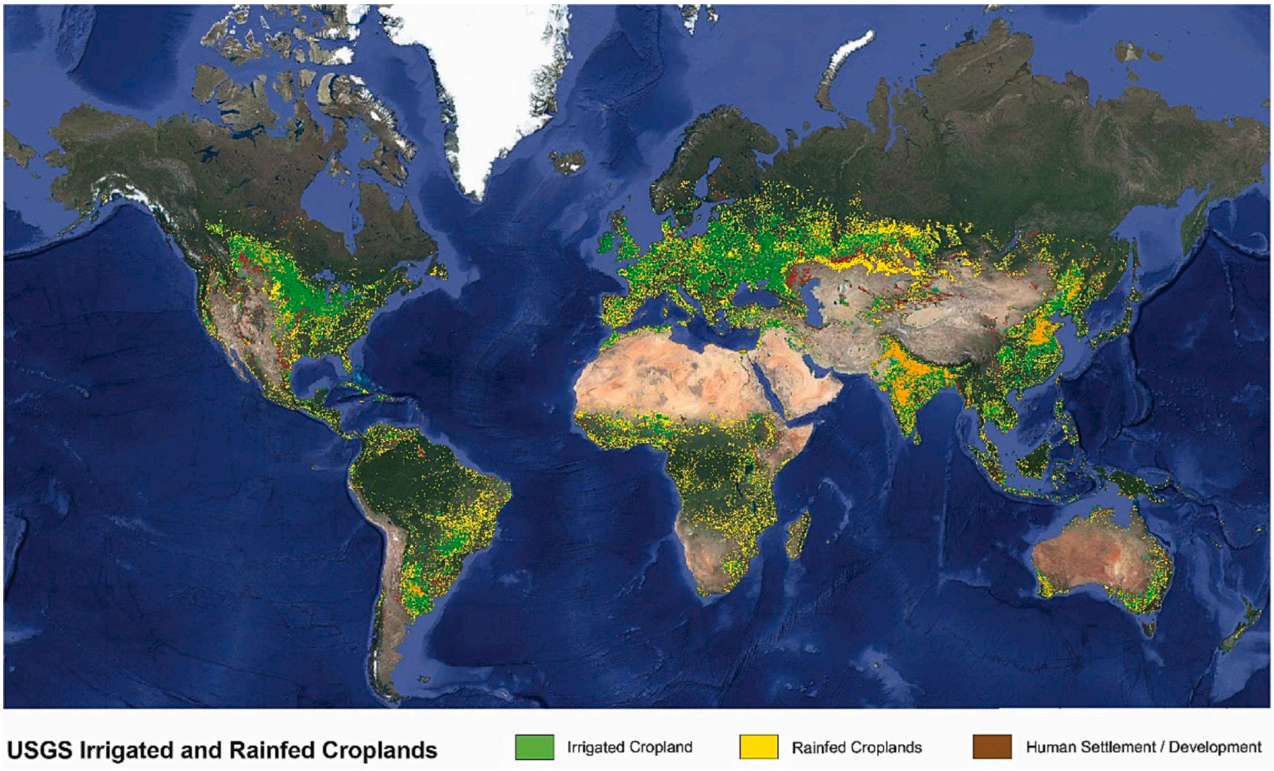


Fig. 9. U.S. Geological Survey Landsat-derived global rainfed and irrigated area produced at 30 m noting the lack of croplands in desert regions where precipitation is low [63].

sustainable power supply from wind and solar PV, especially for distributed energy systems as the number of household solar PV units is expected to quadruple to 100 million by 2030. Here, micro-PHES presents an emerging solution. The high storage capacity may allow prosumers to decrease their electricity bills and carbon emissions through increased solar self-consumption, while extended backup power affords an increased sense of security. Unfortunately, the construction of required water reservoirs remains prohibitively expensive. This bottleneck may be overcome through the use of existing reservoirs; however, no assessment of potential sites has been conducted. This study provided the first assessment of these sites, and conducted it at a continental scale. Specifically, proposing the use of agricultural reservoirs (farm dams) to eliminate reservoir construction costs.

Of 1,694,675 farm dams in Australia, we identified 30,295 promising sites for micro-PHES systems, in dam-to-dam and dam-to-river reservoir configurations. Each of these promising sites had a capacity above 24 kWh, to support increased solar self-consumption. Each also had a slope >17%, to limit component and construction costs. A concept was developed for a representative site and benchmarked against a commercially available lithium-ion home battery. For a high single-cycle load above 40 kWh/day, the estimated LCOS for the micro-PHES was 30% lower than the battery due to the substantial storage capacity.

By identifying thousands of desirable sites for micro-PHES that eliminate reservoir construction costs this study contributes a valuable inventory for the future development of a nascent energy storage technology. Capitalising on existing farm dams presents an advantage for agricultural communities, beyond established cost and emission reduction benefits from solar self-consumption. Specifically, these rural areas may benefit from irrigation hardware synergies and extended backup power during outages affecting vulnerable fringe networks. Although encouraging, there are limitations to the study that require further analysis.

4.1. Limitations and future work

4.1.1. Water availability

Our assessment assumes that farm dams have 70% usable volume. In reality, the water level of farm dams fluctuates substantially between dry and wet seasons. These fluctuations may reduce the usable energy storage capacity of an actual micro-PHES system compared to our prediction. This is particularly important given farm dams in Australia are becoming a less reliable water source under climate change [26].

4.1.2. Australia generalisability

Uncertainty remains for surveys of small water bodies (0.01 ha to 0.1 ha) in regions outside Australia and the U.S. However, previous studies suggest their density increases in agricultural regions with increased precipitation. In this regard, Australia is representative of other arid and temperate regions worldwide including, for example, China, Europe, the United States, Mexico, Argentina, and parts of Africa. However, tropical regions are sparsely represented, and cold-polar regions are missing. The latter is important as freezing temperatures would likely affect the operation of hydraulic and electrical equipment, and thus the cost and performance of a micro-PHES system. The Australian scope was selected due to a lack of survey data in other regions. However, future work may repeat survey and assessment methods to replicate results in other regions of interest, such as those with significant agricultural and solar PV development.

4.1.3. Solar-powered irrigation

The micro-PHES concept assumed all charge and discharge power was produced and consumed locally. This simplifying assumption followed previous micro-PHES pilots [19]. However, more accurate system performance and costs could be estimated through transient simulations, such as those by Mousavi et al. [28,29,41]. The researchers optimised an energy management system based on energy generation-demand-tariffs, water demand, weather forecasts and system losses to maximise profitability. For the current study, local data for the micro-PHES concept was not available. However, future studies should perform numerical optimisations to maximise benefits for potential consumers.

4.1.4. Social and environmental impacts

Previous work suggests that pumped hydro would have lower life cycle impacts than lithium-ion batteries for: global warming potential, mineral-metal use and human health (carcinogens) [32]. However, the results also suggest micro-PHES would have higher for natural land transformation such as visual and noise pollution. Furthermore, hydro has the potential for habitat loss through changes in water quality and disruption of river flow. Although connecting existing, rather than newly constructed, reservoirs may help minimise these impacts. Regardless, the social and environmental impact potential requires dedicated investigation before the deployment of this distributed energy storage technology.

4.1.5. Technological immaturity

Although large-PHES is a mature energy storage solution, micro-PHES is not. This leaves significant scope for efficiency improvements. Using pumps as a turbine is uniquely suited to micro-PHES, with active research seeking to optimise efficiencies in forward and reverse flows. Real-world studies would also help validate potential performance, as few exist, and those that do exist in university campus pilots.

CRediT authorship contribution statement

Nicholas Gilmore: Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Thomas Britz:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Erik Maartensson:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Carlo Orbegoso-Jordan:** Conceptualization, Investigation. **Sebastian Schroder:** Validation. **Martino Malerba:** Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Martino E. Malerba reports financial support was provided by Australian Research Council

Data availability

Data will be made available on request.

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