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Revisiting the potential of pumped-hydro energy storage: a method to detect economically attractive sites.

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ABSTRACT

This study innovatively combines a set of methods to provide a new way to assess the economic potential of pumped hydro energy storage. It first provides a method based on geographic information systems to study the potential of pumped-hydro for different topologies. Second, using cost estimates for each identified site, cost-potential curves are derived. Finally, these curves are used for planning a fully renewable system to assess their impact on investment recommendations. Applications to Chile, Peru, and Bolivia show the usability of the methods.

Over 450 pumped-hydro locations are identified, totaling around 20 TWh (1600 GW of installed capacity with 12 hours of storage). These numbers exceed by 20-fold the projected daily energy demand of the corresponding countries. When taking into account investment costs, most locations are cheaper than current Li-ion batteries, but only some are expected to remain competitive. When using the resulting cost-potential curves to design a future energy system, the planning tool recommends about 1.6 and 5.0 times more pumped-hydro storage compared to using average values and literature values, respectively. These differences underline the significance of the found cost curves.

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These findings are relevant to the energy planning community, policymakers, and energy companies.

Keywords (6): GIS-based siting; optimization; energy storage mix; climate change; energy system analysis;

ACRONYMS

DEM: digital elevation model
GIS: geographic information system
PHES: pumped-hydro energy storage

1 Introduction

Future energy systems based on renewable technologies need a high degree of flexibility, stemming, for example, from transmission systems [1], sector integration [2], demand-side management [3], curtailment of excess energy [4], and storage systems [5]. To plan these future systems, optimization tools are often used. And although there have been strong advances in the last years, especially in what refers to storage and cross-sector modeling, some limitations remain [6]. The present work focuses on energy storage, particularly on the techno-economic potentials of pumped-hydro energy storage (PHES) for energy planning tools.

The last decade has seen increased efforts in understanding the required storage technologies for future energy systems. The review of Cebulla [5], for example, systemized these storage requirements from over 500 scenarios for increasing shares of renewables. Another two reviews [6], [7] looked at the involved modeling tools for energy system planning and derived their trends and open challenges. What comes clear from these three reviews, which together looked at over 300 publications, is that there is no single-supreme storage technology (or one that outperforms all others). Instead, a combination or a mix of storage technologies is often found as a cost-efficient solution [8].

Studies commonly show storage mixes that strongly rely on PHES, complemented with Li-ion batteries for short-term storage. Hydrogen systems, and, to a smaller extent, compressed air energy storage [9], provide long-term storage [10], [11]. In Chile, for example, even in the year 2050 (where battery costs are expected to have decreased significantly), the installed energy capacity of PHES is still 250% larger than Li-ion [8]. Also for the year 2050, very similar numbers are found for Europe and Germany (PHES being 190% and 70% larger than Li-ion, respectively) [10]. Another study found that when rolling out high-temperature and district heating together with gas storage (green methane), Chile's future system could be competitive without PHES [12]. The same model applied to Bolivia revealed that PHES plays a similar role to batteries [13]. The key difference between the two studies lies in the assumptions on the PHES potential, clearly indicating a high sensitivity between Li-ion battery storage and PHES. The probably most comprehensive study on planning the world's all-sector energy supply envisions a much more predominant role for battery systems as the least-cost storage for fully renewable systems, with other storage devices playing a subordinate role only. There, the energy capacity of PHES is 20 times *smaller* than Li-ion [14]. Bloomberg [15] is also projecting strong growth of Li-ion: while until 2017 PHES constituted for over 97% of the world's installed electricity storage capacity, Li-ion will overtake PHES' cumulative capacity in 2028. Deploying these amounts of Li-ion batteries, however, might be limited by the availability of critical materials (such as lithium [16] and cobalt [17]), as well as by the high costs for storing energy beyond a couple of hours (the current economic size of Li-ion is between 2 to 6 hours of energy capacity, as can be derived from [18]). The race between PHES and batteries seems still to be open.

PHES is a well-established and flexible technology. It has been around for over a century and surged especially between the 1960s-1980s as a flexibility provider to slower thermal power plants [19]. Besides simple energy shifting (or arbitrage), PHES is quick enough to provide ancillary services such as frequency regulation, needed for highly renewable systems. This is why the interest in PHES has resurged in the last years [19]. While wind or solar photovoltaic projects are highly modular, PHES comes in many shapes and is highly site-specific. To name a few PHES topologies: closed-loop PHES (upper and lower reservoirs connected with pump-turbines with no natural inflows) or open-loop PHES (with natural inflows to at least one of the reservoirs); and the corresponding reservoirs can be either human-made (classical dams, ring dams, abandoned mines) or natural (such as a lake, river, or sea). For more information refer to the review done by Blakers et al. [20]. Each of these topologies presents diverse investment and operating costs (and environmental impacts [21]) but this manifold is not captured by the energy models yet. In general, costs are a fundamental driver in techno-economic planning exercises, and cost assumptions of energy technologies have shown to be highly distorted in the past, often being too pessimistic in the sense of overestimating actual costs [22]. This is an aspect that the present work wants to address for PHES.

Further exacerbating the above issues, models often recommend deploying all the available potential of PHES [8], [10]. This potential, however, is a coarse estimation—at best—as detailed studies are missing. In other words, the tools recommend strong investments into PHES but the concrete numbers turn out to be assumptions made by the model-user, and, again, do not discern between topologies. The Australian National University has made significant contributions in the last years towards improving the understanding of the world's PHES potential [23]. In 2018, they provided a clear overview of the existing efforts and found seven pertinent studies [19]. The first study [24], looked at existing reservoirs in Europe, identifying thousands of adjacent flatlands for potential conversion into PHES. Another study [25] followed a similar idea for over 600 existing reservoirs in Turkey. Two other studies took a more localized approach, analyzing a handful of dams in Spain [26] and Turkey [27]. The work of reference [28] added new topologies by searching for narrow valleys close to existing lakes in Tibet, finding hundreds of potential pairs. Similarly, the work from [29] looked for natural depressions close to existing lakes in France, identifying over 1000 sites. The seventh and last study [30] looked for off-stream flatlands in a region of Ireland, highlighting five sites. Having identified this gap, the Australian National University recently published the world's first atlas of PHES potentials [23]. This atlas, with over half a million potential PHES sites and 23.000 TWh of storage capacity, is great news for the energy transition and tremendously valuable for the energy community. Note that this is a technical potential only, and the economic feasibility was beyond its scope (as it was for the other seven mentioned studies). Including information from this atlas into energy planning tools would, however, require to have detailed cost curves, to avoid incurring the aforementioned issue of recommending *seemingly* cheap PHES, when in practice Li-ion seems to be favored. Another recent study focused on the PHES potential for seasonal storage, including costs curves, which also is highly valuable information for energy planners. They derived the world's potential but such a wide scope comes at the cost of a lower spatial resolution (100 x 100 km) [31].

In short, PHES is being displaced by Li-ion systems. Nonetheless, PHES seems to have a future when exceeding the economic size of Li-ion systems. This economic size will indubitably change in the upcoming years, but the current cost projections point to a tight race between both technologies. The cited studies underline this idea [8], [10], [12]–[14] because they either recommend both Li-ion and PHES technologies or recommend a single technology that, after a close inspection, has a similar levelized cost as the competing technology. Given the underlying linear optimization models, a small change in costs could flip the results (called "penny switching"). The uncertainty in the winning technology motivates us to explore PHES in more detail regarding costs and technical potentials, especially in the context of the imperfect cost estimates that the existing studies use.

The working hypothesis of the present work is that PHES will remain cost-effective (second least-costs or comparable costs) even when compared to distant-future (and cheap) utility-scale Li-ion battery systems, hence offering an alternative to potential limitations or bottlenecks in Li-ion systems. To test this hypothesis, this work will assess the PHES potential, including cost-potential curves, and use these curves in an expansion planning exercise. With the goal of improving the understanding of the PHES potential, this study contributes to the existing body of knowledge by providing a new method for assessing the cost potential of PHES that combines different approaches. Concretely, it:

- Assesses the technical potential of PHES for different PHES topologies. Promising locations are identified for the lowest-cost topologies, involving PHES based on a) pairs of existing reservoirs, b) existing lower reservoirs, c) seawater as lower reservoir, and d) rivers as the lower reservoir.
- Derives cost-potential curves for the identified PHES locations. These curves are produced for each PHES topology and country.
- Examines whether and how these new cost-potential curves of PHES impact long-term energy planning decisions.

This method can be applied anywhere in the world. The present work illustrates it with a case study in the South Andes: Chile, Peru, and Bolivia. In this way, it provides concrete and timely numbers to aid the ongoing energy transition in South America, which has obtained little scientific attention. The review of reference [32], without the ambition of being exhaustive, identified only a handful of studies on planning the energy transition of South America, compared to hundreds of studies listed for Europe or the U.S. [5], [6], [33], [34]. Moreover, the potential of PHES is not yet well studied in Latin America, probably due to the historically abundant flexibility from large cascading hydropower facilities. For fully renewable systems, flexibility is now becoming more scarce.

The next section will detail the methods, which are based on a geographic information system and optimization-based expansion planning. Section 3 discusses the results, including the PHES potential for the different topologies and countries, the corresponding cost-potential curves, and the impact of these curves on planning Chile's electricity system in 2050. Section 4 concludes and recommends future work.

2 Methods

Recall that the objectives of the present work are: i) to calculate the technical potential for promising topologies; ii) to derive costs curves for each of the PHES topologies; and iii) to test how these new cost-potential curves impact the long-term storage investment decisions. Parts i) and ii) of the methods are applied to the South Andes (Chile, Peru, Bolivia), and part iii) to Chile. This section is structured in direct response to these objectives. Section 2.1 (see Panel 1 of Figure 1) will explain how the technical PHES potential is calculated based on geographic information systems. Section 2 (see Panel 2 of Figure 1) will then detail the cost assessment for the found PHES sites to derive the cost-potential curves. Finally, Section 3.1 (see Panel 3 of Figure 1) will introduce the used optimization tool for expansion planning.

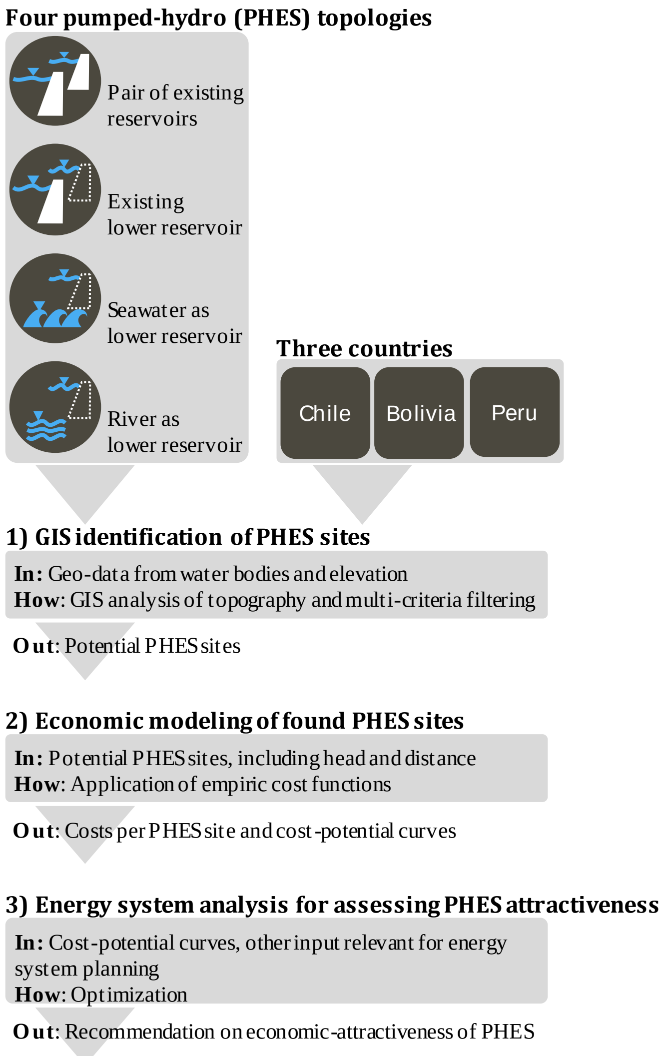

Figure 1 Flowchart of methods.

2.1 GIS identification of PHES sites

The considered PHES topologies, the used method for geographic information systems (GIS), and the collected input data for finally deriving the technical potential of PHES are described next.

2.1.1 Considered PHES topologies

There are many different PHES topologies. Reference [35] lists seven: 1. connecting an *existing pair* of reservoirs (with a penstock, pump-turbine, and a powerhouse); 2. building a new reservoir in the proximity of *an existing reservoir*; 3. *conventional* greenfield PHES (building everything from scratch); 4. *seawater greenfield* PHES (with the lower reservoir being the sea); 5. *multi-reservoir* systems including conventional hydropower and PHES; 6. adding a new reservoir close to a *river* that serves as a lower reservoir; and 7. adding a new reservoir close to an *abandoned open-pit mine* which serves as one of the reservoirs.

From these seven topologies, four are picked in this study (1, 2, 4, and 6), with the following abbreviations for the remainder of the paper:

- *Existing pair*: finding and connecting existing pairs of reservoirs;
- *One reservoir*: building a reservoir and connecting it to an existing lower reservoir;
- *Seawater*: building a reservoir and connecting it to seawater that serves as the lower reservoir;

- *River*: building a reservoir and connecting it to a river that serves as the lower reservoir.

The reasoning behind picking these four topologies is that the authors see them as most promising in terms of costs and energy potentials. Moreover, these four topologies consider the water bodies (and their availability) for the construction of the PHES system. Water is an essential part of a PHES system and should be a central point in any assessment model. Without secure access to water, even the most promising topographical locations are not feasible (and still many studies look at topographies only). Arguing on the discarded options: greenfield building PHES from scratch (topology 3) is costlier than using existing reservoirs. Multi-reservoir PHES (topology 5) and abandoned open-pit mines (topology) are certainly interesting options, but they also show a very limited potential and are for this reason not further explored in the present work. Note that these are *assumptions to limit the scope* of the *present* work and that they should not discourage future research on those topologies.

2.1.2 Description of the GIS methods for finding PHES sites

Two different GIS-based models, written in *python* and based on *QGIS*, are used to find potential PHES sites. The first model focuses on the topology of *existing pairs* of reservoirs, while the second on the topologies *one reservoir*, *seawater,* and *river*. These models can be applied to any reservoir database and region to detect the potential of these PHES topologies, as detailed in reference [36]. Table 1 summarizes the main steps of each model, discussed below.

The first GIS model aims to discover *existing pairs* of reservoirs meeting distance and height difference criteria. The main inputs involve georeferenced data of existing reservoirs and a digital elevation model (DEM) of the country under study. In the first step, for each existing reservoir, the model detects those reservoirs within a 20 km radius. In the second step, the model calculates the elevation difference between the reservoirs and keeps only those with a minimum head of 150 m.

The second model is for the PHES topologies *one reservoir*, *seawater*, and *river*. Here, the model first searches for the corresponding (existing) lower reservoir and then for a possible (yet inexistent) upper reservoir. The difference between these three topologies is the considered water body as a lower reservoir. In the *one reservoir* topology, the inputs are a georeferenced database of the existing reservoirs. In the *river* and *seawater* topologies, the inputs are the rivers and coastlines, respectively. These rivers and coastlines are discretized into points located 40 km between each other (and these points will serve as a lower reservoir). Non-perennial rivers are filtered out. For each prospective lower reservoir (i.e. existing reservoir, river-point, and sea-point for the topologies reservoir, seawater, and river, correspondingly), the model analyzes the surrounding area to discover suitable areas for the construction of the upper reservoir. An area is found to be suitable, when it is flat (maximum slope of 5%) and when it has a minimum area of 70,000 m^2. Assuming that 20,000 m^2 of this area is destined for civil works, a depth of 20 m would allow for a storage capacity of 1,000,000 m^3 (50,000 $m^2 \cdot 20$ m), which is the assumed target volume.

Table 1 *Summary of the GIS methods for finding PHES sites.*

PHES topology	GIS model	Main steps of the GIS model
Existing pairs	Model 1	- Input data: georeferenced reservoir database and DEM[1] - For each reservoir under test, select reservoirs within a 20 km radius - Filter for reservoirs with elevation 150 m above the reservoir under test
One reservoir *Seawater* *River*	Model 2	-Input data: *one reservoir*: georeferenced reservoirs database (considered as the lower reservoir) and DEM; *seawater*: coastline (considered as the lower reservoir) and DEM; *river*: rivers ways (considered as the lower reservoir) and DEM; non-perennial rivers are deleted - Coastlines and rivers are discretized in points of 40 km of distance between each other - For each prospective lower reservoir, scan for flat areas (slope <5%) within 20 km of radius - Select flat areas larger than 70000 m^2 - Select areas with an average elevation 150 m above the lower reservoir

[1] *DEM: digital elevation model*

2.1.3 Filters

The GIS models are the first stage in discovering potential sites for the construction of PHES plants. These sites are then filtered by land occupation and environmental criteria. For sites with more than one possible upper reservoir, the best upper candidate is selected, detailed next.

In particular, prospective PHES close to World Heritage Sites, protected areas, inhabited areas, and transportation infrastructures (roads, railways, and bridges) are discarded. The assumed minimum distance to these key features is 500 m except for transportation infrastructure which is 200 m (in line with reference [24]).

All considered PHES topologies start with a lower water body (existing reservoir, river-point, sea-point) and search for possible locations for an upper reservoir. In the case of multiple locations found, the most promising one is selected based on multi-criteria decision-making. The main drivers for the selection involve the area needed for the upper reservoir, the distance between the water bodies, and the head of the site. For each of these criteria, a weight was assigned based on the values presented in reference [36]. The largest weight was assigned to the head of each site. This was handled differently for the topology *existing pairs*. Here, the model might have, in a first step, resulted in duplicates, meaning that an existing reservoir is chosen as the upper reservoir for more than one existing lower reservoir. Potential duplicates were filtered based on head difference and the distance between each other to select the most attractive pairs.

2.1.4 Input data

The present study derives the technical PHES potential of Chile, Peru, and Bolivia. Each of the different topologies requires a different set of inputs, involving reservoir data, waterways, coastlines, and elevation.

Reservoir data. The PHES topologies *existing pairs* and *one reservoir* require data on the existing reservoirs of each country. The main database used is the Global Reservoir and Dam Database (GRanD, [37]) complemented with the waterbodies informed by DIVA-GIS [38]. The reservoir volumes for the selected reservoirs were filled with public sources. When unavailable, these volumes were approximated with GIS on the contour lines of each site.

Waterways and coastlines. The PHES topology *river* requires information on the inland waterways and the topology *seawater* on the coastlines. The waterways are taken from DIVA-GIS [38], then filtering for perennial flows. The coastline is downloaded from NaturalEarth [39].

Elevation. All topologies require knowing the height difference between (existing and prospective) water bodies. NASA's digital elevation model from the Shuttle Radar Topographic Mission of 3 arc-seconds (90 m) resolution is used [40]. This resolution has proven sufficient in a previous study [36].

2.2 Economic modeling of the PHES sites

The PHES project costs are estimated for each found site. With these costs, cost-potential curves per topology and country are derived.

Investment costs for the following PHES components are considered: reservoirs, turbines, power stations, electrical equipment, penstocks, roads, transmission lines, and additional infrastructure works (for seawater PHES). Cost formulas from Norway's hydropower plant cost database are the main source for the present study [41], as well as from U.S. hydropower tenders and contracts [42]. These sources are complemented whenever necessary. A detailed list, per hydropower component, with the formulas used and their sources, is shown in Table 2.

Next, the main cost assumptions per component are briefly detailed. For the topologies *existing pairs, one reservoir, and river*, this simplifies to a cost estimation of conventional hydropower plants. The seawater topology requires additional assumptions (to be visited shortly after). Construction costs for new reservoirs are assumed to be aligned with the lower end of reference [43]. The turbine cost equation comes from reference [42] and is a direct function of turbine capacity without having to specify the type of turbine. The turbine capacity is calculated by considering the upper reservoir volume, an assumed cycle of 12 hours, and the height difference. The power station costs are expressed in terms of the flow rate [41]. Other electric equipment is calculated based on rated power [41]. The penstock cost is based on length, which in turn is calculated using the distance between the upper and lower reservoir in a raster DEM file [44]. Miscellaneous costs include equipment such as machine hall crane, cooling, and drainage system; related to rated power and flow rate [42]. Contingency cost is assumed to be 16% [44] of the direct costs (i.e. the just mentioned components: reservoir, turbine, power station, electric equipment, penstock, and miscellaneous equipment). Transmission cost is taken from [19] and is a direct function of the distance between the PHES facility and the closest existing power line. The distance is estimated in a distance-line map with GIS. Road costs are taken from [41], which has two possible standards (high and low) and three terrain scenarios (easy, normal, and difficult). For the case of South America, the authors assumed a high standard and normal terrain. Finally, the seawater topology requires addressing two more technical issues: using corrosion-resistant materials for wet components and sealing the upper reservoir to prevent seawater from infiltrating the subsurface. These aspects are grouped under the label "several infrastructure works" from [45]. All components costs are first converted to euros and then actualized to the year 2019.

Table 2 *Summary of cost assumptions for the potential PHES plants.*

Component[1]	Cost assumptions	Nomenclature and units	Source
Reservoir (€2011)	$Cost_{reservoir} = 7.88(10^6)E$	E = Energy in GWh	[43]
Turbine ($2005)	$Cost_{turbine} = 1.19P^{0.76}10^6$	P = Power rate in MW	[42]
Power station (NOK 2010)[2]	$Cost_{power\ station} = -0.0006{Q_D}^2 + 0.67Q_D - 6.95$	Q_D = Discharge in m^3	[41]
Electric equipment (NOK 2010)	$Cost_{electric\ equipment} = 3.91P^{0.66}10^6$	P = Power rate in MW	[41]
Penstock ($2015)	$Cost_{penstock} = 27.40(10^6)L_{Penst}$	L_{Penst} = Length penstock in km	[44]
Miscellaneous ($2010)	$Cost_{miscellaneous} = (-38.79\log Q_D + 309.89)P$	P = Power rate in kW Q_D = Discharge in m^3	[42]
Contingency ($2015)	$Cost_{contingency} = 0.16(Direct\ Cost)$	Direct costs = sum of all components mentioned above	[44]
Transmission ($2015)	$Cost_{transmission} = 0.72(10^6)L_{line}$	L_{line} = Length transmission in km	[44]
Road (NOK 2010)	$Cost_{road} = 1500\ L_{road}10^3$	L_{road} = Length road in km	[41]

For seawater: several infrastructure works (€2013)	$Cost_{infrastructure\ works} = 9(10^7)E^{0.77}$	E = Energy in GWh	[45]

[1]The following values to convert the listed currencies into euros were used: NOK2010=0.12; \$2005=0.74; \$2010=0.70; \$2015=0.83. These values are then updated to €2019 with inflation rates ranging between 1.20 and 2.45.
[2] With a minimum investment of 20 million NOK2010.

For traceability, two examples of the cost calculation are given next. The first example corresponds to the topology of *one reservoir* and the second to *seawater*. The inputs are shown in Table 3, while the resulting costs are displayed in Table 4 and Figure 2. In the first example, most costs result from the penstock and turbines; while in the second example, most costs result from the penstock, transmission line, and adaptations to seawater (infrastructure works). The two latter are mainly responsible for *seawater* costing twice as much as *one reservoir* in this example.

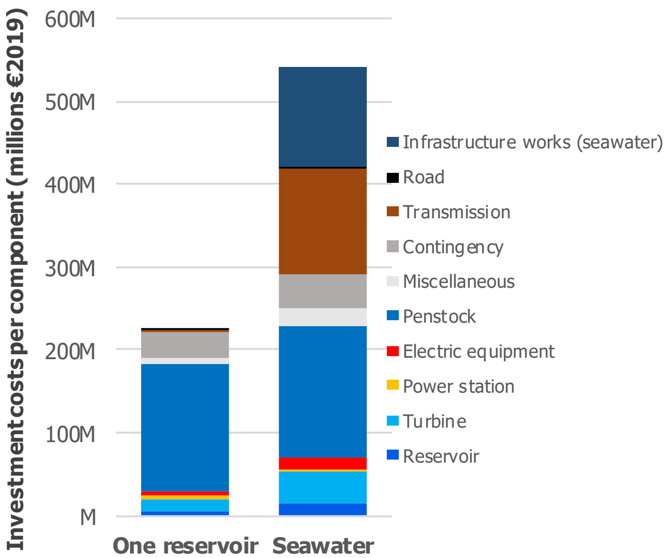

Figure 2 Example of investment costs per component for two selected sites from the topologies *one reservoir* and *seawater*

Table 3 *Main characteristics for each site.*

Topology	Head (m)	Pipe length (km)	Transmission line (km)	Volume UR (m^3)	Energy (GWh)	Q (m^3/s)	P (MW)
One reservoir	150.00	6.43	4.18	1,200,000.00	0.45	27.78	37.49
Seawater	274.00	6.60	205.48	2,134,478.25	1.46	49.41	121.80

After estimating the costs of each prospective PHES site, the cost-potential curves are derived. For each country and topology, these curves will relate PHES costs (sorted from lower to higher costs) with the cumulative PHES capacity. Such curves can then be used in expansion planning exercises.

Table 4 *Example of cost calculation for two sites.*

Component	Cost topology *one reservoir* (€2019)[1]	Cost topology *seawater* (€2019)
Reservoir	$Cost_{reservoir} = 7.88(10^6)0.45(1 + 0.0193)^8 = 4.1M$	$Cost_{reservoir} = 7.88(10^6)1.46(1 + 0.0193)^8 = 13.4M$
Turbine	$Cost_{turbine} = 1.19(37.49)^{0.76}10^6(0.737)(1 + 0.012)^{14} = 16.3M$	$Cost_{turbine} = 1.19(121.8)^{0.76}10^6(0.737)(1 + 0.012)^{14} = 39.9M$
Power station	$Cost_{power\ station} = 20{,}000{,}000(0.12)(1 + 0.0245)^9 = 3.0M$	$Cost_{power\ station} = 20{,}000{,}000(0.12)(1 + 0.0245)^9 = 3.0M$
Electric equipment	$Cost_{electric\ equipment} = 3.91(37.49)^{0.66}10^6(0.12)(1 + 0.0245)^9 = 6.4M$	$Cost_{electric\ equipment} = 3.91(121.8)^{0.66}10^6(0.12)(1 + 0.0245)^9 = 13.9M$
Penstock	$Cost_{penstock} = 27.40(10^6)6.43(0.827)(1 + 0.0134)^4 = 153.7M$	$Cost_{penstock} = 27.40(10^6)6.60(0.827)(1 + 0.0134)^4 = 157.7M$
Miscellaneous	$Cost_{miscellaneous} = (-38.79\log(27.78) + 309.89)37.49(10^3)(0.698)(1 + 0.0245)^4 = 7.3M$	$Cost_{miscellaneous} = (-38.79\log(49.41) + 309.89)\ 121.80(10^3)(0.698)(1 + 0.0245)^4 = 22.9MW$
Contingency	$Cost_{contingency} = 0.16(Direct\ Cost) = 30.5M$	$Cost_{contingency} = 0.16(Direct\ Cost) = 40.1MW$
Transmission	$Cost_{transmission} = 0.72(10^6)4.18(0.827)(1 + 0.0134)^4 = 2.6M$	$Cost_{transmission} = 0.72(10^6)205.48(0.827)(1 + 0.0134)^4 = 129.0MW$
Road	$Cost_{road} = 1500(6.43)10^3(0.12)(1 + 0.0245)^9 = 1.4M$	$Cost_{road} = 1500(6.60)10^3(0.12)(1 + 0.0245)^9 = 1.5M$
Infrastructure works	Does not apply	$Cost_{infrastructure\ works} = 9(10^7)1.46^{0.77}(1 + 0.0231)^6 = 120.4M$
Total	$Cost_{total} = 225.4M$	$Cost_{total} = 559.5$M

[1]The conversion factors following the formulas correspond to currency conversion and adjustment for inflation (see footnote of Table 2).

2.3 Energy system analysis for assessing PHES attractiveness (LEELO)

To test whether these more precise PHES cost-potential curves impact long-term energy decisions, a case study is performed. LEELO (long-term energy expansion linear optimization) is used. This is a tool to find the cost-optimal configuration of the power system, by choosing how much storage, generation, and transmission systems to deploy. This tool is detailed in reference [8] and has been validated in multiple journal publications [46]–[49]. In summary, LEELO:

- Minimizes the power system's total costs, composed by the annuities of investments and the operating costs;
- Sizes and locates generation, storage, and transmission systems;
- Decides the optimal operation for the power system for a milestone year of hourly resolution (i.e. 8760 timesteps);
- Models the nodal energy balance of the power system, the energy balance of each storage device, the water balance of the hydropower cascades, the capacity of the deployed technologies, among other technical constraints.

The present work uses a similar base case as in reference [8] but will vary the costs and potentials of PHES (as derived from 2.2) in scenarios (see below). The main technologies to be considered are Li-ion battery energy storage systems, PHES, and power-to-gas-to-power; solar photovoltaic wind power plants, and (existing) hydropower cascades; and overhead transmission lines. Chile's power system for the year 2050 will be modeled in four zones. A complete overview of these inputs can be found online in a permanent online repository [50].

A difference to this repository is the newly found PHES cost-potentials, here to be evaluated in five different scenarios (shown in Table 5), next to the base case, to test how these potentials impact the investment decisions. The base case (BC) follows the approach of using one capital cost value for PHES (averaged over all topologies and sites), very frequently observed in planning exercises. A slightly more detailed way is modeling each PHES topology as distinct technology, each using its cost average (Scn1). The most detailed approach in the present study (Scn2) is using three cost levels (high, medium, and low) for each topology (dividing the found potential of each topology into three same-sized groups), resulting in 12 entries to the optimization model (stemming from 4 PHES topologies multiplied by 3 cost levels). Three more scenarios are defined, excluding the emerging PHES topologies (rivers and seawater) to study the investment decisions if these emerging technologies are unsuccessful in practice. Consistently, again three cost levels per topology are used but once without the seawater topology (Scn3), once without the river topology (Scn4), and once without both the seawater and river topologies (Scn5).

Table 5 *Definition of scenarios for evaluating the new PHES cost-potential curves in energy system expansion planning.*

Scenario	Explanation
BC: Base case	Conventional approach: one average (across all topologies and sites) capital cost input for PHES
Scn1: Cost average per topology	More detailed approach: each PHES topology modeled as distinct technology with its corresponding (average) costs
Scn2: Three costs levels per topology	Most detailed approach: each PHES topology modeled as distinct technology with three cost levels (high, medium, low)
Scn3: Three costs levels per topology – no *seawater*	Same as above (Scn2), but without the seawater topology
Scn4: Three costs levels topology – no *rivers*	Same as above (Scn2), but without the river topology
Scn5: Three costs levels topology – no *seawater/rivers*	Same as above (Scn2), but without the seawater topology nor river topology

3 Results and discussion

The results and discussion section is divided into three parts, in direct response to the three objectives of the study. Recall that the present work aims to i) study the potential of selected PHES topologies (*existing pairs*, *one (existing) reservoir*, *river*, and *sea*; see section 2.1.1) for the countries Chile, Bolivia, and Peru, ii) derive the corresponding cost curves, and iii) assess if these new curves impact investment decisions. The first part of this section will present the found PHES potentials per topology and country; the second, the cost-potential curves per topology and country; and the third, the case study on planning the energy expansion of Chile with the newly found PHES cost-potential curves.

3.1 PHES potentials for the different regions and PHES topologies

This subsection will focus on the PHES potential found for Chile, Bolivia, and Peru, for each of the selected topologies: *existing pair*, *new reservoir*, *river*, and *sea*. As detailed in Table 6, the method found 472 promising projects in total. Most PHES correspond to *river* (174), followed by *one reservoir* (151) and *seawater* (129), and only a few based on *existing pairs* (18). In terms of countries, most PHES sites are in Peru (260), followed by Chile (160) and Bolivia (52). Chile has much promising seawater PHES, while Peru has a particularly high number of river-based PHES. Most PHES of Bolivia are river-based (and as a land-locked country, it has no seawater PHES).

Table 6 *Number of PHES sites identified, per country and topology.*

	Existing pairs	*One reservoir*	*Seawater*	*River*	**Total**
Chile	3	64	82	11	**160**
Bolivia	1	16	0	35	**52**
Peru	14	71	47	128	**260**
Total	**18**	**151**	**129**	**174**	**472**

In terms of energy capacity (see Table 7), the detected PHES projects account for almost 20 TWh. Most capacity corresponds to the seawater topology (8.5 TWh), followed by one reservoir (6.0 TWh) and river (5.2 TWh), with only a minor portion of existing pairs (0.1 TWh). Nonetheless, existing pairs may offer a low-cost basis, which is why these numbers should not be neglected (see next subsection). Chile offers the largest energy capacity potential (9.9 TWh), followed by Peru (7.5 TWh) and Bolivia (2.5 TWh). Most of Chile's, Bolivia's, and Peru's energy capacity stems from the topologies *seawater*, *one reservoir*, and *river* correspondingly.

Table 7 *Energy capacity of the identified PHES sites (GWh), per country and topology.*

	Existing pairs	*One reservoir*	*Seawater*	*River*	**Total**
Chile	84	3200	6200	400	9900
Bolivia	3	1271	0	1266	2500
Peru	25	1600	2300	3600	7500
Total	100	6000	8500	5200	19900

The numbers of power capacity (Table 8) are analogous to the energy capacity. They are directly linked to the energy capacity, as the energy-to-power ratio was an assumption (12 h) to the made calculations.

Table 8 *Power capacity of the identified PHES sites (GW), per country and topology, assuming an energy-to-power ratio of 12h.*

	Existing pairs	*One reservoir*	*Seawater*	*River*	**Total**
Chile	7	267	518	32	824
Bolivia	0	106	0	106	211
Peru	2	131	190	299	622
Total	9	503	708	436	1657

The spatial distribution of the found projects is displayed in Figure 3. Panel a, b, and c show Chile, Bolivia, and Peru. Columns one to four show the four PHES topologies *existing pairs*, *one reservoir*, *seawater*, and *river*. The size of each bubble indicates the energy capacity following the legend shown on the lower right of each panel. The source files can be found in a permanent repository [51]. This figure reflects the number analyzed above, in particular, the large potential of PHES for Chile, Bolivia, and Peru for the topologies *seawater*, *river*, and *one reservoir*, respectively.

To put the found numbers into the local context, the found PHES energy capacities are compared to the daily average load of each country. Reference [52] (Table F) informs a yearly load for Chile, Bolivia, and Peru of 130, 40, and 100 TWh, respectively (the last value stemming from the regional average). Daily, these translate to average loads of 360, 110, and 270 GWh/day per country. Consequently, the found PHES energy capacities of Chile, Bolivia, and Peru (9.9, 2.5, 7.5 TWh) are equal to over 27, 23, and 27 times the corresponding country's daily load. In other words, the technical PHES potential is generous and could accommodate several days (over 20) of system autonomy, allow for significant load growth, and provide a margin of safety in the estimation of these potentials.

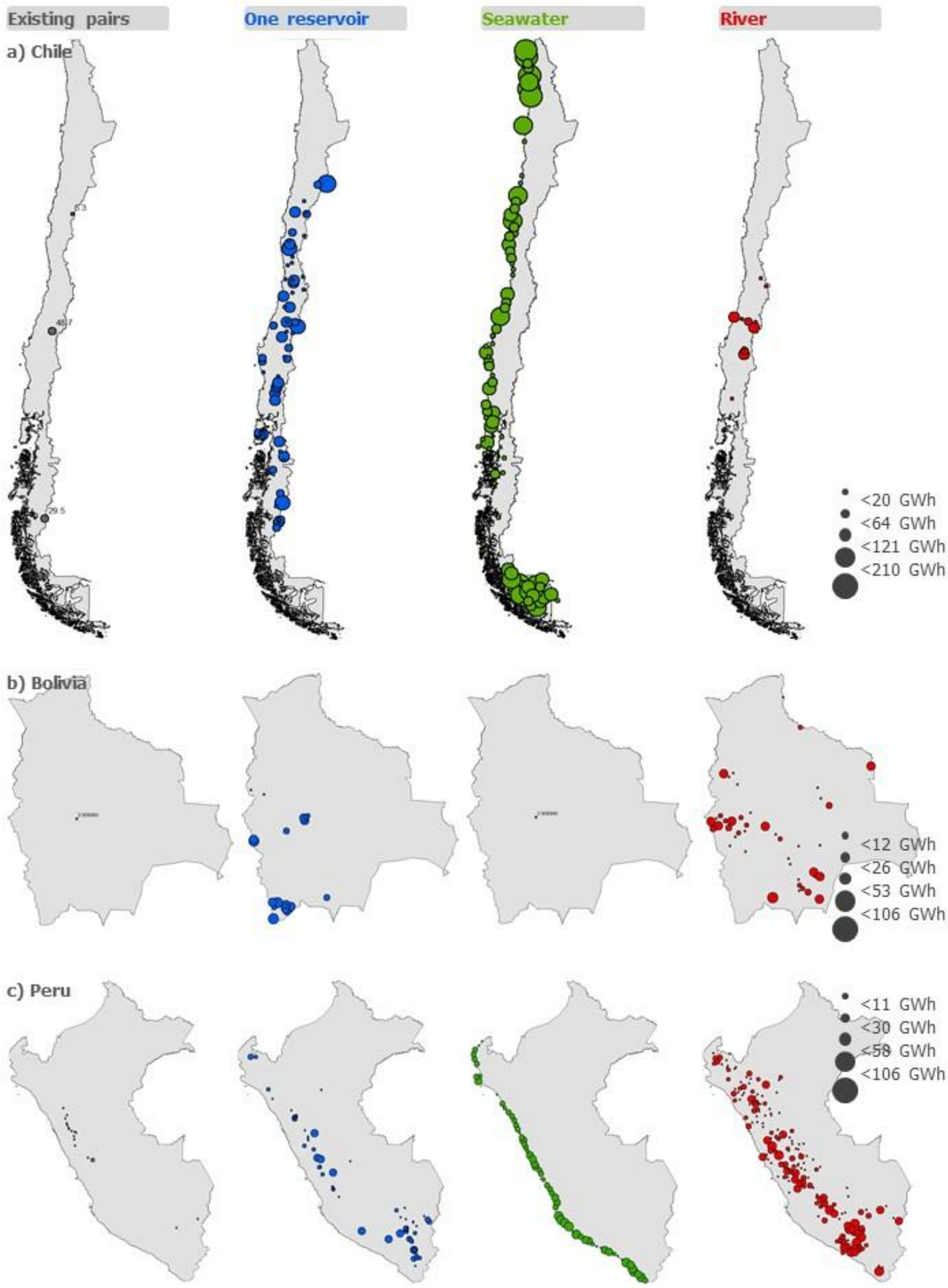

Figure 3 *Technical potential of PHES for a) Chile, b) Bolivia, and c) Peru for the four PHES (existing pairs, one reservoir, seawater, and river).*

How do these numbers compare to other available studies? As mentioned in the introduction, there are only a couple of studies on worldwide PHES potentials. The first one, from an Australian team [23] (with more detailed numbers in the studies [53] and [54]), found that the PHES potential exceeds about 100 to 1000 times the requirements for allowing renewable grids in the U.S.

[53] and East Asia [54]. The second study [31] found over 1000 TWh of PHES storage in South America. Assuming that about half (500 TWh) corresponds to Chile, Bolivia, and Peru, this number exceeds the values of the present study by a factor of 25. The comparatively lower potentials found here are consistent with the motivation of providing more conservative and precise numbers by taking into account only those PHES sites with water availability, which differs from the other studies available. This assumption (water availability) shows a strong impact on the found PHES potential, but still, the final numbers exceed the required storage of each energy system. The technical potential of PHES does not seem to be a limiting factor for the energy transition. On the contrary, it shows to be abundant.

In short, the found technical potential of PHES for Chile, Bolivia, and Peru is 9.9, 2.5, and 7.5 TWh, correspondingly. These values exceed the daily average load of these countries by over 20 times, which seems to be generous for enabling the energy transition. At the same time, these values are by at least one order of magnitude more conservative than existing studies, as the present study accounted for the water availability at each PHES site.

3.2 Cost-potential curves for the different countries and PHES topologies

This section will discuss the found PHES cost potentials for each country and topology. Note that while the following paragraphs (and Figure 4) focus on *total* investment costs, the investment costs *specific* to the *power capacity* and *energy capacity* can be found in the online repository [51]. These numbers can be useful inputs to expansion models that separately decide the power and energy capacity. As a reference, costs related to the power capacity resulted to be about 2-20 times higher than those to energy capacity. Our energy capacity costs are lower because of the chosen topologies, which all have at least one existing water body.

The costs curves, as shown in Figure 4, show the investment costs of PHES (expressed in €/$kWh_{installed}$ for a system with 12h of storage capacity), against the cumulative energy capacity that the GIS routine found (as discussed in section 3.1). Panel a), b), and c) show the results for Chile, Bolivia, and Peru. The series in gray, blue, green, and red, indicate the topologies of *existing reservoirs*, *one reservoir*, *seawater*, and *river*, correspondingly. The dashed black series shows the total energy capacity, summing over the topologies.

First taking a look at the total PHES energy capacity per country, Figure 4 shows that Chile, Bolivia, and Peru have over 9.0, 2.5, and 7.0 TWh of projects below a cost of 130 €/kWh. Optimistic cost projections for Li-ion *systems* (with 4 h of storage capacity) expect this cost level to be reached shortly after the year 2030, according to the newest review by NREL that consulted almost 20 different publications (see [55]). One recent study was even more optimistic projecting these 130 €/kWh already in 2027 [56]. Anecdotally, Tesla commented at their Battery Day 2020 to be able to reach a *cell* cost of around 60 €/kWh in the next five years. Furthermore, these countries show over 3, 2, and 4 TWh of PHES sites that are cheaper than 50 €/kWh. This cost level is below the most optimistic Li-ion costs for the year 2050 [55]. In Chile, most PHES potential under 50 €/kWh is provided by the *river* topology; in Bolivia by *river* and *one reservoir;* and in Peru by *river*. Strictly speaking, levelized storage costs should be used to compare costs between technologies. For the above direct comparison between capital costs to make sense, the present work assumed that i) the lower capital costs for (less risky) battery systems compensate for the longer lifetime of PHES; and ii) both technologies have similar cycling. Together, this should yield equivalent (and thus comparable) technologies.

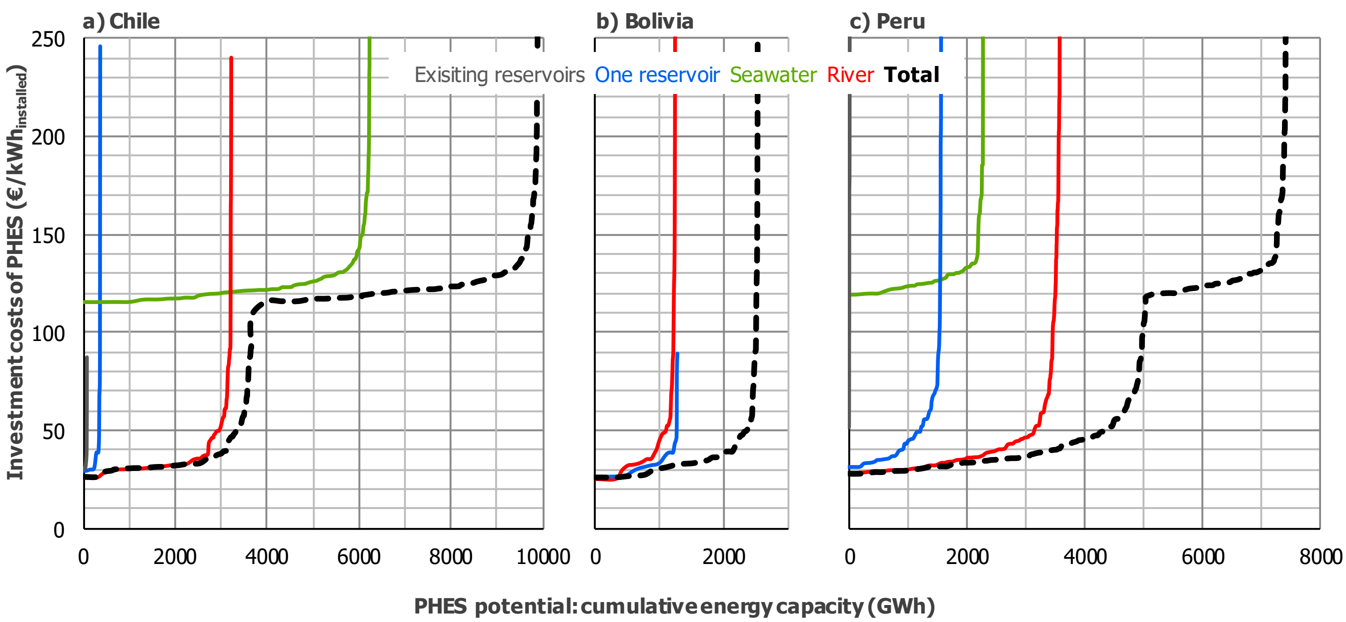

Figure 4 *Costs versus the potential of the different PHES topologies (A,B, C, D) for Chile (panel A), Bolivia (panel C), and Peru (panel C). Black-dotted lines show the cumulative potential.*

Comparing the cost-potential between the topologies, o*ne reservoir* and especially *river* show to have most potential at cheap costs (much energy capacity for example under 50 €/kWh, as mentioned in the above paragraph). *Existing pairs*, maybe surprisingly, show only a couple of projects that are as cheap as the lower range from *river* or *one reservoir*. *Seawater* offers much potential but starts at higher costs (around 120 €/kWh). Although the seawater topology is highly competitive against today's battery costs, this window might close during the 2030s [55] when battery systems are expected to match these costs. A persistent advantage might be the larger energy-to-power ratio coming from seawater PHES when compared to Li-ion batteries.

Recalling the average loads per country (as discussed in section 3.1: 360, 110, and 270 GWh/day for Chile, Bolivia, and Peru), even when taking into account only the most cost-effective PHES locations (say those under 50 €/kWh), these can serve the daily load with ease. The PHES potential under 50 €/kWh exceeds the daily load by a factor of 10 for each country. To put these numbers into the context of power systems, a previous study on a fully renewable system for Chile in the year 2050 recommended between 20 to 25% of the daily load to be covered by PHES for most scenarios (100 and 140 GWh of PHES for a daily load of 550 GWh in the year 2050) [8].

In summary, all three countries assessed show a large PHES potential that is competitive with Li-ion costs even in the year 2050. This potential exceeds the daily electricity demand by a factor of 10. The seawater topology offers even further potential but is costlier and, thus, could become uncompetitive against Li-ion systems in the 2030s.

3.3 How these PHES potentials impact long-term investment decisions: Example of Chile

This section will discuss if and how the newly found cost-potential curves (section 3.2) impact the long-term investment decisions of power systems. Chile is picked as an example for the milestone year 2050.

The optimization tool LEELO plans the cost-optimal electricity mix, of which the storage technologies are part. The present work will not present all possible investment decisions stemming from the tool (like in reference [8]) but limit the discussion on storage technologies that serve the short-term: Li-ion batteries and PHES. The optimal sizes of PHES (and its topologies) for the different scenarios are shown in Figure 5.

The **base case** (using one average cost overall PHES topologies) recommends investing about 350 GWh of PHES energy capacity. In **scenario 1** (using one average cost per PHES topology), the optimization recommends building over 500 GWh of PHES, which is an increase of almost 50% relative to the base case. Here, 90% of the deployed capacity corresponds to the topology *one reservoir* and the remainder to *existing pairs*. Note that although the *river* topology indeed has some cheaper sites (recall Figure 4), the model does not recommend its deployment due to the artifact of using one cost average per topology. In **scenario 2** (when distinguishing three cost levels per topology), these cost-effective *river* sites are indeed deployed, amounting to around one-third of the recommended PHES capacity. Another 60% corresponds to the *one reservoir* topology and the rest to *existing pairs*. Deployment of the topology *seawater* is minimal. Only the potentials corresponding to the lowest cost average are deployed. Recall that **scenario 3** builds on scenario 2, but without the seawater topology. Deployment in *seawater* turned out to be minimal in scenario 2, hence there are no important differences between the model outcomes in scenarios 2 and 3. Excluding the *river* topology, **scenario 4** resulted in similar sizes as scenario 1 (about 90% *one reservoir* and 10% *existing pairs*, with only 1.5% of *seawater* PHES. Excluding both seawater and river topologies, **scenario 5** yielded comparable results as in scenario 1. Li-ion batteries (not shown in the figure) have a minor relevance only, with 2 GWh in the base case and 25, 33, 11, 40, and 40 GWh in scenarios 1 to 5.

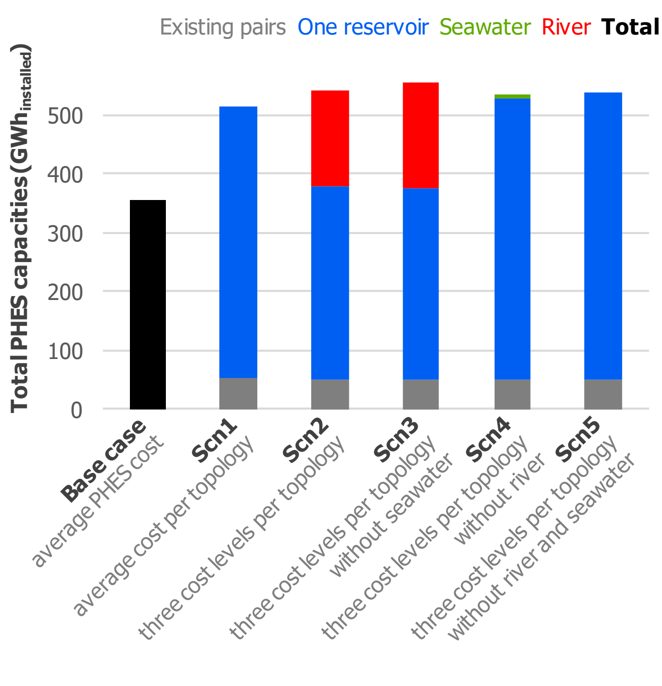

Figure 5 *Resulting investment sizes of PHES in Chile for the different topologies (A, B, C, D) under different scenarios of costs and allowed technologies.*

These results show that the common practice in expansion planning of using one cost average of PHES leads to underestimating the optimal PHES sizes by 50% (difference between scenarios 1 and 2). Going from using one cost average (per topology) to three cost-levels (per topology), further increases the optimal PHES sizes, but only by a minor 5%. Here, the major changes occur in the topology mix of PHES, with river jumping to 30% (up from 0% in scenario 1). The seawater topology is virtually not deployed in any scenario.

Furthermore, the base case relies on little Li-ion systems. This means that PHES together with hydrogen systems (not shown in Figure 5) could cost-effectively enable fully renewable systems, even if Li-ion batteries faced production constraints from raw materials (and Li-ion could therefore be prioritized for the transport sector).

Compared to the available literature, these revised PHES potentials resulted in recommending up to 5 times more PHES than a previous study (that used the same model and inputs) [8]. (The present study obtained 350 to 550 GWh of PHES, while the previous study yielded 100 to 140 GWh of PHES.) The only difference between these studies are the revised cost-potential curves, which meant not only using a cheaper (and more precise) cost for PHES but also allowing for a larger potential than originally prescribed in [8].

Note that Li-ion battery systems are strongly recommended in scenarios 1 to 5. This says two things. First, there is a high sensitivity to costs assumptions on competing flexibility technologies. To underline this idea, another recent study on Chile with sector coupling did not recommend any deployment of PHES [12], while ours –as mentioned– recommended at least 350 GWh. And second, there is a need for both technologies. This is consistent with a recent study for Bolivia [13], where strong investments in PHES are recommended between the years 2030 and 2040 as the most cost-effective storage solution (note that in earlier years, there seems to be little need for massive electric storage). After 2040, Li-ion battery systems arise as the most convenient option. However, in that study [13], only average PHES costs are used. It can be expected that when using more detailed cost-potential curves –as derived in the present work–, some PHES sites will remain attractive also in the long run.

As a concluding remark, the newly derived cost-potential curves for PHES do significantly impact investment decisions. The base case recommends 5 times as much PHES as a comparable study [8]. Further detailing the costs per topology results in another 60% increase in the optimal sizes of PHES. Cheap PHES sites look to remain attractive even in the year 2050. Yet, the selected PHES projects by the planning tool correspond to about 5% of the available PHES potential. Especially for these selected projects, future studies to elaborate even more precise cost estimates are recommended.

3.4 Limitations and outlook

This study performed an important step towards better assessing the potential of pumped-hydro installations in the South Andes. Nevertheless, some limitations remain, as detailed next.

First, river-based pumped-hydro is a cost-effective topology in all countries studied. Thus, future studies should focus on improving the estimates of this topology, for example by verifying that the water flow of the corresponding river is large enough to sustain the operation during the whole year and that water extractions (although them being restituted a couple of hours later) are compatible with ecological services.

Second, the upper reservoir was assumed to have a fixed ratio regarding the installed power capacity (i.e. to hold 12 hours of energy). This is a clear simplification to be tackled in the future. Choosing a larger size can be favorable on total costs (i.e. economies of scale), and choosing a smaller size could be positive for feasibility (e.g. allowing to use smaller rivers, in the corresponding river-based topology) and cost-effectiveness (i.e. achieving higher plant factors). Furthermore, here only one single type of upper reservoir (ring dams) is evaluated when in practice other options (e.g. classical dams) could be more cost-effective given the right topography.

Third, further steps could involve improving the filtering for the cases in which multiple possible upper reservoirs are found. A multi-criteria approach was used to select the most promising upper reservoir (section 2.1.3). The involved weights were defined in a previous study. Refining these weights to the local context could further improve the found upper reservoirs.

And fourth, there are other factors –often off the radar in expansion exercises– (e.g. weighted and localized average cost of capital, future lifetimes of technologies, the timing of investment throughout the transition period) that impact the actual technology deployment in the future. For example, the large asymmetry between the lifetime of PHES (>40 years) and batteries (>10 years) implies that regions with cheaper capital costs will tilt in favor of PHES. At the same time, the shorter lifetime of batteries allows a quick reinvestment into then cheaper battery systems (currently with a learning rate above 15% [57], [58]). These aspects can overshadow even the most precise cost-potentials PHES and should be addressed in future planning exercises.

4 Conclusions and future work

This work studied the pumped-hydro energy storage (PHES) potential in the Andes of Chile, Peru, and Bolivia. The work contributes in three aspects. First, based on a GIS routine, it detects attractive PHES sites for four different system topologies. These topologies include existing reservoir pairs, one existing lower reservoir, seawater as the lower reservoir, and large rivers as the lower reservoir. Second, a cost estimate is provided for each site detected. With these estimates, cost-potential curves a generated for each country and topology. Finally, these curves are used in a case study on optimizing a fully renewable system to gain further insights into how these newly derived curves impact investment decisions.

The resulting PHES potential for the Andes is tremendous. Over 450 promising locations were found, which totalize over 20 TWh of energy storage capacity (or 1600 GW of power capacity with an energy-to-power ratio of 12 hours), distributed as 9.9, 7.5, and 2.5 TWh, for Chile, Peru, and Bolivia, correspondingly. In all three countries, the potential of pumped-hydro exceeds by 20-fold the projected daily electricity demand [52], which seems generous for the energy transition. At the same time, these numbers are by one order of magnitude more conservative than previous studies because of the stricter requisites that are here requested from each potential site, especially in what refers to the water availability. This is a fundamental contribution of the present work.

In terms of capital expenditure, most found PHES sites are significantly cheaper than current Li-ion battery systems. Even in the context of rapidly falling battery prices, about half of the found PHES potential seems to remain competitive until the year 2050. Especially, the PHES topologies based on two existing water bodies, as well as based on rivers as the lower reservoir, seem promising even in the long run. Seawater PHES, on the other hand, is more expensive by about a factor of two (adaptations to seawater and sometimes longer transmission lines) but does provide a large potential.

When using the resulting PHES cost-potential curves in a case study for planning Chile’s energy system 2050, the energy optimization tool recommends 5.0 times and 1.6 times as much PHES (with the new curves) when compared to using literature values and average values. These large differences underline the relevance of the here found and more detailed cost curves. The selected PHES projects by the planning tool correspond to about 5% of the available potential. Especially for these selected projects, future studies are recommended to elaborate even more precise cost estimates, with a focus on access to the sites, on other water uses that might constrain the PHES operation, and on different reservoir construction geometries.

Identifying attractive PHES locations also contributes to tackling the mineral scarcity that batteries are facing. Altogether, these findings are relevant to the energy planning community, policymakers, and power and energy storage companies.

Data availability

The found potentials for pumped-hydro energy storage for Chile, Peru, and Bolivia, as well as the cost curves for these potentials, are openly accessible [51]. This database includes both the cumulative curves, as well as the individual projects.

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References

[1] K.-K. Cao, T. Pregger, J. Haas, and H. Lens, "To Prevent or Promote Grid Expansion? Analyzing the Future Role of Power Transmission in the European Energy System," *Front. Energy Res.*, vol. 8, Feb. 2021.

[2] D. Bogdanov, A. Gulagi, M. Fasihi, and C. Breyer, "Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination," *Appl. Energy*, vol. 283, p. 116273, Feb. 2021.

[3] J. M. Ortiz, W. Kracht, G. Pamparana, and J. Haas, "Optimization of a SAG Mill Energy System: Integrating Rock Hardness, Solar Irradiation, Climate Change, and Demand-Side Management," *Math. Geosci.*, Jul. 2019.

[4] A. A. Solomon, D. Bogdanov, and C. Breyer, "Curtailment-storage-penetration nexus in the energy transition," *Appl. Energy*, vol. 235, pp. 1351–1368, Feb. 2019.

[5] F. Cebulla, J. Haas, J. Eichman, W. Nowak, and P. Mancarella, "How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany," *J. Clean. Prod.*, vol. 181, pp. 449–459, Apr. 2018.

[6] J. Haas *et al.*, "Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review," *Renew. Sustain. Energy Rev.*, vol. 80, no. May, pp. 603–619, Dec. 2017.

[7] W.-P. Schill and A. Zerrahn, "Long-run power storage requirements for high shares of renewables: Results and sensitivities," *Renew. Sustain. Energy Rev.*, vol. 83, pp. 156–171, Mar. 2018.

[8] J. Haas, F. Cebulla, W. Nowak, C. Rahmann, and R. Palma-Behnke, "A multi-service approach for planning the optimal mix of energy storage technologies in a fully-renewable power supply," *Energy Convers. Manag.*, vol. 178, pp. 355–368, Dec. 2018.

[9] A. Aghahosseini and C. Breyer, "Assessment of geological resource potential for compressed air energy storage in global electricity supply," *Energy Convers. Manag.*, vol. 169, pp. 161–173, Aug. 2018.

[10] F. Cebulla, T. Naegler, and M. Pohl, "Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch," *J. Energy Storage*, vol. 14, pp. 211–223, 2017.

[11] J. Haas, "Supplementary material (inputs) to the publication 'Copper mining: 100% solar electricity by 2030?'" 2019.

[12] J. C. Osorio-Aravena, A. Aghahosseini, D. Bogdanov, U. Caldera, E. Muñoz-Cerón, and C. Breyer, "Transition toward a fully renewable-based energy system in Chile by 2050 across power, heat, transport and desalination sectors," *Int. J. Sustain. Energy Plan. Manag.*, vol. 25, pp. 77–94, 2020.

[13] G. Lopez *et al.*, "Pathway to a fully sustainable energy system for Bolivia across power, heat, and transport sectors by 2050," *J. Clean. Prod.*, vol. 293, p. 126195, Apr. 2021.

[14] D. Bogdanov *et al.*, "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," *Energy*, vol. 227, p. 120467, Jul. 2021.

[15] Bloomberg New Energy Finance, "Electric vehicle outlook 2020."

[16] P. Greim, A. A. Solomon, and C. Breyer, "Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation," *Nat. Commun.*, vol. 11, no. 1, p. 4570, Dec. 2020.

[17] T. Junne, N. Wulff, C. Breyer, and T. Naegler, "Critical materials in global low-carbon energy scenarios: The case for neodymium, dysprosium, lithium, and cobalt," *Energy*, vol. 211, no. Li, p. 118532, Nov. 2020.

[18] National Technology & Engineering Sciences of Sandia, "Global Energy Storage Database," 2021. [Online]. Available: https://www.sandia.gov/ess/global-energy-storage-database/. [Accessed: 01-Feb-2021].

[19] B. Lu, M. Stocks, A. Blakers, and K. Anderson, "Geographic information system algorithms to locate prospective sites for pumped hydro energy storage," *Appl. Energy*, vol. 222, no. April, pp. 300–312, Jul. 2018.

[20] A. Blakers, M. Stocks, B. Lu, and C. Cheng, "A review of pumped hydro energy storage," *Prog. Energy*, Mar. 2021.

[21] A. Kuriqi, A. N. Pinheiro, A. Sordo-Ward, M. D. Bejarano, and L. Garrote, "Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition," *Renew. Sustain. Energy Rev.*, vol. 142, p. 110833, May 2021.

[22] M. Xiao, T. Junne, J. Haas, and M. Klein, "Plummeting costs of renewables - Are energy scenarios lagging?," *Energy Strateg. Rev.*, vol. 35, p. 100636, May 2021.

[23] M. Stocks, R. Stocks, B. Lu, C. Cheng, and A. Blakers, "Global Atlas of Closed-Loop Pumped Hydro Energy Storage," *Joule*, vol. 5, no. 1, pp. 270–284, Jan. 2021.

[24] M. Gimeno-gutiérrez and R. Lacal-arántegui, *Assessment of the European potential for pumped hydropower energy storage storage potential*. 2013.

[25] N. Fitzgerald, R. Lacal Arántegui, E. McKeogh, and P. Leahy, "A GIS-based model to calculate the potential for transforming conventional hydropower schemes and non-hydro reservoirs to pumped hydropower schemes," *Energy*, vol. 41, no. 1, pp. 483–490, May 2012.

[26] J. A. Jiménez Capilla, J. A. Carrión, and E. Alameda-Hernandez, "Optimal site selection for upper reservoirs in pump-back systems, using geographical information systems and multicriteria analysis," *Renew. Energy*, 2016.

[27] S. Kucukali, "Finding the most suitable existing hydropower reservoirs for the development of pumped-storage schemes: An integrated approach," *Renewable and Sustainable Energy Reviews*, vol. 37. Elsevier Ltd, pp. 502–508, 01-Sep-2014.

[28] X. Lu and S. Wang, "A GIS-based assessment of Tibet's potential for pumped hydropower energy storage," *Renewable and Sustainable Energy Reviews*, vol. 69. Elsevier Ltd, pp. 1045–1054, 01-Mar-2017.

[29] A. Rogeau, R. Girard, and G. Kariniotakis, “A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale,” *Appl. Energy*, vol. 197, pp. 241–253, Jul. 2017.
[30] D. Connolly, S. MacLaughlin, and M. Leahy, “Development of a computer program to locate potential sites for pumped hydroelectric energy storage,” *Energy*, vol. 35, no. 1, pp. 375–381, Jan. 2010.
[31] J. D. Hunt *et al.*, “Global resource potential of seasonal pumped hydropower storage for energy and water storage,” *Nat. Commun.*, vol. 11, no. 1, p. 947, Dec. 2020.
[32] A. Aghahosseini, D. Bogdanov, L. S. N. S. Barbosa, and C. Breyer, “Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030,” *Renew. Sustain. Energy Rev.*, vol. 105, pp. 187–205, May 2019.
[33] A. Zerrahn and W. P. Schill, “Long-run power storage requirements for high shares of renewables: review and a new model,” *Renew. Sustain. Energy Rev.*, vol. 79, pp. 1518–1534, Nov. 2017.
[34] K. Hansen, C. Breyer, and H. Lund, “Status and perspectives on 100% renewable energy systems,” *Energy*, vol. 175, pp. 471–480, May 2019.
[35] R. Lacal-ar and M. Gimeno-guti, “Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs *,” vol. 75, pp. 856–868, 2015.
[36] N. Ghorbani, H. Makian, and C. Breyer, “A GIS-based Method to Identify Potential Sites for Pumped Hydro Energy,” *Energy*, 2018.
[37] B. Lehner *et al.*, “High-resolution mapping of the world’s reservoirs and dams for sustainable river-flow management,” *Front. Ecol. Environ.*, vol. 9, no. 9, pp. 494–502, Nov. 2011.
[38] DIVA-GIS, “DIVA-GIS,” 2021. [Online]. Available: http://www.diva-gis.org/gdata. [Accessed: 01-Feb-2020].
[39] N. V. Kelso, T. Patterson, and et mult., “Natural Earth,” *2021*. [Online]. Available: https://www.naturalearthdata.com/. [Accessed: 01-Feb-2020].
[40] NASA, “Consortium for Spatial Information (CGIAR-CSI SRTM).” [Online]. Available: https://srtm.csi.cgiar.org/srtmdata/.
[41] Norwegian Water Resources and Energy Directorate, “Cost base for hydropower plants,” 2012.
[42] D. E. H. J. Gernaat, P. W. Bogaart, D. P. van Vuuren, H. Biemans, and R. Niessink, “High-resolution assessment of global technical and economic hydropower potential,” *Nat. Energy*, vol. 2, no. 10, pp. 821–828, Oct. 2017.
[43] D. Connolly, H. Lund, P. Finn, B. V. Mathiesen, and M. Leahy, “Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage,” *Energy Policy*, vol. 39, no. 7, pp. 4189–4196, 2011.
[44] Z. Liu, A. Blakers, M. Stocks, and B. Lu, “An Economic Feasibility Analysis on Pumped Hydro Energy Storage at Kidston and the Modelling of Co-located PV and Wind Integration,” in *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, 2016, p. 12.
[45] D. Al Katsaprakakis, D. G. Christakis, I. Stefanakis, P. Spanos, and N. Stefanakis, “Technical details regarding the design, the construction and the operation of seawater pumped storage systems,” *Energy*, vol. 55, pp. 619–630, 2013.
[46] J. Haas, D. Hagen, and W. Nowak, “Energy storage and transmission systems to save the fish? Minimizing hydropeaking for little extra cost,” *Sustain. Energy Technol. Assessments*, vol. 35, 2019.
[47] J. Haas, W. Nowak, and R. Palma-Behnke, “Multi-objective planning of energy storage technologies for a fully renewable system: Implications for the main stakeholders in Chile,” *Energy Policy*, vol. 126, no. March, pp. 494–506, Mar. 2019.
[48] C. F. H. Boyle, J. Haas, and J. D. Kern, “Development of an irradiance-based weather derivative to hedge cloud risk for solar energy systems,” *Renew. Energy*, vol. 164, pp. 1230–1243, Feb. 2021.
[49] J. Haas *et al.*, “Copper mining: 100% solar electricity by 2030?,” *Appl. Energy*, vol. 262, p. 114506, Mar. 2020.
[50] J. Haas, “Inputs for LEELO (Long-term Energy Expansion Linear Optimization) (Version v38/v39) [Data set],” *10.5281/zenodo.1344412*, 2018.
[51] J. Haas, “Supplementary material: Pumped-hydro potential Chile, Peru, and Bolivia [Dataset],” *10.5281/zenodo.4715497*, 2021.
[52] L. de S. N. S. Barbosa *et al.*, “Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America,” *PLoS One*, vol. 12, no. 3, p. e0173820, Mar. 2017.
[53] A. Blakers, B. Lu, M. Stocks, K. Anderson, and A. Nadolny, “Pumped hydro storage to support 100% renewable power,” *IEEE 7th World Conf. Photovolt. Energy Convers.*, pp. 3672–3675, 2018.
[54] C. Cheng, A. Blakers, M. Stocks, and B. Lu, “Pumped hydro energy storage and 100 % renewable electricity for East Asia,” *Glob. Energy Interconnect.*, vol. 2, no. 5, pp. 386–392, 2019.
[55] W. Cole and A. Frazier, “Cost Projections for Utility-Scale Battery Storage: 2020 Update,” Golden, CO (United States), Jun. 2020.
[56] E. Vartiainen, G. Masson, C. Breyer, D. Moser, and E. Román Medina, “Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity,” *Prog. Photovoltaics Res. Appl.*, vol. 28, no. 6, pp. 439–453, Jun. 2020.
[57] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, “The future cost of electrical energy storage based on experience rates,” *Nat. Energy*, vol. 6, no. July, p. 17110, 2017.
[58] M. S. Ziegler and J. E. Trancik, “Re-examining rates of lithium-ion battery technology improvement and cost decline,” *Energy Environ. Sci.*, vol. 14, no. 4, pp. 1635–1651, 2021.