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Chapter

Prospection of Neighborhood Megawatthours Scale Closed Loop Pumped Hydro Storage Potential

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Abstract

Energy is at the center of the global socio-economical, geopolitical, and climate crisis. For this reason, countries are looking to boost their energy independence through the integration of distributed green electricity. However, the bottleneck of intermittent renewable energy as an alternative to fossil fuel energy remains the high cost of large-scale energy storage. The study explored the existence of megawatt-hours scale closed-loop pumped hydro-storage reservoirs near communities. A MATLAB algorithm has been developed to detect 1, 4, 9 hectares reservoirs with a separation distance less than 1000 meters, and a head over 100 meters, corresponding to an energy capacity of 20 to 400 megawatt-hours per pairs. For the cities studied (Banfora, Syracuse, Manisa), the results revealed the existence of more than 10.000 megawatt-hours storage capacity in each city, which exceed the need of the communities. In the 4 hectares sites category, all cities have over 80 pairs of reservoirs ideal for distributed storage system implementation. Therefore, a 100% renewable energy power grid that is resilient, reliable, can be achieved faster by adopting distributed closed-loop pumped hydro-storage, which has limited environmental impact and is likely to attract a large number of smaller investors.

Keywords: pumped hydro storage, energy resilience, utility storage, long duration battery, community energy

1. Introduction

There is a worldwide urgency to solve the energy crisis sustainably in order to reverse climate change-induced socio-economic problems. To limit carbon emissions, renewable energy (RE) such as solar and wind power have been promoted by governments through subsidies in the last two decades. Nowadays, in many countries, RE became competitive even without subsidies. However, as intermittent RE penetration ratio increases, it also becomes mandatory to add energy storage system for grid stability, and to make the system a full alternative to fossil fuel power plants. The research on storage systems often categorizes the technologies based on the duration

of usage, (long-short duration), and the discharge rate or power capacity [1]. However, it is not uncommon to see others performance indicators such as efficiency, cost, footprint, environmental friendliness, and so on be used [2]. In the short duration, high power density categories, there are chemical batteries such as lithium-ion batteries, there are flywheels, super-capacitors, and magnetic coils. In the long duration, low power density categories, there are pumped hydro storage (PHS), compressed air energy storage (CAES), and hydrogen storage [3]. For the energy transition purposes, the interest is in technologies capable of providing bulk storage cost-effectively in addition to scalable grid-level power output. In the literature, PHS and CAES appear to be the leading technologies regarding these criteria [2]. When efficiency is added into consideration, PHS is the net winner as its round efficiency is around 80% versus 40–60% for CAES [4, 5]. PHS has the benefit of loads shifting, avoiding RE curtailment, allowing black start of the grid, and transforming solar/wind plants into a fully dispatchable power unit [6]. Also, the mass of the turbine and the generator provides a natural inertia which contributes to grid stability. Given these characteristics, PHS capacity is projected to double by 2050 from 168 GW to over 300 GW. To revive the interest in hydropower, studies have been conducted to estimate the potential of small (< 10 MW) hydropower sites worldwide [7]. It concluded with findings revealing that the installed capacity is far less than the non-used potential. In Africa, there are 595 MW installed plants and over 10.000 MW potential plants. In America, the ratio is 6 GW / 41 GW. In recent years, the factors affecting the development of hydro plants have been subject to studies [8]. Among the driving factors can be cited the need for more RE integration, revenue generation, support for rural development, and energy security. The barriers are mostly the high capital expenditure, the lack of accompanying infrastructure (roads, power lines), the lack of suitable land, and environmental issues. In fact, depending on the source, the cost of hydro plants varies widely from 600 $/kW up to 8000 $/kW [8, 9]. This is much above the cost of thermal plants and solar plants which are around 700 $/kW, and 1000 $/kW respectively [10, 11]. However, on the levelized cost of energy side, hydro plant is by far the cheapest option since no fuel is used and the plant can run 24/7. To reduce the cost for storage-only applications, closed-loop systems which do not require continuous water flow from a river are becoming more and more popular in the research. Usually, site exploration is done for suitable pair of upper reservoir and lower reservoir [12, 13]. Such a pair of sites have been already mapped by several studies including Australia global pumped hydro storage atlas which unveiled over half million potential pairs, totaling more than 20-million-gigawatt hours capacity [13]. In the United States, similar study uncovered the existence of more than 10 thousand suitable pairs of reservoirs mainly in the west coast [14]. However, the development of these giga scale infrastructures is capital intensive and is far from being an unanimous solution among decision markers. Therefore, it is necessary to push further the research to make the technology more acceptable by the society.

1.1 Objectives

In the literature, pumped hydro storage is often associated to large giga-scale projects. Due to these sizes, projects environmental risks and safety risks are so high and the implementation from permitting, construction to operation is a lengthy process that can take up to a decade [15]. Also, projects sites are often in remote areas, requiring expensive high power capacity transmission infrastructure. To mitigate the drawbacks of giga scale PHS, this study aims to:

- Assess the existence of lower capacity megawatt-hours scale PHS sites.

- Search for PHS site only in the neighborhood of communities.

- Fill the gap by prospecting 100 m – 300 m head sites.

- This choice is expected to have the following benefits:

- Integrate more easily distributed energy resources such as community solar PV.

- Reduce projects environmental risks, and implementation timeline.

- Attract more smaller investors to boost projects number faster.

2. Grid scale long duration energy storage technologies

There are much research efforts being conducted worldwide by both academics and industries to provide grid scale energy storage solutions. Technologies are competing for application specific technical suitability and costs over benefits ratio. These observations imply that, the future of energy storage is likely to be populated with a mix of solutions complementing each other.

2.1 Existing technologies

There is no consensus on the storage size that qualify as grid scale neither on the storage duration that qualify as long duration. However, in many countries, solar PV plant over 5 MW or hydro power plant over 10 MW are registered as utility scale facilities. On the storage sides, several projects with less than 4 hours have been tagged as short duration storage. In the context of this paper, grid scale, long duration storage are technologies capable of delivering MWs of power for a period from 10 hours to several days. A 1 MW, 20 MWh energy storage module is considered as a unit block to build grid-scale long duration storage. This is done as it was observed that modularity is one of the biggest factors that contributed to the success of solar or wind power in the market. With reduced unit capital expenditure (CAPEX), the system can be standardized, and built-in factory to reduce cost. Also, a wider range of investors small or big can be reached which is not the case for giga scale system where only a handful of international institutions and governments are the soles actors. Grid scale storage solutions can be grouped into 3 categories: electrochemical, thermal and mechanical. In the first group, there are lead acid batteries, lithium batteries, hydrogen fuel cell, redox flow batteries. Due to their small footprint, they have been deployed at strategic nodes of the grid to provide ancillary services mainly. In the second group, molten salt is the most popular technology. As phase change materials offer high latent heat at nearly constant temperature, they are ideal energy source for steam to electric systems. In Morocco for example, in 2019 a utility scale thermal storage has been combined to concentrated solar thermal to build a dispatchable electric power plant. In the last group, CAES and PHS can be cited. While CAES recorded few projects, PHS is up to date the largest contributor of the world storage capacity with over 90% of the share. To build on the success of PHS, other form of gravity energy storage using a denser fluid or solid blocks are being explored. Before

going into details about gravity-based energy storage, it is worth reviewing the performance of different technologies.

2.2 Performance comparison

The typical power rating and discharge duration of some storage technologies are displayed in **Figure 1a**. PHS, CAES, flow battery, and hydrogen storage are the most promising for grid-scale long duration energy storage. A common point of these technologies is their ability to decouple energy capacity and power rating, which provide greater flexibility for system planning. In the contrary lithium batteries, nickel metal batteries or lead acid batteries have their power and energy linked by the cell chemistry. Often, high energy capacity batteries come with an unnecessary high-power rating. However, this situation makes them an excellent technology for grid frequency and peak regulation which need high burst of power in the seconds to hours time scale.

From an efficiency and lifespan perspective, **Figure 1b** shows that PHS is the optimum technology with a round trip efficiency of 80% and an extremely long life over a century, assuming a daily charge discharge. These characteristics make PHS an ideal solution to combine with solar PV or wind power plant which can last 30 years. On the lower left corner, lead acid and nickel metal batteries are the worst solutions because of the low number of cycles at 80% deep of discharge (DoD). From this fact, it can be concluded that they are not suitable for applications that require daily cycling. However, for emergency backup power need for example, they can be a good solution. Lithium batteries efficiency and number of cycles are well improved compared to lead acid batteries. For mobile applications such as electric vehicle, they are the current optimum solution. For grid scale storage, pilot projects of lithium battery are being rolled worldwide. As the lifecycle is limited to 10 years for 80% DoD, combining them with solar or wind power require 2–3 replacement per project life. This can represent a serious bottleneck that suppress the high efficiency benefit of lithium battery. Lastly for hydrogen fuel cell and CAES, they both suffer from a low round trip efficiency of 40%. However future development in fuel cells and electrolyzers efficiencies may improve hydrogen storage solution while heat recovery can boost the overall efficiency of CAES systems.

In terms of cost performance, **Figure 1c** shows that PHS and CAES are the best solution for grid scale application although CAES is much less widespread than PHS. From surveyed manufacturers, the 2022 cost of lithium battery is 300–500 $/kWh, that of flow battery 500–700 $/kWh which are much over the 50–100 $/kWh for PHS [19]. Even if chemical batteries cost drops to 100 $/kWh in the future, the rarefication of minerals, mining environmental cost, geopolitical instability, logistics costs, and other costs are likely to make PHS the preferred option for countries. In addition, the ongoing electrification of transportation will certainly divert an important portion of chemical batteries into mobile applications which have more value than grid storage stationary applications. By considering together discharge duration, efficiency, and cost performance, PHS outrank both CAES and chemical batteries for long duration grid scale applications. The biggest drawback of PHS is the dependency of terrain so research is focused on quantifying the existing exploitable potential.

3. Gravity based energy storage

Although water potential energy storage is the most used gravity-based storage (GES), the system can use other liquids, solid and even gas to work. Many GES
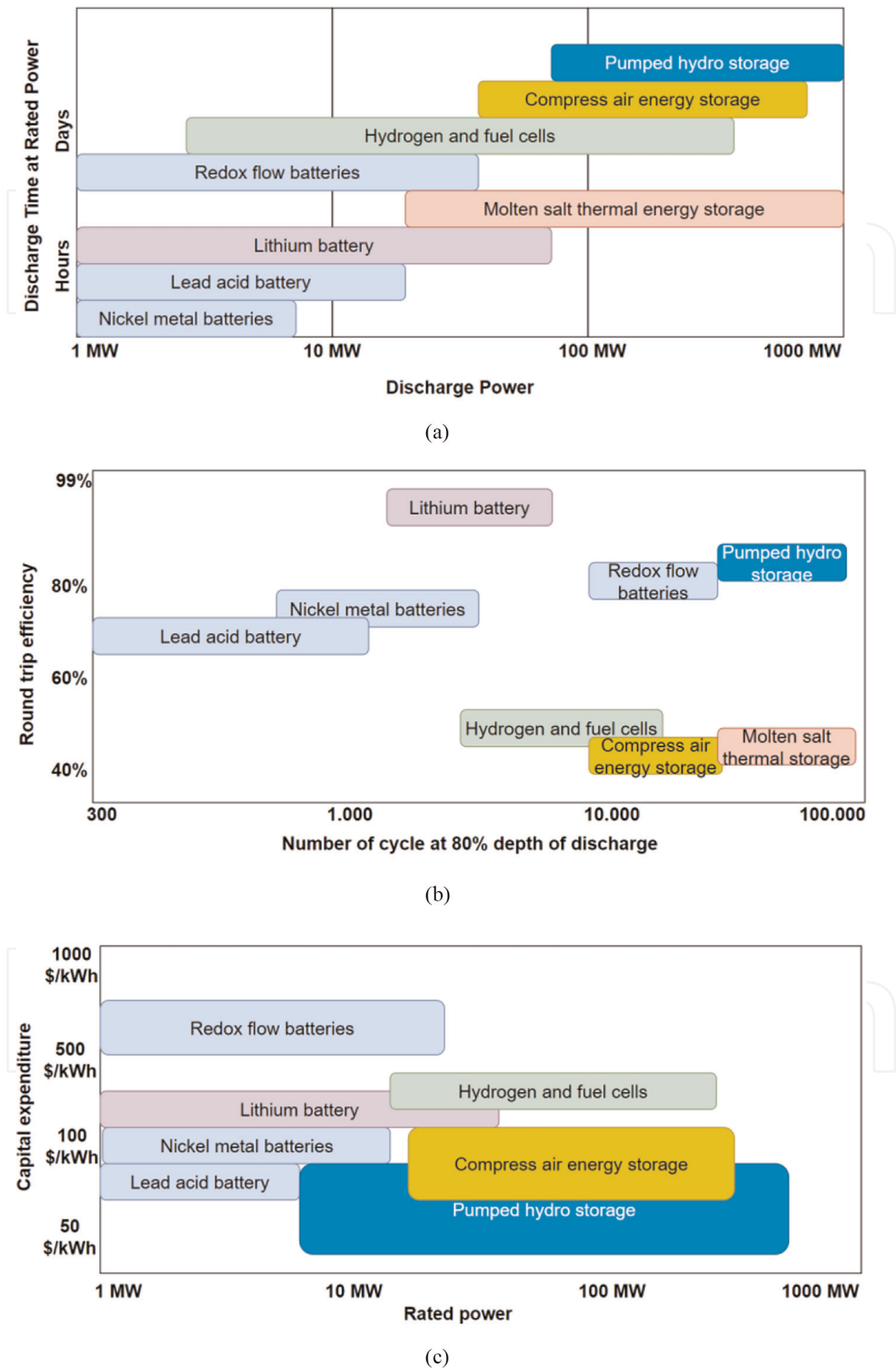
(a)

(b)

(c)

Figure 1.
a: Energy storage technologies discharge time [16]. b: Energy storage technologies efficiency [4]. c: Energy storage technologies capital cost [17, 18].
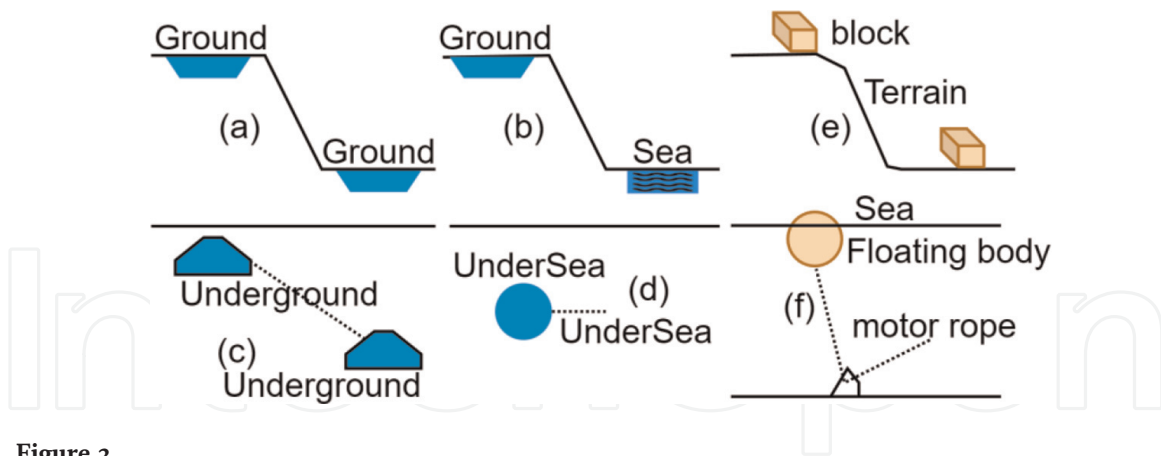
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Figure 2.
Gravity energy storage systems topologies.

designs have been proposed by both academics and industries. **Figure 2** summarizes few topologies of GES systems as follow:

3.1 Water based systems topologies

3.1.1 Surface reservoir- surface reservoir

The standard GES is a PHS using a pair of upper-lower reservoirs, both on the ground surface. Existing hydro power plants can be converted into PHS by adding the pumping equipment. The reservoirs are done with a dam wall or from natural depressions. Globally, from the 77 existing PHS plants and the 64 plants under construction, the majority uses dam wall which can range from 10 m up to 150 m in height [16].

3.1.2 Surface reservoir -sea reservoir

To avoid conflict over land usage, and to be close to load centers, using an upper ground surface reservoir and the sea as the lower reservoir has been proposed since 1999 in Japan. However, finding a seaside cliff with a suitable head, near load centers may not be easy globally. In addition, this solution faces the challenges of salt corrosion for the equipment. In Australia, a study concluded that installing a desalination plant to provide fresh water to the system is much cheaper than using corrosion-proof materials or running active corrosion protection equipment [17]. Several projects in Greece, Ireland, Chile, and the USA have been scheduled for years, but not implemented because the funding issues.

3.1.3 Sea reservoir -sea reservoir

This configuration avoids land use by building a spherical storage cavity in the seabed as a lower reservoir and using the sea as an upper reservoir. Studies estimate that such configuration is cost-effective at a deep ranging from 200 to 800 m [18, 20, 21]. Due to the massive weight of concrete used for the sphere (over 2 m thickness, over 30 m diameter), installation is as challenging as the size of the system! Small-scale prototypes have been tested in Europe and USA, however, so far, no commercial proof of concept has been realized.

3.1.4 Underground reservoir -underground reservoir

Underground PHS is attractive as it can be built anywhere, thus eliminating the need of special site or transmission cable. Digging is the most challenging activity of this method. However, sectors such as mining or road tunneling may contribute to a cost-effective implementation of this configuration. The cost drops significantly if underground natural or man-made cavities already exist. For example, some authors proposed the use of decommissioned mines chambers as reservoirs [22, 23]. Also, a single underground reservoir can be connected to a ground surface reservoir made of wall.

3.2 Solid-gas based systems topologies.

3.2.1 Buoyancy energy storage

Buoyancy energy storage (BEST) is another form of GES. By forcing a low-density object (eg. a pressurized air balloon) into the water, the uplift buoyancy force is equal to the weight of the displaced water. This principle is used as the driving force of BEST. A rope attached to a generator allows the pull-down and the uplift of the object for a charge–discharge operation. Studies recommended an anchoring deep of over 3000 m to obtain an energy cost in the range of 50–100 $/kWh [24]. The challenge with BEST is the anchoring stiffness requirements to hold such astonishing force, and the slow speed of the object (<0.1 m/s) needed to minimize the drag losses, meaning the charge–discharge power is also limited. A BEST prototype of 25 m3 balloon at 2 m deep has been tested so far. However, the system suffers from low efficiency due to its small scale [25]. Therefore, more R&D is still needed to get the system to a commercial level.

3.2.2 Solid block gravity energy storage

Instead of using water for power transfer, heavy solid blocks have been proposed as potential energy carrier. As earth or concrete density is nearly 3 times more than water, solid blocks offer more energy density compared to water. In the USA, a company started the testing of an advanced rail energy storage system (ARES) that uses special rails to move tons of blocks uphill to store energy [26]. The ARES can deliver 10 MW of power in 3 seconds while driving downhill. According to company notes, the power cost is expected to be 1200 $/kW compared to 600–8000 $/kW for PHS. Another company conceptualized the use of a large cylinder drilled out of the earth to be used as a hydraulic piston head to store energy in the form of pressurized water [27, 28]. The cost is projected to be 120–380 $/kWh. There are plenty of GES proposals such as using a crane to stack-unstack blocks of concrete in Lego style or using skyscrapers and their elevators to lift-descend blocks. If these methods work in theory, in practice they face extremely challenging factors such as structural cost, wind resistance, limited storage capacity, safety, and more.

4. Megawatt hours scale pumped hydro storage site detection

Due to their relatively small size, modular megawatt hour scale closed loop PHS can be built near communities. Therefore, their site requirements in terms of foot-print, head, safety and so on, are much less constraining than those of gigawatt hour

scale PHS. In case of a rupture of a reservoir for example, only few hundred thousand cubic meter of water will spill without causing much damage. Given the small foot-print of the system, the major requirement of the site is only the height difference as minor excavation or wall construction is sufficient to build the reservoirs. The potential energy and power of water are given in Eq. (1), Eq. (2) as function of water volume, head, flow rate and system efficiency. By assuming a lossless conversion of potential energy from the upper reservoir to kinetic energy at the lower reservoir, the maximum velocity can be expressed as in Eq. (3). The power equation can then be rearranged in Eq. (4), Eq. (5) as a function of water flow diameter, head, and system efficiency. The water specific energy at different heads, as well as the power at different heads and flow diameters are given in **Figure 3**. By assuming a reservoir depth of 10 m, the storage capacity varies from 20 MWh per hectare at 100 m head to 65 MWh per hectare at 300 m head. Therefore, a 10 hectares reservoir can provide up to 650 MWh storage using 1 million cubic meters of water. Regarding the power, for 100 m head, it varies from 2.45 MW at 0.3 m flow diameter to 22 MW at 0.9 m flow diameter. Despite the relatively small flow diameter, these power levels are above the minimum required for 10 hours storage. By increasing the head and the flow diameter, a significantly high power comparable to that of lithium battery can be generated.

$$E(V, \Delta h, \eta) = \rho \, V \, g \Delta h \, \eta \tag{1}$$

$$P = \rho \, \dot{V} \, g \Delta h \, \eta \tag{2}$$

$$v_{\max} = \sqrt{2 \, g \, \Delta h} \tag{3}$$

$$P = \rho \, \sqrt{2 \, g \, \Delta h} \, \frac{\pi D^2}{4} \, g \Delta h \, \eta \tag{4}$$

$$P(D, \Delta h, \eta) = \rho \, \sqrt{2} \, g^{1.5} \, \frac{\pi D^2}{4} \, \Delta h^{1.5} \, \eta \tag{5}$$
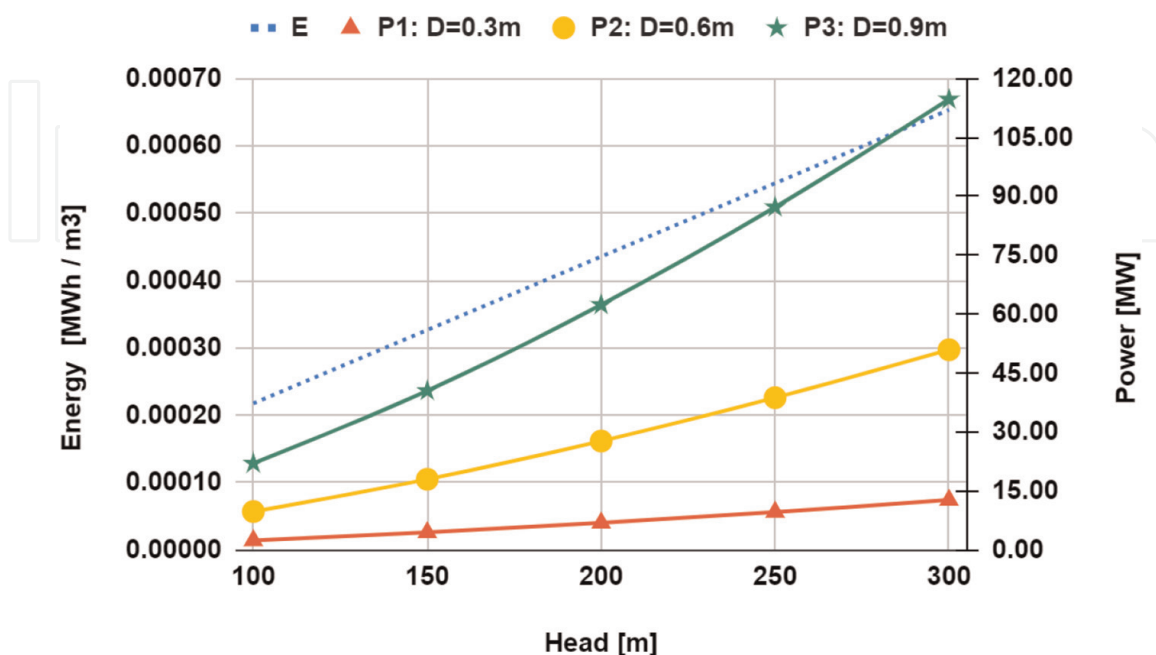
E : Energy in joule

Figure 3.
Water energy and power graph.

P : *Power in watt*

$v_{\max}$: *a body free fall maximum velocity in meter per second*

V : *water volume in m^3*

$\dot{V}$: *water flow rate in cubic meter per second*

Δh : *reservoirs elevation difference or head in meter*

η : *Energy conversion efficency in percentage*

ρ : *water density in kilogram per cubic meter*

g : *earth gravity in meter per second square*

D : *water flow diameter in meter*

4.1 Site detection methodology

Pumped hydro storage site detection methods follow the same fundamental flow processes [29, 30]. First, geographical information system (GIS) is used to collect digital elevation model and region-specific characteristics such as river, protected areas, ocean and so on. In a second step, GIS data are processed to identify reservoirs. As mentioned previously, there are various topologies of interest such as a pair of dry gully reservoirs, a dam and a river, a dam and the ocean, a dam and an underground reservoir and more [31]. For small scale closed loop PHS, this study is looking for inland, above ground reservoirs to avoid the cost of dealing with corrosive sea water and underground construction. In a third step, the reservoirs are matched according to user criteria such as head, separation distance, and energy capacity. More complete studies add a last step to optimize the reservoirs combination by further taking into consideration the development cost. The illustration in **Figure 4** shows an example of
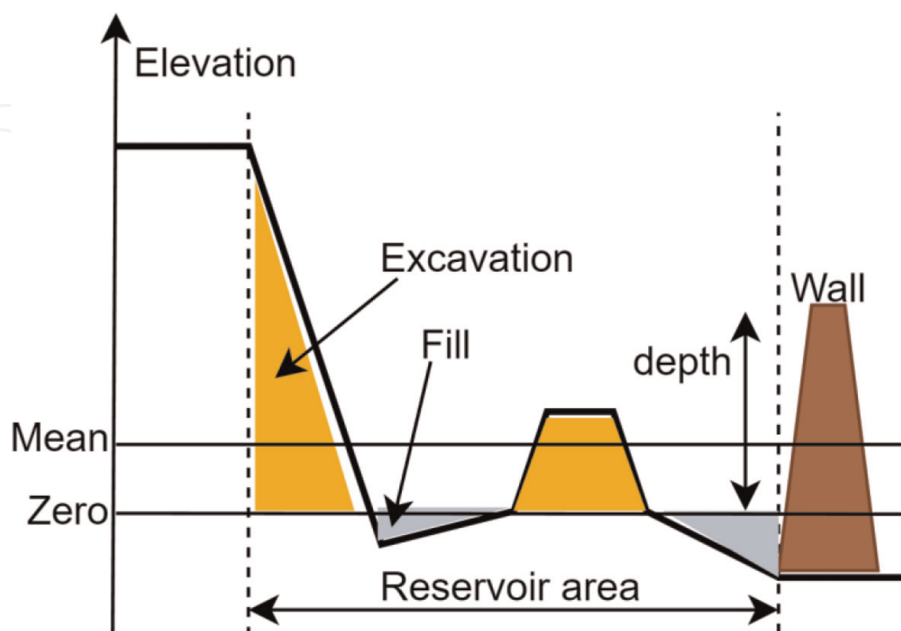

Figure 4.
Reservoir terrain illustration.

reservoir terrain. To build the reservoir, the earth above the marked zero elevation is moved to fill the depression below the zero elevation, and the remaining used to build the wall. On a flat terrain, the excavation work might be few dozen centimeters below the surface to reach the zero level of the reservoir. As the reservoir area increases, less and less excavation is needed to build a wall of certain thickness. Stated differently, to get a fixed volume (wall) the larger the surface (reservoir area), the smaller the depth need to be (excavation).

The methodology summarized in **Figure 5** describes how a pair of reservoirs are detected.

In steps (1)–(2), using global human settlement layer, a community center with population between 100.000 to 500.000 is chosen, then the search zone is delimited by setting a 50 km by 50 km perimeter around the center [32]. This is done to constrain the storage site close to the community. For megawatt hour scale PHS, limiting the eventual connection power line length is important to keep the project unit cost low. A summary of the chosen cities' population, energy consumption per capita and required storage draft estimation is provided in **Table 1**. The storage capacity is calculated by multiplying the daily energy usage by the number of people. The actual number might be lower as some energy may be consumed immediately after production without going through storage first. There is a huge gap in energy consumption between low-income city (Banfora) and high-income city (Syracuse).

In steps (3)–(4), digital elevation model data is pulled from online, a median filter is applied to eliminate eventual outliers, then no go zones are marked [33–35]. If the algorithm find a reservoir that overlap partially or entirely with a marked zone, the solution is discarded. For simplicity, only the region around the city center with visible housing concentration has been excluded.

In step (5) a mask for both reservoirs which are assumed to be 10 m height is created. The elevation standard deviation is set to maximum 5 m to limit the civil
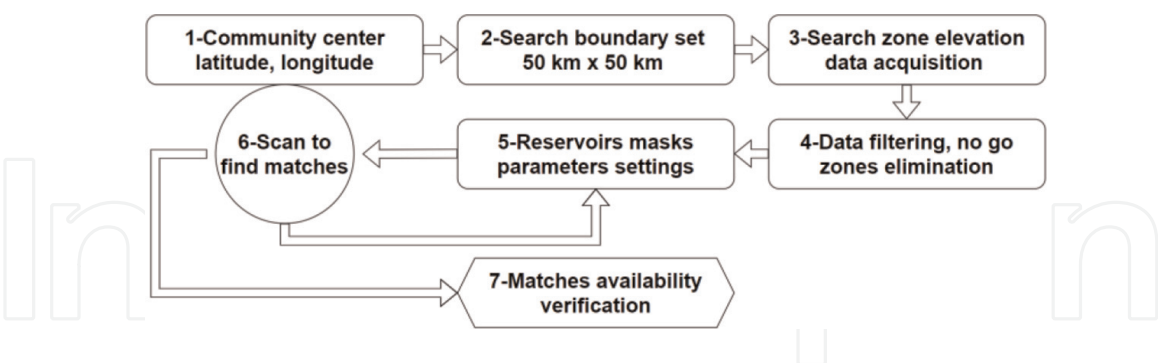

Figure 5.
Pumped hydro storage reservoirs pairs detection method.

City	Population	kW/Capita/year	MWh needed
Banfora	122.000	100	33
Syracuse	253.000	12.000	8.318
Manisa	294.000	3.000	2.416
World	8.000.000.000	3.000	65.753.425

Table 1.
Selected cities data.

engineering work required to build the reservoirs. The surface parameters are set to a square of 1 ha, 4 ha, and 9 ha while the head parameter is set to a minimum of 100 m. Lastly, the distance between two reservoirs is set to a maximum 1000 m. By reference, giga scale PHS reservoirs can have a separation distance tens of kilometers, making the construction process more difficult and costly.

In step (6) iteration is done to find pairs of reservoirs that satisfy each set of parameters described in (5). From an elevation point, the average surface elevation corresponding to the first reservoir is calculated, then within 1000 m from that point, a surface with average elevation that satisfy the head requirement is kept as a second reservoir. The excavation and fill volumes are calculated as they can serve to rank the attractiveness of the sites, the less the civil work the best. The water volume is 100.000 m3/ha corresponding to 20 MWh per 100 m head at 75% round trip efficiency. This leads to a storage capacity of 20 MWh at least to 540 MWh if the largest surface is matched with 300 m head. If the head reach 500 m the maximum capacity increases to 900 MWh which is still in the sub gigawatt hour scale.

In step (7), candidate sites are displayed in a map. A local inspection which is out of scope of the study must be carried out to confirm the availability of the site. Also, the type of the soil must be sampled to assess the technical and economical attractiveness of the land for project development. The aims of the paper is to simply to orient researchers and industry attention toward potentially feasible storage option that is under looked by standard search criteria.

4.2 Site detection results

The results of megawatt-hours scale neighborhood closed loop PHS sites detection is shown in **Table 2** for 3 cities, Banfora, Syracuse and Manisa. When the reservoirs areas are set to 1 ha, there are 556, 711 and 1966 pairs detected for the above cities respectively. For Manisa, the number is exceptionally high as the city is surrounded by mountains and depressions. For Banfora and Syracuse, when each reservoir area is increased to 4 ha or 9 ha, the number of pairs reduce significantly by a factor of 10 approximately. For Manisa, the reduction is more pronounced. In general, the more uneven a terrain is, the more challenging it is to find larger reservoir with the 5 m standard deviation set to reduce civil engineering work. Manisa terrain is more accidented than Banfora and Syracuse which explain the drastic drop in the number of reservoirs with 4 ha or 9 ha area. However, it is worth noting that the reduction in pair count does not necessarily reduce significantly the total storage capacity. For Banfora and Syracuse, 9 ha reservoirs capture over 87% of 1 ha capacity. This means that modular storage projects (1 ha) can be done on areas with higher potential (9 ha) to save cost on future expansion by sharing existing infrastructures (roads, power lines). The available storage capacities are 39,300%, 192%, and 1945% of the required

	Banfora (Burkina)			Syracuse (New York)			Manisa (Turkey)		
Area [ha]	n [−]	H [m]	E [MWh]	n [−]	H [m]	E [MWh]	n [−]	H [m]	E [MWh]
1 ha	556	118	13,000	711	116	16,000	1966	119	47,000
4 ha	85	124	8400	93	118	8800	109	124	10,000
9 ha	54	127	12,000	65	120	14,000	11	123	2400

Table 2.
Sites detection results.

capacities for Banfora, Syracuse, and Manisa respectively. Even for 9 ha reservoirs, in all cases, the storage potential is enough to meet or exceed the need of the cities, giving the opportunity to power system planners to choose the reservoirs configurations that fits the best to local economic, social, and environmental requirements.

A MATLAB plot of pairs of reservoirs as well as their display on a map are given in **Figures 6** and 7. The slope of the head can be visualized to assist in practical sites selection. On the plots, the upper and lower reservoirs are visible in color scale. Both reservoirs are on a nearly flat terrain, indicating the algorithm performance in detecting sites with minimal elevation standard deviation. The sites tend to be away from the cliff, thus avoiding unstable and expensive construction. As each grid cell is approximately 30 m by 30 m, the proximity of the pairs can be seen from the plots.

The map shows that for Banfora and Syracuse, the pairs are clustered in four or five regions, while for Manisa they are more dispersed. With clustered sites, more pairs can be combined to create larger storage capacity if needed. Also, infrastructure such as power transmission cable, roads and water pipes can be shared among pairs. With distributed sites, a more resilient energy system can be achieved by connecting each pair to a group of loads in the cities.

The PHS heads distribution is shown in **Figure 8**. The majority of sites have heads between 100 m and 140 m approximately. **Table 2** above shows a mean head around 120 m for all sites. As the cut off head was set to 100 m, the algorithm registers sites as soon as the requirement is met and mark the land unavailable for further usage. This can eliminate the possibility of having higher head with different reservoirs combination. To avoid this missed opportunity, the search started with head set to 400 m, 300 m and 200 m to isolate eventual best sites. The results revealed the existence of few pairs with high head, so the whole study was done with 100 m cut off head. The minor sites with head between 150 m and 230 m are still detected as shown in **Figure 8**. For project implementation it is important to make an extensive parametric study to detect the optimum sites by taking into account not only the head, but also other factors such as the ground characteristics, power line availability, access roads, initial water and top up water collection system, and the acceptance of project by locals.

5. Benefit of multi-disciplinary problem solving

Modern energy system implementation involves many people from various backgrounds. With the increasing complexity of the system, it is crucial to coordinate in a smart way, the integration of ideas and solutions to avoid future problems generation or a solution being outdated before the project end life. Therefore, both engineering and social science aspects of the system must go through a deep analysis and experiments before large scale field applications.

5.1 Engineering

As simple as it seems, gravity energy storage system require knowledge from different engineering fields. For the specific case of PHS, traditionally, civil engineering for excavation and dam construction has been the main work. However, in a closed loop system, other requirements such as water ground infiltration barrier, top up water collection from rain or from underground well may call for new expertise from material science and hydrology fields. Water evaporation also must be minimized for good system performance. Electrically, hydropower systems operations in the last decades were based
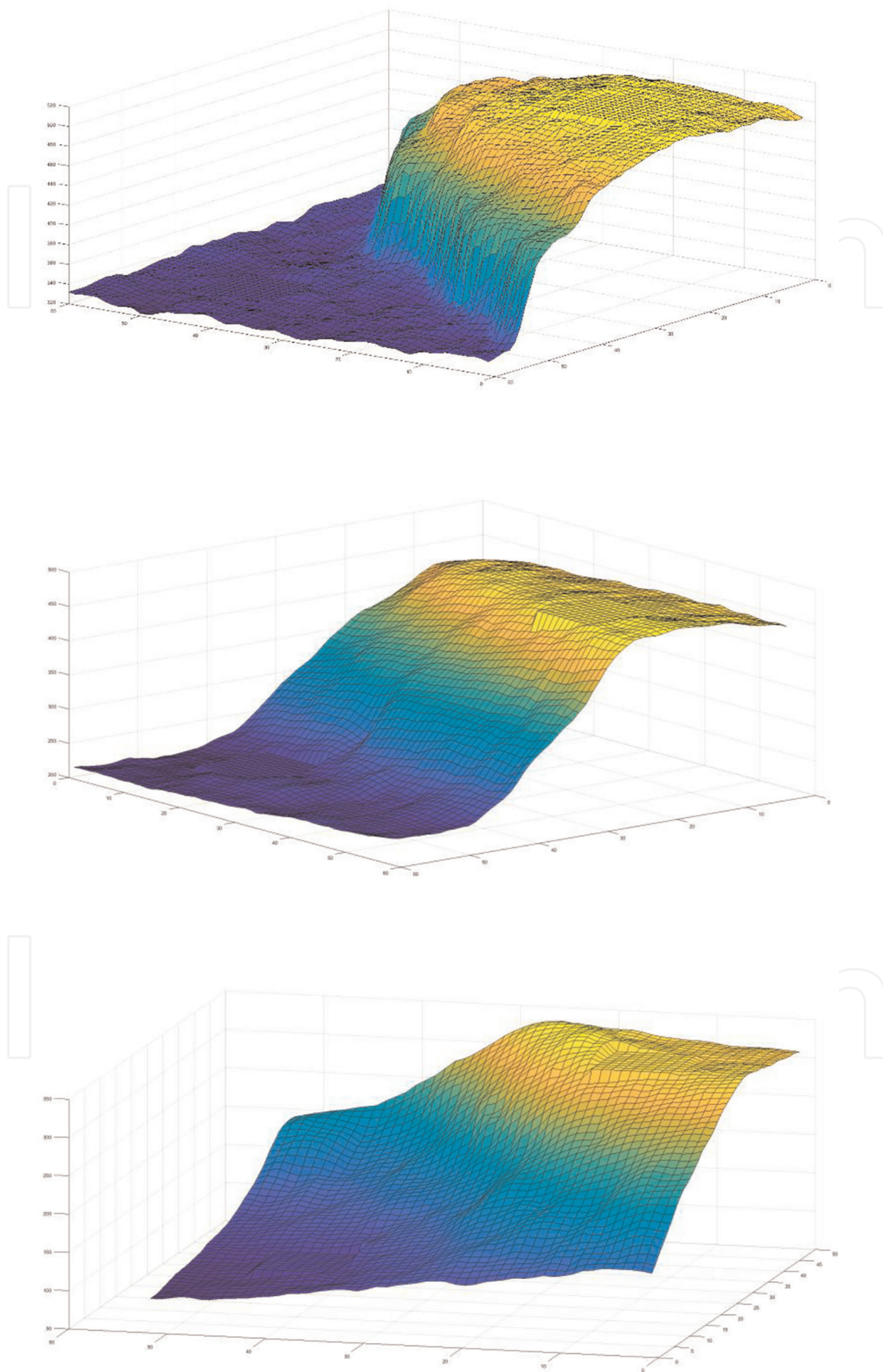
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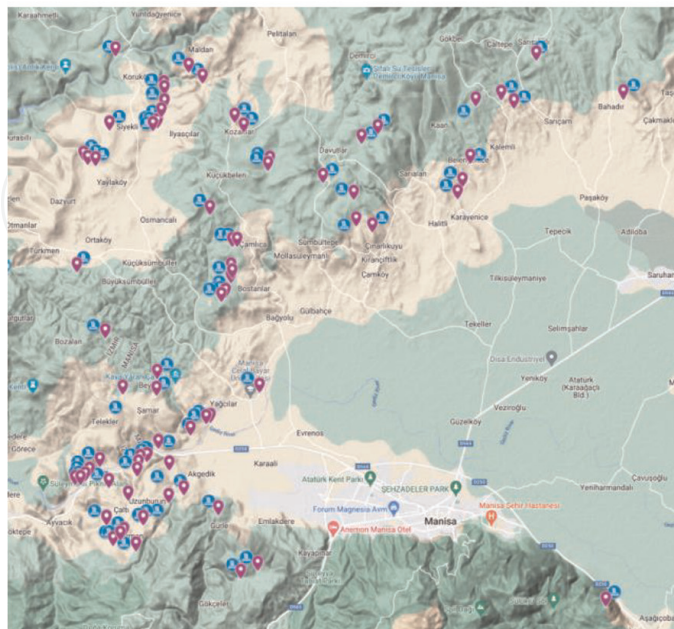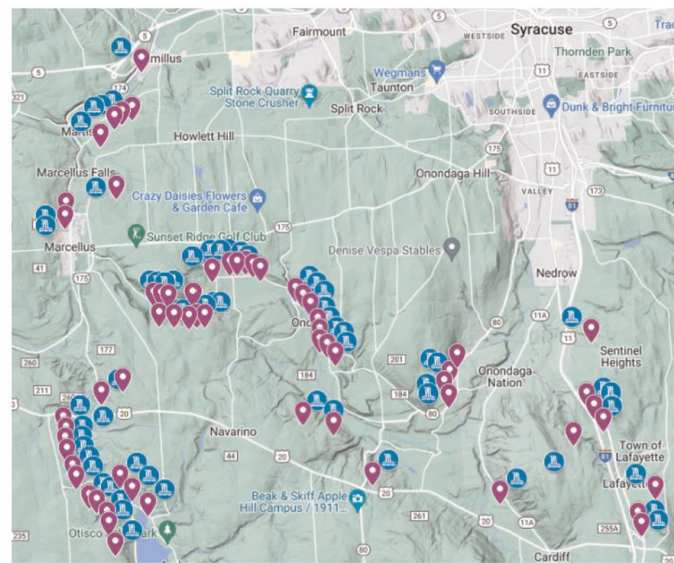*Sample upper and lower reservoirs detected. (top-Banfora, middle-Syracuse, bottom-Manisa).*
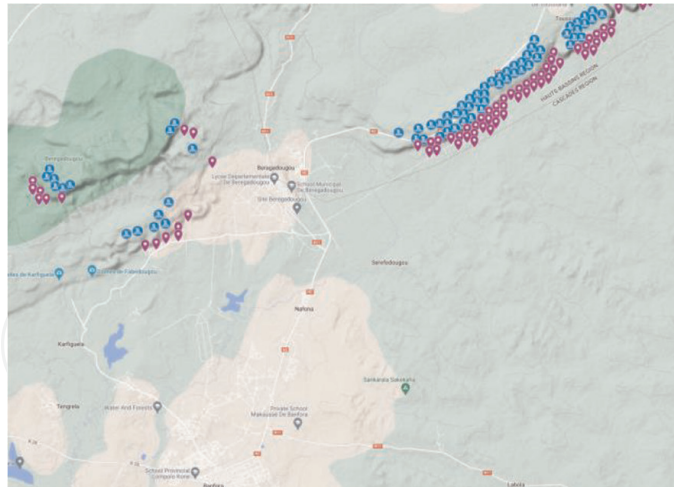
Figure 7.
Mapping of reservoirs pairs. (top-Banfora, middle-Syracuse, bottom-Manisa).
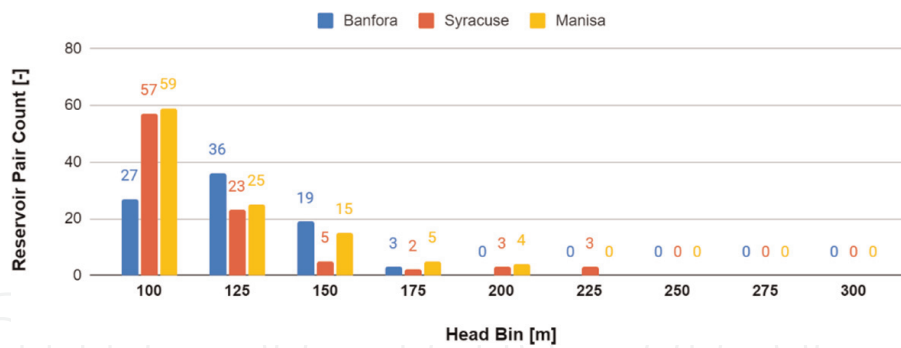
Figure 8.
Sites head distribution.

on a lookup table style optimization which is not ideal when more variable factors such as loads, wind, solar radiation, water quality, system age are taken into account. New fields such as artificial intelligence, machine learning provide better performance for multi-variables optimization and forecasting so they can boost the operation performance of modern PHS. In the case that sea reservoir must be used, decades long experience in offshore oil and ships industries can help to solve corrosion issues. Although multi-disciplinary approach to energy problem is recommendable, caution must be taken to avoid transferring costly methods from other applications to energy storage applications. For this reason, the input of people without a link to the areas mentioned above can be useful for reaching out-of-the-box innovative, cost-effective solutions.

5.2 Regulations

On the social side, the support of both private and public institutions will be beneficial to starting gravity energy storage industry. As the numbers show, energy infrastructures capital expenditures are costly so financial subsidies, research grants, and startups funding will be necessary to experiment with different possibilities before reaching commercial-level solutions. The permitting paperwork constitutes a barrier for some projects, meaning that regulations must be adapted to capture multiple objectives optimized socio-economic values. In the USA for example getting only approval for hydropower project may take 3–5 years, the construction process also 3–5 years, dragging project completion lead time to a decades. Very few private investors can cope with such long-term market uncertainties [36]. A differentiated regulation for giga scale storage project and mega scale projects can be a tool to shorten the development time of closed loop megawatt hours PHS. Also, from country to country, there is a huge gap in energy storage valuation which can be addressed to speed up investments. For example, in the USA, time of use rates and ancillary services market provide distinct value to storage system, while in many other countries, such market operation does not exist. As the world is moving toward solar and wind, power system inertia will be reduced, threatening the system stability. By designing a market for inertia supply, PHS can capture naturally a value without the need of a virtual inertia generation system which is required for storage such as chemical batteries.

6. Conclusion

There are many candidate technologies for large-scale electric energy storage. Up to date, PHS is the dominant technology with over 90% of world storage capacity.

Pumped hydro storage is the future for firming intermittent renewable energy from technology maturity and cost perspective if a suitable site is available. The study revealed that for the selected cities, the storage potential is sufficient to meet the need for 100% renewable energy scenario, even under the assumption that all energy used will go through storage first, without a direct consumption. Banfora with a lower consumption per capita has storage capacity 393 times the current need which means that it can meet future need and become power exporter. Even if the study is limited geographically, previous works from NREL in the USA and IRENA in Australia highlighted that the available global PHS capacity far exceed the need. This study limited the search to neighborhood small PHS sites to serve as a top priority for distributed, resilient energy infrastructure development. This avoids a high transmission cost and environmental disturbance. it is highly recommended to explore distributed megawatt-hours scale closed loop pumped hydro energy storage along with community solar PV or wind projects. The following recommendation can help accelerated PHS investments:

- Provide grants for closed loop megawatt hours scale PHS pilot projects.

- Develop regulatory framework for quick licensing of 20–500 MWh storage projects.

- Design a market that rewards PHS for ancillary services.

- Develop a special feed in tariff to pay for all the values provided by the project, not only limited to energy sales, but also to deferred investment on grid upgrade, peak reduction.

- Develop an algorithm that map investment ready PHS sites (with environmental impact analysis report, construction permit and grid connection authorization).

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