Building integrated pumped-storage potential on a city scale: an analysis based on geographic information systems

By: Jakub Jurasz[1, ✉], Adam Piasecki[2], Julian Hunt[3,4], Wandong Zheng[5], Tao Ma[6] & Alexander Kies[7]

[1] Wrocław University of Science and Technology, Wrocław, Poland
[2] UMK University, Toruń, Poland
[3] International Institute of Applied Systems Analysis (IIASA), Austria
[4] Federal University of Espírito Santo, Brazil.
[5] Tianjin University, Tianjin, PR China
[6] Shanghai Jiao Tong University, Shanghai, PR China
[7] Frankfurt Institute for Advanced Studies, Goethe Universität, Franfurt, Germany

✉ jurasz.jurasz@pwr.edu.pl

Submitted to: Energy

Abstract: Energy storage is essential for the successful transformation of the existing power system to one based on variable renewable energy sources. The portfolio of existing possible storage technologies at a given location within the power system is often severely constrained by a multitude of factors. Therefore, there is a need to explore the potential of thus-far neglected and uncharted territories. The prefeasibility study presented in this article addresses the theoretical potential of small-scale pumped-storage stations located in urban areas and utilizing height differences provided by built infrastructure (buildings). Geographic information system tools are applied for a selected case study (Toruń, Poland). The results revealed that a city with a population of 200 000 has a hosting capacity for small-scale pumped storage of slightly over 19 MWh or 11.3 MWh if stricter building selection criteria are considered. The article also provides a preliminary discussion of a concept of several buildings with pumped-storage upper tanks that share the same lower reservoir and estimates the role of such storage in covering city lighting needs. The discussion section is based partially on strengths-weaknesses-opportunities-threats analysis highlights the concept's main limitations and some future research directions.

Keywords: energy storage, small-scale pumped-storage, potential capacity, GIS-supported energy studies, building integrated pumped-storage.

Highlights:

- Proposes a method for city integrated pumped-storage potential estimation.
- Estimates the storage potential for a city of 200 000 people to be 19.2 MWh.
- If discharged once a day could deliver 6.4 GWh (0.9% of city energy demand).
- Economic performance depends mainly on building height and density.

1 Introduction

Power systems of various scales across the globe are undergoing a rapid change from supplying electricity demand based on a fleet of almost fully dispatchable generators to being dominated by solar- and wind-energy-based power plants.

Solar and wind energy, although usually abundant and associated with low cost of generation [1], comes with high variability on both spatial and temporal scales. Recently, the non-dispatchability of solar and wind generators has been well summarized in several review articles from the perspective of their complementarity, and in research articles like for example [5] that have studied the impact of capital cost on optimal power system configurations at the European level. The mentioned review articles addressed the issue of mitigating renewables' variability by exploiting their frequently observed complementary energy yield. Waschenfelder et al. [2] focused on complementarity from the perspective of grid-connected systems, whereas Yan et al. [3] concentrated on indices used for complementarity assessment and measuring ramp rates. The review by Jurasz et al. [4] studied the development of research on renewables complementarity, summarized mathematical apparatus uses, and highlighted future research directions. Even though hybridized systems exhibit higher reliability in terms of energy supply [6], the occurrence of energy droughts – defined by Raynaud et al. [7] as periods of low supply from renewables or a high deficit in production relative to demand – is still a significant challenge. This remains of particular importance in the light of a significant complexity of modern economy and water-food-energy interlinkages [8].The whole simulation and optimization of a power system driven by weather related renewables becomes even more complex considering multitude of potential meteorological datasets available [9].

From the rich body of scientific literature on renewable integration into the power system, it is clear that energy storage[1] is the panacea that everyone is looking for. Whether from the perspective of off-grid [10] or on-grid systems [11] storage systems emerge as vital solutions in enabling the efficient integration of renewables and is a significant flexibility measure in modern power systems [12]. The literature is regularly enriched with new research or review articles summarizing recent advances in storage technologies [13, 14] among which Olabi et al. [13] presented a review of recent trends in energy storage, whereas McIlwaine et al. [14] discussed energy storage at the distribution level in the light of the market readiness of technologies and policy regulations. The storage will undoubtadly play a significant role in achieving the goals of fully renewable power systems, regardless the investment dynamics [15], and various power system expansion models [16].

Apart from the conventional storage technologies such as batteries, compressed-air, pumped-storage, power to gas or flywheels, over the last few years several interesting new concepts have been proposed to increase the portfolio of available storage technologies:

- de Andrade Furtado et al. [17] and Stenzel and Linssen [18] analysed the potential of pumped storage using federal waterways. The use of existing infrastructure of water supply for small-scale pumped-storage units has also been proposed by Emmanouli et al. [19] for Connecticut in the USA.
- Hunt et al. [20] proposed a mountain gravity energy storage concept that bridges the gap between short- and long-term storage technologies by using elevation difference and storing electrical energy in sand/gravel transported uphill by a set of ingenious cranes.
- Farfan and Breyer [21] proposed the concept of a virtual battery consisting of hydropower reservoirs with floating PV.
- Fan et al. [22] investigated in detail the concept of using abandoned coal mine goaves for pumped-storage facilities. A similar study has been conducted also for Spain, focusing on lower reservoir and energy balance [23]. The use of mine shafts has been proposed by Morstyn et al. [24], too, although this time not in the form of pumped storage but, rather, suspended weights.
- The use of a railway as energy storage has been proposed by Cava et al. [25] and investigated in follow-up articles, such as one relating to West Virginia [26].
- Significant attention has also been given recently to storage options utilizing water bodies and underwater "energy bags" [27] or spheres [28,29], which have been developed and tested by the Fraunhofer Institute.

But despite the development of new technologies, pumped-storage hydroelectricity represents the overwhelming majority of installed capacity in terms of both power and energy. As of December 2019, it accounted for 96.2% of global rated power storage potential [30]. Not only is this storage technology mature in terms of its market penetration and technological development but it can also serve loads of various sizes and provide benefits on the water–energy–food nexus level [31] or, as presented by Novosel et al. [32] in combination with desalination plants on a country level. The machinery pumps/turbines (power) and reservoirs (energy) can be sized to meet specific system requirements providing, for example, daily or seasonal balancing. Naturally, since pumped-storage facilities are geographically constrained to sites that can host two reservoirs in close proximity and with significant elevation difference, the global potential is limited. Most commonly, geographical information tools [33] are applied to investigate potential sites.

Recently, some attention has also been paid to the energy storage possibilities on a residential and commercial scale. This aspect is particularly important when considering the increased role of small-scale (single installation capacity-wise) local renewable energy sources that can be installed even in densely populated urban areas. As already shown in studies for cities in China [34], India [35] and Poland [36], cities have a significant hosting capacity of rooftop photovoltaic systems that can, for example, increase their energy self-sufficiency. But, as usual, PV generation comes with high variability and significant changes in residual load. Therefore, energy storage is

---

[1] Recent years have also revealed the growing importance of flexibility within the power system and its components as an efficient way of integrating variable renewable energy sources. As indicated by P. Denholm [39] the flexibility measures, ordered by cost, are: improved operation, demand response, grid infrastructure, fast ramping capacity and, finally, energy storage.

often needed to balance supply and demand. One storage technology that is commonly investigated and applied at the residential scale is battery storage [37] or a vehicle-to-grid concept [38]. However, a still-promising alternative lies in utilizing the built environment, with its natural elevation differences.

The idea of utilizing pumped storage in buildings has so far been investigated in at least three research articles. Therefore, it has been decided to provide a detailed overview of these studies, since the number of papers on this topic is limited and it is important to highlight all their assumptions that will be later used in the analysis herein. A study by Zhang and Zhang [40] investigated a case study of a conceptual pumped-storage system located in a high-rise building in Shanghai, China. The considered system utilized an upper reservoir whose capacity was constrained by the roof dimensions (100×100 meters) and roof load capacity, according to Chinese standards (from 2 kN/m^2 to 7 kN/m^2), which are similar to the rules followed in other countries like USA or UK. For that particular case, the standard value for uniformly distributed load in a roof garden is 3.0 kN/m^2. The upper tank can therefore accumulate 3 100 m^3 of water, whereas the lower tank has a capacity of 5 000 m^3 – as it initially serves water supply purposes. The proposed system should consist of a turbine with a capacity of 2 400 kW and a pump with a capacity of 3 600 kW. It is envisioned that such a system could support the emergency power supply system and absorb fluctuating generation from the PV system. The simulations revealed that the building structure can support such additional weight, and taking advantage of the time-of-use tariffs and varying electricity prices makes the pumped-storage scheme cost effective.

A study published two years later by e Silva and Hendrick [41], and followed up later by a popular science discussion article in *International Water Power and Dam Construction* by e Silva [42], analysed the only existing pumped-storage facility situated in a residential building (Goudemand residence, which is an apartment building complex located in Arras, France – 50.291387, 2.787054). The pumped-storage scheme utilizes the 30-meter height of the building to store electrical energy in the form of water potential energy accumulated in a tank with a 60 m^3 capacity.

Similarly to the limitations discussed by Zhang and Zhang [40], this upper tank has an area of 200 m^2 and a depth of 0.3 meters. The lower reservoir is situated in the basement and is equipped with five plastic water tanks each of 10 m^3 capacity. The power is generated by a 0.45 kW Pelton turbine, while water is pumped to the upper reservoir by means of a 1.5 kW multistage pump. The storage capacity of such a pumped-storage system is 3.5 kWh. E Silva writes that the economic aspects of this project are not publicly available, but that the reality looks rather grim. Pumped storage is a mature technology, so cost and efficiency improvements are somewhat unlikely. The systems are rather small so they tend not to benefit from an economy of scale. At the same time there is a lack of potential synergies between existing infrastructure due to varying requirements, and the cost of alternative solutions is rapidly decreasing.

A very recent paper by Lin et al. [43] has yet again investigated the case of pumped-storage in Shanghai, China. Two case studies have been analysed, comprising a villa and a residential apartment building. Unlike in the case of the residential building in France, here Lin et al. [43] proposed that the upper reservoir should be a closed tank to avoid evaporation losses. For simulation purposes, the capacity of the pump was set to 5 kW (which allows potential maximal energy surpluses from the PV generator to be absorbed) and the turbine capacity was set to 3 kW to cover the maximal load. For both case studies, the upper tank capacity was set to 100 m^3. The bearing capacity of the building/roof is mentioned by the authors but not discussed further. In the case of the villa, the head (water drop) was set to 13 meters, and 22 meters for the residential apartment building. For those two cases, respectively, this means that 24 m^3 and 14.2 m^3 of water have to be used to generate 1 kWh of energy. Taking this into account, one can see that the storage capacity in both cases is respectively 4.2 kWh and 7.0 kWh. The economic analysis revealed a payback time of fewer than 10 years for both cases studied.

Inspired by the ideas described above, this paper aims at answering the following question: *What is the potential capacity of pumped storage in an urban area considering the existing built environment?* and *What role could such a storage system play in covering city energy demand?* Considering the lack of similar studies or answers to the above questions, this article aims to fill the existing knowledge gap by presenting our approach and analysis results from a case study. To add to the existing studies that have focused on single buildings, this work introduces the concept of multiple buildings integrated into a pumped-storage scheme by sharing a single lower reservoir. The next section presents the methods and data used in this work. The paper ends with a detailed discussion shedding some light on the concept's feasibility and applicability, potential research directions, an economic analysis and unanswered questions.

2 Methods and data

This section describes the methods applied in this study and the data necessary to perform the analysis and the simulations required for it.

Pumped-storage facilities store electrical energy by converting it into the potential energy of water pumped from a lower to upper reservoir/tank. In the generation mode, this process is reversed and water is released from the upper reservoir to the lower one.

To identify potential locations for pumped-storage systems within city boundaries, one needs access to *Building stock data* (Fig. 1). This information should be available in a format readable by the geographical information system (*GIS Tool*) that enables spatial analysis and the automated selection of suitable buildings based on a *Set of criteria for building selection.* Regarding the selection criteria, the mass of water that can be stored in the upper tank depends on the roof dimensions and the roof load-bearing capacity. In the simulations, all roofs, regardless of size and shape, have been considered. Aerials, elevator shafts and similar building components have not been taken into account. The assumption regarding roof load-bearing capacity was set to 200 kg/m^2 (roughly 2 kN/m^2) (similar as in [40]), which also follows Polish standards. This perhaps conservative assumption is due to the unknown technical condition of roofs that were put into operation during the last century. A discussion of the potential reinforcement and improvement actions needed to increase the upper tank capacity is given by Zhang and Zhang [40]. The above approach enables the modeller to create a *Database of selected buildings* or, in other words, of those suitable for accommodating a pumped-storage system.

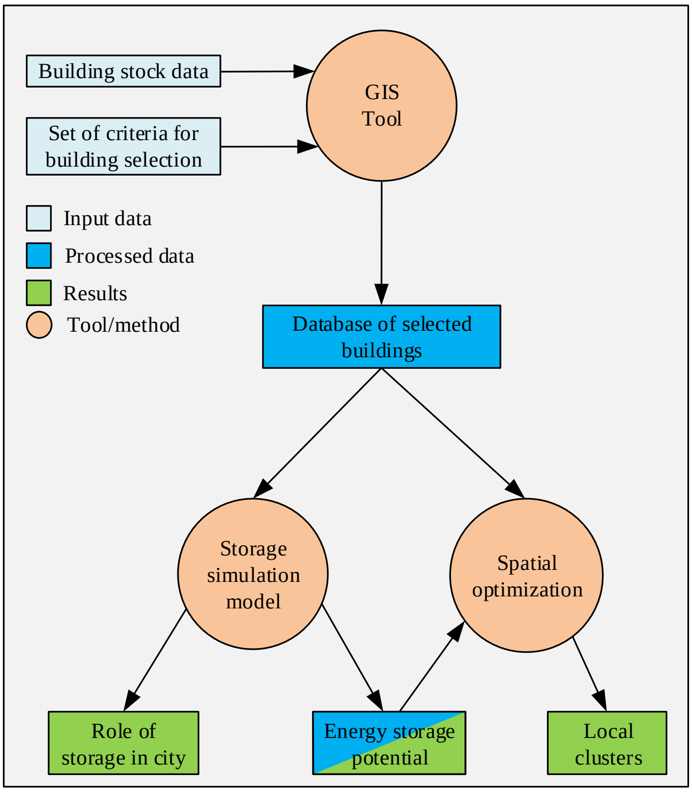

Fig. 1. Flowchart of the research procedure

Such processed data can later be used to estimate the energy storage potential and as an input to the *Storage simulation model*. The energy storage potential (E) of the upper tank located at the roof of the building can be calculated by Eq. 1:

$$E = m \times g \times h \times e \qquad (1)$$

where: m is the mass of water in the upper tank [kg], g is gravitational acceleration [m/s^2], and h is the effective head [m], here assumed as the height of the building and e is the efficiency of the system.

The above formula gives a good first-step approximation of the available storage potential. A further, site-specific analysis should take into account the friction losses (pipes), generator and turbine efficiency, evaporation losses and precipitation gains. For pumped-storage projects a commonly found number for round trip efficiency is from 70% to 80%, with some potential outliers, and typically assumed charging/discharging efficiencies are each 90%.

The formula and assumptions presented above were applied to data extracted from GIS. Two scenarios for city-wide storage potential have been considered. The first considers all buildings, regardless of height and roof area. The second selects only buildings with heights of at least 10 meters and roof area of 100 m^2 for further investigation.

This work employed data from airborne laser scanning (ALS) as input for geographical system analysis tools. This data is part of a programme run in Poland during the years 2011–14 titled Informatyczny System Osłony Kraju [Informatic System for Country Protection]. The data was available in the form of a point cloud with a density of 12 points per square meter. This data allowed us to calculate the height of each building in the city. The information about the roof area was acquired from a database evidencing all land and buildings. The database was verified by comparing it with data available from ALS. During the data screening, buildings with roof area of less than 10 m^2 and height smaller than 2 m were excluded from further analysis. Buildings serving religious purposes, big shopping malls (knowing for their roofs often being glazed) and buildings considered as historical monuments were excluded from analysis. For the analysis, a software called ArcGIS 10.5 was used. The resulting database was created in MS Excel, and the data itself was processed in Matlab R2020a.

Once the energy storage potential of each building has been estimated, a *Spatial optimization* procedure can be applied. The objective of this is to identify a location for the lower reservoir for a group of selected buildings that will be optimal for minimizing penstock length while not exceeding imposed constraints such as penstock-to-head ratio. From the mathematical point of view the problem is to find minimum value of *Z* in Eq. 2:

$$\min Z = \sum_{i=1}^{n}\sum_{j=1}^{m} d_{i,j} * x_{i,j} * y_i \qquad (2)$$

where: *Z* – total length of the penstock (m); $d_{i,j}$ – distance matrix from the potential location *i* of the lower reservoir to the building *j*; $x_{i,j}$ – binary decision variable: 1 – if building *j* has been selected for inclusion in the multiple buildings pumped-storage scheme and connected to the reservoir at site *i*, 0 – otherwise; y_i – binary decision variable: 1 – if location *i* has been selected for the lower reservoir, 0 – otherwise.

subject to Eq. 3:

$$\frac{d_{i,j} * x_{i,j} * y_i}{h_j} \leq PH_{ratio}^{max} \qquad (3)$$

where: h_j – height (head) of building *j* (pumped-storage on building *j*), PH_{ratio}^{max} – maximal acceptable penstock-to-head ratio.

Penstock-to-head ratio is a metric defined a total length of penstock (can be pipes, tunnels sometimes also acquaducts) divided by the effective head used by the hydro generators. The head is the elevation difference between the upper and lower reservoir.

Furthermore, the optimization problem is subject to the following constraint: the number of selected potential locations for the lower reservoir has to be exactly 1, as shown in Eq. 4

$$\sum_{j=1}^{m} y_i = 1 \qquad (4)$$

Additionally, one should specify the minimal number of buildings (*A*) that should constitute the multiple-building pumped-storage scheme. The decision regarding the minimal number of buildings connected to the system can be subject to the investor decision or a part of yet another optimization problem (not elaborated here) Such constraint reads as shown in Eq. 5:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} x_{i,j} y_i = A \qquad (5)$$

Alternatively, the number of buildings can be replaced by a minimal required storage capacity of such multiple-building pumped-storage scheme. The minimal storage capacity can be dictated by the intended purpose of the system. In such case the constraint would read as shown in Eq. 6:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} x_{i,j} y_i e_j \geq B \tag{6}$$

where: B – minimal required storage capacity, and e_j – storage capacity of pumped-storage system integrated with building j.

In this work, for the chosen local case study, it was assumed that all buildings considered should be included in the multiple-building pumped-storage scheme.

3 Results and discussion

Within this part of the manuscript the following subsection will present the results of the analysis conducted for the selected case study. The obtained numerical results will also be discussed in the light of available literature, analysed from the perspective of the city energy demand, and scrutinized based on strength-weaknesses-opportunities-threats analysis.

3.1 Buildings portfolio analysis

After extracting the data based on GIS tools, each building was described by its height and area of its roof. As indicated earlier, both the shape of the roof and its slope have been neglected in our analysis. The roof slope angle has been neglected since the preliminary analysis revealed that: 85.1% of the roofs can be categorized as flat roofs with slope angles ranging from 0° to 5°. Furthermore, roofs with slopes of less than 10° constitute 95.4% of all roofs. For buildings taller than 10 meters it has been found that 94.5% have a slope of less than 10°. The selected subset numbered 14 972 buildings. Table 1 summarizes the basic statistical parameters of their characteristics (height and roof area).

Table 1. Statistical parameters of subset of selected buildings

Parameter	Height [m]	Roof area [m^2]
Mean	7.7	242.1
Max	35.9	49 849.4
Min	2.0	17.7
Standard deviation	4.3	659.0

Furthermore, in the considered sample of buildings, 81.5% were buildings of less than 10 meters tall. Three buildings were more than 35 meters tall, 133 were more than 30 meters tall, and 160 were more than 25 meters. In total, 2 766 (18.5%) buildings were identified to be more than 10 meters tall, of which 93% were not taller than 20 meters; the classification of buildings by height is presented in Fig. 2. As indicated in Table 1, the average roof area is roughly 240 m^2. In the investigated subset (buildings taller than 10 meters), 3.2% of the buildings have an area greater than 1 000 m^2. A few outliers with very large roof areas were identified, one of 23 000 m^2 and the other of 50 000 m^2. The spatial distribution of the buildings is illustrated in Fig. 3.

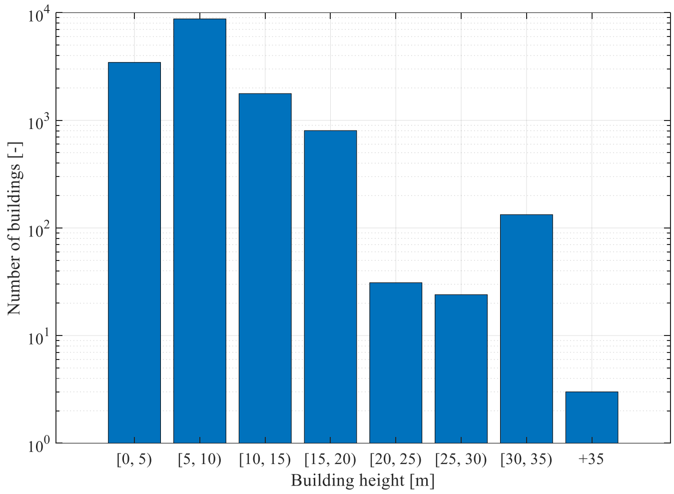

Fig. 2. Distribution of buildings by height

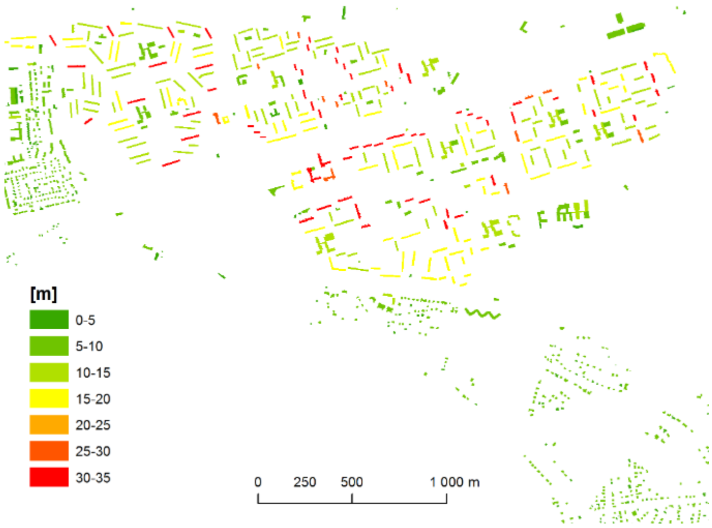

Fig. 3. Part of the city with extracted building shapes and heights. Colors reflect building height.

3.2 City-wide storage capacity

As described in Section 2, the city-wide storage potential of building integrated pumped-storage was estimated for two scenarios. The first took into account all buildings regardless of roof area and height. The second limited the number of buildings to those taller than 10 meters and with a roof area of greater than 100 m^2. The storage capacity for a building meeting the minimal (height and roof area) criteria whilst neglecting efficiency losses of the turbine and assuming a roof bearing capacity of 2 kN/m^2 is slightly above 0.5 kWh. The results for both scenarios are presented in Fig. 4. Figure 4 shows that the total building integrated pumped-storage potential of buildings in Toruń, Poland reaches 19.2 MWh. If only buildings meeting specific criteria of minimal height and minimal roof area are selected, this storage potential is reduced by over 40% to 11.3 MWh.

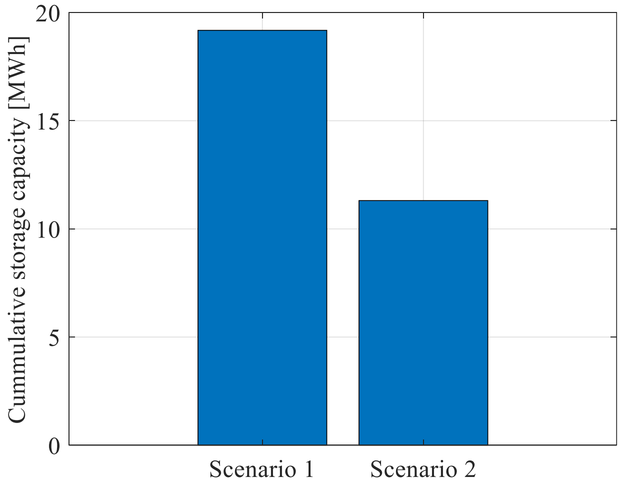

Fig. 4. Estimated maximal storage capacity for two scenarios, assuming 2 kN/m^2 load-bearing capacity

The impact of the building selection criteria (namely minimal height and minimal roof area) are shown in Fig. 5. The peak storage capacity (far back corner) is naturally reached when all buildings are considered regardless of size. By contrast, when one starts to limit the subset of selected buildings based on roof area, as shown in Fig. 5, considering only roofs of greater than 250 m^2 reduces the storage capacity to slightly over 14 MWh. A much greater impact on storage capacity is observed when one starts to eliminate buildings that do not meet height criteria. As illustrated in Fig. 5, with increasing constraints on minimal building height, storage capacity decreases much faster. Once only buildings of more than 20 meters tall are considered, the storage potential decreases to less than 4 MWh.

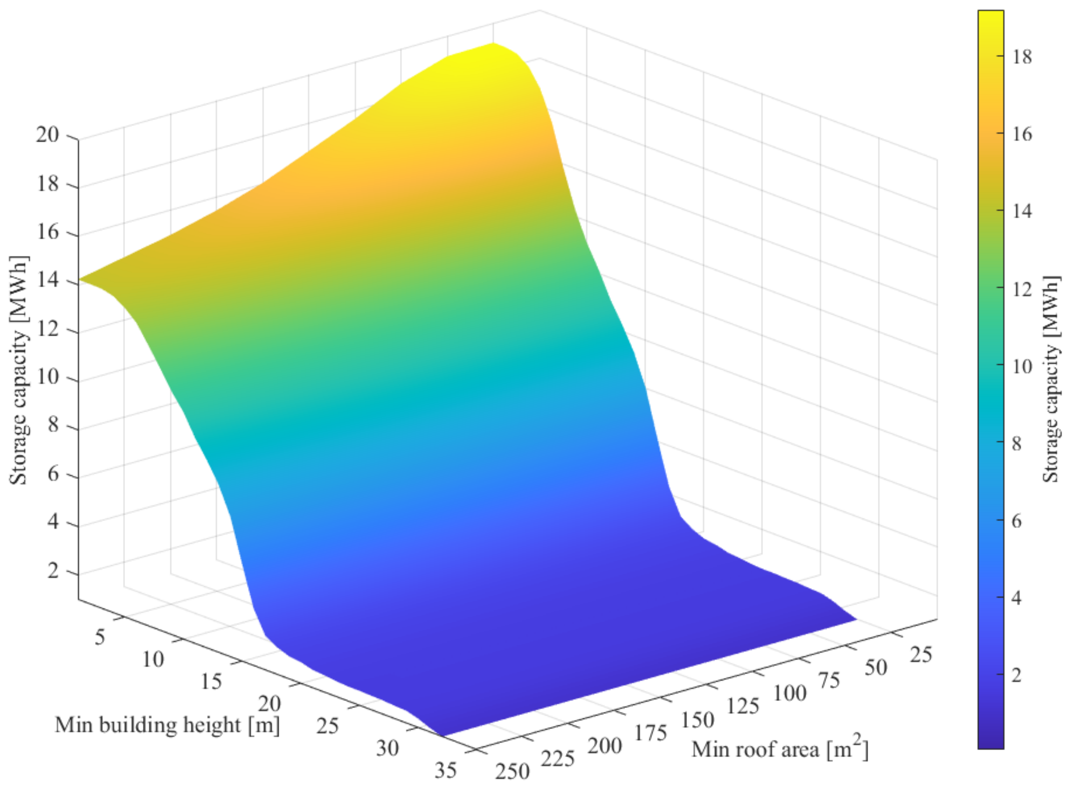

Fig. 5. City-wide storage capacity considering different minimal roof areas and minimal building heights

3.3 Linking several buildings

The infrastructure cost of the pumped-storage scheme can be reduced by, for example, utilizing a shared lower reservoir. The upper reservoirs/tanks are naturally linked to individual buildings. Figure 6 presents such a concept, where three buildings share one lower reservoir, whose capacity should be no smaller than the combined capacity of the upper reservoirs.

The location of the lower reservoir can either be dictated by existing water bodies (ponds or small lakes) or optimized. The optimization procedure would then depend on the desired outcome. One can imagine a situation in which the objective is to achieve the highest possible storage capacity by coupling nearby buildings into a multiple-upper-tank pumped-storage scheme. A natural constraint may be imposed on the capacity of the lower reservoir: it can be limited either by the capacity of an existing water body or by natural and technical conditions. Lower reservoirs could be also potentially used for storm-water storing purposes as long as it would not disrupt the pumped-storage operation.

The selection of buildings that should be connected to the considered pumped-storage scheme can take into consideration parameters that are well known from industrial-scale pumped-storage – namely, penstock-to-head ratio. This parameter usually should not exceed 10, though systems in which this value is much higher are known (for Castaic Pumped-Storage Plant in USA, this ratio is close to 40). By knowing the height of the buildings and their storage capacity, an optimization problem can be formulated that will aim to determine the optimal placement of the lower reservoir and which buildings should be connected to it, whilst maximizing, for example, total storage capacity. The formulation of the optimization problem is straightforward and is similar to common problems investigated in the operational research, such as optimal warehouse placement.

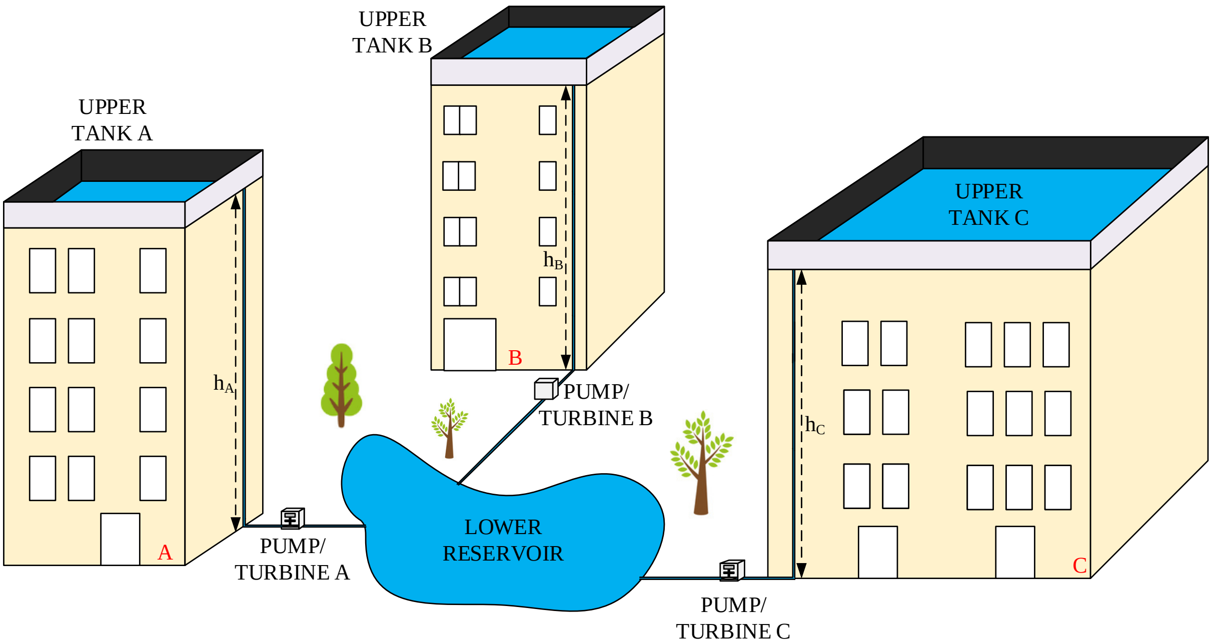

Fig. 6. System configuration coupling several buildings into a multi-upper-tank, single-lower-reservoir, pumped-storage scheme

As a case study of the above-described concept of multiple buildings sharing the same lower reservoir, the building capacity is shown on a map (similar to Fig. 3) that was then screened visually for clusters of buildings in close proximity to one another with high storage potential. An alternative approach, as described in the previous paragraph, can be based on the optimization algorithm linked directly to the GIS tool. Figure 7a presents a satellite view of an area that has been investigated from the perspective of a pumped-storage scheme of multiple upper tanks and a single lower reservoir. It shows that the area has multiple, relatively large and tall multifamily buildings.

For the chosen area, buildings of taller than 25 meters (arbitrary decision) were selected for further analysis. In total, 15 such buildings were identified. Their location is shown in Fig. 7b, which represents the centroids of their shapes.

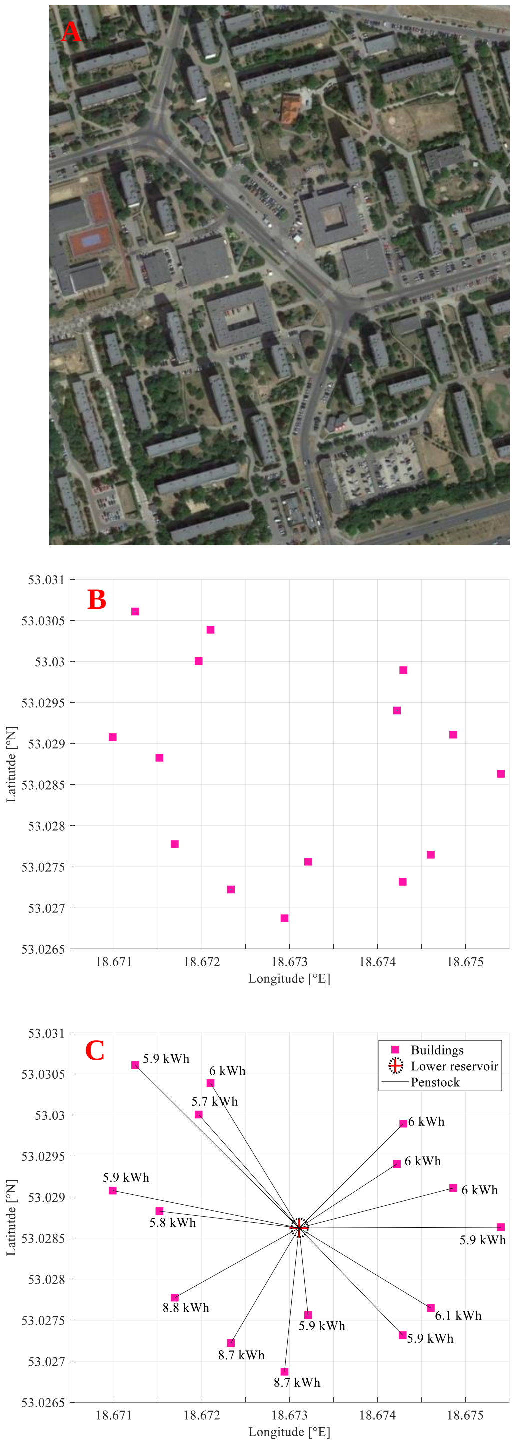

Fig. 7. A) satellite image of a selected part of the city with a significant concentration of buildings of high energy storage potential. Source: Google Maps, B) Location of buildings considered for the optimization problem, C) Location of lower reservoir and connected buildings, with building storage capacities

The first step in the analysis focused on calculating the distance matrix between the centroid of each building and the arbitrarily selected location of the lower reservoir. In practice, the location of the lower reservoir can be preselected from a set of possible sites (existing water bodies or areas where new ponds/reservoirs will be desired). The distance between the building and the lower reservoir was calculated based on the *spherical law of cosines*, which reads:

$$d = acos\ (sin\varphi_1 \times sin\varphi_2 + cos\varphi_1 \times cos\varphi_2 \times cos\Delta\lambda)$$

where: d is the distance between two points [m], φ is latitude, λ is longitude. Indices *1* and *2* represent two different points between which the distance is being calculated, and $\Delta\lambda$ is the difference between points' longitude.

After calculating the initial distance matrix between buildings and theoretical lower reservoir location, the optimization problem was formulated and solved. The objective function was to minimize the total length of the penstock of buildings connected to the lower reservoir. A constraint was set that buildings with penstock-to-head ratios greater than 10 should not be connected. From the above, one can reason that the problem boils down to finding a location for the lower reservoir that minimizes the total of distances from all buildings combined. In our analysis, the potential constraints on locations where the lower reservoir cannot be located were neglected, but could easily be incorporated. Considering the non-linear, but convex nature of the optimization problem, a Generalized Reduced Gradient method with default settings under the MS Excel Solver add-in was applied. The analysis of the obtained results is presented in the following paragraph.

As expected (visual analysis of Fig. 7b), the optimal location for the lower reservoir was found to be in the middle between all considered buildings (Fig. 7c). For that particular set of buildings, it was found that all of them meet the constraint of penstock-to-head being lower than 10. Figure 7c shows the theoretical layout of the penstock. It follows the shortest path between the building and the lower reservoir. Depending on the local conditions the penstock layout may vary, but its optimal setup should be designed considering hydraulic principles, which are beyond the scope of this study.

After optimally locating the lower reservoir with an objective function to minimize total penstock length, the total length of pipes connecting all buildings' upper tanks to the lower reservoir was found to be 2 861 meters. The resulting average penstock-to-head ratio would be (Table 2) 4.9, which is significantly lower than for typical pumped-storage projects. For some buildings, it would be as low as 4.3, whereas the highest observed is 9.8. Clearly, further optimization expansions can be considered, such as limiting the maximal penstock-to-head ratio to a certain value while simultaneously minimizing total penstock length and maximizing total energy storage potential. Other scenarios might, for example, consider optimally connecting buildings taking into account a reduced lower reservoir capacity.

Table 2. Summary of basic parameters of selected buildings serving as pumped-storage. Penstock-to-head ratio given for results presented in Fig. 7c

Bulding	**Roof area [m2]**	**Storage [kWh]**	**Height [m]**	**Penstock [m]**	**Penstock to head [-]**	**Energy density [m^3/kWh]**
1	480.5	8.8	33.7	133.6	5.0	10.9
2	324.4	5.7	32.5	171.6	6.3	11.3
3	327.7	6.0	33.3	207.4	7.2	11.0
4	479.4	8.7	33.4	164.1	5.9	11.0
5	477.0	8.7	33.7	195.0	6.8	10.9
6	366.5	5.9	29.5	118.2	5.0	12.4
7	322.0	6.0	33.9	114.4	4.4	10.8
8	324.3	6.0	33.8	162.1	5.8	10.9
9	322.0	6.0	34.2	129.2	4.8	10.7
10	328.0	5.9	32.9	153.7	5.7	11.2
11	369.6	5.9	29.3	165.3	6.7	12.5
12	370.1	6.1	30.1	147.8	5.9	12.2
13	322.3	5.9	33.8	150.6	5.5	10.9
14	320.3	5.8	33.0	108.7	4.3	11.1
15	374.3	5.9	28.7	253.6	9.8	12.8

For the considered set of 15 buildings (presented in Fig. 7c), the combined storage capacity of the upper reservoirs amounts to 97.2 kWh. This energy is stored as the potential energy of water at building roofs. Considering various building heights, each 1 m^3 corresponds to a different amount of potential electrical energy that can be recovered. Neglecting the efficiency losses in Table 2, producing one 1 kWh of energy would take from 10.7 to 12.8 m^3 of water. The combined volume of water in the upper tanks should indicate the required volume of the lower reservoir. For the considered set of 15 buildings, one can calculate that the lower reservoir should not be smaller than 1 101 m^3. If the lower reservoir is located in the open (for example, in the form of a pond or small lake in a park) it should be ensured that water level fluctuations will not impact its visual aspects or, for example, fish habitat. Therefore, in such a situation, the lower reservoir should be much larger than the combined volume of the upper tanks. If the lower tank is located underground, visual and other aspects can most likely be neglected, but it should also be ensured that the reservoir is big enough to compensate for evaporation losses or gains from precipitation in the case of the upper reservoirs if these are not closed tanks.

Assuming a 90% turbine efficiency [43] a storage system with a capacity of 97.2 kWh can be estimated to cover 87.5 kWh of energy demand. There is also the question of the optimal generating capacity of the turbines and the pumping capacity of the pumps. In conventional pumped-storage schemes, the ratio of energy to power (storage capacity to turbine capacity) is usually 6:1, 8:1 or 10:1 depending on the local conditions and the role of the facility in the system. Applying the first ratio to the available storage capacities found in this study would yield generator capacities ranging from 1.0 kW to 1.5 kW. The optimal generator capacity should, however, be determined based on the role that the scheme would play in the system. If short-term peak load shaving were desired, larger capacity generators would be preferred. Alternatively, if the system is intended to cover, for example, building interior lighting during the night, generators with small capacity would probably be better suited to providing certain power during the longer winter nights. The size of the pumps should also be determined based on the system objective. If the intention were to benefit from time-of-use tariffs, then the pumps should be large enough to charge the upper tank in the time available. If, however, the system were to be connected to some nondispatchable energy source, like PV or wind generators, then pump size could potentially be determined based on the residual load (max(demand-nondispatcheble_generator;0)).

3.4 System cost estimation

This section is dedicated to a techno-economic analysis of the proposed PSH scheme integrated with buildings in a city.

To assess the economic feasibility of the proposed system and enable its comparison with different storage technologies, the levelized cost of storage (LCOE) metric has been applied. The formula used for LCOE calculation was adopted from Schmidt et al. [44], and is shown in Eq. 7.

$$LCOS = \frac{CAPEX + \sum_{i=1}^{n} \frac{OPEX}{(1+r)^i} + \sum_{i=1}^{n} \frac{Charging\ cost}{(1+r)^i} + \frac{End-of-life\ cost}{(1+r)^{n+1}}}{\sum_{i=1}^{n} \frac{Electricity\ discharged}{(1+r)^i}} \quad (7)$$

where: CAPEX – investment cost [€], OPEX – operation and maintenance cost [€], Charging cost – cost of energy bought or generated that has been stored in the upper reservoir [€], End-of-life cost – cost of dismantling and recycling the infrastructure components [€], Electricity discharged – amount of electricity discharged from the storage per year [kWh].

The typical PSH cost structure involves: pump and turbine, upper and lower reservoir, pipes/penstock connecting the two reservoirs, control system and manual labor costs. The upper/lower reservoirs can be executed in various ways. In this case, the size and parameters of the upper reservoir are constrained by the roof-bearing capacity. This will limit the tank height. Therefore, the upper reservoir most likely will cover the whole roof area and will be relatively shallow.

The application of a conventional plastic water storage tank is not feasible, as this would require much greater roof-bearing capacity. An alternative to plastic storage tanks is a polyurethane waterproofing membrane. Assuming that walls are already available that could serve as the outer walls of the upper reservoir, these would need to be covered with a membrane. According to Cleverpolymers.com [45], an appropriate waterproofing membrane can be acquired for €230 (€1.0 = PLN 4.46 as of 08.06.2021) for 24 kg of substance, which is sufficient for 13.3 m^2 of surface. The analysis for this case indicates that 1 m^3 of reservoir requires roughly 5.45 m^2 of area. From the above one can conclude that each 1 m^3 of upper reservoir might cost €94.24.

However, another potentially cheaper alternative to polyurethane waterproofing membrane is waterproofing foils. A foil of 1 mm thick costs 2.55 €/m^2 [46]. This solution for the upper reservoir would cost 13.93 €/m^2 and [47] labor costs in this particular region should be roughly 3.6 €/m^2.

The lower reservoir is most likely not constrained in such a way that its shape would be much affected. The cost of earthworks [47] can range from €26.9 to €51.6 (depending on whether done manually or with mechanical equipment). The cost of earthworks done by mechanical equipment is given in €/hour, whereas manual labor is given in €/m^3. Simplifying, the costs of excavations have been assumed as the average of the two (39 €/m^3). Additionally, one should consider the cost of insulating the lower reservoir, which would be 2.55 €/m^2 for material and 3.6 €/m^2 for labor. For the lower reservoir, it has been assumed that its side projection is a trapezoid and plane view is a square. The inclination of external cut slopes was set to 1:1.5 (angle of 33°41'). The maximal depth of the lower reservoir was set arbitrarily to 3 m. From the above assumptions it can be estimated that, for example, a 1 000-m^3 lower reservoir (truncated pyramid) would have a surface area requiring 724 m^2 of waterproof material. Therefore, it can be concluded that the cost of the lower reservoir per 1 m^3 could be €43.5.

Considering the limited head of the considered PSH scheme, it is assumed that the pipes would not require special resistance to high pressures. The total penstock length for the considered PSH scheme is 2 861 m. Piping that meets the required water flow costs on average 30 €/m. There is a lack of information on how much such specific civil works might cost in the case of hydropower. As a reference, the cost of installing 1 m of sewage pipe provided by [48] has been taken. According to [48] this cost amounts to 21 €/m (and includes the pipe). Putting the pipe underground would cost an additional 22 €/m. Data from Table A1 indicates that 2 375.4 m of penstock would have to be installed underground. Therefore, for the considered scheme the cost of installing 1 m of pipe is €39.2.

The pump should have a relatively low nameplate capacity and the ability to efficiently raise water by 30 meters. According to [49], the cost per kW of such pumps is around 2612 585 €/kW. However, small scale pumps (1 kW) are not capable of raising enough water within 6–10 hours, so a unit of at least 10 kW capacity would have to be installed.

Although small turbines are also available (with capacities well below 1 kW), for the considered head of approximately 30 meters and upper reservoir volume of over 1 100 m^3 it is necessary to size the pump accordingly, in order to use the full potential of the upper reservoir. The pump provided by [50] meets those requirements as its design head is 25–30 meters and rated flow is 50–60 L/s. The later number translates to 6 and 5 hours, respectively, of continuous discharge from the upper reservoir, assuming it was fully charged.

According to [51], the control system for such a small-scale system is about €160. Discussion with a consulting company revealed that installing such a system, taking into account its electrical components, control system and connection to the grid, would require 80 man-hours (2 technicians, 8 hours per day, 5 working days). Qualified technicians are currently being paid 10 €/hour, so installation should cost around €800.

The end-of-life costs are hard to estimate for a project whose projected life-time is so long. Furthermore, it is an open question as to whether the equipment could not be used for other purposes: the lower reservoir can be renovated and used as a pond, the pipes do not necessarily have to be removed from the ground and the pump and turbine set can be either renovated or sold as scrap metal. Considering the above, the end-of-life costs have been set to €0. The projected life-time of the project is 40 years, which is a lower bound for typical hydropower/pumped-storage projects. The discount rate was set to 5%. It has been assumed that the electricity used to pump the water from the lower to the upper reservoir is purchased from the national grid. The cost increase of electricity purchased for pumping the water from lower to the upper reservoir (2.5% *per annum*) has been estimated based on data available from Eurostat [52] for non-commercial customers in Poland. The operation and maintenance costs are taken from the ETRI 2014 study [53] and are equal to 1.5% of CAPEX. The investment costs are summarized in Table 3.

Table 3. Costs and parameters assumed for calculating the LCOE for small-scale energy storage

Component	Cost	Case study	Total for this case study [€]	Source
Pump [€/kW]	585.0	10 [kW]	5 850.0	[49]
Turbine [€/kW]	307.5	10 [kW]	3 075.0	[50]

Pipes/penstock [€/m]	39.2	2 861 [m]	112 341.5	[48]
Upper reservoir [€/m^3]	16.99	1 101 [m^3]	18 706.0	[46, 47]
Lower reservoir [€/m^3]	43.5	1 101 [m^3]	47 893.5	[46, 47]
Control system [€]	160	1 [-]	160.0	[51]
Installation [€/h]	10	80 [hours]	800.0	Own source
Energy purchased [€/kWh]	0.14	-		[52]
Change in cost of energy purchased [% *per annum*]	2.5	-	-	[52]
Operation and maintenance [% of CAPEX]	2.5	-	-	[53]
Discount rate [%]	5	-	-	*Assumed as investor's decision*

For the considered PSH scheme the final capital investment cost is almost €190 000. Figure 8 presents the cost structure. This is dominated by the installation of the penstock (~59.5%) followed by the lower and upper reservoir (respectively, 25.4% and 9.9%).

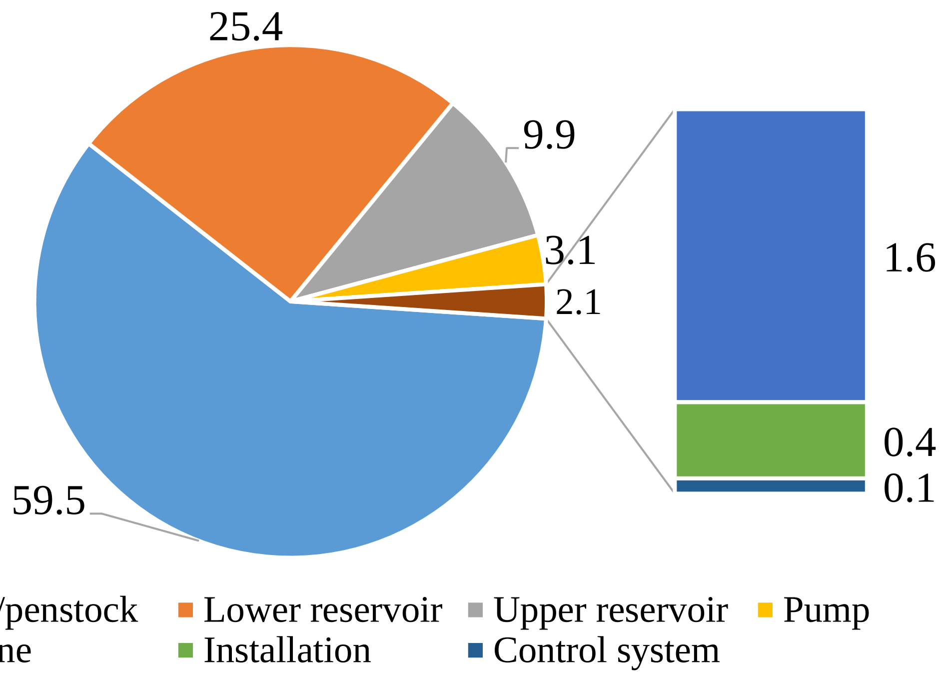

Fig. 8. Cost structure (in %) of the considered pumped-storage scheme

Based on the above assumptions, the LCOS was estimated to be 0.806 €/kWh, which is far beyond the values reported by for example Lazard [54]. For residential PV and storage, Lazard [54] reported LCOS ranging from 495 to 617 $/MWh (EUR 1 = USD 1.22 as of 08.06.2021). If it were somehow possible to avoid the earthworks related to the penstock, its cost could go down by 45.7% and the LCOS for such a system would be 0.661 €/kWh (meaning an 18% reduction). Avoiding an underground penstock seems to be a feasible solution if it is possible that the water will not freeze (given suitable climate or insulation) and a penstock at ground level will not impair the visual quality of the surrounding area. Nevertheless, the LCOS of such a system remains relatively high. The above indicates that one alternative to reduce the LCOS might be to limit the length of the penstock and to create independent PHS systems for individual buildings. If such an approach is applied, the length of the penstock is reduced significantly to 534 meters (sum of all heads × 1.1 to enable the location of the lower reservoir outside the building outline). If a decentralized system is selected, each has to be equipped with its own pump, turbine and control system. If the assumption is made that each system has to be equipped with pumps and turbines of the same capacity as the original system, the resulting LCOS is even higher and amounts to 0.879 €/kWh. For such a system, the investment cost is dominated by pumps (40.8%) and lower reservoir (22.3%).

For the PSH scheme with the lowest LCOS, a sensitivity analysis has been performed with regard to the input data. The results are in line with Fig. 8 and indicate that penstock cost has the highest impact on the LCOS value. Assuming that such a system could operate in combination with PV or a wind generator and would be absorbing otherwise curtailed excess renewable generation (meaning the cost of energy purchased is 0 €/kWh) the LCOS could be further reduced to 0.381 €/kWh. But even at this cost, it is not competitive with technologies already available on the market. Furthermore, absorbing excess solar and wind generation would be characterized by high variability and most likely would result in a low capacity factor/utilization of the storage system, and LCOS will be higher than the best case indicated above (0.381 €/kWh).

3.5 On the operation and role of the considered storage system

It is important to discuss the role of such an energy-storage technology and its potential in the context of the considered buildings, and of the whole city and its specific energy demand. The total pumped-storage capacity of the 15 buildings presented in Table 2 is approximately 6 kWh per building (considering discharge losses and 90% turbine efficiency). The estimated 6 kWh per building is very little, considering that the average household consumes roughly 3 MWh per year (in Poland), which translates into 8.2 kWh/day – and each such building might have up to 30 apartments. This makes it clear that such a storage system cannot serve all the needs of its occupants and their dwellings on, for example, days of cloud or low wind speeds. However, each building also has a shared space that usually requires a ventilation system as well as a lighting system (air conditioning is not common in older buildings, nor in this climate zone). This leads to the conclusion that the proposed small-scale pumped-storage schemes have the potential to theoretically absorb locally generated energy surpluses from PV (rooftop, land-based or floating PV) or small wind turbines and then to release them during the night to power some appliances. Again, the above leads to the conclusion that such a system would operate with a daily routine (daytime charging / nighttime discharging). If it were possible to run it in such a manner for 6 hours charging and six hours discharging per day, that would yield a capacity factor of 25% for the turbine/pump. Future studies should discuss this solution and compare it against battery storage.

Another question regarding such a storage system is what its potential role might be in covering the city's energy demand in times of need. For that purpose, information regarding electricity consumption in Toruń city was obtained. The following document, which discusses the city needs and supply options with regard to heat, electricity and gas [55], explains that the city uses 726.7 GWh of electrical energy in a year (2019). Furthermore, the document states that lighting streets and important buildings consume approximately 14 GWh of electricity per year. With the 19 MWh storage capacity of the proposed system, a 6-hour discharge capacity and operation 365 days per year, the system could deliver 6.24 GWh of electricity (90% efficiency of discharge), which translates into covering 44% of the lighting system energy consumption. (This is of course assuming that the storage was charged before the night.) From the city electricity demand perspective, such a system would therefore cover 0.9% of the annual electricity demand. Naturally, it remains an open question as to whether the use of such storage would not be more economically justified for peak-shaving when the electricity prices are high. A detailed economic analysis is presented in the Appendix section. It shows, firstly, that the cost of the proposed storage technology is quite high compared to more modern alternatives like battery storage and, secondly, that it is subject to local conditions like suitable climate conditions for on ground penstock or such simple factors as labor costs.

3.6 Given that a water distribution company consumes significant amounts of water. Water store on the top of the building can be a demand side management solution, without the need to add turbines to generate electricity. However, if the storage capacity on the top of the buildings exceeds the required storage for demand side management, assuming that the energy storage services are managed by the water distribution company, and the only change to the existing infrastructure apart from the upper reservoirs, is to replace of old pumps from the network with pump-turbines, then the costs of the system could be competitive with other energy storage solutions.Strengths-weaknesses-opportunities-threats analysis

As indicated in the introduction, the concept of building integrated pumped-storage schemes has gained some attention from the research community in recent years. The literature shows that some concepts are being tested based on real case studies, whereas other studies consider more theoretical concepts. This work aimed to answer the question of what potential such systems have from the city perspective, assuming reasonable capacities of upper reservoirs/tanks. The analysis followed the assumptions made by predecessors and standards/parameters commonly seen in conventional pumped-storage systems. Table 4 assesses this concept's prospects using a strengths-weaknesses-opportunities-threats analysis (SWOT).

Table 4. SWOT analysis of pumped-storage integrated with buildings in cities

Strengths	**Weaknesses**
• Low operating cost. • Technology is mature with a long lifetime. • High cycle efficiency, though possibly lower than average for small-scale systems. • On a single building level, length of penstock will most likely not significantly exceed the useful head (if lower reservoir is located, for example, underground).	• At small scale cannot benefit from economy of scale, which is a major benefit for large-scale pumped-storage schemes. • Although the urban environment possesses significant numbers of sites suitable for small-scale pumped-storage, the load-bearing capacity of typical roofs is a severe obstacle to developing the concept. • From the city perspective, the pumped-storage potential has relatively little energy-balancing value.
Opportunities	**Threats**
• The system could potentially be coupled with rainwater harvesting systems, though a proper management strategy and operational objective would need to be developed. • The system could be integrated with a water provision system by adding a generator. Such a system operating within the limits set by the principal operation (water provision) could provide services to the grid such as mFRR, and gain additional revenue.	• Rapid decreases in the price of alternative storage technologies (Li-Ion batteries) will outcompete building integrated pumped-storage from the market – as also shown by e Silva and Hendrick [41] • The pumped-storage system could potentially benefit from existing water supply infrastructure, but maintaining water quality might be an issue.

3.7 Future work proposals

The analysis has shown the proposed concept to have a limited applicability potential. The work focuses on buildings in neighborhoods of prefabricated concrete buildings [Pol. *wielka płyta*] in Poland. Such buildings, due to their geometry (usually tall cuboids) and construction material, seemed a good fit for implementing the technology. This technology for building housing estates was used in Poland and other countries in Eastern Europe in the second half of the 20th century. Currently, there are about 10 million Poles living in such buildings, which is more than one quarter of the country's population.

The global analysis of the proposed solution should cover three main stages:

a) Quantitative and spatial analysis – this stage uses GIS tools and spatial data (including LIDAR data), which can be used to indicate a potential location that meets the height and spatial requirements.

b) Qualitative analysis – in this stage, selected locations are analyzed in more detail in terms of building type, structure, roof slope, etc.

c) Economic analysis – for locations that meet requirements in the qualitative analysis, an analysis of the economic profitability of the investment is performed. As part of this analysis, local conditions related to natural factors (climate, especially precipitation and evaporation) and anthropogenic factors (pro-ecological policy and co-financing for pro-environmental investments, current sources of obtaining energy) should also be taken into account.

4 Concluding remarks

Energy storage plays a vital role in the energy system. It allows demand and supply to be matched without compromising the quality of supplied power, while enabling power stations to operate smoothly. However, with the advent of large-scale variable renewable energy sources such as wind and solar energy, the paradigms that have been governing the operation of the power system are undergoing significant changes. The variable nature of solar and wind energy, which often have priority access to the grid, leads to significant changes in the residual load. The growing concerns associated with the need to integrate the constantly increasing share of solar and wind energy into the power system call for urgent action in exploring, developing and proposing new energy-storage concepts.

This article briefly introduced recent intensive studies on various possible energy-storage technologies. Next, it focused on the available literature that has discussed the possibility of integrating pumped-storage into the built environment. These works inspired the formulation of a research question regarding the storage potential of pumped-storage systems integrated with buildings on a city scale. To answer this question, well-known GIS tools were applied, accompanied by a set of rules and assumptions made in earlier works. This analysis has revealed that for a city in northern Poland (population ca 200 000) the storage potential for pumped-storage amounts to 19.2 MWh or 11.3 MWh, depending on the selection criteria applied to buildings. On the scale of a building or cluster of buildings, the storage potential is not sufficient to cover the typical demand of all or individual dwellings. Therefore, the proposed storage system should instead focus on covering the building lighting needs (shared space) or peak shaving, rather than bulk energy storage. On the city scale, the storage system could, if operated daily at full potential, contribute to covering city lighting energy demand (up to 44%), but this is less than 1% of the city's total energy demand. The remaining part of the paper briefly proposed a concept of coupling several buildings into a pumped-storage scheme with multiple upper reservoirs and a single lower reservoir.

The research conducted and reported in this article has answered the research question. But it simultaneously created some potential research directions that could be addressed in further works. From this point of view, the most important issue would be to discuss the civil engineering implications of building large water reservoirs on the tops of buildings. Also, the results presented here should be compared against analyses performed for other cities that have different built environments, such as those with more high-rise structures.

5 References

[1] Rosa-Clot, M., & Tina, G. M. (2020). Levelized Cost of Energy (LCOE) Analysis. In Floating PV Plants (pp. 119-127). Academic Press.

[2] Weschenfelder, F., Leite, G. D. N. P., da Costa, A. C. A., de Castro Vilela, O., Ribeiro, C. M., Ochoa, A. A. V., & Araújo, A. M. (2020). A review on the complementarity between grid-connected solar and wind power systems. Journal of Cleaner Production, 120617.

[3] Yan, J., Qu, T., Han, S., Liu, Y., Lei, X., & Wang, H. (2020). Reviews on characteristic of renewables: Evaluating the variability and complementarity. International Transactions on Electrical Energy Systems, e12281.

[4] Jurasz, J., Canales, F. A., Kies, A., Guezgouz, M., & Beluco, A. (2020). A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions. Solar Energy, 195, 703-724.

[5] Schyska, B. U., & Kies, A. (2020). How regional differences in cost of capital influence the optimal design of power systems. Applied Energy, 262, 114523.

[6] Solomon, A. A., Kammen, D. M., & Callaway, D. (2016). Investigating the impact of wind–solar complementarities on energy storage requirement and the corresponding supply reliability criteria. Applied energy, 168, 130-145.

[7] Raynaud, D., Hingray, B., François, B., & Creutin, J. D. (2018). Energy droughts from variable renewable energy sources in European climates. Renewable Energy, 125, 578-589.

[8] Sehn, V., & Blesl, M. (2021). Implications of national climate targets on the energy-water Nexus in Germany: a case study. Journal of Sustainable Development of Energy, Water and Environment Systems, 9(1), 5-0.

[9] Kies, A., Schyska, B. U., Bilousova, M., El Sayed, O., Jurasz, J., & Stoecker, H. (2021). Critical review of renewable generation datasets and their implications for European power system models. Renewable and Sustainable Energy Reviews, 152, 111614.

[10] Javed, M. S., Ma, T., Jurasz, J., & Amin, M. Y. (2020). Solar and wind power generation systems with pumped hydro storage: Review and future perspectives. Renewable Energy, 148, 176-192.

[11] Koohi-Fayegh, S., & Rosen, M. A. (2020). A review of energy storage types, applications and recent developments. Journal of Energy Storage, 27, 101047.

[12] Seefried, A., Müller, B., & Förster, E. (2020). Regional analysis of potentials of flexibility options in the electricity system for the study regions Prignitz in Brandenburg and Anhalt-Bitterfeld-Wittenberg in Saxony-Anhalt. Journal of Sustainable Development of Energy, Water and Environment Systems, 8(1), 162-183.

[13] Olabi, A. G., Onumaegbu, C., Wilberforce, T., Ramadan, M., Abdelkareem, M. A., & Al–Alami, A. H. (2020). Critical review of energy storage systems. Energy, 118987.

[14] McIlwaine, N., Foley, A. M., Morrow, D. J., Al Kez, D., Zhang, C., Lu, X., & Best, R. J. (2021). A state-of-the-art techno-economic review of distributed and embedded energy storage for energy systems. Energy, 120461.

[15] Hrnčić, B., Pfeifer, A., Jurić, F., Duić, N., Ivanović, V., & Vušanović, I. (2021). Different investment dynamics in energy transition towards a 100% renewable energy system. Energy, 237, 121526.

[16] Schyska, B. U., Kies, A., Schlott, M., von Bremen, L., & Medjroubi, W. (2021). The sensitivity of power system expansion models. Joule, 5(10), 2606-2624.

[17] de Andrade Furtado, G. C., Mesquita, A. L. A., Morabito, A., Hendrick, P., & Hunt, J. D. (2020). Using hydropower waterway locks for energy storage and renewable energies integration. Applied Energy, 275, 115361.

[18] Stenzel, P., & Linssen, J. (2016). Concept and potential of pumped hydro storage in federal waterways. Applied energy, 162, 486-493.

[19] Emmanouil, S., Nikolopoulos, E. I., François, B., Brown, C., & Anagnostou, E. N. (2021). Evaluating existing water supply reservoirs as small-scale Pumped Hydroelectric Storage options–A case study in Connecticut. Energy, 120354.

[20] Hunt, J. D., Zakeri, B., Falchetta, G., Nascimento, A., Wada, Y., & Riahi, K. (2020a). Mountain Gravity Energy Storage: A new solution for closing the gap between existing short-and long-term storage technologies. Energy, 190, 116419.

[21] Farfan, J., & Breyer, C. (2018). Combining floating solar photovoltaic power plants and hydropower reservoirs: a virtual battery of great global potential. Energy Procedia, 155, 403-411.

[22] Fan, J., Xie, H., Chen, J., Jiang, D., Li, C., Tiedeu, W. N., & Ambre, J. (2020). Preliminary feasibility analysis of a hybrid pumped-hydro energy storage system using abandoned coal mine goafs. Applied Energy, 258, 114007.

[23] Menéndez, J., Loredo, J., Galdo, M., & Fernández-Oro, J. M. (2019). Energy storage in underground coal mines in NW Spain: Assessment of an underground lower water reservoir and preliminary energy balance. Renewable Energy, 134, 1381-1391.

[24] Morstyn, T., Chilcott, M., & McCulloch, M. D. (2019). Gravity energy storage with suspended weights for abandoned mine shafts. Applied Energy, 239, 201-206.

[25] Cava, F., Kelly, J., Peitzke, W., Brown, M., & Sullivan, S. (2016). Advanced rail energy storage: green energy storage for green energy. In Storing Energy (pp. 69-86). Elsevier.

[26] Bottenfield, G., Hatipoglu, K., & Panta, Y. (2018, September). Advanced Rail Energy and Storage: Analysis of Potential Implementations for the State of West Virginia. In 2018 North American Power Symposium (NAPS) (pp. 1-4). IEEE.

[27] Pimm, A. J., Garvey, S. D., & de Jong, M. (2014). Design and testing of energy bags for underwater compressed air energy storage. Energy, 66, 496-508.

[28] Hahn, H., Hau, D., Dick, C., & Puchta, M. (2017). Techno-economic assessment of a subsea energy storage technology for power balancing services. Energy, 133, 121-127.

[29] Puchta, M., Bard, J., Dick, C., Hau, D., Krautkremer, B., Thalemann, F., & Hahn, H. (2017). Development and testing of a novel offshore pumped storage concept for storing energy at sea− Stensea. Journal of Energy Storage, 14, 271-275.

[30] EEI (2019). https://www.eei.org/about/members/international/Documents/2019_EEI_GlobalStorageTrends.pdf, accessed: 06.04.2021

[31] Hunt, J. D., Zakeri, B., Lopes, R., Barbosa, P. S. F., Nascimento, A., de Castro, N. J., & Wada, Y. (2020b). Existing and new arrangements of pumped-hydro storage plants. Renewable and Sustainable Energy Reviews, 129, 109914.

[32] Novosel, T., Ćosić, B., Krajačić, G., Duić, N., Pukšec, T., Mohsen, M. S., ... & Ababneh, A. K. (2014). The influence of reverse osmosis desalination in a combination with pump storage on the penetration of wind and PV energy: A case study for Jordan. Energy, 76, 73-81.

[33] Rogeau, A., Girard, R., & Kariniotakis, G. (2017). A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale. Applied Energy, 197, 241-253.

[34] Wong, M. S., Zhu, R., Liu, Z., Lu, L., Peng, J., Tang, Z., & Chan, W. K. (2016). Estimation of Hong Kong's solar energy potential using GIS and remote sensing technologies. Renewable Energy, 99, 325-335.

[35] Singh, R., & Banerjee, R. (2015). Estimation of rooftop solar photovoltaic potential of a city. Solar Energy, 115, 589-602.

[36] Jurasz, J. K., Dąbek, P. B., & Campana, P. E. (2020). Can a city reach energy self-sufficiency by means of rooftop photovoltaics? Case study from Poland. Journal of Cleaner Production, 245, 118813.

[37] Zhang, Y., Ma, T., Campana, P. E., Yamaguchi, Y., & Dai, Y. (2020). A techno-economic sizing method for grid-connected household photovoltaic battery systems. Applied Energy, 269, 115106.

[38] Ashique, R. H., Salam, Z., Aziz, M. J. B. A., & Bhatti, A. R. (2017). Integrated photovoltaic-grid dc fast charging system for electric vehicle: A review of the architecture and control. Renewable and Sustainable Energy Reviews, 69, 1243-1257.

[39] Denholm P., Ela, E., Kirby, B., & Milligan, M. (2010). The role of energy storage with renewable electricity generation. Technical report NREL/TP-6A2-47187. National Renewable Energy Laboratory, Golden, CO, USA.

[40] Zhang, J., & Zhang, Q. (2014, July). High-rise building mini-hydro pumped-storage scheme with shanghai Jinmao Tower as a case study. In 2014 IEEE PES General Meeting| Conference & Exposition (pp. 1-5). IEEE.

[41] e Silva, G. D. O., & Hendrick, P. (2016). Pumped hydro energy storage in buildings. Applied energy, 179, 1242-1250.

[42] de Oliveira e Silva, Guilherme. (2017). Pumped storage - How small can you go?. International Water Power and Dam Construction. 69.

[43] Lin, S., Ma, T., & Javed, M. S. (2020). Prefeasibility study of a distributed photovoltaic system with pumped hydro storage for residential buildings. Energy Conversion and Management, 222, 113199.

[44] Schmidt, O., Melchior, S., Hawkes, A., & Staffell, I. (2019). Projecting the future levelized cost of electricity storage technologies. Joule, 3(1), 81-100.

[45] Cleverpolymers (2021). Cost of polymer. Retrived from: https://www.cleverpolymers.com/en/ Accessed: 20-25.06.2021.

[46] Master-fol (2021). Cost of isolation foil. Retrived from: https://master-fol.pl/folia-hydroizolacyjna/ Accessed: 20-25.06.2021.

[47] KalkulatorBudowlany (2021). Cost of earthworks: Retrived from: https://kb.pl/porady/cennik-robot-ziemnych-w-roznych-regionach-polski/ Accessed: 20-25.06.2021.

[48] Przedsiębiorstwo Wodociągów i Kanalizacji (2021). Cost of hydraulicworks. Retrived from: https://www.pwik-wodzislaw.pl/cenniki/cennik-uslug-zwiazanych-z-przylaczem-kanalizacyjnym Accessed: 20-25.06.2021.

[49] Pompysanok (2021). Cost of pump: Retrived from: https://pompysanok.pl/search/fraza,pompa+wysoko%C5%9B%C4%87+podnoszenia+30+m//s,1 Accessed: 20-25.06.2021.

[50] Micro-hydro (2021). Cost of turbine. Retrived from: https://www.micro-hydro-power.com/Micro-Hydro-Turbine-Power-Dual-Nozzle-XJ30-10DCTF4_6-Z.htm Accessed: 20-25.06.2021.

[51] Javed, M. S., Song, A., & Ma, T. (2019). Techno-economic assessment of a stand-alone hybrid solar-wind-battery system for a remote island using genetic algorithm. Energy, 176, 704-717.

[52] Eurostat (2021). Cost of electricity change. Retrived from: https://ec.europa.eu/eurostat Accessed: 20-25.06.2021.

[53] Carlsson, J., Fortes, M. D. M. P., de Marco, G., Giuntoli, J., Jakubcionis, M., Jäger-Waldau, A., ... & Weidner, E. (2014). ETRI 2014—Energy Technology Reference Indicator Projections for 2010–2050. European Commission, Joint Research Centre, Institute for Energy and Transport, Luxembourg: Publications Office of the European Union.

[54] Lazard (2021). Levelized Cost of Energy Analysis. Retrived from: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/ Accessed: 20-25.06.2021.

[55] Toruń – Supply, 2019.
https://www.konsultacje.torun.pl/sites/default/files/pictures/2016/konsultacje/zalozenia_torun_12.pdf. Accessed: 01.04.2021.