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Seasonal thermal energy storage using natural structures: GIS-based potential assessment for Northern China

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ABSTRACT

Seasonal thermal energy storage (STES) allows storing heat for long-term and thus promotes the shifting of waste heat resources from summer to winter to decarbonize the district heating (DH) systems. Large-scale STES for urban regions is lacking due to the relatively high initial investment and extensive land use. To close the gap, this study assesses the potentials of using two naturally available structures for STES, namely valley and ground pit sites. Based on geographical information system (GIS) methods, the available locations are searched from digital elevation model and selected considering several criteria from land uses and construction difficulties. The costs of dams to impound the reservoir and the yielded storage capacities are then quantified to guide the choice of suitable sites. The assessment is conducted for the Northern China where DH systems and significant seasonal differences of energy demand exist. In total, 2,273 valley sites and 75 ground pit sites are finally identified with the energy storage capacity of 15.2 billion GJ, which is much larger than the existing DH demand. The results also prove that 682 valley sites can be achieved with a dam cost lower than 20 CNY/m^3.

Keywords: Seasonal thermal energy storage, Geographical information system, District heating, water reservoir

1. INTRODUCTION

In 2021, the energy consumption of the Chinese building accounts to 21% in the whole country, equaling to 22% of the entire society's carbon emission [1]. Within the building sector, around 19% of the energy is used for the space heating demand in Northern China during winter [2,3], making it an important factor in the plans towards carbon neutrality. The seasonal thermal energy storage (STES) technology can coordinate the temporal differences between the heating and electricity sectors in an efficient and cost-effective manner [4]. By storing and shifting excess energy in the form of hot water over a long term, the STES reduces the fossil fuels needed by the DH and improves the utilization of renewable energy. Besides, great potentials of industrial surplus heat are found in Northern China [5]. A major obstacle in utilizing such resources is the unmatching of excess heat in summer and DH demand in winter, which can also be solved by STES. Thereby, the STES can facilitate the decarbonization of energy sectors using the existing grid and facilities.

STES is mostly utilized in a small community with water storage capacity between 1,000 m^3 to 50,000 m^3 to increase renewable energy integrations [6]. However, such configuration is far less than the seasonal demand differences presented in large cities, whose heated floor area are normally over millions of m^2. A major reason for the lack of large-scale STES is the limitations in available sites. Considerations from geo-hydrological conditions, climate, and construction works are needed [7]. Besides, the huge investment for constructing large-scale STES also slows down the application. It is concluded that the cost of STES still needs to be reduced by half in order to be economically competitive on the heating market [6].

Recently, most studies on the improvement of STES are placed on the artificial one that is completely built from scratch [8]. Indeed, there are naturally available terrain structures such as ground pits or valleys that can be reformed into large hot water reservoirs for STES. Compared with manually built STES, a great amount of construction works can be saved. Besides, natural structures save the extensive land uses, which is a critical issue for manually excavated sites in urban regions. Similar idea of using natural structures have been developed in hydrology and power systems but is still missing for STES.

With the aim of identifying available locations and storage capacities of prospective STES, a GIS-based methodology is developed in this study, including site searching from digital elevation model (DEM) and selection procedures for integration into DH systems. The geometries and construction difficulties for STES based on two natural geo-structures, namely valley and ground pit, are analyzed. The assessment is applied for the Northern China where DH systems and significant seasonal differences of energy demand exist.

2. METHODOLOGY

2.1. Valley sites

A typical example of a valley site that is transformed into a water reservoir is shown in Figure 1. Through the construction of a dam along the virtual river network, the valley is closed, which is capable of impounding a certain amount of water. The entire land that holds all possible flowing water is called the watershed. The impounded area becomes the potential water reservoir, whose size is largely depending on the height of the dam.

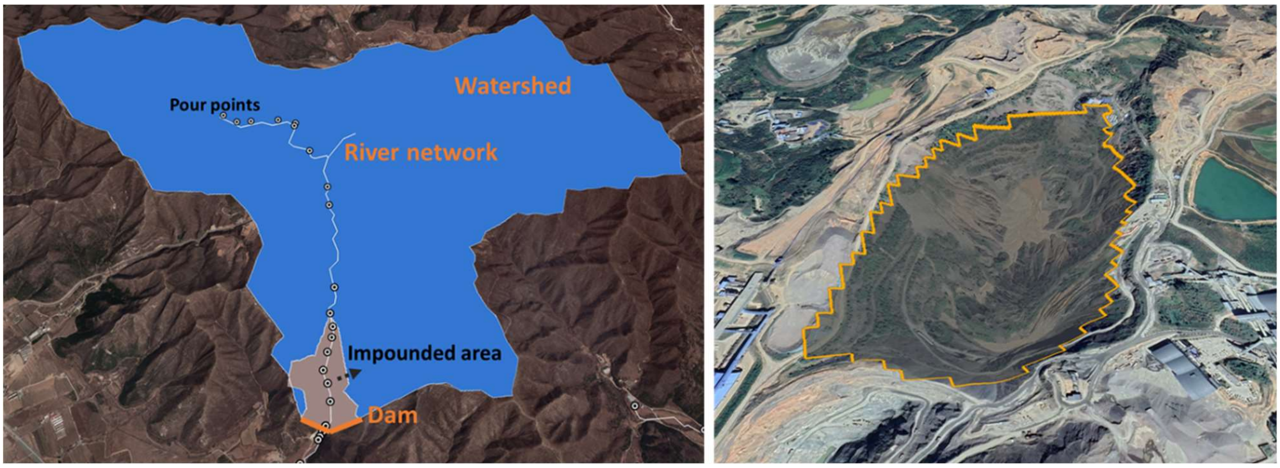

Figure 1. Typical examples of valley (left) and ground pit (right) sites.

The main input data is DEM, which represents the topographic surface of the Earth. 1 arc-second data from the shuttle radar topography mission with the resolution of approximately 30 m is used. The searching procedures for potential valley, see Figure 2, are based on the hydrology toolset in ArcGIS Pro. The drainage line is a channel where surface water naturally flows and is regarded as the valley line, generated by the flow accumulation and flow direction tools. Then, the pour points are created along the drainage lines with an interval of 10 m in altitude. These points are the locations where water flows out of the basin, which are also potential sites for the dams to impound water.

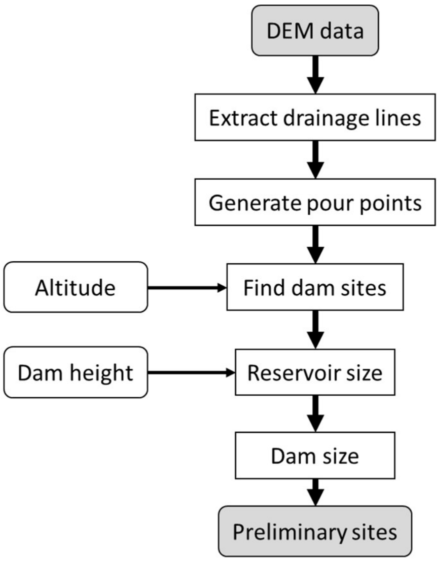

Figure 2. Flowchart for searching valley sites.

The design static water pressure for DH systems is commonly smaller than 1.5 MPa (equaling to around 150 m water head), considering the safety of pipes and valves. In this study, the average ground altitudes of all urban regions in Northern China are analyzed based on DEM data. The pour points with relative elevations of smaller than 30 m are selected as potential sites to build dams and STES units, based on pressure safety and pumping energy cost concerns. For each potential dam site, a watershed is created by the hydrology toolbox and the shape of the reservoir is generated by selecting rasters within the watershed that have lower altitude than the water surface. With the help of 3D Analyst tool, the area and volume of the potential reservoir are calculated.

A simplified structure of a concrete dam is considered in this study, as shown in Figure 3. The dam height is designed as 60 m considering the practical issues with constructions. The crest width is designed as 10 m to accommodate a road. The base width is set the same as the dam height, which is a common practice for concrete dam. The dam construction cost calculated with the empirical functions from investigations of 80 large dams in Australia [9], as shown in Equation (1). The original cost data is in Australian Dollar and is converted to Chinese Yuan (CNY) considering an average exchange rate of 4.6.

$$Cost = \frac{4.6 \times 0.0039 \times 10^6 \times height^{1.5681} \times length^{0.6148}}{V_{water}} \quad (1)$$

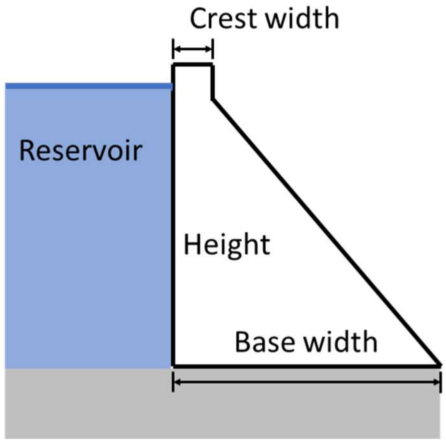

Figure 3. Simplified structure of a concrete dam.

2.2. Ground pit sites

Ground pits can be created by natural causes and human activities. Utilizing these pits for STES would save the construction cost while having little impact on the environment and landscape. A typical example of a desolated surface mining pit (latitude 40.06, longitude 118.54) with an average depth of 10 m below ground is shown in Figure 1. To locate ground pits, the lidar package developed by Qiusheng Wu [10] is applied. Based on level-set method, it is capable of delineating the nested hierarchy of surface depressions (pits) in DEMs and can be performed with Python or ArcGIS software. Similar as the searching procedures for valley sites, a minimum surface area of 10,000 m^2 and a maximum volume of 50 million m^3 are set. As the ground pits STES are designed to be connected with DH systems, limitations of elevations to nearby urban region is also effective.

2.3. Site selection

The identified preliminary valley sites are selected using several levels of criteria (see Table 1) to find the feasible ones for STES. To prevent redundant reservoirs that might even intersect with each other, a searching radius of 2 km is set. Within this area, the reservoir with the largest depth and its corresponding site is selected, to ensure a low thermal loss and lowest possible construction cost. The searching criterion assumes that the distance between two distinctive drainage lines (valleys) is generally larger than 2km. Thereby, for every valley, one site is selected.

To avoid the negative impact on the environment, the reservoir cannot be built in natural reservations designated by the Ministry of Ecology and Environment. Built-up areas, roads, and railways, derived from the most recent data (2022) in OpenStreetMap, indicate intensive land uses and are not suitable for STES.

For valley site reservoirs, the construction of dam makes up a significant part in the overall project cost. The dam with construction cost higher than 150 CNY/m^3 is also excluded. This threshold refers to the currently lowest cost for artificially building a pit STES from scratch.

Table 1. Selection criteria for valley sites.

Criteria	Valley
Searching radius for redundant sites	2 km
Infeasible areas	Natural reservations
	Built-up area
	Roads and railways
Dam cost	≤ 150 CNY/m^3
Pipeline through mountains	Elevation changes along the route ≤ 50 m
Distance to urban regions	≤ 20 km

The STES cannot be built on the hilltop due to the issues with large elevation and water pressures. Nevertheless, even with a small elevation, the STES located in the valley surrounded by mountains is still not an attractive option because the pipeline to the urban region goes through mountains, which requires huge investment and construction works. This study uses an alternative method to determine if the STES site is within the mountains. For every reservoir site, the nearest urban region is found and connected with a straight line. Then, several observation points with the interval of 200 m are created along the line. The altitude of these points is compared with the altitude of the reservoir. If the relative elevation changes are smaller than 50 m, it can be assumed that there are no obvious obstacles along the route and the reservoir is selected.

This study uses the location of the municipal building as the representation of the urban center. The STES sites located within 20 km from the urban center are selected because the current DH networks can be easily expanded to reach that distance. According to experience from Chinese DH networks and long-distance transportation projects, a longer distance would require specially designed pipeline and systems.

For the finally selected reservoirs, the energy storage capacity is calculated using a temperature difference of 75 °C to maximize the storage benefit with a certain water volume. To achieve that, the return water temperature shall be reduced to around 20 °C.

3. RESULTS

3.1. Characteristics of valley sites

Using the GIS-based searching methodology, a total of 402,363 preliminary valley sites are identified in Northern China. After several steps of selection procedures, 2,273 sites that can be developed into STES units are included in the final set, as shown in Table 2. These potential sites would not interrupt the land use status and are located within 20 km from nearby urban regions. The geographical distributions of the final valley sites are presented in Figure 4, based on the map provided by ESRI ArcGIS.

Table 2. *Searching procedures and the numbers of selected valley sites.*

Procedures	No. of sites
Step 1: GIS-based searching	402363
Step 2: Remove redundant points	155634
Step 3: Area and volume requirement	85788
Step 4: Exclusion of reservations, built-up area	46801
Step 5: Dam size and construction cost	29815
Step 6: Pipeline through mountains	6095
Step 7: Distance to urban region ≤ 20 km	2273

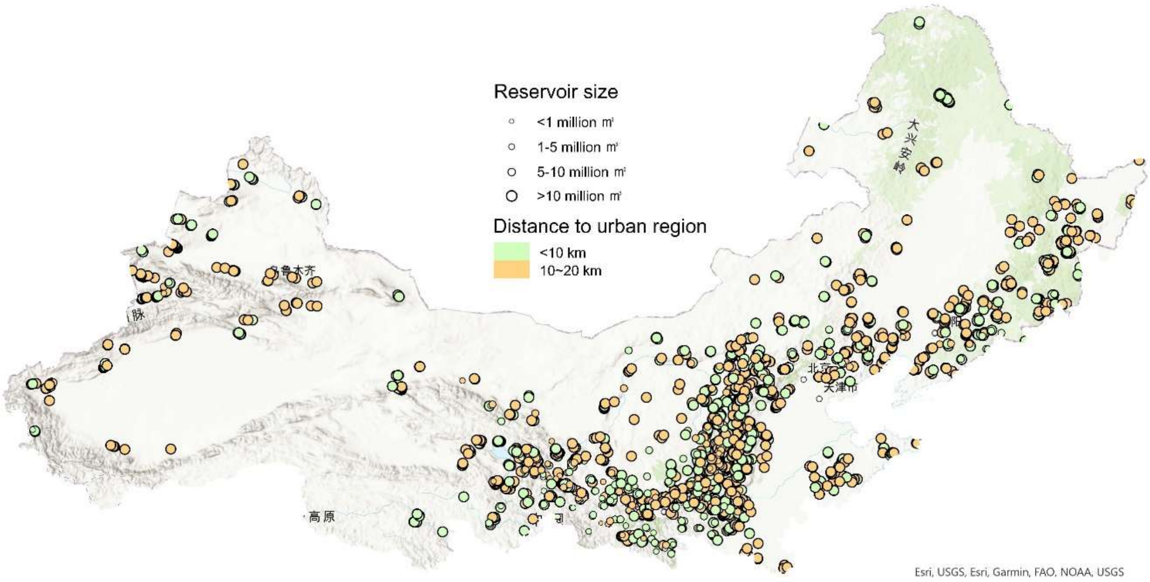

Figure 4. Selected valley sites in Northern China, classified by the reservoir size and distance to the nearest urban region.

Due to their specific geo-structures, the valley sites are gathered around major mountains in Northern China. It is seen that a large number of valley sites are distributed in the middle, around Qinling Mountains and Taihang Mountains. Although the Northwestern part of China is famous for having huge mountains, only limited numbers of potential sites are found. The main reason is that there are few cities in this area while the searched sites are located far from urban regions. In contrary, the Eastern part of Northern China, including Henan, Shandong and Hebei provinces, have dense populations and numerous cities. The available STES sites in this region are also rare due to flat terrain features.

A general description of the main characteristics of selected sites is provided in Figure 5. The reservoirs have an average water storage capacity of around 21 million m^3, which is much larger than the currently common storage unit used in small communities. By transforming these reservoirs into STES units, a total water volume of 47.8 billion m^3 is achieved, with the energy storage capacity of 15.1 billion GJ. This aggregated value is already larger than the total DH demand of Northern China (around 5.4 billion GJ). The distribution of volumes also reveals that more than half of the potential sites have water capacity larger than 10 million m^3, while only 152 reservoirs are smaller than 5 million m^3.

The average cost of the dams is 29.3 CNY/m^3. According to the previous estimation about large-scale STES [11], the costs for geotechnical works, excavation and cover are the three most important parts in the project investment. Since the STES sites investigated in this study are built from natural structures that save excavation costs, the overall expenditure of the proposed STES is still attractive compared to the current practices of STES that usually cost more than 200 CNY/m^3.

The design dam height of 60 m defines the maximum depth of the reservoir, while the average depth, also known as the characteristic length, is 24.5 m. Considering an average water surface area of around 870,000 m^2, the impounded reservoir has a flat and shallow shape. Such shape brings new challenges such as the thermal loss and temperature stratification issues during practical operation. In order to maintain a good thermal storage performance, more research works from bottom-level design and optimization aspects are needed.

To further highlight the most promising sites within the selected data set, the ones with the least dam cost and shortest distance to urban regions are summarized in Table 3. It can be seen that there are still 57 sites located within 5 km radius with dam costs lower than 20 CNY/m^3. By slightly increasing the tolerance of distance to 10 km, 125 more sites are found.

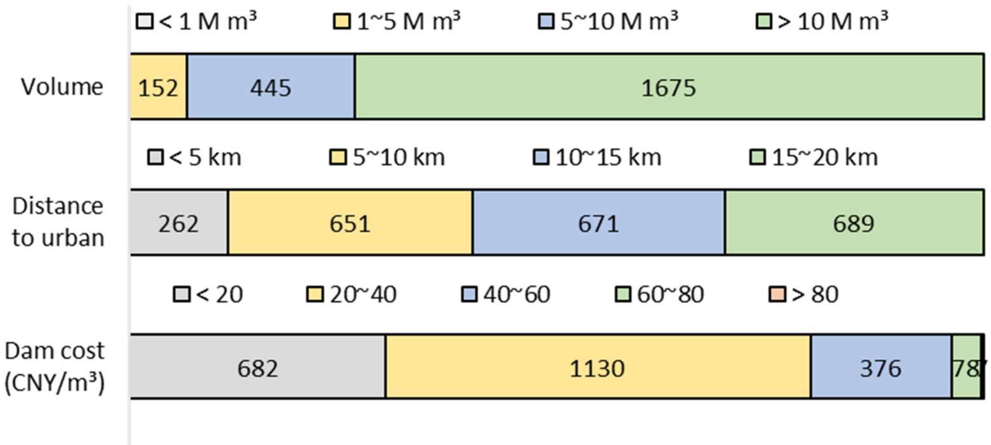

Figure 5. Distributions of storage volume, distance to urban regions, and investment in the selected valley sites.

Table 3. *Summary of promising valley sites considering criteria of dam cost and distance.*

	Criteria	No. of sites	Volume (billion m^3)	Storage capacity (billion GJ)
(1)	Dam cost ≤ 20 CNY/m^3 Distance ≤ 5 km	57	1.68	0.53
(2)	Dam cost ≤ 20 CNY/m^3 5 km < Distance ≤ 10 km	182	5.89	1.85
(3)	Dam cost ≤ 40 CNY/m^3 Distance ≤ 10 km	696	15.56	4.90

3.2. Characteristics of ground pit sites

Compared to valley sites, less ground pit sites are identified by the GIS-based searching procedure. The main reason is that pit sites are more demanding for terrain structures that shall naturally impound a certain area of water. In contrary, the valley sites rely on the constructions of dams to create reservoirs. Due to the same reason with structures, the dams and associated costs are not analyzed for pit sites. After several steps of selections, as shown in Table 4, only 75 sites remained as potential STES units. The geographically distributions of these sites are presented in Figure 6.

Table 4. *Searching procedures and the numbers of selected ground pit sites*.

Procedures	**No. of sites**
Step 1: GIS-based searching	64030
Step 2: Area and volume requirement	59465
Step 3: Exclusion of reservations, built-up area	44948
Step 4: Sink size, shape	25106
Step 5: Elevation requirement	11043
Step 6: Pipeline through mountains	3156
Step 7: Distance to urban region ≤ 20 km	75

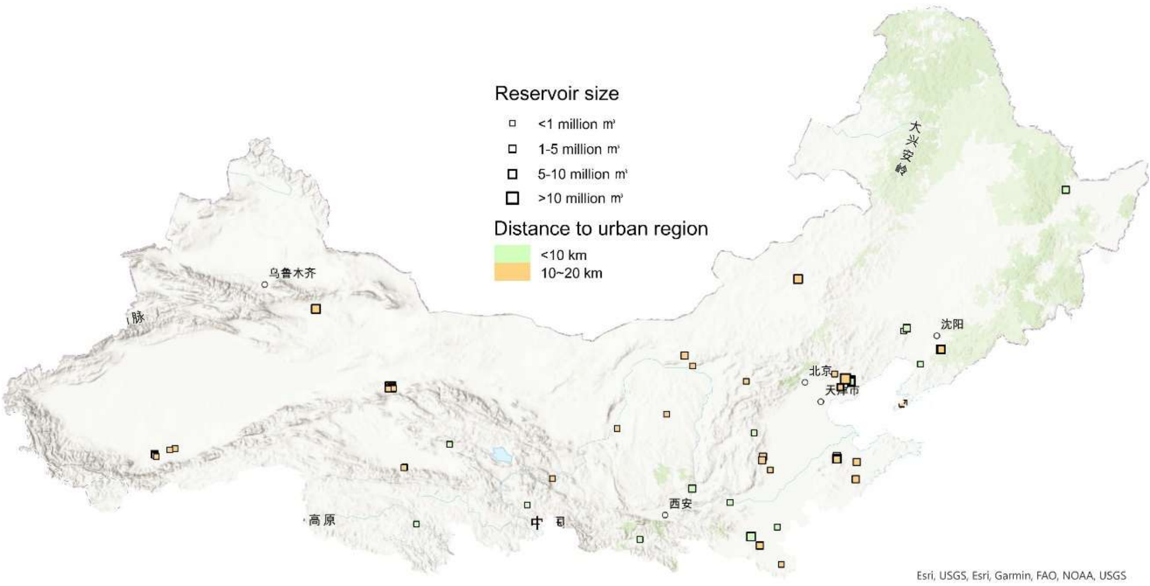

Figure 6. Selected ground pit sites in Northern China, classified by the reservoir size and distance to the nearest urban region.

The main characteristics of the selected pit sites are generally described in Figure 7. In total, the water storage volume of all 75 sites is 0.166 billion m^3, corresponding to an energy storage capacity of 52.4 million GJ. The average volume is 2.2 million m^3, which is also significantly smaller than the valley sites. As is shown in Figure 7, 46 pit sites have volumes smaller than 1 million m^3. From the perspective of practical construction, the STES based on pit sites are more easily achieved compared to those larger reservoirs impounded in valleys.

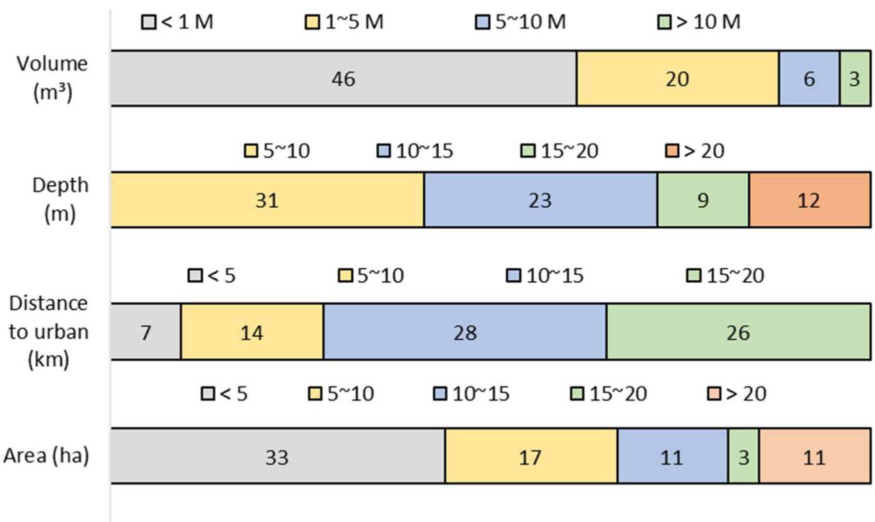

Figure 7. Distributions of storage volume, depth, distance to urban regions, and water surface area in the selected ground pit sites.

The average depth of the pit sites is 14.2 m, which is close to the current practices of manually built pit STES. The deepest pit is found in an open coal mine near Qian'an city, whose depth is around 70 m. As for the water surface area, an average value of 11 ha (110,000 m^2) is found. Considering these parameters, the shape of pit-based reservoir is less shallow than the valley-based reservoir.

4. DISCUSSION

The huge seasonal differences of DH demand in Northern China and extensive waste heat resources call for effective and economic energy storage solutions that can be applied in urban regions. From the scope of top-level planning, the findings of this study have identified the potentials of large-scale STES. However, to effectively put the idea into reality, more research works from bottom-level implementation stage are needed. The identified valley and pit reservoirs have shallow shapes that would create huge thermal losses to the environment. As the cost of insulation is an important factor in the overall project cost, economic solutions from material and structural design perspectives are needed. Besides, innovative measures such as diffusers and vertical partitions are also required to preserve the hot water for a seasonal period.

As for the utilization of STES, the reservoirs are prioritized for using in urban regions, so a distance limit of 20 km is set. This design is based on the availability of existing DH networks. However, there are flexible ways of connections between the heat source, STES, and the urban DH demand. A longer pipeline can be built to transport the waste heat into urban regions, as demonstrated by several projects in China [12,13]. This increases the freedom of choices for STES sites but requires more detailed evaluations on the project costs. Moreover, the STES can also be integrated with waste heat sources to improve the overall energy efficiency of industrial regions. Considering various application scenarios of STES, the combined planning of large-scale STES with energy supply and demand locations is an interesting topic to facilitate the co-decarbonization of multiple sectors.

5. CONCLUSION

This study identifies the locations and potentials of large-scale STES developed from two natural structures including the valley and ground pit, using a GIS-based searching methodology in Northern China. The most promising sites are selected considering various criteria from dam construction, land reservation, and reservoir sizes.

With the dam height of 60 m and elevations smaller than 30 m, 2,273 valley sites and 75 pit sites are finally identified, which in total has the energy storage capacity of 15.2 billion GJ. The reservoirs built from valley sites contribute most of the yielded capacity and have generally larger sizes than the pit reservoirs. The typical characteristics of identified sites including dam size, reservoir size, and average depth are analyzed. 682 valley sites are found to be achieved with a dam cost lower than 20 CNY/m^3. Based on the average depth and water surface area, the reservoirs are depicted as shallow shapes.

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