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# A GIS-based assessment of Tibet's potential for pumped hydropower energy storage☆

Xu Lu[a,*,1], Siheng Wang[b,c,1]

[a] Clark University, 950 Main Street, Worcester, MA 01610, United States
[b] State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Science, Beijing 100101, China
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The cost reduction of photovoltaic (PV) module makes solar energy a promising renewable energy for large-scale electricity generation, further controlling the green house gas emissions. A primary obstacle for the connection of PV generation into electric grid is its poor stability, due to the variation of solar radiation, which determines the PV output. Pumped hydroelectric storage (PHS) is an efficient energy storage method to stabilize the intermittent PV output. Tibet, where solar radiation is in abundance, presents an opportunity to install PV stations across China, and unified construction of PHS is necessary for grid-connected utilization of the solar energy there. The objectives of this study are to evaluate the PHS potential in Tibet and to provide promising locations of the PHS stations, through Geographic Information Science (GIS) analyses. A review of the existing GIS methods (T1-T7) for PHS site selection was firstly given. Two new GIS models (S1 and S2) appropriate for Tibetan area were proposed then, and the T1, S1 and S2 were considered for this assessment. Results showed that the total PHS potential in Tibet was about 997.2 GW h, 946.2 GW h and 2552.0 GW h under T1, S1 and S2, respectively. All the promising sites were mapped, and an assessment of these sites were made according to their distances to grid connections. The results were supposed to benefit the planning of the PHS facilities in Tibet.

## 1. Introduction

Tibet's annual average solar radiation reaches 6000–8000 MJ $m^2$ $year^{-1}$, ranking the first in China and the second worldwide after the Sahara desert [1]. Arid deserts account for about 18% of Tibet's land area in 2008 [2]. Thus, Tibet is supposed to be one of the most suitable areas to exploit solar energy in China because of the abundance of solar radiation and ample space for construction of photovoltaic (PV) generation stations. Meanwhile, the state's government has launched a series of projects concerning domestic PV industry. In June 2014, the General office of the state council of the People's Republic of China [3] issued No. 31 document ([2014]31), which set a aim of 100 GW of PV power installed in 2020 and emphasized on accelerating the development of solar power. By the end of June 2015, the total installed PV capacity of China was 35.78 GW. However, the total installed PV capacity of Tibet was only 150 MW, far behind the other remote provinces or autonomous regions in China, like Qinghai (4.70 GW), Ningxia (2.39 GW), Inner Mongolia (4.03 GW), Xinjiang (5.70 GW), and Gansu (5.78 GW) [4]. Apart from the harsh natural environment, another main obstacle for the utilization of Tibet's solar energy is its poor electricity infrastructure. By the end of 2014, the total installed capacity of the Tibet grid is only 1.697 GW [5]. A high penetration of renewable energy generation will have a detrimental effect on the power distribution network (e.g. wide-spread blackouts) because of the intermittency of the output [6]. Thus, large-scale integration of fluctuating renewable energy power into the existing Tibet grid system is not technically or economically practical for the moment. However, these problems are expected to be solved by Pumped Hydroelectric Storage (PHS) in the future.

PHS is a method of storing energy by pumping water from a lower reservoir to an upper reservoir and producing electricity by converting the water's gravitational potential energy (Fig. 1). PHS accounts for more than 99% of worldwide bulk storage capacity and contributes to about 3% of global electricity generation and it is currently the only commercially-proven fuel free energy storage technology with large volume, long lifetime, relatively long discharge time and high efficiency [9]. Up to now, PHS is still one of the most cost-efficient options for

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* Corresponding author.
*E-mail address:* luxurdfz@sina.com (X. Lu).
[1] These two authors are equally contributed to the work.

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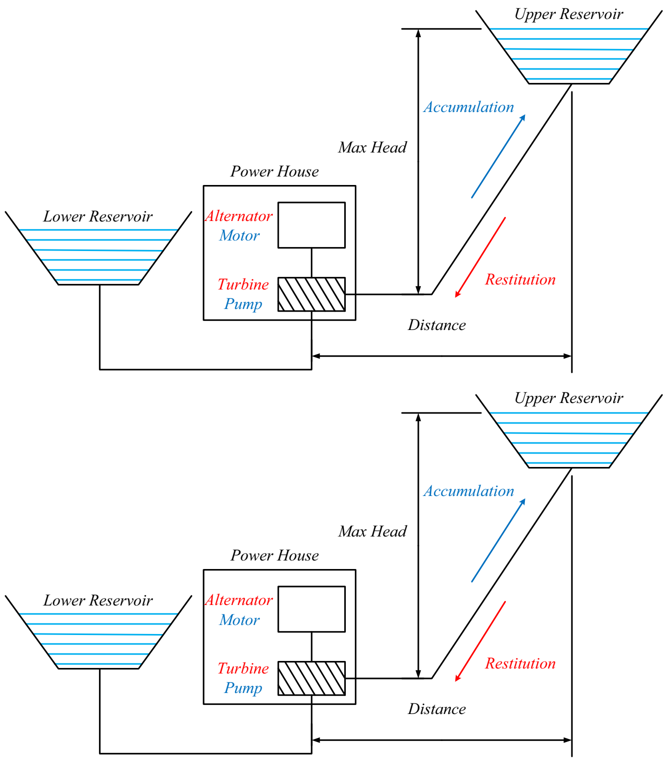


**Fig. 1.** Schematic diagram of a pumped hydroelectric storage system [7,8]. The lines between reservoirs and power house are penstock.

bulk energy storage [9,10]. Energy storage can increase the penetration of renewable energy sources significantly by eliminating the intermittency and instability [11–14]. Coupled with renewable sources, PHS has the lowest greenhouse gas (GHG) emissions significantly less than other electrical energy storage technologies [15]. Previous studies [16–21] had exploited the feasibility of developing the hybrid system combining the photovoltaic (PV) power generation and the PHS system through mathematical model and operational principle, presenting a promising prospect.

The government of China has been consistently launching a series policies to promote the domestic development of PHS. In August 2014, the National Development and Reform Commission (NDRC) [22] issued No. 1763 document ([2014]1763) and proposed a new price mechanism of PHS station. In November 2014, NDRC [23] issued No. 2482 document ([2014]2482) and set a target of 100 GW of PHS by 2025, which expected to account for 4% of the total installed power capacity. In March 2015, the Central Committee of the Communist Party of China and the State Council of the People's Republic of China [24] issued No. 9 ([2015]9), which aimed to establish an effective competitive market structure and market system, and to make the energy price mainly determined by the market. Once the social capital could gain profit from operating the PHS station in the market, the previous obstacles, like the management mode and price mechanism of operation and policy barriers [25], will be overcome.

Moreover, China has been continually strengthening the electricity infrastructure of Tibet's grid, which could support the development of PHS. In the past, Tibet's harsh environment and poor electricity infrastructure resulted in a few people paying attention to PHS potential in Tibet. By the end of 2013, China's total PHS capacity was 21.5 GW [23] where the capacity for Tibet was only 90 MW [25,26] and there is no newly constructed PHS station since 2010. In the recent five years, the government built many new substations and upgraded existing substations in Tibet during the 12th Five-Year Plan to enhance the capacity of Tibet's grid. At the same time, Qinghai-Tibet grid interconnection project connected Tibet's isolated grid with north-western grid of China in 2011 and the long-term goal of maximum power of electricity delivery is 1.2 GW [27]. Although the project was designed to solve the electricity shortage in Tibet, it can deliver electricity to Qinghai at summer now [28]. The project shows the ability that the total installed capacity of the Tibet grid can exceed the local power consumption and export extra power to other provinces. Sichuan-Tibet grid interconnection project was completed in 2014 [29]. The two projects are similar and latter one can directly deliver Tibet's electricity to inland China in the future. In addition, the costs of large-scale solar power in Tibet will be close to thermal power in the near future due to the high solar radiation intensity and long sunshine duration in Tibet and a substantial drop in price of solar power equipment. Thus, capacity of Tibet's grid will expand a lot in the future and the capacity of PV generation will increase as well. The demand of using PHS to regulate PV generation would be stronger than before. If there are adequate available PHS sites in Tibet, China can exploit solar power at large scale coupled with PHS in Tibet and be less dependent on coal, reducing the GHG and pollution emissions. Thus, unified construction of PHS is necessary for grid-connected utilization of the solar energy in Tibet.

Many previous studies applied Geographic Information Science (GIS) methods to discover the latent sites for PHS, because the scarcity of available site for two large reservoirs is the most impactful constaint [30]. Connolly et al [31] developed a computer program to identify potential PHS sites based on digital terrain maps. Fitzgerald et al. [32] proposed a GIS-based model to calculate theoretical potential of a large area for the development of PHS schemes from existing conventional hydropower stations and from non-hydropower reservoirs. The Joint Research Centre of European Commission [33] reported that there are seven different topological relations (Table 1) between two reservoirs and analyzed the theoretical potential sites for new PHS station in countries of the European Union under categories T1 and T2 using GIS-based model and a series of social, infrastructure and environmental constraints. Idaho National Laboratory [34] also conducted a comprehensive research assessing the theoretical potential for PHS under categories T1 and T2 in the US. Using GIS model can assess the potential for PHS more comprehensively and economically without long field trip, especially for the remote areas with harsh environment like Tibet.

**Table 1**
Brief description of the different PHS topologies from the point of view of assessing PHS potential [33,35].

| Topology | Description |
|---|---|
| T1 | Linking two existing reservoir with one or several penstock(s), and adding a powerhouse to transform them to a PHS scheme |
| T2 | Transformation of one existing lake or reservoir to PHS by detecting a suitable site for a second reservoir. The second reservoir could be on a flat or non-sloping area, by digging or building shallow dams, on a depression or in a valley |
| T3 | A greenfield PHS based on a suitable topographical context: either valleys which can be closed with a dam, hill tops which could be slashed, tec. This topology is broader i.e. neither based on existing lakes or reservoirs nor assuming a flat area for building the second reservoir |
| T4 | Sea-based PHS: a greenfield PHS that uses the sea as the lower reservoir and a new nearby reservoir, or the sea as upper basin and a cavern as lower reservoir |
| T5 | Multi-reservoir systems including both PHS and conventional hydropower |
| T6 | The lower reservoir is basically a large river providing sufficient inflow into the PHS system |
| T7 | Use of an abandoned mine pit as the basis for the PHS. The methodology to be used would be similar to the T2 one |