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A generic GIS-based method for small Pumped Hydro Energy Storage (PHES) potential evaluation at large scale

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HIGHLIGHTS

- A novel methodology to evaluate the micro-PHES potential of a region is presented.
- Both water bodies and natural terrain depressions are included in the evaluation.
- In a case study for France the potential has been calculated to approx. 78 GW h.
- A global sensitivity is applied to the case study to detect influential parameters.
- The range of variation of the potential is quantified depending on these parameters.

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ABSTRACT

The increasing share of weather-dependent renewable energies in power systems creates a need for energy storage technologies to reduce the impacts of variable production. The most mature technology to store energy on the grid remains Pumped Hydro Energy Storage (PHES). The potential of high-energy sites has already been assessed in Europe by the EU JRC, considering mostly dams and reservoirs from global European databases which include only massive water bodies. This paper focuses on estimating the potential for small-PHES, proven to have lower environmental impact and an positive impact on grid balance and reliability. A generic method is designed, able to evaluate a global PHES storage capacity at large scale. It considers both existing lakes and natural depressions suitable to be filled for PHES purposes. The volume of filled lakes is estimated using the surrounding topography. The method is organized so that the "heavy" calculations, i.e. sink detection, volume evaluation, constraints verification, etc. are run only once. Consequently, the actual potential estimation phase only includes fast calculations and can be integrated in a loop for carrying out a sensitivity analysis. The proposed method is then applied considering France as a test case. Suitable environmental, land-use and structural constraints are applied to eliminate irrelevant sites. The analysis leads to an estimated value of the small-PHES potential in France, which ranges from 14 GWh when only existing lakes are considered to 33 GWh when lakes and depressions are considered. These estimations represent respectively 8% and 18% of the current hydro storage capacity in France. Thanks to a global sensitivity analysis, factors like the maximum distance between lakes, the maximum altitude of the sites, and the distance to the electrical grid are shown to have the most influence on the global evaluated potential, which is further sensitized. Lastly, another application is suggested that makes it possible to select the connections to be built first within a restricted area, based on a cost-per-energy-like approach. It uses the connections between reservoirs detected at large geographical scale.

1. Introduction

Over the last few decades, renewable energy sources (RES) have continuously increased their share in the world energy market. In fact, worldwide RES installed capacity went from 800 GW in 2004 - mostly from hydropower sources (715 GW) - to almost 1850 GW

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by the end of 2015 [1] - 1064 GW from hydropower. During this period, the capacities of wind power (WP) and solar photovoltaic (PV) installations have multiplied by thirteen, going from 50 to 660 GW [1]. Both PV and WP production are highly variable and not entirely dispatchable due to their inherent dependence on weather conditions. To handle RES production fluctuations, different solutions exist, such as demand management, the combination of RES plants with other means of conventional generation, and also energy storage. Several storage technologies exist [2], including electrochemical devices such as batteries or fuel cells and mechanical solutions such as pumped hydro energy storage (PHES). Water lifting devices have been invented, used and improved by humans for thousands of years [3]. Following the evolution of these technologies, PHES is now one of the most mature and cost-effective solutions for absorbing RES power fluctuations. Rehman et al. [4] and Uniyal [5] estimated the global pumped storage installed capacity as slightly more than 100 GW in 2010.

Large PHES facilities are usually employed as grid-scale solutions to ensure that electricity production matches demand at any time, especially thanks to their fast response. PHES offers considerable storage capacities at affordable prices [6]. In Europe, high-potential sites for large PHES have been assessed by an EU JRC study [7], which considered artificial reservoirs larger than 100,000 m^3 separated by at least 150 m of head. This resulted in a total European feasible potential varying from 36 to 4000 GWh for reservoirs at a distance of between 3 and 20 km. For France, this potential reaches 4 GWh if the distance between lakes is limited to 3 km and rises to 500 GWh at 20 km. Large PHES schemes were initially considered as the only viable type of pumped storage due to elevated inversion costs and scale effects [6]. However, small pumped hydro energy storage (small-PHES) has recently been studied more deeply. Small-PHES has a lower environmental impact in terms of CO_2 equivalent [8]. Large-PHES has a national and continental role to play, while the role of small-PHES is local and regional. The use of local small-PHES utilization can reduce peak demand and thus avoid or defer electrical grid reinforcement [9,10]. Small-PHES can also mitigate voltage issues in medium and low voltage lines, due to the injection of decentralized production [11]. In brief, small-PHES can contribute to the decentralized integration of intermittent RES. In this perspective, PHES systems have been miniaturized and are even starting to be used in cities, installed on top of buildings [12]. The present paper thus focuses on evaluating the potential of sites connecting close reservoirs of limited volume that are suitable for installing small-PHES plants. This method does not aim to reduce the PHES costs in itself. It aims to find spots requiring few civil work and thus exploitable with little expenditure. For this purpose, a new computationally efficient methodology applicable at large scale (i.e. national) is proposed. The method employs Geographic Information Systems (GIS) to detect reservoirs, associate those that could host a small-PHES plant, and finally apply the different constraints to derive a feasible potential. One disadvantage of small pumped hydro energy storage is the investment cost, given the low storage capacity. Small PHES indeed suffers from scale effects [13]. The method developed considers natural opportunities, such as existing lakes and natural terrain depressions, which could be operated at a limited cost. The proposed methodology is applied to the case of France to evaluate small-PHES potential at national scale.

For both the conventional an pumped hydropower systems, the location of the power plant is important, as the extracted energy and power depend, among other factors, on the gross head, water flow and volume of water available. Selecting optimal spots that respect these parameters thus appears to be crucial. For this purpose, automatic numeric methods have been developed to select the best spots, taking advantage of the emergence of GIS. Thereby, Larentis et al. [14] present a method to detect the optimal location in a river basin to install a run-of-river hydropower plant. They use GIS to detect where to install a dam and build the powerhouse. Kusre et al. [15] evaluate suitable places in an Indian valley, using hydrological tools and soil, land use and weather data. Both focus on power generation, without storage and optimize the location within restricted areas, mostly valleys.

Other studies concern the PHES scheme, and are carried out in limited areas to evaluate either the potential of a zone, or a particular spot to install a PHES plant. Ahmadi and Shamsai [16] focus on a single massive lake, looking for the best location to construct the corresponding reservoir using criteria ranking through raster analysis. This is a localized analysis, with an emphasis on very detailed geological or environmental data, which makes application of this method at a larger scale difficult. Mailler et al. [17] focus on small hydropower schemes, taking advantage of existing reservoirs in Switzerland, such as artificial snow reserves. GIS data are not used and the study is conducted in a very restricted area. Kucukali [18] estimates the best location for conversion of existing hydropower plant to PHES schemes comparing a few sites in Turkey, with ranking based on geological, social and environmental criteria. Garcia [19] focuses on one very restricted region, looking for PHES opportunities within a group of many lakes. Several potential connections were identified and the selection was then optimized depending on criteria such as stored energy potential, and the cost of stored energy potential.

A common characteristic of these four studies is that they are conducted on a small scale and based on very detailed datasets (geological composition, ground slopes, urban planning, etc.), which are difficult to obtain for a large area.

Other works are based on the detection of high power (and energy) capacity PHES sites. Connolly et al. [20] proposes a method that exploits a Digital Elevation Model (DEM) to identify restructurable hills and build reservoirs in the south of Ireland. This method implies considerable investment costs, which are only profitable if they correspond to high-power projects. Four major works [21,22,7,23] study energy storage possibilities at a larger scale. The first one is focused on taking advantage of existing dams, but also includes a section on matching existing lakes in the United States. It is oriented to large PHES schemes, but only focuses on specific sites and does not offer a global potential evaluation in terms of energy or power. Similarly, the second study only searches for high-power locations throughout Turkey, with high head or volume characteristics (150 m and more than 10^6 m^3). It also includes a search for flat locations to dig new reservoirs. Likewise, the third document is a global study of potential PHES sites. However, it includes a European assessment of energy available per country, depending on a maximum authorized distance between reservoirs of 3–20 km. Only heads greater than 150 m are considered. Lu and Wang [23] present an evaluation of Tibet's potential for PHES. It considers connection with very high heads (greater than 500 m) and large reservoir areas (greater than 60,000 m^2).

All the above works exclude connections with low head and low potential, which might be beneficial for small-pumped storage due to restricted civil works, as we aim to evaluate here.

Pauwels et al. [24] conducted a study at the scale of a French county (about 4000 km^2). It matches natural terrain depressions within a wide constrained zone. Existing lakes are not taken into account. Moreover, no optimization through interconnected lakes is performed, thus leading to an over-estimation of energy potential. The evaluation by Gimeno-Gutirrez and Lacal-Arntegui [7] presents a substantial shortfall in the potential reservoir dataset, by considering only existing artificial reservoirs.

Considering only a share of potential reservoirs can result in a considerable shortfall in evaluations. Moreover, in order to avoid matching one lake with several others, it is necessary to select