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Geographic information system algorithms to locate prospective sites for pumped hydro energy storage

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HIGHLIGHTS

- Developments of the "dry-gully" and "turkey's nest" site models.
- A software "STORES" to locate prospective sites for pumped hydro energy storage.
- 190 sites identified in South Australia, with a storage capacity of 441 GL, 276 GWh.
- A comprehensive literature survey of Geographic Information System-based site searches.

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ABSTRACT

Pumped hydro energy storage is capable of large-scale energy time shifting and a range of ancillary services, which can facilitate high levels of photovoltaics and wind integration in electricity grids. This study aims to develop a series of advanced Geographic Information System algorithms to locate prospective sites for off-river pumped hydro across a large land area such as a state or a country. Two typical types of sites, dry-gully and turkey's nest, are modelled and a sequence of Geographic Information System-based procedures are developed for an automated site search. A case study is conducted for South Australia, where 168 dry-gully sites and 22 turkey's nest sites have been identified with a total water storage capacity of 441 gigalitres, equivalent to 276 gigawatt-hours of energy storage. This demonstrates the site searching algorithms can work efficiently in the identification of off-river pumped hydro sites, allowing high-resolution assessments of pumped hydro energy storage to be quickly conducted on a broad scale. The sensitivity analysis shows the significant influences of maximum dam wall heights on the number of sites and the total storage capacity. It is noted that the novel models developed in this study are also applicable to the deployments of other types of pumped hydro such as the locations of dry-gully and turkey's nest sites adjacent to existing water bodies, old mining pits and oceans.

1. Introduction

Photovoltaics (PV) and wind constitute approximately half of the world's new generation capacity installed in 2014–16. At the end of 2016, the global installations of PV and wind were beyond 300 gigawatts (GW) and 480 GW respectively [1,2]. Rapid growth of PV and wind energy in the electricity sector is expected to continue, driven by a broad range of issues associated with climate change, energy security and economics.

High shares of intermittent PV and wind energy in electricity grids bring significant challenges to the economics and security of the system as is the case in South Australia (SA), where nearly half of the state's electricity production come from rooftop PV and wind farms [3]. SA has a low level of interconnection with the rest of the Australian National Electricity Market (NEM) and there is no existing hydroelectric or pumped hydro facility established within the region. This brings significant challenges to power system operation and the state's energy security due to supply intermittency and lack of sufficient inertial energy to support PV and wind electricity, especially in light of continuing rapid growth of PV and wind energy investment. In July 2016, when upgrades to the Heywood interconnector coincided with low wind generation at peak times, the average wholesale electricity prices in SA surged to $229/MWh (Australian dollars per megawatt-hour) with 3 extreme price events on 7, 13 and 14 July beyond $5000/MWh [4]. By contrast, the long-term average price in SA when the interconnector is available to import brown coal electricity from Victoria is $50/MWh. Additionally, a range of system events such as load shedding and islanding occasionally occurred in 2016–17 [5,6]. This included a

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state-wide blackout on 28 September 2016, when three 275 kilovolts (kV) backbone transmission lines were damaged by a major storm event [7].

Pumped hydro energy storage (PHES) is capable of large-scale energy time shifting and a range of ancillary services such as frequency regulation, which can facilitate high levels of photovoltaics and wind integration in electricity systems. Developments of PHES began in the 1890s and surged through the 1960s, 70s and 80s in Europe, the United States and Japan where the rapid growth of nuclear energy and coal-fired units continued. These large thermal steam plants lack sufficient operational flexibility to accommodate changing demand and required the capability of load levelling. PHES was also regarded as a more economical alternative to oil and natural gas-fired plants for peak shaving, especially during the post-periods of energy crisis in the 1970s [8,9]. In recent years, the prosperity of PV and wind developments has led to a resurgence of interest in PHES. Open-loop PHES, which is continuously connected to a naturally flowing water feature [10], dominates the deployment of existing PHES. However, developments of conventional river-based hydroelectric including PHES are usually constrained by the availability of water resources and a variety of environmental concerns such as the interactions with ecology and natural systems [11]. Consequently, expansions of pumped hydro were generally not included in many high renewables future studies such as [12–14]. By contrast, short-term off-river PHES, which incorporates closed-loop pumped hydro systems, consumes modest amounts of water and has little impacts on the environment and natural landscape.

Recent studies [15,16] from the Australian National University show Australia can build an affordable and reliable electricity network with 100% renewable energy, using PV, wind, existing hydroelectric and biomass with the support of short-term off-river PHES. Preliminary Geographic Information System (GIS)-based works [15,17] suggested a large potential for off-river PHES to be deployed in the extensive hills and mountains close to population centres from North Queensland down the east coast to South Australia and Tasmania. This study focuses on the development of a series of advanced GIS algorithms which are capable of:

- Highlighting promising regions for PHES developments from a large region such as a state or a country, which can facilitate the planning of renewable energy development zones incorporating PV, wind, PHES and high-voltage direct current (HVDC) transmission.
- Rapid identification of prospective PHES sites with different characteristics of topography. For example, pairs of medium-sized reservoirs (dozens or hundreds of hectares) can be built on large flat lands as turkey's nest dams or located in enclosed dry gullies.
- Selection of optimal locations by ranking the sites identified from site searching on the basis of topography suitability and land use classes. Additionally, detailed site information such as the volumes of reservoirs, dam wall heights and lining areas will be helpful to integrate a costing tool in the next level of study.

Section 2 is a brief summary of the reviewed GIS-based studies on locating sites for the development of hydroelectric/PHES projects. Section 3 describes the mathematical models developed in this study. Section 4 outlines the GIS algorithms used to identify two different types of PHES sites. Section 5 illustrates the results from site searching by applying the models and algorithms introduced in Sections 3 and 4 to South Australia.

2. Literature review

PHES is a mature technology of large-scale energy storage. At the end of 2016, there were over 160 GW (rated power) of PHES in operation around the world with more than 85% of the installations deployed in Europe (> 50 GW), China (32 GW), Japan (26 GW) and the United States (23 GW) [18]. Recent studies on PHES focus on:

- Its significant roles as large-scale energy storage to facilitate large fractions of variable renewable energy integration while maintaining system reliability and security [19–21]. Our NEM and Western Australian studies [15,16] also demonstrated that energy affordability can be maintained in a system dominated by PV, wind, PHES and HVDC transmission.
- Operation strategies to maximise profits from energy arbitrage in competitive electricity markets and providing inertial response and ancillary services such as frequency control [22–24].
- Analyses of mechanisms and policy reform in electricity markets to facilitate development of PHES which is typically capital intensive and has a long lead time [25–28].
- Seawater and underground PHES which have minimum environmental impacts to ecology systems [29–33].
- Modern adjustable-speed PHES with wide operating ranges and higher efficiency, as well as improved dynamic stability under grid disturbances [34].
- GIS-based siting to locate sites by utilising contemporary advanced GIS and remote sensing technology.

2.1. GIS-based siting

Developments of advanced GIS and remote sensing techniques in recent years allow efficiency and accuracy improvements in the assessments of hydroelectric and water supply schemes such as computerised site identification utilising high-resolution digital elevation models (DEM). Table 1 is a brief summary of the reviewed GIS-based studies on hydroelectric/PHES site searching.

A number of studies focused on small hydro with power capacities ranging from hundreds of kilowatts (kW) to dozens of megawatts (MW), including both run-of-the-river and storage types of hydroelectric generation. Larentis et al. [35] developed a computerised "Survey & Selection" methodology for the evaluation of small run-of-the-river and storage hydroelectric systems within a river basin of Brazil. The study included a section-by-section analysis of dam and powerhouse locations and flow regulation and at-site optimisation for the assessment of total hydropower potentials of the basin. Kusre et al. [36] conducted a GIS-based site location with hydrological analyses for small run-of-the-river hydroelectric in northeast India by searching upstream from the outlet of a watershed to the fifth order of streams at an interval of 500 m. Yi et al. [37] undertook a cell-by-cell analysis to identify potential small hydro sites along rivers and a scoring system was established in the modelling, incorporating a variety of issues including topography, hydrology and environmental impacts. Petheram et al. [38] also examined the opportunities for developing water supply schemes with a minimum catchment area of 10 square kilometres (km^2) in northern Australia.

For PHES, most studies concentrated on examining opportunities for existing waterbodies to be utilised as upper and/or lower reservoirs of PHES systems. This includes the investigation of existing artificial reservoirs belonging to hydroelectric or water supply schemes as well as natural lakes as greenfield projects. Hall & Lee [39] investigated the potentials of utilising existing waterbodies in close proximity to hydroelectric or water supply schemes to serve as open-loop PHES reservoirs on the basis of 4 critical criteria (capacity, area, distance and elevation difference) derived from the characteristics of 43 existing PHES in the contiguous United States. Gimeno-Gutierrez & Lacal-Arantegui [40] investigated the potentials of matching pairs of existing reservoirs as PHES facilities within distances of 1–20 km (elevation difference > 150 m) across 31 countries of Europe, where thousands of sites were identified with a realisable storage capacity of 29 terawatt-hours (TWh), especially in Turkey, Spain and the Alps countries. Jimenez Capilla et al. [41] demonstrated a multi-criteria GIS-based analysis of site selection for an existing dam to be retrofitted into PHES systems, which incorporated the aspects of topography, land use, geology and meteorology by applying the analytic hierarchy process into a decision model. Fitzgerald et al. [42] investigated the adjacent

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