Renewable Energy 75 (2015) 856–868

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs☆

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ARTICLE INFO

Article history:
Received 12 May 2014
Accepted 16 October 2014
Available online

Keywords:
Pumped hydropower storage
Potential
Europe
GIS

ABSTRACT

Flexible electricity systems allow a higher penetration of variable renewable energy, and flexibility can be achieved through pumped hydropower storage (PHS). This assessment of European PHS potential focuses on linking two existing reservoirs to form a PHS system, the reservoirs must have adequate difference in elevation (head) and be close enough so that they can be reasonably linked. The results show that the theoretical potential energy storage is significant as it reaches 54 TWh when a maximum distance of 20 km between the existing reservoirs is considered. When constraints are applied, e.g. discounting populated areas, protected natural areas or transport infrastructure, the so-called maximum realisable potential is halved to 29 TWh. Comparing with the existing PHS storage capacity reported for 14 countries suggests that the theoretical potential is 3.5 times the existing capacity, whereas the realisable potential is still twice the existing capacity.

1. Introduction

The contribution of renewable energies to the world's total energy demand has increased particularly during the last two decades, and they will continue gaining market share. Because the natural resources that fuel those renewables (e.g. insolation, wind or precipitation) follow their own pattern of availability, the renewable energy production from them may not be forced to follow energy demand. Therefore, a mismatch occurs between generation (in particular of electricity) from renewables and consumer demand.

The electricity systems offer several alternatives to solve this mismatch, some of which were originally developed as a response to the fluctuations in demand and to protect against the loss of large generation power plant. These alternatives are: interconnections between electricity systems; energy storage; smart networks; and demand-side response (DSR) [1]. Utility-level energy storage for electricity systems is limited to pumped hydropower storage (PHS) – although the storage effect of reservoir-based conventional hydropower schemes is also considered energy storage depending on the authors. Compressed air energy storage (CAES) is still a technology under development whereas batteries and other technologies offer smaller capacities.

The European energy and climate policies have as one of their targets 20% of final energy from renewable origin by 2020 [2]. This target entails an even higher penetration of renewable energy in the electricity mix, possibly between 35 and 40%, and a high component of this will be non-dispatchable[1] renewables such as wind and solar. Moreover, the EU's 2050 decarbonisation objectives, with a target of 80–95% reduction in greenhouse gas emissions [3], will require a significantly higher share of renewables in the electricity mix.

In its 2012 Communication *Renewable Energy: a major player in the European energy market* [4], the European Commission points out the need for storage facilities to contribute to the flexibility encouraged in the electricity market. As part of its review of that Communication, the (Energy) Council of the European Union required that consideration is given "*on ways and means to strengthen the potential for development of RES* (renewable energy sources) in an integrated, secure and cost-efficient and effective way, in relation to grid infrastructure (e.g. addressing loop flows), ***storage***, *back-up capacity and better operational solutions*" [5].

☆ The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

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[1] Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators; that is, generating plants that can be turned on or off, or can adjust their power output on demand.

http://dx.doi.org/10.1016/j.renene.2014.10.068
0960-1481/

Table 1
Electricity generated in 2011 from some renewable energies in the EU. Source: Eurostat table nrg_105a [7].

Electricity	Hydropower without PHS	Wind	Solar	PHS production	PHS demand	Total gross production	Final consumption
TOTAL (TWh)	335	179	46	29	38	3280	2768
Percentage of gross production	10.2	5.5	1.4	0.9	1.15	100	84

Different studies suggest that energy demand in Europe could double by 2025 and still increase afterwards, and a storage capacity of 40 TWh will be necessary by 2040 for periods from days to weeks, and sometimes months in the EU [6].

A gross total of 567 TWh of electricity was generated from non-biomass RES in the EU during 2011. Of this, hydropower excluding PHS contributed with 335 TWh from 104 GW of installed capacity [7].

Table 1 shows EU electricity production and consumption data. Total gross production reaches around 3280 TWh, non-PHS hydropower contributes 10% of the total annual consumption, and a further 1% is contributed by PHS plants from water previously pumped.

Conventional hydropower is one of the means of using stored energy. When not based on an existing lake, a hydropower system is built by creating a reservoir generally by closing a valley with a dam and allowing the corresponding river to fill up the reservoir, then generating renewable energy by releasing the water through a turbine. The unwanted effects of this approach include river disruption and other environmental issues, e.g. when the river natural distribution and timing of stream flow is altered, affecting riparian areas, altering the geomorphological process and thus dramatically disturbing the aquatic biodiversity by preventing free migration of many aquatic species including fish. Another undesirable effect is, in some cases, forced relocation of people or important landscape changes caused by filling up the entire valley with water [8,28]. Finally, conventional reservoir hydropower is not capable of storing excess electricity when it occurs in the system, e.g. when wind electricity is abundant and demand is low.

Table 2
Brief description of the different PHS topologies from the point of view of assessing PHS potential. Source: SETIS expert workshop on the assessment of the potential of pumped hydropower storage [9].

Topology	Description
T1	Linking two existing reservoirs 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[a]
T3	A greenfield PHS based on a suitable topographical context: either valleys which can be closed with a dam, depressions, hill tops which could be slashed, etc. 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[b]
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. An example is the Jochenstein-Riedl PHS where the Danube acts as lower reservoir[c]
T7	Use of an abandoned mine pit as the basis for the PHS. The methodology to be used would be similar to the topology 2 one. An example is the old coal mine of As Pontes, in Spain[d]

[a] In this study we do not consider valleys due to the environmental issues.
[b] For an example of the former see the Okinawa Yanbaru PHS at http://en.wikipedia.org/wiki/Okinawa_Yanbaru_Seawater_Pumped_Storage_Power_Station. For the details of the latter option see http://www.psh-offshore.com/en/concept/?
[c] See the web of Verbund where a clear scheme shows this topology: http://www.verbund.com/pp/en/pumped-storage-power-plant/riedl.
[d] For more information see http://www.lagodeaspontes.com/.

An alternative or complement to conventional hydropower is PHS, which is the most established technology for utility-scale electricity storage. By pumping water to the upper reservoir PHS schemes allow the storage of surplus electricity in the form of the potential energy of water; by releasing it through a turbine they allow the transformation back to electricity. This has traditionally been used to support the integration of electricity from non-flexible power plant (such as nuclear and base load coal plant), and is lately being used to help integrating variable renewable energies.

When analysing the potential for new PHS several topologies are possible – as shown in Table 2.

Even when there are no official figures for ***storage capacity*** in PHS in Europe or the EU, there are figures for PHS electricity ***installed*** generation ***capacity***: around 42.6 GW in the EU [7]. In terms of electricity generation and consumption, in total in Europe, Platts [10] gives the figures of 40 TWh generated per year consuming 54 TWh in pumping, these from 232 operational PHS plants. The corresponding Eurostat figures for the EU in 2011 are 29 TWh of electricity generated from 38 TWh used for pumping.

The objective of this work is to assess the potential for energy storage in pumped hydropower schemes in Europe based in two existing reservoirs (T1 in Table 2 above). For this, the methodology defined by a team of the Joint Research Centre (JRC) and University College Cork (UCC) staff [11,12] was applied, after it was validated in a workshop of international experts [9].

The chosen approach of assessing the potential only under topology 1 introduces some limitations, the most important of which is that the results only reflect a part of the European PHS potential, and possibly a small part of the total. Despite these limitations, this approach was chosen because of its expected much lower environmental impact than, for example, creating a new reservoir.

Through this innovative study, the purpose to assess a PHS potential in Europe has been reached for the first time, and this was made possible by developing and applying a GIS-based software model.

The next section includes a basic description of the methodology applied and a more thorough indication of the limitations encountered, and how these were addressed. Section 3 presents the results for the EU and other European countries, as well as Turkey.[2] Section 4 concludes and provides with some recommendations for further work in the area.

2. Application of the methodology and issues

2.1. Methodology definition

The methodology is based on a geographical information system (GIS) model fed with a digital elevation model (DEM) – which is a topographical description- and with data of existing reservoirs including the geographical coordinates of the centre of the dam and

[2] Although the majority of the Turkish territory is not in Europe, and the majority of the Turkish PHS potential is not in the European continent, to the effects of this assessment the Turkish potential has been considering European because of the status of Turkey as candidate country for accession to the European Union.