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Optimal site selection for upper reservoirs in pump-back systems, using geographical information systems and multicriteria analysis

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A B S T R A C T

The proliferation of renewable energies in the last decade coupled with their low processing capacity on the grid is bringing old power storage methods back into consideration, as is the case with pumped hydro power plants. In our case, we have taken as a reference an existing dam from which water will be pumped to the reservoir to be constructed, using surplus or off-peak power generated by a nearby wind farm, taking advantage of the potential energy acquired in order to run the turbines at peak times. We therefore want to determine the optimal location of the upper reservoir for it to comply with a number of construction and economic criteria that would make its construction viable. For this, multicriteria analysis methods will be used, assisted by the versatility of geographical information systems. The results obtained have been validated via on site verification based on the authors engineering experience, as well as on their extensive knowledge of the area studied, so that the methodology applied in this study can be extrapolated to other geographic areas, making it a valuable tool.

1. Introduction

Power generation from renewable energy sources has undergone considerable growth worldwide in the last few decades for various reasons. For example, in the 1990s, Spain committed to the development of renewable energies as a means of reducing its dependence on external energy supplies at the same time as cutting greenhouse gas emissions.

However, renewable energy comes with various disadvantages, such as the impossibility of processing the power they generate, and as a consequence, the difficulty in adapting this power to the electricity demand curve (Fig. 1). This situation means that renewable energy systems are inadvisable in countless instances, causing this great potential to be missed out on and compromising the viability and efficiency of power plants such as wind or solar farms. This is due to the inertia of the large thermal and nuclear power stations whose systems in place do not allow them to easily connect/disconnect to/from the grid for short periods.

To deal with these problems, the emergence of different types of power storage systems, based on accumulating power during off-peak or low consumption periods to later be released during high consumption periods, is being encouraged. Obviously, during the storage operation, there are energy losses that vary depending on the system used. One of the most used and most interesting systems, due to the amount of energy accumulated, the duration of the storage and the relatively low rate of losses, is the pump-back system between two reservoirs located at different elevations.

This is a very mature system, having been used since the middle of the 19th century. The way it works is simple: during the period of surplus power, water is pumped from the lower reservoir to one at a higher elevation, functioning like a pumping station, while in the periods of demand the water is released through the turbines from the upper reservoir to the lower one, in the same way as in a normal hydroelectric plant. In this process the losses are approximately 30%, even reaching 20% in some underground power stations.

These Pumped-storage Hydroelectric Stations (PSHS) [2–4] enjoy favourable legislation in many countries [5], where the tendency of the EU to support the improvement in the processing capacity of renewable energies is demonstrated. In Spain, large projects have been developed such as La Muela II with some 1200 MW of power, whose objective is to soften the consumption curve, in addition to other projects of less magnitude based on the creation of hybrid power plants combining wind energy and PSHS. With the governments new plan [6], Spain intends to give a boost to this type of power stations, and hopes to increase the 2700 MW of

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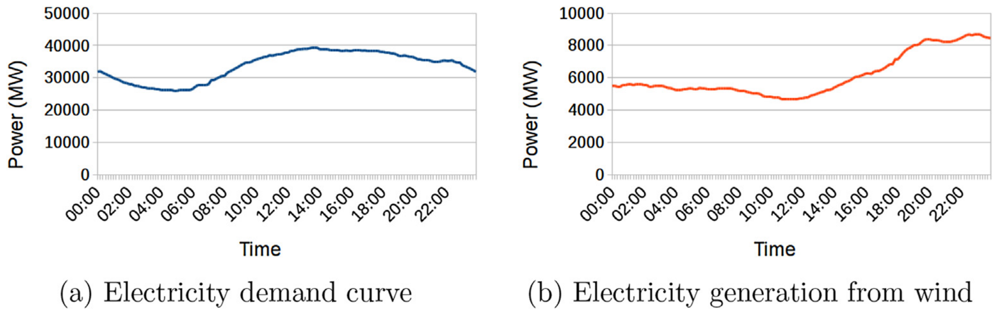

Fig. 1. Instance day when electricity generation from wind peaks when electricity demand declines —from 20:00 onwards. Electricity demand curve (MW versus time in hours, left) and generation from wind energy (MW versus time in hours, right) on the 8th July 2015 [1] in Spain.

power for existing pure pumped-storage plants in 2011 to 8850 MW in 2020, a rise of more than 300%, offering very high growth perspectives for this sector.

Hybrid renewable energy/water storage power systems have lately become the object of serious research [7–10]. Among the hybrid plants developed in Spain, the hydro-wind park of Gorona del Viento [11] on El Hierro island (Canary Islands – Spain) stands out as being one of the first joint systems. It supplies the whole island with electricity, making El Hierro the first totally self-sufficient island in the world, energetically speaking, with 100% of its supply coming from renewable energies. Smaller scale efforts in other parts of the world also exists [12].

Over the course of this study a methodology has been developed to help in the implementation of pump storage systems. A method has been established for the site selection of the upper reservoirs of the PSHS or of the new generation hybrid stations, analysing the factors affecting the optimal site selection and implementing Multicriteria Analysis (MA) systems to subsequently transfer the results obtained to Geographical Information Systems (GIS) that will allow us to do an extensive territorial analysis.

This work provides a valuable tool to pump storage hydroelectric systems project engineers, facilitating the determination of the optimal location of upper reservoirs in a simple way and allowing wide area study at minimum cost.

MA assisted GIS is being used in various studies to obtain the best location of different power plants [13–17], and other authors have more than proven its usefulness [18]. Specifically, in [19], GIS have been applied to PSHS design, provided that a number of lower and upper reservoirs already exist. In this case, the goal is to stablish which pipe connection permits the best performance PSHS. But, no multicriteria analysis seems to have been implemented. In this paper, an existing lower reservoir with sufficient capacity and important elevations of land in its vicinity has been established as a basis for the analysis and main hypothesis of the proposed method, in order to look for the optimal location of the upper reservoir from this starting point. In the case study for this paper the southern region of Spain has been chosen, taking the Rules Dam as the lower reservoir on which to base the design of our PSHS.

This work is structured in the following way. In section 2 we construct the decision model, specifically for the problem that we are dealing with, identifying all the aspects that are relevant to it, for which a brief description of MA and AHP is included. In section 3 the resulting methodology is summarised, and it is applied to the case study in section 4. Finally, in section 5 we put forward our conclusions.

2. Construction of the decision model

Fig. 2 represents the sequence of actions, and the interrelation between them, taken to establish the decision model. First of all the objective to be achieved is defined, as shown in the diagram. Based on this objective, a decision rule adapted to the problem posed is chosen and structured, that also incorporates the criteria established using this objective. This decision rule is determined by the choice of criteria and subcriteria of different levels (called here factors and indicators), that will intervene in the selection process and the priorities and weights that the author allocates to each of these factors, both those that have a relatively important influence and those that have a limiting function. For a coherent combination of the different criteria that will intervene in the decision rule, MA will be applied.

2.1. Multicriteria analysis

We use MA because we need a methodology that can combine the different dimensions, objectives, agents and scales that are involved in the decision making process without sacrificing quality, reliability and consensus in the results.

The MA methods can be classified into three large groups:

i) compensatory,
ii) non-compensatory and
iii) fuzzy.

The first ones need a larger cognitive weight, given that they demand that the decision centre assigns the weights to the criteria as a decision rule, while the second ones need a lesser cognitive weight because they only assign an ordinal value to the criteria. Likewise, compensatory techniques rely on the assumption that a high value of one alternative can be balanced with a low value of the same alternative in other criterion. For example, it could be possible that land with excellent orographic properties loses priority when the 'land uses' factor is considered. Different methods are included among the compensatory techniques [21,22], while for this study we have chosen the analytical hierarchy process (AHP) or Saaty method [23]. Supporting our decision, MA based GIS using AHP is used for example in Refs. [24] and [18] arguing that a review of MA-GIS methods applied to renewable energy conducted by Ref. [25] showed that AHP is the predominant technique. Besides, it has numerous advantages [26–28].

2.1.1. The analytical hierarchy process

The AHP is based on the comparison of pairs within a reciprocal matrix, in which the number of lines and columns is defined by the number of criteria. Consequently, a comparison matrix needs to be established that measures relative importance of one member of the pair with respect to the other, using [23] a weight scale based on 18 values that vary between 9, which indicates an extremely great difference within the pair in favour of one member of the pair, and 1/9 to indicate the same difference but in the opposite