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Design study of a stand-alone desalination system powered by renewable energy sources and a pumped storage unit

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ABSTRACT

The aim of this work is to investigate in detail the optimum design and operation strategy of a stand-alone hybrid desalination scheme, capable to fulfill the fresh water demand of an island or other remote coastal regions. The scheme consists of a reverse-osmosis desalination unit powered by wind and solar electricity production systems and by a pumped storage unit.

A specific computer algorithm is developed to simulate in detail the entire plant operation and also to perform economic evaluation of the investment. A stochastic optimization software based on evolutionary algorithms is implemented to accomplish design optimization studies of the plant for various objectives, like the minimization of fresh water production cost or the maximization of water needs satisfaction. Miscellaneous parametric studies are also conducted in order to analyze the effects of various critical parameters, as population, water pricing, water demand satisfaction rate and photovoltaics cost are.

The results demonstrate not only the performance, the role and the contribution of each subsystem but also the production and economic results of the whole plant. An optimally designed scheme is found to be economically viable investment, although energy rejections are significant and there is a clear need for better exploitation of renewable energy production surplus.

1. Introduction

Nowadays it is observed, globally, an extensive phenomenon of drought. Especially in Greece, many isolated areas, such as Aegean islands, suffer from drought [1]. The problem becomes worse in summer when the water demand increases up to 4–5 times compared to winter because of tourism [2]. In most islands the existing water stocks cannot satisfy such increasing demand; thus the problem that comes up must be solved with permanent and viable solutions. At present, this water demand is being satisfied by tank transportation with the considerably high cost of about 5–8 €/m^3 for Cyclades and Dodecanese complex [1].

Seawater desalination can play an important role towards a permanent confrontation of the problem [2]. The installation of desalination units is a common solution throughout the world, in areas with drought. In the last decades the number of desalination applications has greatly increased, while desalination is the subject of several research works. As a result, new desalination methods have been developed, experience has been gained, system operation has been amended and the equipment production has become massive [3]. Thus, the two most important performance characteristics of such applications, which are the quality of produced water and the water production cost are continuously being improved.

A critical technical parameter of desalination applications is the way the system is powered. This decision is taken according to the selected method of desalination and the characteristics of the candidate area [4]. Nowadays the method of reverse osmosis dominates globally; it requires only electricity, has a quite low specific energy demand, and can cooperate with technologies of renewable energy sources (RES) such as wind turbines and photovoltaics [4–7]. Concerning Aegean islands that suffer from drought, most of them are isolated and the electricity is provided by local conventional power stations operating at very high production costs. In addition, the power demand of large desalination units may not be satisfied by the existing power stations. On the other hand, Aegean islands feature an abundance of RES like solar and wind energy. Consequently, a desalination system powered by hybrid renewable energy technologies would be a very promising solution for those regions.

Several simulation studies of desalination units cooperating with RES and conventional thermal units have already taken place [8–11]. Stand-alone reverse-osmosis desalination units powered by wind turbines and/or photovoltaics and supported by batteries have been the research topic of several works that have shown that such systems could be a viable solution at present conditions [12–14]. Energy storage is an important aspect of such autonomous systems, although some systems without storage have been simulated and tested

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[15,16]. Because of the stochastic and intermittent nature of RES, a storage system is usually required in order to avoid excessive rejection of the energy production, as well as to guarantee the desalination unit operation during unfavorable weather conditions. The most common system for energy storage are batteries which are included in most studies. The use of batteries has the disadvantages of short life cycle, high-cost maintenance and environmentally unfriendly content [17,18]. As a result, batteries have been proposed only for small-scale plants.

The present work aims to study an alternative means of energy storage, a pumped storage subsystem, in stand-alone desalination plants, and to investigate its role on the operation of the whole scheme. Pumped storage in hybrid wind-hydro power production plants has been studied applying numerical design optimization methodologies in some previous works [19,20]. The optimum sizing of all desalination system components that maximize its energy and/or economic results for small to large islands constitutes an objective of the present work, as well.

2. System description

The considered system is schematically shown in Fig. 1. The stand-alone desalination unit is powered by a hybrid RES system (wind-photovoltaics), and includes a fresh water tank to provide autonomy to the area for a determinate time period, in case that the system is out of order for some reason (e.g. maintenance, failure).

Due to the intermittent nature of those RES and the difficulty in predicting the energy production rate, a means of energy storage is required to operate the desalination unit even during unfavorable weather conditions. A pumped storage subsystem is considered, as an alternative to batteries. A typical pumped storage unit consists of a pumping and a turbining station, two water reservoirs at different altitude, and the necessary pipelines (Fig. 1). A number of pumps are usually installed in parallel operation, equipped with variable speed motors in order to be able to absorb the fluctuating production of RES with no power gaps [19]. On the other hand, the type of hydroturbine(s) depends mainly on the available head between the reservoirs.

During periods of excessive RES production, the power surplus is used to operate the pumps and store hydraulic (dynamic) energy in the upper reservoir (Fig. 1). On the other hand, when the primary energy production cannot satisfy the desalination demands, then the hydroturbine re-transforms the stored energy into electricity, which powers the desalination unit. Details on the energy transfer rules and constrictions are given in Section 3.

3. Algorithm description

In order to simulate the entire system operation and its subsystems interaction, a specific computer algorithm is developed. The software makes also an economic evaluation of the system, based on empirical cost relations for all its main components (pumps, hydro and wind turbines, photovoltaics, pipelines, etc.) [19,20]. The algorithm is divided into three sections: data input, application of system's logic operation, and techno-economic evaluation. These parts are described in more detail in the present section.

3.1. Data input

Data needed for the simulation of system's operation are either fixed or free variables, the value or the range of which is predetermined by the

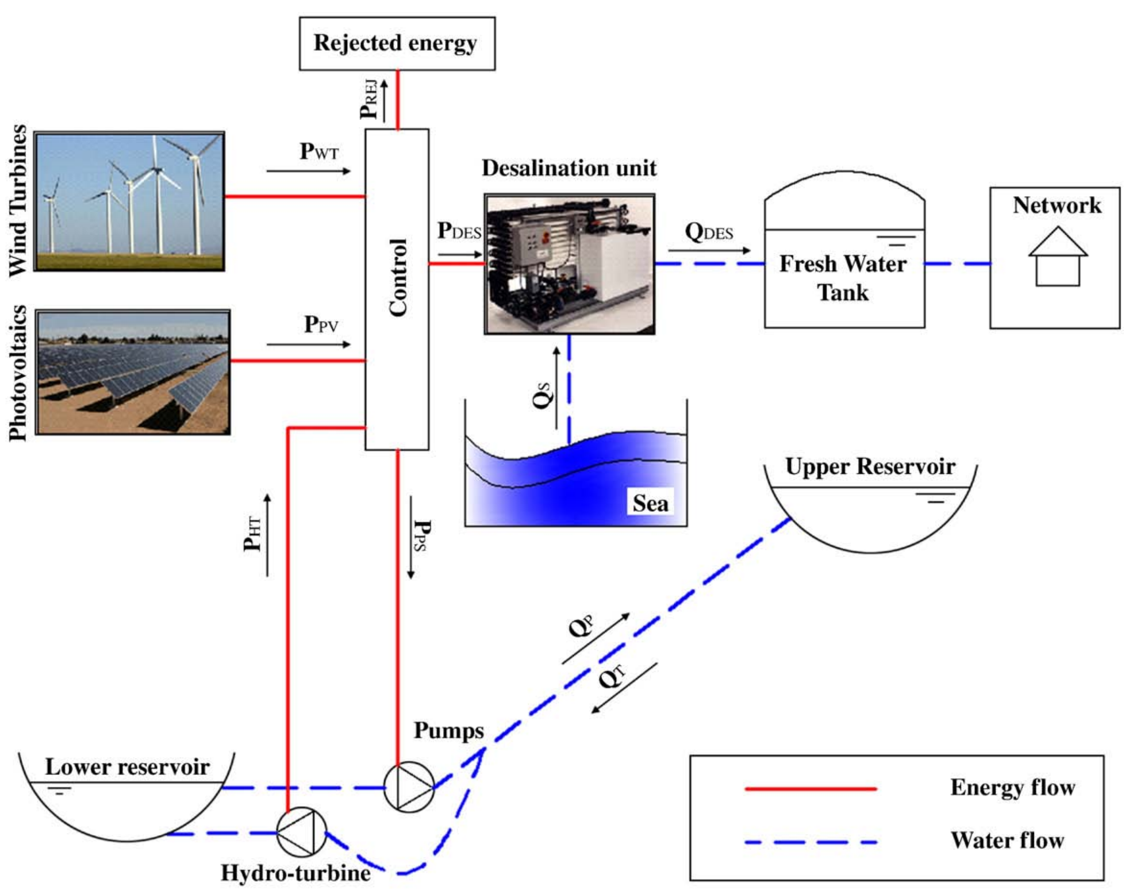

Fig. 1. Sketch of the examined desalination system set-up.