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Optimization of a wind powered desalination and pumped hydro storage system

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HIGHLIGHTS

- Operational strategy and sizing optimization of an integrated power and water supply system.
- Multiobjective optimization using the Direct Multisearch method.
- Significant increase in RES production of total electricity production is feasible.
- Significant cost and CO_2 emissions reductions are achievable.

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ABSTRACT

The penetration of intermittent renewable energy sources, for instances wind power, in the power system of isolated islands is limited, even when there is large potential. The wind power that cannot be directly injected in the power grid is usually curtailed. In addition, some islands need to desalinate seawater to produce fresh water, increasing the pressure on the power system, because desalination needs electricity. Nevertheless, the water scarcity problem of an island can be part of the solution of the problem of its integration of intermittent renewable energy sources. To tackle this issue, a system was proposed to use the excess wind power in desalination units and in a pumped hydro storage, resulting in an integrated power and water supply system that would minimize the wind power curtailed. This paper proposes a methodology to optimize the size and operational strategy of this wind powered desalination and pumped hydro storage system. The objective is to minimize the total annualized production costs, maximize the percentage of renewable energy sources in the total power production and minimize the wind power curtailed. To solve this optimization problem, a derivative free multiobjective optimization method (Direct MultiSearch) is used. This methodology is applied to the integrated power and water supply system proposed for the island of S. Vicente, in Cape Verde. The results show that the penetration of renewable energy sources can reach 84% with a 27% decrease of power and water production costs and 67% decrease of CO_2 emissions, in relation to the values foreseen for 2020.

1. Introduction

The penetration of intermittent Renewable Energy Sources (RES), for instances wind power, in the power supply systems of isolated islands depends on the dynamic penetration limit that is usually applied for grid stability (intermittent limit) [1]. This limit is the maximum instantaneous wind power directly supplied to the electricity grid; it is expressed as a percentage of the load and usually it is not higher than 30% [2]. The excess wind power is the one that cannot be injected in the electricity grid due to that limit. If this wind power is not stored or used to desalinate seawater, it will be curtailed. This study considers the possibility of using the excess wind power to produce fresh water that is stored in a lower reservoir of a Pumped Hydro Storage (PHS) system. The remaining wind power can be stored in this energy storage system.

Erdinc et al. [3] provide an overview of insular power system structures and operational requirements, particularly under increasing penetration of RES. The authors focused on the challenges of these systems and on opportunities to tackle them [3].

A number of studies have been carried out on the feasibility of integrating RES in isolated regions, namely islands, and all of them rely on energy storage and/or demand side management strategies.

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Kaldellis et al. [4] presents a methodology for the sizing of wind powered PHS systems in the Island of Lesbos, in Greece. This system exploits the excess wind power produced by wind farms, otherwise curtailed due to imposed power grid limitations [4]. In [5], the authors examine the economic viability of this system and find the optimum system configuration, reaching results that are able to increase the RES contribution for the total power production of the island [5].

Katsaprakakis [6] reviews the design and dimensioning of hybrid power plants in autonomous insular power systems of different sizes in Greece, with different technologies for energy generation and storage. The optimization of the dimensioning of the examined hybrid power plants is usually based on either the maximization of the RES penetration or on the optimization of economic indices of the required investments [6].

Zhao et al. [7] review the state of the art of the energy storage technologies for wind power integration. The authors conclude that these technologies are an effective solution to handle the reliability and stability challenges of power systems with large scale wind power integration [7].

A number of analyses have been also carried out on the feasibility of using RES in desalination plants [8]. Spyrou and Anagnostopoulos [9] investigated the optimum design and operation strategy of a stand-alone reverse osmosis desalination unit powered by wind and solar power and by a PHS unit, capable to fulfil the fresh water demand of areas such as the Greek Islands. The resulting water production costs are very competitive in comparison to the current water transportation prices. The PHS is necessary to guarantee the desired water production throughout the year. The authors conclude that the capacity factors of the power generators are low, while a signification part of the RES production is curtailed, hence they propose the use of the power for other uses in order to increase the capacity factor of the generators and minimize the amount of power curtailed, improving the economic results of the desalination plant.

1.1. Integrated supply of energy and water

As seen above, energy and water supply are two types of systems modeled and analyzed frequently, but often in a separate way. Most studies focus either on the energy or the water supply system. Some studies consider water as a means of storing energy in a energy supply system (PHS). Moreover, some analyze the energy demand of the water supply system with the use of RES in desalination units. More rarely these two supply systems are analyzed together in an integrated way [8]. There is a significant difference between the issues concerning the power supply and the water supply. Power production must meet demand at all times, while water can be easy stored. Hence, the studies that analyzed the integrated water and power supply in some cases do not consider the water demand curve explicitly, but only determine the amount of water that can be supplied with the system proposed.

Corsini et al. [10] compared a hydrogen based system and a desalinated water production system as two effective alternatives for renewable energy seasonal buffering in an island context (Ventotene Island in Italy). The hourly behavior of the proposed system is analyzed in terms of fuel consumption and hydrogen system energy storage or desalination capacity. The study demonstrates the suitability of both scenarios for the winter renewable energy buffer, in order to improve to the matching of peak energy and water demands [10].

Henderson et al. [11] studied the feasibility of a wind diesel hybrid system that also includes a desalination system component, on Star Island, in New Hampshire, in the United States. The proposed system aimed to supply electricity during the peak demand summer months and to balance the seasonal mismatch between wind resource and electricity demand load via the production and storage of potable water during winter months. Although this study concludes that it is better, from an economical point of view, to waste wind energy than to install a desalination system, the authors conclude that seawater desalination offers an interesting solution, from a technical point of view, to energy storage or long-term load management for wind diesel hybrid systems [11].

Setiawan et al. [12] analyzed a scenario for supplying electricity and fulfilling demand for clean water in remote areas using RES and a diesel generator with a desalination plant as deferrable load. The authors simulate the performance of the proposed system in a remote area in the Maldives with about 300 inhabitants and concluded that the proposed system is economically and environmentally viable [12].

Novosel et al. [13] proposed a combination of desalination, pump storage that use the produced brine and RES to tackle the issue of water scarcity in Jordan. The results demonstrate that an increase of the flexibility of the desalination units and the use of the brine operated PHS system greatly benefit the reduction of excess RES, increasing the penetration of wind and solar power and water availability [13].

The effects of large scale desalination on the Jordanian energy system was analyzed by Østergaard et al. [14], with a particular focus on the large scale introduction of wind power into the energy system. The authors use desalination to decrease excess electricity production and conclude that water storage has some implication on the system's ability to integrate wind power [14].

Santhosh et al. [15] addressed the issue of coupling the infrastructure systems that deliver energy and water by focusing on the supply side of this integrated engineering system, developing a multi-plant real-time simultaneous economic dispatch of power and water. In this analysis, the production costs are minimized subjected to capacity, demand and process constraints. The authors demonstrated that the coproduction minimum capacity limits and process constraints can lead to scenarios where the dispatch can chose the multi-plant instead of the cheaper single product plants. Such results suggest that water and/or power storage can have an important role in reducing process constraints and reducing costs [15].

Bognar et al. [16] analyzed the effects of integrating desalination into an island grid with a high share of renewable energies. The authors present options to include a desalination unit into an optimized wind diesel energy supply system for the Island of Brava, in Cabo Verde. Different scenarios were analyzed and simulated using hourly data. The authors conclude that the scenario that could provide the lowest and most stable electricity and water costs considering the increasing oil prices is the one that considers the electricity and water production with a discontinuously operating desalination plant. These results show that energy supply systems with a high wind power share can benefit from deferrable loads like a variable desalination plant [16].

From the examples mentioned, it is clear that the integrated planning of energy and water supply is crucial to tackle some of the problems arid islands face in the providing quality power and water to their population.

1.2. Optimization of renewable energy systems

Optimization methods play a crucial role in the design, planning and control of renewable energy systems. Baños et al. [17] presents a review of the current state of the art in computational optimization methods applied to renewable and sustainable energy. It concludes that the research that uses optimization methods to solve renewable energy problems has increased dramatically in recent years, especially for wind and solar energy systems [17].