Energy 92 (2015) 639–648

Contents lists available at ScienceDirect

Energy

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

Integrated analysis of energy and water supply in islands. Case study of S. Vicente, Cape Verde

R. Segurado [a, *], M. Costa [a], N. Duić [b], M.G. Carvalho [a]

[a] IDMEC, Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[b] Department of Energy, Power Engineering and Environment, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia

A R T I C L E I N F O

Article history:
Received 30 October 2014
Received in revised form
31 January 2015
Accepted 5 February 2015
Available online 6 March 2015

Keywords:
Energy and water supply
Renewable energy
Islands
Intermittent integration
Desalination
Pumped hydro

A B S T R A C T

The electricity production in S. Vicente is based on fossil fuel and wind power and, although there are significant wind resources, they are not fully used because of its intermittent nature. In a previous work, we proposed solutions to tackle this issue. Since this island does not have fresh water available, excess wind power can be provided to desalination units to produce desalinated water to supply the population. Other solution studied previously was the use of desalinated water in a pumped hydro system to store the remaining excess wind power. In this article, the scenarios modelled previously are updated with more recent data on energy and water consumption and the respective annual costs are estimated. The results show that with the current installed wind power and desalination capacity, and with the installation of a pumped hydro system, it is possible to have, by 2020, 36% of electricity production from renewable energy sources, with costs 7% lower than those forecasted for that year. If the installation of more wind power and desalination capacity is considered, renewable energy sources production can reach 72% (51% wind power, 21% pumped hydro), with about 19% decrease of costs in relation to those predicted for 2020.

1. Introduction

For small islands that are not interconnected with the mainland, the penetration of intermittent energy sources, e.g., wind power, in the electricity supply system is limited, even when there is a large renewable energy potential. This is due to technical constraints of the conventional generating units (namely their minimum loading level) and the dynamic penetration limit that is usually applied for grid stability [1]. In these cases, in order to minimize the curtailed wind power, the installed wind power is limited.

The electricity supply system of S. Vicente, Cape Verde, is based on fossil fuel and wind power (cf. Section 3.1) and, although this island has important wind resources (cf. Section 3.1), they are not fully used because of its intermittent nature. In addition, this island does not have any source of fresh water, being forced to desalinate seawater to produce water suitable for human consumption (cf. Section 3.2). This puts more pressure to the electricity supply system, since desalination requires a significant amount of energy. This can be an opportunity to implement renewable energy driven desalination.

To date, a number of studies have been carried out on the feasibility of integrating renewable energy sources (RES) in islands, and all of them rely on energy storage and/or demand side management strategies. Duić et al. [2] proposed a wind powered pumped hydro system (PHS) for the island of Corvo in The Azores. This study showed that only by adding storage to energy and water resource systems is it possible to significantly increase the penetration of locally available renewable energy resources, and thus increase the security of supply and decrease the import dependence. Krajačić et al. [3] concluded that with an energy storage system based on hydrogen, the island of Mljet in Croatia could become 100% renewable island concerning electricity and simulated transport needs and also could export additional power to the mainland power grid. The prospect of creating a combined wind-hydro energy production station for Aegean Sea islands in Greece has been analyzed by Kaldellis and Kavadias [4]. Bakos [5] discussed the operation of a hybrid wind/hydro power system aimed at producing low cost electricity for the island of Ikaria in Greece.

* Corresponding author. Mechanical Engineering Department, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal. Tel.: +351 218417592.
E-mail address: raquelsegurado@tecnico.ulisboa.pt (R. Segurado).

http://dx.doi.org/10.1016/j.energy.2015.02.013
0360-5442/

A number of analyses have been also carried out on the feasibility of using RES in desalination plants. Spyrou and Anagnostopoulos [6] investigated the optimum design and operation strategy of a stand-alone hybrid desalination scheme, capable of fulfilling the fresh water demand of an island. The scheme consisted of a reverse osmosis desalination unit powered by wind and solar electricity production systems and by a pumped storage unit. Fadigas and Dias [7] proposed an alternative configuration to conventional reverse osmosis desalination systems by incorporating the use of both gravitational potential energy and wind energy.

All of the cited studies have examined either the energy or the water supply system. The studies in Refs. [2–5] focus on the energy supply systems and the studies in Refs. [6,7] concentrate on the water supply systems, although they deal with the energy demand of such systems. Novosel et al. [8] stated that an important concept for a wide scale implementation of desalination units is the integration of energy and water resources. Siddiqi et al. [9] conclude that joint consideration of both water and energy domains can identify new options for increasing overall resource use efficiencies. Østergaard et al. [10] investigated a Jordanian energy scenario with different desalination technologies; they use desalination to decrease excess electricity production and conclude that water storage has some implication for the system's ability to integrate wind power.

This article discusses ways to increase the penetration of RES in the island of S. Vicente, Cape Verde, by coupling the energy and water supply systems. The scenarios established propose two ways of storing excess wind power in this island. One way is to provide the excess wind power to the desalination units and the other is to use this excess in a pumped hydro system, which is possible in S. Vicente, since it has the suitable topography.

The use of excess wind power in the desalination units can be considered a demand side management strategy since the water cannot be turned back to electricity with a reasonable efficiency. However water can be stored. In our previous work [11], these solutions have already been proposed and modelled. The results showed that it is possible to have more than 30% of yearly power production from RES (33% wind power and 3% PHS) and 50% of the water supplied to the population from wind power. It was concluded that there was the need to calculate the cost of the scenarios developed, in order to assess their economic viability and compare the solutions proposed to the current systems [11]. It was also previously demonstrated that to decrease the wind power curtailed, the capacity of the desalination units need to increase; however, it is very important to ensure that the load of the desalination units is high enough to guarantee the financial viability of the system [11].

The main objective of this study is to find a solution that minimizes the costs, while keeping the penetration of wind power the highest possible. The scenarios modelled previously are updated with more recent data on energy and water consumption of the island, and the electricity and water production costs are estimated. This study intends also to understand how the electricity and water production costs vary with the wind power curtailed and with the load of the desalination units in order to find an optimum configuration.

2. Methodology

As in our previous work [11], the simulation tool used is the H2RES model, which simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations. It is based on hourly time series analysis of demand (water, electricity, hydrogen, heat); storage (pumped hydro, batteries, hydrogen, heat) and resources (wind speed, solar radiation, precipitation) [3]. More information on the H2RES model can be found in Ref. [3] and, more specifically, on the desalination module in Ref. [11].

The wind power produced is used firstly to cover the load, according to the dynamic (hourly) penetration limit allowed. The wind power that surpasses this limit (excess) is used in the desalination units. The desalination units use this wind power to fill the reservoir used to supply water to the population (lower reservoir). After that, if there is still wind power available it is stored as pumped water into an upper reservoir. The energy that is stored can be retrieved later, and supplied to the system as electricity. The remaining energy needs are covered by fossil fuel-based systems.

Østergaard [12] investigated how energy systems can be designed to achieve the optimal integration of fluctuating energy sources. Such systems can be designed from an economic perspective or from a technical-operational perspective, which render different results. The optimization criteria used in this study is the minimization of the costs, while keeping the wind power integration in the water and energy supply systems the highest possible.

Since the H2RES model does not allow performing optimization, it is necessary to run all potential configurations and verify their technical feasibility (i.e., if they are able to supply the required electricity and water demand at all hours) and identify the one with lower total annual costs. The optimization performed in this study is an investment and operational optimization. On one hand each iteration has a specific potential configuration (capacity of the equipments installed), and, on the other hand, certain operational conditions could be changed in order to avoid the overflow of the reservoirs, namely the maximum amount of wind powered desalinated water in each hour.

The total annual costs are estimated using the simplified levelised cost of energy method. The term levelised cost of energy emphasizes the fact that this cost is determined over a certain time (technical lifetime of a specific technology). In practise, the objective is to find the price of energy that sets the sum of all future discounted cash flows to zero [12]. Each production cost includes the investment cost of the components used to produce the specific output (electricity and water).

2.1. Electricity production cost

The electricity production cost of each scenario is estimated as follows:

$$\mathrm{EPC} = \frac{\mathrm{IC}_e \times \mathrm{CRF} + \mathrm{OMC}_e + \mathrm{FC}}{E} \quad (€/\mathrm{kWh}) \tag{1}$$

where IC_e is the total investment cost of the system. This value includes the investment costs of all necessary equipment in the energy supply system. The investment costs of equipments already installed on the island, but within lifetime, are considered. *CRF* is the capital recovery factor (annuity factor) that is used to annualize the investment cost and depends on the lifetime of the equipments (n) and on the discount rate considered (i) as follows:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

In Eq. (1), OMC_e is the total yearly operation and maintenance cost of the system that usually is, according to the technology, a given percentage of the investment cost, *FC* is the yearly fossil fuel costs, and E is the total yearly electricity production. The total