Energy Conversion and Management 118 (2016) 63–74

Contents lists available at ScienceDirect

Energy Conversion and Management

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

On the economics of stand-alone renewable hybrid power plants in remote regions

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 17 March 2016
Accepted 25 March 2016

Keywords:
Stand-alone power electricity
Renewable hybrid power plants
Remote regions
Energy autonomy
Economic analysis

ABSTRACT

In recent years ever more examples of regions that have managed to achieve or orientate themselves toward renewable energy sufficiency are emerging. However, actions to create energy autonomy are mainly the result of isolated activities and they are less driven from fully organized movements. In addition, total energy independence without the support of a centralized electrical grid is yet to be achieved. The objectives of this work are to investigate the associated costs of stand-alone renewable hybrid power plants on a Greek island and compare them to the cost of the currently used fossil-fuel-based conventional plant. The plants examined here are designed to fully cover the electricity needs of the island. Islands may face numerous energy problems and rely heavily on foreign and environmentally-harmful fuels. It is shown that the relatively high cost of electricity of such a remote region can increase the competitiveness and promote the wider incorporation of technologies based on renewable energy sources that may, in other cases, seem economically inferior to business-as-usual energy solutions.

1. Introduction

The increase of the world population and industrialization in developing countries continuously raise global energy needs. Without significant change in present energy practices, greenhouse gas emissions related to energy use will continue to increase, stressing the climate to extreme and, until today, unknown conditions [1]. The European Union has committed to reducing anthropogenic greenhouse gas emissions from the combustion of fossil fuels by implementing energy-saving measures [2]. Measures proposed to reduce man-made emissions include reducing energy demand, increasing the efficiency of energy conversion and/or energy utilization, switching to less carbon-intensive fuels, increasing the use of renewable energy resources (RES) and nuclear energy and utilizing carbon capture and storage [3]. While none of these measures can directly solve the energy problem on its own, their appropriate combination can help us achieve more sustainable living.

Although the use of renewable resources is increasing, it is mainly the result of the initiative of isolated activities of individual communities and less from fully organized movements at the national level [4]. The relatively high cost of electricity of isolated areas and non-interconnected islands requires large amounts of public subsidies to balance the cost for both the energy company and the inhabitants of the regions. This may undermine the overall financial condition of a community. At the same time, this situation increases the competitiveness and promotes the wider incorporation of renewable energy technologies (e.g., [5,6]) that may, in other cases, seem economically inferior to business-as-usual – fossil-based – energy solutions [7].

In recent years, several islands – both connected to their country's national grid and non-interconnected – have been studied for renewable energy self-sufficiency and a few have achieved it. The island of Samsø in Denmark is an example of a community connected to a mainland grid with electricity generation fully based on wind energy. In addition, the energy surplus of the island is further used for powering renewable-based heating systems [8]. Other examples of islands in the process of renewable energy autonomy are the islands of Graciosa in Portugal, Gotland in Sweden, Bozcaada in Turkey, Maldives, Sumba in Indonesia, the

Abbreviations: COE, cost of electricity; CSP, concentrating solar power plant; EH, electric heat exchanger; FCI, fixed capital investment; HX, heat exchanger; O&M, operating and maintenance cost; PEC, purchased-equipment cost; PV, photovoltaic; TCI, total capital investment.

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http://dx.doi.org/10.1016/j.enconman.2016.03.070
0196-8904/© 2016 Published by Elsevier Ltd.

Cook islands and the isle of Wight in the UK [9–11]. The island of Hierro in Spain is equipped with a hybrid wind/pump hydro storage facility to serve the electricity needs of its residents, its tourist needs and the requirements of three water desalination plants [12]. However, the Red Eléctrica de España (REE) reports that renewable energy use is much lower than 100% [13]. Total renewable energy independence without the support of a centralized electrical grid is yet to be achieved.

Hybrid power plants initially attracted scientific attention as energy systems that combined conventional fuels with RES, with the purpose to reduce the environmental impact of conventional fuels, increase the penetration of renewables in national energy schemes and balance their relatively high cost. Bernardos et al. [14] suggest that the combination of fossil fuels with solar energy can be energetically advantageous, when compared to the operation of individual conventional or renewable technologies. Also, Peng et al. [15] show that hybridization scenarios operate more satisfactorily, when compared to renewable-only solutions. Solar-coal hybridization was found to have a more efficient and economical performance when compared to solar-only operation [15]. Depending on the area of application and the magnitude of renewable energy penetration, government subsidies may be required to realize a large-scale hybrid plant [16].

Renewable hybrid power plants combine more than one renewable source with complementary character for more reliable and continuous operation. An important factor in the operation of renewable hybrid power stations is the choice of energy sources and their sizing for robust operation and relatively reduced costs. Ayub et al. [17] study the economics of a hybrid solar–geothermal system involving organic Rankine cycle, Ebaid et al. [18] evaluate the costs of the hybridization of PV with a hydrogen gas turbine plant and Nixon et al. [19] evaluate the costs of the hybridization of solar with biomass. These studies show that hybridization is not yet economical enough or it is economically less favorable than the individual systems. It has been shown that such structures can only become competitive under specific conditions (e.g., [20]).

The profitability of hybrid renewable plants increases when stand-alone conditions apply (e.g., [5,6]). Off-grid operation of hybrid power plants implies particular operational characteristics and restrictions. In addition to the environmental benefits, stand-alone and fully renewable-based plants can have a positive socio-economic impact on an isolated community [21].

Wind energy is a very important resource for islands, but it requires advanced systems to control its inconsistent nature (e.g., [22]). Ntomaris and Bakirtzis [23] present the stochastic optimization of hybrid stations based on wind and hydropower for insular systems in Greece. Papaefthymiou et al. [24] also deal with the combination of hydropower with wind energy for higher wind penetration on islands. They present the case of a real hybrid power plant planned to operate on the autonomous island of Ikaria in Greece. Furthermore, the combination of solar and wind has been studied widely due to the complementary character of the two energy sources. A review of solar–wind energy systems and the analyses based on which each plant was evaluated, can be found in Ref. [25]. For example, a micro-grid system combining solar and wind energy in Brazil was found to be a good solution for isolated communities such as islands [5]. Other promising technologies for future applications, such as fuel cells, have been studied as well. A hybrid micro-grid based on solar PV, fuel cells and batteries was studied by Patterson et al. [26] and different scenarios based on these three technologies were optimized using the modeling software HOMER.

This paper presents the economic analysis of three stand-alone renewable hybrid power plants for the sustainable energy self-sufficiency of a Greek island (e.g., [27–30]). The proposed power plants aim to fully satisfy the electricity demand of the island with 100% use of renewable resources. The combination of four factors comprise the novelty of this work: (a) real case-study data for a relatively large population, (b) fully renewable operation of new plant structures, (c) stand-alone considerations for energy autonomy and (d) estimates and comparison of the associated costs of three alternatives under similar conditions.

To develop and optimize the stand-alone RES plants, while at the same time minimizing the probability of operational failures, the systems are tested under extreme conditions of energy demand and climatic conditions [31,32]. To achieve reliable and robust operation, the power plants are substantially oversized, combine renewable technologies with complementary character and include storage systems. The existing diesel generator currently used on the island is expected to be used only as a back-up technology for the prevention of power outages in the case of unpredicted events. Theoretically, this has a twofold purpose: to provide the necessary time to the personnel operating the new plants to familiarize themselves with the function and requirements of the new technologies and to replace the diesel generator in a more gradual manner.

2. The hybrid power plants

The simulations of the power plants are realized using the commercial software EbsilonProfessional [33], while their operational characteristics are determined through sensitivity analysis realized in the programming language R [31,32]. The proposed systems aim to fully satisfy the electrical energy demand of the Greek island of Skyros with 100% use of renewable resources throughout their economic life (25 years). The RES technologies incorporated in the power plant analysis include solar–thermal, solar photovoltaic, wind turbines and hydroelectric generators.

The nominal capacity of each RES technology incorporated in a hybrid plant depends on parameters specified individually for each case. The most important factor that determines the capacity of the hybrid plants is the maximum demand on Skyros. To ensure construction and operation able to fully cover the electricity needs of the island, the peak energy demand and total annual demand are derived from the hourly demand time series of the island. These are adjusted to the year 2045, the last year of the economic life of the power plants, i.e., the year with the highest demand.

The plants are assumed to start operation in 2020. The 2012 hourly time series of electricity demand on Skyros was extrapolated to 2045 with an annual energy increase of 1.4% [34]. The examined hybrid plants have an annual net energy output equal to the predicted energy demand of the island in 2045 (approximately 25,000 MW h/a).

The input data used in the simulation of the hybrid plants are shown in Fig. 1. The solar data were derived from Ref. [35]. The wind speed time series (third panel) represents the mean wind speed of the years 2010–2013. The wind speed data [36] was extrapolated from the height of the meteorological station (4 m) to the height of the hub of the considered wind turbines (84 m) using the logarithmic profile of wind sheer [37]:

$$V = V_{ref} \cdot \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)} \quad (1)$$

where V is the velocity of the wind to be calculated at the height z, V_{ref} is the known velocity at the height z_{ref}, z is the height above ground level for velocity V (84 m), z_{ref} is the reference height (4 m) and z_0 is the roughness length in the current wind direction