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Optimal design and techno-economic analysis of an autonomous small isolated microgrid aiming at high RES penetration

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A B S T R A C T

Electrification demand in small isolated power systems is typically covered by autonomous power stations, mainly diesel-generators. The technical constraints introduced by diesel-generators along with the high cost of storage options confine the penetration of renewable energy sources (RES) in these systems. This paper examines the possibility of utilizing a RES-hybrid system for a small Greek island by exploring three different case scenarios. The first two include system configurations with gradual conventional fossil-fuel power reduction while in the third one we investigate if a nearly 100% renewable system is feasible. Techno-economic analyses ensure the technical feasibility of the systems and address their economic viability. Results showed that the conventional fossil-fuel power required for the first and the second scenario could be decreased 52% and 74% compared to the existing system and the system's overall by 17% and 26% respectively. RES-penetration reached 68% (first-scenario) and 74% (second-scenario) while the NPC value was calculated to 1.84 and 2.25 million euro respectively. A nearly 100% renewable energy system (third scenario) could be technically feasible but it would require the installation of enormous RES equipment capacity dramatically increasing the total cost. Finally, the social aspect and local acceptability of RES-projects in Greece are discussed.

1. Introduction

Electrification of remote areas and non-interconnected islands relies to a great extent on Autonomous Power Stations (APS) which mostly consume diesel or heavy oil (mazut). This is the case for most islands located in the Aegean Sea, Greece. Although there is a great potential of renewable energy sources in the islands (mainly wind and solar), the achievable level of renewable energy sources (RES) penetration is low and it is typically limited to 15–20% of the annual energy demand [1]. The main reasons behind those limitations are the constraints introduced by conventional generators [2]. The scope of this study is to examine the potential for reaching very high RES penetration levels on small island systems through the design and implementation of a hybrid system comprising photovoltaics (PVs), wind turbines (WTs) and electrical storage. Initially we investigate the operation of the hybrid renewable system in parallel to the existing APS considering in each scenario a different number of operating APS units. As a second step we examine the operational and economic feasibility of the power system with the APS considered totally absent. The main objective of this study is to consider various renewable energy technology options in combination with realistic inputs on their physical, operating and economic characteristics in order to optimally design a renewable energy microgrid and decide its operating policies aiming at very high levels of RES penetration.

Electricity generation in stand-alone hybrid power systems requires various aspects to be met. Two of the most significant aspects are reliability and cost [3]. Previous research [4,5] showed that hybrid stand-alone electricity generation systems are usually more reliable and less costly than systems depending on just a single source of energy. The economic viability of Hybrid Renewable Energy Systems (HRES), specifically in off-grid remote locations, has been addressed in past literature [6–8] with many studies highlighting the important role of the climate on the hybrid system configuration and profitability. For instance, authors in Ref. [9] conducted an economic analysis of hybrid Photovoltaic (PV)-diesel system in different climate zones and concluded that the optimum climate zone for installing a PV-diesel hybrid power

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system is the arid interior. Authors in Ref. [10] reached a similar conclusion supporting that photovoltaic hybrid systems (PV–Diesel–Battery) are ideal in areas with warm climates.

HRES consist of a combination of one or more renewable and of one or more conventional energy source that work in stand-alone or grid connected mode. It is possible that a conventional energy source is totally absent from the system but renewable is a prerequisite for HRES. The development in renewable energy technologies and power electronic converters made HRES notably popular for stand-alone power generation in isolated sites. The most significant feature of HRES is the potential combination of two or more renewable power generation technologies to make best use of their operating features and to achieve efficiencies higher than the ones attained from a single-type power source [11]. Fortuitously, remote areas are generally rich in locally available renewable energy resources. The rapidly declining cost of renewable energy technologies in combination with the increased cost and the environmental consequences caused by the use of diesel fuel have widely encouraged the utilization of renewable energy systems for off-grid power supply [12]. Research on RESs has been mostly carried out in the field of system modeling, simulation, component sizing, economic analysis, and particularly system optimization [13–16].

Design, optimization, and simulation of stand-alone HRES on islands have been of recent interest in the literature. Common configurations of HRES include PV–Wind, PV–Diesel, PV–Wind-Diesel, and Wind–Diesel with or without energy storage in batteries. The most commonly used ones include dynamic programming, probabilistic approach, multi-objective design, artificial intelligence methods, linear programming and iterative techniques [17,18]. Authors in Ref. [19] developed an energy management system for a stand-alone microgrid adopting a hierarchical control structure to tackle the different operation objectives. In Ref. [20] authors focused on energy storage to enhance increased penetration of renewables in islanded systems while Rahman et al. [21] developed a hybrid energy system for an off-grid community in Canada covering several scenarios based on renewable energy fractions. Koutroulis et al. [22] used genetic algorithms (GA) for optimal sizing of stand-alone PV/WG (Wind Generation) systems while Zhao et al. [23] presented an optimal unit sizing method for the design and development of a real microgrid system on Dongfushan Island, Zhejiang Province, China, consisting of wind turbine generators, solar panels, diesel generators and battery storage units.

Although the present study considers only electrochemical storage with its system's configuration, special attention should be given to two other widely studied storage technologies, the pumped hydroelectric energy storage (PHES) and the compressed air energy storage (CAES). An upper reservoir is used in PHES facilities into which water is pumped from another reservoir located at lower elevation, usually during periods of low electricity demand. Then, during periods where electricity demand is high, power is generated by releasing the stored water. PHES systems have been addressed thoroughly in literature [24,25], often in combination with systems utilizing wind power [26–28]. The authors in Ref. [29] proposed the installation on Gran Canaria island of an appropriately administered wind powered pumped hydro storage system. The results obtained by their optimum-sized economic model indicated an increase of RES energy by 1.93%. An economic evaluation of wind-powered PHES systems can be found in Ref. [30].

A largely equivalent storage system with PHES is CAES where instead of pumping water, ambient air is compressed and stored under pressure. When electricity is needed, the under-pressure air is heated and driven to an expansion turbine coupled with a generator for power production. In literature, CAES systems have been addressed in combination with hybrid RES systems [31,32] as well as with other forms of storage like thermal [33]. Authors in Ref. [34], as a case study, evaluated the economics of two hypothetical merchant CAES and distributed-CAES (D-CAES) facilities performing energy arbitrage in Alberta, Canada. They resulted in a superior economic and environmental performance of D-CAES leading to a negative abatement of cost. CAES have been investigated also in mobility concepts like air hybrid vehicles. More specifically, the authors in Ref. [35] proposed a novel compression strategy for air hybrid engines utilizing two storage tanks which increases the efficiency of regenerative braking of air hybrid vehicles.

2. Background information and present energy system

2.1. Electricity infrastructure and load profile

It is selected as a study case the small island of Agios Efstratios located in the North Aegean Sea, Greece (latitude 39° 27′ to 39° 34′, longitude 24° 57′ to 25° 05′) (see Fig. 1). Agios Efstratios had been selected in the past by governmental authorities to implement a “Green Island” project. Agios Efstratios covers a total area of 44 km^2 and has a population of approximately 300 people. However, this number greatly increases in summer due to tourism. The landscape is mostly rocky, with scarce and low vegetation. The economy is based on fishing, livestock breeding and tourism. The main settlement of the village is located northwest and it comprises public buildings (city hall, post office, general citizens' services, school) and inhabitants residences.

Agios Efstratios island's electricity is operated and managed by Public Power Corporation of Greece (PPC), the main electric utility in Greece. Similar to the majority of Greek islands, Agios Efstratios is not connected with undersea cables neither to the mainland grid nor to any nearby islands. The energy system of the island consists of a thermal power station and a 20 kW wind turbine which is the only RES component in the island. The thermal power plant is currently based on an APS including 3 × 220 kW and 2 × 90 kW diesel generators.

The daily load profile for the island was obtained from PPC for the year 2010. According to the obtained hourly load data, the island's annual electricity demand was 1223 MWh. The peak load was 360 kW in August and the average daily electricity consumption was 3.35 MWh, which doubles in summer months mainly due to tourism activities, indicating the high seasonal variations of demand. The load profile had been used to illustrate the seasonal electrical load behavior during each season and is illustrated in Fig. 2.

The average daily load profile for Agios Efstratios island is depicted in Fig. 3 while in Fig. 4, a typical winter and summer day are compared in terms of electricity demand highlighting the seasonal variations.

The thermal load is the demand for heat energy. Heat in general is needed for space heating, water warming or some minor industrial process. The thermal load is assumed to be 5% of the electrical load [36] and is added mainly to examine the impact of excess energy feeding the thermal load. In this work, the primary objective is to serve the thermal load by surplus electricity of the hybrid system through dump load. When this is not possible, thermal load is served by a boiler, namely a generator from which waste heat can be recovered.

2.2. Assessment criteria

The Hybrid Optimization Model for Electric Renewables (HOMER) is a powerful tool for designing and analyzing off-grid