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Simulation and analysis of a stand-alone solar-wind and pumped-storage hydropower plant

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ABSTRACT

This work presents the simulation and evaluation of a renewable hybrid power plant for off-grid fully autonomous operation on an intermediate-sized island in the Aegean Sea. A stand-alone energy system including storage facilities is simulated, optimized and analyzed relying on real-case weather and demand data of a relatively large remote community. Optimization of the power plant structure shows that to ensure continuous off-grid energy generation, even under extreme conditions, the combination of more than one renewable technology is required. The hybrid power plant consists of a pumped-storage hydropower plant, photovoltaic cells and wind turbines. Energy surplus of the power plant is used in the incorporated electrolyzer to generate a secondary product, hydrogen. Robust operation of the plant results in 48% of the energy generated stemming from the photovoltaic system and 52% from the wind turbines. The pumped-storage hydropower plant has a mean annual power output of 1.0 MW. The total mean annual efficiency of the hybrid plant is found to be 14.4%. Although stand-alone operation was achieved with the proposed plant, this requirement led to net energy output restrictions, capacity oversizing and large storage facilities.

1. Introduction

Robust and efficient electricity generation on islands and remote regions is an issue of significant interest, especially in countries heavily reliant on fossil resources. Renewable power plants can offer an environmentally and economically sustainable alternative to conventional energy sources that may currently exist in such areas [1–4]. In addition, renewable hybrid plants establish a more competitive environment for RES (renewable energy sources) [1,5,6] taking advantage of the benefits of individual technologies and allowing their complementary coupling [7]. This paper presents the simulation and thermodynamic evaluation of a renewable hybrid power plant for stand-alone operation on an island in Greece.

Greece has 6000 islands and islets scattered in the Aegean and Ionian Seas, from which 227 islands are inhabited [8]. The minimum target of Greece for RES contribution by 2020 is 18% with 40% of this share stemming from electricity generation. The islands present a challenge to develop a unified energy development policy due to their unique characteristics. Additionally, geomorphological particularities offer highly diversified topography and geo-characteristics of the islands, unparalleled landscape, volcanic soil and fascinating local traits.

Non-interconnected islands are islands not yet connected with the electrical system of the mainland, mainly due to logistical, technological and financial difficulties. On the non-interconnected islands, the main priority of the country's strategy is the installation of RES plants, including hybrid RES plants and offshore wind parks. These plants will operate either as autonomous systems or they will be connected to the existing interconnected system as additional energy resources. In the electricity sector it is expected that lignite and petroleum will gradually give way to mainly natural gas and wind power.

In recent years various efforts towards energy self-sufficiency with renewable technologies have been noted and ever more examples of regions that have managed to achieve or orientate themselves towards that goal are arising [9,10]. However, although the use of renewable resources is increasing, it is mainly the result

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of isolated activities and less of fully organized movements, while total energy independence without the support of a centralized electrical grid is yet to be achieved.

This work presents results of the project GENERGIS (European project entitled: Green Energy for Islands) related to the energy autonomy of isolated areas, specifically of islands [11]. A novel aspect of the project was to include energy storage technologies in original hybrid power plants, to cover demand when renewable resources weren't available. This holistic view of the project was necessary for assuring complete energy independence in remote regions. For the purpose of the project, one medium-sized non-interconnected island was studied and energy strategies towards its 100% renewable energy autonomy were proposed. GENERGIS constituted the first complete study of stand-alone renewable energy power plants for the energy autonomy of a community of approximately 3000 people.

According to the Greek RAE (regulatory authority for energy), most of the islands in Greece today (mainly in the Aegean Sea) are electrified by autonomous electrical systems generating electricity primarily using local thermal power plants that operate with heavy (mazut) or light (diesel) oil and RES stations (wind and photovoltaic) [12]. The small and medium-scale autonomous islands in the Aegean Sea represent approximately 10% of the country's total energy consumption [13]. The electricity market of the non-interconnected islands consists of 32 autonomous systems. Some of them consist of several islands (clusters of islands).

The demand (consumption in MWh) of electricity on the non-interconnected islands varies from several hundred MWh in the smaller islands (e.g., Antikythera, Agathonisi, etc.), up to several TWh in the biggest non-interconnected island (Crete). According to the Hellenic Electricity Distribution Network Operator (HEDNO/DEDDIE), in December 2014 84% of the energy generation on non-interconnected islands came from thermal power plants, 13% from wind parks and 3% from PV (photovoltaic) stations. Most of the wind and PV stations have been installed by far on the island of Crete, followed by the island of Rhodes. The contribution of RES stations to the electricity generation on the non-interconnected islands in December 2014 was 15.6% [14].

1.1. Presentation of the case study

The island of Skyros in the Aegean Sea was chosen as the case study of the project GENERGIS based on specified quantitative and qualitative criteria [11]. Skyros belongs to the prefecture of Evvoia and the region of Central Greece. The island is situated in the most southern part of the northern Sporades in the Aegean Sea and it is the biggest island (208,594 km^2) in the group of Sporades [15]. According to the census of 2011, Skyros had 2994 permanent residents (increased from 2711 in 2001 [16]) with 1638 men and 1356 women [17]. The low population density of the island reveals good potential for developing applications with RES, however it should be noted that environmental and property restrictions limit the available land that can be accounted for in energy development plans. The current electricity energy needs of Skyros are covered through the combustion of diesel oil. Electricity is currently used to cover part of the space and water heating needs of the island, as well as operate lighting and electrical and cooling appliances.

Based on information provided by the Hellenic National Meteorological Service, Skyros enjoys approximately 2500 h of sunshine annually [18]. Satellite-based data on the global irradiation on an optimally-inclined surface for Skyros are shown in Map 1 and for a larger area in Greece in Map 2. The data were provided by the Institute for Energy and Transport of the Joint Research Centre of the European Commission (CMSAF data set) [19] and their visual representation was realized using the open-source software QGIS [20].

As seen in Map 2, the solar potential of Skyros is very high in comparison to other areas in mainland Greece, approaching that of islands in the southern part of the country. Skyros also has great exploitable wind energy potential (see Fig. 1). Higher wind speeds surpassing 10 m/s are observed in the southern part of the island. Map 3 shows daily wind speed measurements from one station on Skyros and Map 4 the wind potential for a larger area of Greece [21]. In order to calculate energy generation using the variation of wind speed, specific technological characteristics of the utilized wind turbines must be used.

The significant potential for Skyros to export wind energy to the mainland to increase national renewable energy generation has been reported numerous times in various reports. Although various large-scale wind farm projects have been proposed for construction on the island, they face social opposition. The present work proposes the installation of a power plant for energy autonomy on the island, i.e., a facility that will exclusively cover the current and future energy needs of the island.

The future electric energy demand of Skyros, as anticipated by the DEDDIE in 2012, is shown in Table 1 [22]. Assuming an

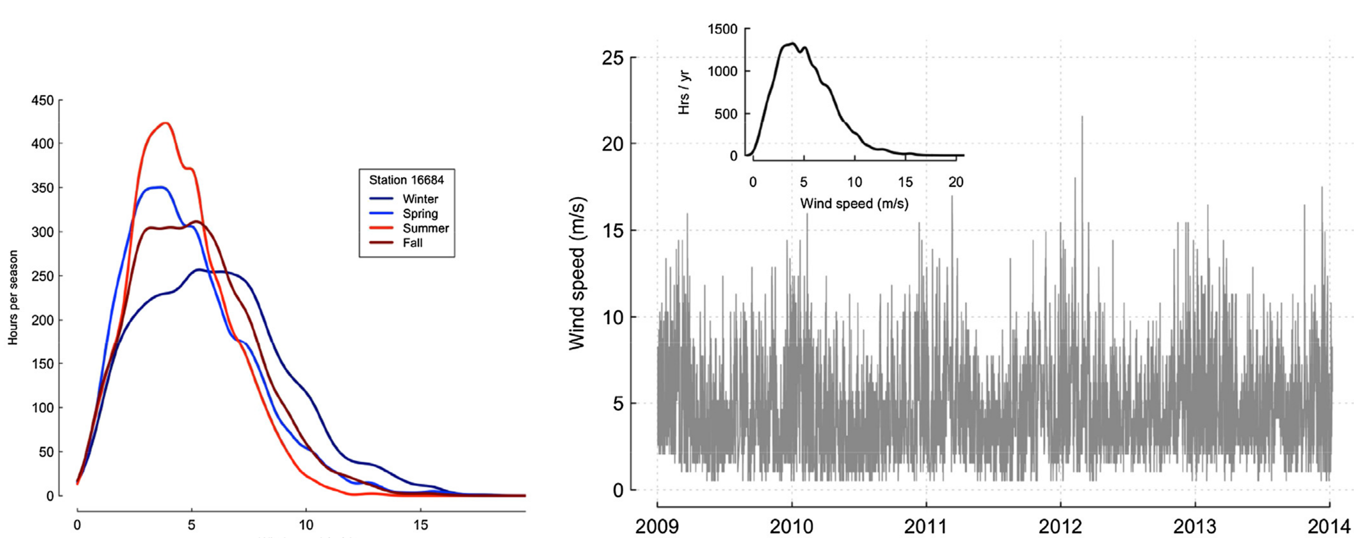

Fig. 1. Seasonal and daily variation of wind speed for the years 2009–2013.