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Viability assessment of a combined hybrid electricity and heat system for remote household applications

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A R T I C L E I N F O

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A B S T R A C T

The purpose of this paper is to address the problem of satisfying the energy needs in electricity and heat of a typical remote household in an integrated autonomous manner, employing environmental friendly and sustainable power systems. A hybrid PV/diesel/battery power system is designed to satisfy reliably the electric needs, using the HOMER simulation software. The present work showed that a PV/diesel/battery power system with 1 kW of PV arrays, 1.8 kW sized diesel generator, 2 battery units each of 1 kW h and 1 kW sized power converter is the optimal system for a representative off-grid remote house located in Metsovo, Greece, with the cost of energy rising to 0.553 €/kW h. The optimal hybrid power system presents a cost-effective alternative to conventional electricity grid-extension. The paper also investigates the installation of a 14.8 kW wood biomass burning thermodynamic fireplace alongside a diesel oil burner to cover space heating and hot water requirements, employing the renewables assessment software tool 'RETScreen'. The proposed heating system is viable with Internal Rate of Return of 24.8%. The initial investment of the combined hybrid electricity and heat autonomous system is about 13,600 €. The mitigation of GHG emissions to be achieved is estimated to 13.5 tons $CO_{2\text{-eq}}$/yr, presenting a major improvement of the environmental footprint of the town.

1. Introduction

A concern about the drain on natural resources and the effects of environmental pollution of fossil fuel-based electricity generation has initiated research in new, clean and renewable energy sources, as well as, the associated technologies. Wind and solar energy are gaining popularity simply because they represent non-depleting and non-polluting alternative energy sources options. For certain remote and rural areas, where electricity grid extension is not cost-effective, wind and/or photovoltaic (PV) power generation, seems to be the most convenient and effective way of generating electricity. Nevertheless, the energy output of both wind and PV power systems relies heavily on local weather conditions, inevitably, adversely affecting the reliability of a continuous, uninterrupted, electricity supply. Hybrid systems that combine wind turbine and solar energy conversion units and/or, possibly, fossil fuel generators, with and/or without battery backup options, could represent, perhaps, the most appropriate approach as far as the solution of the uninterrupted supply of electricity is concerned. It is reasonable to expect that hybrid systems exhibit higher power supply reliability and a lower power generating cost, compared to power systems that employ just a single energy source (Rehman et al., 2012).

A great deal of research related to the performance, optimization and economic viability of hybrid energy (electricity) generating systems, such as wind-diesel, PV-diesel and wind-PV-diesel with or without battery storage options has been carried out. Chedid and Rahman (1997) studied the optimal design of a hybrid wind/solar power system for either grid connected or autonomous applications. The authors proposed linear programming techniques to minimize the average production cost of electricity while meeting the load requirements in a reliable manner. They also considered environmental factors in both the design and the operation phase. Merei et al. (2013) presented an optimum size procedure for an off-grid hybrid PV/wind/diesel/battery power system that supplied different remote sites in Germany and Syria using genetic algorithms. The optimization variables they employed, were the nominal power, the azimuth and tilt angles of PV generator, the nominal power, the rotor diameter and installation height of wind turbine, the nominal power, the partial load factor and minimal runtime of diesel generator, as well as, the type and nominal capacity of the batteries. Their study showed that the energy cost of the hybrid PV/wind/diesel/battery power system is reduced by 50%

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compared to a diesel only-based power generation unit. Moreover, it was found that redox-flow batteries exhibited a higher efficiency and cost-effectiveness compared to lead acid and lithium-ion batteries. Yang et al. (2007) recommended an optimal sizing method to optimize the configurations of a hybrid solar/wind/battery power system. The authors also used a genetic algorithm to calculate the optimum system configuration that could meet the loss of power supply probability (LPSP) figure, specified by the customer, with the minimum annualized cost of system (ACS). Jeyaprabha and Selvakumar (2015) proposed a methodology for the optimal sizing and tilting of a hybrid PV/diesel/battery power system for different remote locations in India using Artificial Intelligence Techniques (AIT). They employed a simple graphical solution procedure to determine the optimal sizes of PV, diesel generator and battery for loss of load probability (LLP) of 0.01 based on the minimum life-cycle cost (LCC). The results of this study indicate that the LCC of the optimized hybrid system is much lesser than the LLC of the stand-alone PV and the diesel generator system. The validity of this sizing procedure was also demonstrated with LLP of 0.0026. Finally, Yahyaoui et al. (2016) introduced a Fuzzy-based approach that incorporated autonomy, power supply stability and battery bank protection with a minimum cost function to model and optimize an off-grid hybrid PV/wind/battery system in a rural region in Northern Tunisia. The optimal system had the lowest installation's operating cost.

Apart from the abovementioned mathematical procedures, HOMER (Hybrid Optimization Model for Electric Renewables) has been also used as a sizing and optimization software tool (HOMER). Hiendro et al. (2013) employed HOMER software and showed that a hybrid PV/wind power system with 1 kW of PV arrays, 1 kW sized wind turbine, 45 battery units and 0.7 kW sized power converter was the optimal system to meet the demand of a remote site in Temajuk, Indonesia, with the COE rising to 1.06 $/kW h. The authors pointed out that wind turbine and batteries are required to satisfy the load demand during the night, although both contribute the greatest cost to the system. Li et al. (2013) carried out a techno-economic analysis of an autonomous hybrid PV/wind/battery power system for a household in Urumqi, China. The researchers considered the effects of ambient temperature and load variations, as well as, the PV panels tilt angle using the HOMER software. The results of this study indicate that the hybrid PV/wind/battery power system is much more cost-effective, compared to either a PV/battery or a wind/battery power system alone. Sen and Bhattacharyya (2014) analyzed the economics and the technical feasibility of an off-grid hybrid hydro/PV/bio-diesel/battery power system employing HOMER software to meet the electricity requirements of a typical remote village in the state of Chhattisgarh, India. The authors concluded that the hybrid hydro/PV/bio-diesel/battery power system with 10% and 14% solar energy and bio-diesel penetration, respectively, and a corresponding 76% hydro power contribution, was a cost-effective energy-efficient alternative to grid-extension, with a COE of 0.420 $/kW h. The proposed hybrid system could also result into emissions reduction of 33,832 kg CO_2/yr in the local atmosphere of the village. Maatallah et al. (2016) investigated the technical and economic potential of a hybrid PV/wind/diesel/battery power system using HOMER software for electricity generation in the city of Bizerte, in Tunisia. The authors concluded that the wind/diesel power system was the most efficient, economic-wise, system with a COE of 0.26 $/kW h. The suggested hybrid system also presented a cost-effective alternative to both overhead and underground conventional electricity grid-extension. Bentouba and Bourouis (2016) evaluated the technical and economic feasibility of a hybrid PV/wind/diesel power generation system employing HOMER software to supply electricity to Timiaouine town, in the southwestern part of Algeria. In their study, the cost of electricity generated by this system was found to be 0.176 $/kW h. In addition, the hybrid system could save 593.125 tons CO_2/yr compared to a diesel only-based power generation system.

The literature review presented above shows that there are quite a few studies for different countries investigating autonomous PV/wind/diesel/battery electric power systems. In Greece, however, information concerning the technical and economic performance of such energy systems is rather limited and concerns almost exclusively isolated islands. Bakos and Soursos (2002) presented an economic analysis of an autonomous hybrid PV/diesel power system installed in a bungalow complex in Elounda, Crete. The authors considered different financing scenarios with different levels of subsidy and showed that a hybrid PV/diesel system could be a feasible investment even if the project was not subsidized at all. Moreover, Vrettos (2010), Georganteas (2011) and Katsafaros (2011) analyzed the potential implementation of hybrid PV/wind/diesel/battery power systems in off-grid/isolated islands in the Aegean Sea, namely Saint Eustratius, Ikaria and Astypalaia islands, respectively. All three studies found that hybrid energy generating systems with very high levels - ranging from 77% to 90% - of renewable energy penetration could be an economically attractive solution for the electrification problem of off-grid/isolated Greek islands, whose primary energy supply is based, almost exclusively, on cost-inefficient oil-fuel imports and diesel electric generators.

The present research work provides an integrated techno-economic assessment and an optimal design of an autonomous hybrid power system capable of meeting the electricity and thermal energy demand of a typical household in the remote rural town of Metsovo, in northwest mainland Greece. The present work involves: (i) a hybrid PV/diesel/battery electricity power supply system whose relevant economic indices have been optimized using the HOMER Pro Microgrid Analysis version 3.5.3 Simulation Software (HOMER), (ii) the simulation of a wood biomass burning thermodynamic fireplace alongside a diesel oil burner, proposed to meet the space heating and hot water thermal loads of the household, using the RETScreen Clean Energy Project Analysis version 4.0 Software (RETScreen International), (iii) a detailed economic analysis, and (iv) an analysis concerning a potential annual greenhouse gas (GHG) emissions reduction. The results of the present research work are expected to provide useful information to policy makers and interested individuals as well as organizations regarding technical, economic and environmental feasibility of autonomous hybrid power systems capable of satisfying both electricity and thermal load requirements of decentralized residential households in remote rural areas in southern European, Mediterranean and Middle East countries, whose climate is quite similar to that of Greece.

2. Site and data description

Metsovo is a remote rural town in the Region of Epirus, in northwest mainland Greece, lying at an altitude of 1250 m (Fig. 1). It is located on 39°46.2′ North latitude and 21°11.0′ longitude. It has 750 residential households (Boutetsiou, 2010). The region is mountainous, rugged in terrain, extensively faulted and folded, and represents the southern extremity of the European Alps. Metsovo belongs to the continental climate of the temperate zone; summers are hot with few local rains and winters are long and cold with affluent rains and snow. The combination of mountain terrain and high-altitude climate leads to abundant renewable energy potential in the area.