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Combined heat and power design based on environmental and cost criteria

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ABSTRACT

This paper proposes a hybrid renewable energy system (HRES) consisting of photovoltaic (PV), wind and forest wood biomass power for cogeneration, and applies a multi-objective optimization methodology to study the trade-offs between life-cycle cost and environmental impact (EI) of such a system. The optimization is achieved by applying an operation strategy that maximizes the efficiency of the biomass power subsystem coupled with an optimization model based on the use of genetic algorithm (GA) to obtain the optimal system sizing. The system is designed to supply the electricity demand of a rural township and the thermal demand – both heating and sanitary hot water (SHW) – of a neighborhood in a district heating (DH) scheme. Indigenously available renewable energy sources (RES) are used, taking special care in the case of biomass to not exceed the self-growth rate of local tree species. Results show that by taking advantage of the thermal energy produced, the payback time of the investment required to install the system is significantly reduced, being profitable after 9 years. Furthermore, it is also observed that layouts with low costs have greater EI and vice versa. However, it is shown that moderate cost increases have great returns on EI reduction.

1. Introduction

Hybrid renewable energy systems (HRES) have gained relevance as an effective way to deploy energy production from renewable energy sources (RES). This is because of the importance of renewable energies in the current context of rising and volatile energy prices and their role as an alternative to fossil fuels, widely recognized as one of the causes of climate change. HRES have the ability to counteract the weaknesses of the stochastic nature of one RES with the strengths of another, for instance taking advantage of the daily and seasonal complementariness of solar irradiation and wind speed patterns [1].

Several papers are focused on HRES optimization, the vast majority of them dealing with stand-alone systems [2–16], although some of them deal with grid-connected layouts [17–21]. Regarding the applied optimization methodology, whereas some of them base the optimization on the usage of specialized software [3,6,15,16,22–25], others rely on heuristic methodologies [2,7,9,10,13,26–33]. Concerning the energy sources, the preferred hybridization is PV and wind with battery storage [6,9,23,27,34] or pumped hydro storage (PHS) [7,12,13,22,35,36]. When a backup energy source is used, it is usually a diesel engine [2,10,11,24,37,38] or a fuel cell [33] instead of a biomass conversion system which is the focus of the research in this work. In the literature review performed by the authors, no combined heat and power (CHP) HRES optimization were observed aside from Ref. [39] or [40], which is focused on storage size.

Therefore, the main differential aspect of the proposed research is that it deals with a system that uses the excess heat produced by the CHP subsystem at an appropriate scale to effectively revalue such energy that otherwise would be wasted. Moreover, this research also performs a comprehensive cost and environmental impact assessment. The analysis applied in the life-cycle cost includes all life-cycle costs, from the basic upfront investment and expected incomes of the project to all sorts of different costs and revenues of the system during its lifetime [27,41]. Similarly, to evaluate the life-cycle environmental impact, the equivalent CO_2 emissions have been considered since they are a representative metric of environmental impact derived from electricity and heat generation.

Another original aspect of this work is its accuracy in the analysis of electricity generation patterns by using data with hourly

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accuracy for weather variables, electricity demand and market and retail electricity prices, as well as by the utilization of an evolutionary optimization algorithm. This kind of optimization methodology allows taking into account several input parameters and system operation and modeling strategies. Once having introduced all these parameters the model presented here is able to calculate costs and revenues derived from electricity and heat sale or purchase, these variables being considered as dynamic cost/revenue terms.

The proposed model also is flexible in terms of system scale. Through the open design that allows the user changing the existent heat and power demands, weather patterns and system components' efficiencies, the methodology developed can be used in a range of different scales and locations.

It is noted the use of an operation strategy focused to optimize the performance of the whole system. The biomass power system will always operate at full load, thus maximizing its efficiency. Hence, the optimization model used in the context of an optimal operation strategy leads to an optimal performance in terms of efficiency, resulting in minimum cost and environmental impact.

The entire methodology has been tested in a real location for the sake of methodology validation.

2. System description

The proposed HRES consists of a CHP HRES based on the use of solar PV, biomass and wind power sources. This layout, thanks to the grid connection and to the biomass subsystem, which can be used to back up the stochastic RES due to its short response time, has the advantages of increased flexibility and reliability. Therefore, initial investments can be reduced with respect to a HRES only relying on RES that cannot be dispatched on demand or with respect to a stand-alone HRES that requires storage systems [12]. Besides, the biomass subsystem is also used to supply a certain heating demand during winter days. The proposed system is shown in Fig. 1.

System components include the UpSolar UP265 M modules, PV modules with 265 Wp of nominal power and 1.629 m2 of area [42] and 200 kW SUT200 turbines [43]. Similarly as done in Refs. [17,44], system sizing is optimized using the area of the PV installation and the number of wind turbines as the independent variables. These two subsystems are combined with a CHP biomass gasification equipment of 500 kWe of electrical power. Such equipment produces a surplus of approximately 1000 kWth of thermal power. The scale of the biomass subsystem has been set according to the average hourly electricity demand, and the associated thermal demand has been scaled to a number of households that can be supplied, provided that the district heating (DH) installation is viable.

To determine the number of households that can be included in the DH network, a first estimation of the thermal demand of the different typologies of household in the township under study (see Table 1) was performed according to the methodology proposed by the Spanish Institute for Energy Diversification and Saving (IDAE in its Spanish acronym) [45].

After that, the number of households that could be supplied was estimated. A diversity factor of 60% was supposed and a neighborhood in which it would be technically feasible to install a DH network without exceeding installation lengths of 500 m was chosen in order to keep the distribution network efficient and, consequently, reduce losses.

The resulting DH proposal is shown in Fig. 2 and Table 2. The procedure used to calculate the thermal energy demand and the ratio of coverage is shown in the methodology section, and the results obtained are presented in the results chapter.

Regarding the prioritization of energy sources, it is relevant to highlight the recently increasing importance of the operation strategy [46]. In this case, the following strategy was set up: on the one hand, the PV and wind power systems are the first option for electricity generation, whereas the biomass subsystem supplies electricity whenever these stochastic RES are insufficient to match the existent demand and due to efficiency and environmental reasons, it is used at engine full load.

Hence, only when the three RES are not enough to match the electricity demand, the system takes advantage of its grid connection to purchase the lacking energy. A midway situation may occur when PV and wind energy systems cannot supply the existent load, but turning the biomass subsystem on at its full power exceeds such demand. In these cases, the surplus energy produced will be sold at market price.

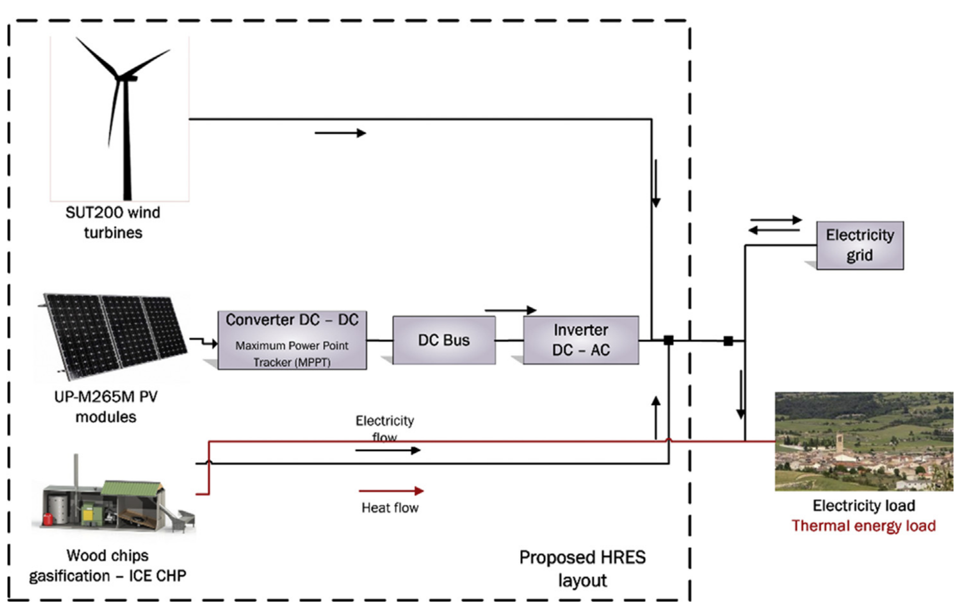

Fig. 1. HRES sought to optimize.