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Optimal sizing of a hybrid grid-connected photovoltaic and wind power system

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HIGHLIGHTS

- Hybrid renewable energy systems are efficient mechanisms to generate electrical power.
- This work optimally sizes hybrid grid-connected photovoltaic–wind power systems.
- It deals with hourly wind, solar irradiation and electricity demand data.
- The system cost is minimized while matching the electricity supply with the demand.
- A sensitivity analysis to detect the most critical design variables has been done.

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ABSTRACT

Hybrid renewable energy systems (HRES) have been widely identified as an efficient mechanism to generate electrical power based on renewable energy sources (RES). This kind of energy generation systems are based on the combination of one or more RES allowing to complement the weaknesses of one with strengths of another and, therefore, reducing installation costs with an optimized installation. To do so, optimization methodologies are a trendy mechanism because they allow attaining optimal solutions given a certain set of input parameters and variables. This work is focused on the optimal sizing of hybrid grid-connected photovoltaic–wind power systems from real hourly wind and solar irradiation data and electricity demand from a certain location. The proposed methodology is capable of finding the sizing that leads to a minimum life cycle cost of the system while matching the electricity supply with the local demand. In the present article, the methodology is tested by means of a case study in which the actual hourly electricity retail and market prices have been implemented to obtain realistic estimations of life cycle costs and benefits. A sensitivity analysis that allows detecting to which variables the system is more sensitive has also been performed. Results presented show that the model responds well to changes in the input parameters and variables while providing trustworthy sizing solutions. According to these results, a grid-connected HRES consisting of photovoltaic (PV) and wind power technologies would be economically profitable in the studied rural township in the Mediterranean climate region of central Catalonia (Spain), being the system paid off after 18 years of operation out of 25 years of system lifetime. Although the annual costs of the system are notably lower compared with the cost of electricity purchase, which is the current alternative, a significant upfront investment of over \$10 M – roughly two thirds of total system lifetime cost – would be required to install such system.

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1. Introduction

Renewable energies are a promising alternative that could help to face climate change hurdles, in particular reducing greenhouse gases emissions from electricity and heat generation. In addition to their cleanliness and indigenous availability [1], they allow reducing energy dependency of countries that implement them at mid-scale. These energy sources are expected to take a leading role in the future transition from a centralized to a distributed generation scheme that is closely linked with the concept of smart grid. In fact, they are currently considered viable and even the best available solution in certain conditions for microgrid implementation [2] thanks to the easy scalability of small modular units in which the generation from these source rely on [3]. Hence, renewable energy sources (RESs) could address several issues, highlighting

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Nomenclature

$V_{H,t}$	estimated wind speed at height H
$V_{H_0,t}$	measured wind speed at height H_0
H	wind turbine rotor height
H_0	wind speed measurement height
N	system lifetime
Y_{wt}	wind turbine lifetime
Y_{inv}	solar PV DC–DC converter lifetime
IR	interest rate
TR	Spain's Value Added Tax (VAT) rate
g	general inflation rate
$g_{electricity}$	electricity selling price inflation rate
g_{wt}	wind turbines selling price inflation rate
g_{inv}	converter selling price inflation rate
L_{g_wt}	cost reduction limit due to technological maturity for wind turbines
L_{g_inv}	cost reduction limit due to technological maturity for converters
C_{PV}	PV capital cost
C_{WT}	wind capital cost
C_{INV}	converter capital cost
$C_{PV_{fixed}O\&M}$	PV fixed O&M costs
$C_{WT_{fixed}O\&M}$	wind fixed O&M costs
$C_{PV_{var}O\&M}$	PV variable O&M costs
$C_{WT_{var}O\&M}$	wind variable O&M costs
C_{pool}	electricity market price
C_{electr}	electricity retail price
$pvArea$	area covered by PV modules
$panelArea$	area covered by each PV module
$pvNumber$	number of PV modules installed
$wtNumber$	number of wind turbines installed
P_{module}	nominal power of PV modules
$P_{turbine}$	nominal power of wind turbines
NPV	Net Present Value
$C_{investment}$	cost of system initial investment
$NPV_{O\&M}$	cost of system operation & maintenance (O&M)
NPV_{repl}	cost of system' components replacement
$NPV_{electricity}$	electricity selling and purchasing balance
$NPV_{endLife}$	profit from equipment sale at end of life
$C_{O\&M\_k}$	cost of O&M of component k
C_k	acquisition cost of component k
g_k	expected inflation rate of the acquisition cost of component k
Y_k	component k lifetime
Y_{g_k}	number of years required for technology k to reach technological maturity
N_{repl_k}	total number of replacements of component k during system lifetime
$N_{first_{repl}\_k}$	years that the price of component k is changing at g_k inflation rate
L_{g_k}	cost reduction limit of technology k at a point of maturity
NPP	net power production
P_{PV}	power production of PV modules
P_{WT}	power production of wind turbines
$demand$	electricity demand
$PopulationSize$	size of GA population
$numberOfVars$	number of independent variables of GA fitness function
$EliteCount$	counting of GA elite (best-fit) individuals

an improvement of security of supply, reduction of CO_2 emissions, improvement of energy systems' efficiency [4] as a result of energy transport requirements reductions. RESs would also help to develop rural areas with the creation of job opportunities and revaluation of local resources currently misused [5]. Besides, in isolated regions or communities, they could help to reduce electricity generation costs because they are currently economically competitive [6,7].

A very promising alternative to exploit these energy sources are the hybrid renewable energy systems (HRESs), electricity generation systems that combine two or more energy sources being at least one of them a RES. These systems can be installed in different places according to the available RESs on-site. Usually, the production pattern of one source helps to counteract the production pattern of another one [8]. That is the case of solar photovoltaic (PV) power and wind power, the topics at hand in this study.

To effectively size a HRES it is required to assess the main constraints, including the load demand profile that restricts the demand of the system, as well as the wind speed and solar irradiation that restrict the supply. When performing such assessment, optimization technologies are a useful tool that support and inform decision-makers providing optimal designs according to pre-established criteria.

A thorough literature review has been performed to properly assess the current state of the art on the topic of HRES optimization. Most of the accessed HRES design and optimization papers are focused on stand-alone HRESs [2–7], [9–15] rather than grid-connected ones because the formers show better economic feasibility than the latters as they are intended to substitute small grids fueled with non-indigenous fossil fuels [2,6,7,9]. Some of these researches rely on existent optimization software usage, such as HOMER [3,7,16–18] while others develop some optimization methodologies based on different optimization methodologies such as genetic algorithms (GA) [2,9,11,12,15,19,20] or dynamic programming methods [21], such as the mixed integer linear programming (MILP) [6]; whereas others only model and simulate the problem with different input values to analyze the results [10,22,23].

Regarding the reliability of supply, which is a critical issue of RE-based generation systems, some of the systems propose storage mechanisms such as pumped hydro storage (PHS) [9,14,15,17,24,25] or, the vast majority, battery storage [6,7,11,17,20]. Conversely, other researches propose internal combustion engine (ICE) such as diesel engines backup generation [18,21] or a combination of backup generation and battery storage [2,12,13] to counteract the stochastic variability of RE generation. Another alternative is to connect the system to the grid, thus using the grid as the backup technology [23].

One of the key aspects of HRES optimization problems is the input data. For HRES optimization, both the atmospheric data related with RE generation, that is, solar irradiation and wind speed, and the load demand data are of critical importance. From the performed literature survey, it was observed that some works do not use actual data sets and instead, estimate weather-related variables [6,16,17,21] and/or the electricity demand [7,9,13,15–17]; whereas others use full year actual data sets for these variables [2,3,11,18,20].

Many of the accessed papers do not include real on-time data in the analysis, a circumstance that we believe that weakens the analysis due to the lack of accuracy when capturing both daily and seasonal patterns. We also observed a scarcity of grid-connected HRES optimization researches and, particularly, none that introduced on-time electricity sale and purchase

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