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Business optimal design of a grid-connected hybrid PV (photovoltaic)-wind energy system without energy storage for an Easter Island's block

F. Caballero, E. Sauma*, F. Yanine

Pontificia Universidad Católica de Chile, Industrial and Systems Engineering Department, Santiago, Chile

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ABSTRACT

This paper presents a method for the business optimal design of a small grid-connected HES (Hybrid Energy System) comprised of photovoltaic panels and wind turbines, which seeks to minimize the LCC (Life Cycle Cost) of the system, ensuring at the same time certain level of system reliability. This is measured in terms of LPSP (Loss of Power Supply Probability), which is computed by simulation. The proposed method allows the possibility to supply excess power generated by the HES to the utility grid at a fixed sales price or through a Net Metering scheme. The system and design method proposed represent a viable alternative for grid-only power supply in rural/remote communities. As an example, a concrete case study is presented involving 15 homes (1 block) in Hanga Roa city of Easter Island, Chile. Results indicate that the grid-connected HES is highly beneficial for the block since it reduces long term costs of electricity generation and supply while at the same time supporting their energy consumption with cleaner, renewable energy sources, and contributing to reduce the load size of the utility grid power supply.

1. Introduction

The rising fossil fuel prices, their limited reserves and the ongoing concern for global warming have determined over the last 15 years an intense and increasing search for new alternatives of energy sources, especially at the residential level. In particular, solar and wind are potentially good sources for gradually substituting the still widespread use of fossil fuels in electric power generation. Both solar and wind energies are pollution-free and freely available everywhere in the world [1,2]. However, they are also intermittent; therefore in power generation systems employing either wind or solar PV (photovoltaic) resources, there exists the need to account for the deficiencies and limitations which arise as a result of such intermittency in the energy supply capacity of such systems. Thus there comes the need to make these systems more robust, resilient, manageable and reliable in terms of their electric power generation and supply capabilities. One solution to this need is the appropriate design of HES (Hybrid Energy System) [3,4], particularly when connected to the grid and without energy storage. Here the grid acts as the energy back-up source from which the system may draw energy to supply the homes if RES (renewable energy sources) run low.

Likewise, to account for the times when both sun and wind do not allow generating sufficient amount of energy to meet the power demand by each operating alone or together, an alternative is to incorporate diesel generators as a back-up source which can be a good solution for the community. In the particular case analyzed in this paper, the power plant comprised of 6 large diesel generators has nominally enough power supply for the whole community yet the price of electricity paid by consumers is quite high. Therefore the paper envisages the use of such renewable energy systems as affordable and efficient DG (distributed generation) initiatives linked to EE (energy efficiency) which may help to reduce energy consumption costs, increasing the overall efficiency of the hybrid system while at the same time lowering carbon emissions in the area.

In order to make a better, more cost-efficient use of renewable energy sources (RES) such as the wind and sun, an optimal design of the HES is critical as over dimensioning the system may determine high investment costs and other unnecessary drawbacks going forward. On the contrary, under-dimensioning the system may imply lower investment costs, but a higher likelihood of

* Corresponding author. Tel.: +56 2 2354 4272; fax: +56 2 2552 1608.
E-mail address: esauma@ing.puc.cl (E. Sauma).

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operational limitations and hence potential deficiencies in energy consumption, requiring that conventional generators work longer to make up for the lack of additional installed capacity the HES is incapable of supplying in order to counteract this deficiency. Therefore, an optimal design of the system may guarantee lower investment costs with a reasonable, more efficient and complete use of the different energy sources being evaluated [4,5].

Many studies about optimal HES design have been reported in the literature. Borowy and Salameh [6] presented a methodology based on the iterative calculus of the Loss of Power Supply Probability (LPSP) for different combinations of a number of PV panels and batteries in a hybrid solar-wind stand-alone (island mode) power system, using an extensive database of solar radiation and wind speed readings recorded every hour of each day for 30 years, without interruption. However this methodology considers a known and fixed number of wind generators that might not be optimal. Hocaoglu et al. [5], in a study similar to [6], presented a methodology based on the same mathematical approach regarding LPSP, yet the difference they introduced lies in the fact that the number of wind generators is not fixed and predetermined, but may vary and is to be determined. Nafeh [7] proposed a methodology based on the minimization of the Life Cycle Cost (LCC), for a stand-alone PV-wind hybrid energy system, subject to a certain predetermined performance level (measured in terms of LPSP), utilizing GA (genetic algorithm). Likewise, in a different approach to the problem from the ones used by previous authors, Supriya and Siddarthan [8] presented a LP (linear programming) model which aims to minimize the LCC of a PV-wind hybrid energy system connected to the utility grid, subject to the energy balance condition. This model determines the optimal number of solar PV panels and wind generators of the system, aside from the total amount of energy required per year. However, it does not consider the limited size of the electric network or the possibility to be able to sell excess energy in cases when over generation is present. On the other hand, Nelson et al. [9] present an economic evaluation of a hybrid wind/photovoltaic/FC (fuel cell) generation system for a typical home in the Pacific Northwest. The combination of a (fuel cell) FC stack, an electrolyzer and hydrogen storage tanks is used as the energy storage system. The system is compared to a traditional hybrid energy system (HES) with battery storage and authors employ a computer program to size system components in order to match the load of the site in the most cost effective way. A cost of electricity, an overall system cost, and a break-even distance analysis are also calculated for each configuration therein. Their model also considers a battery bank to increase the plant's installed capacity, operating as a back-up system that is ready to dispatch at times of blackouts due to plant's insufficient generating capacity at peak power demand hours or due to equipment malfunction. Nema et al. [10] provide a thorough review of current and future aspects of the state-of-the-art in the design and development of HES using wind and PV-solar showing the myriad of issues that must be accounted for with the various designs and RES hybridization options [10]. Mathiesen et al. [11] show interesting analyses and results of a 100% renewable energy system design for Denmark aimed to be achieved by the year 2050, considering a complete energy system infrastructure based on RES including transport. Two short-term transition target years in the process towards this goal are analyzed for 2015 and 2030 [11] to make the transition smoother and more feasible. The energy systems are analyzed and designed with hour-by-hour energy system analyses, revealing that implementing energy savings, renewable energy and more efficient energy conversion technologies can have very positive socio-economic effects, creating employment and potentially leading to large earnings on exports [11]. Externalities such as positive health effects add even more benefits to the project and build even stronger arguments in favor of a 100% renewable energy systems, which are not only technically possible, but necessary for the future in terms of economic growth and energy independence. The question then is poised by the authors: what consequences might arise as a result of following a path towards a 100% renewable energy system? They conclude based on the analyses that it might even be more economically beneficial compared to the business-as-usual energy system [11]. Similarly, in Ref. [12] authors investigate the prospects of realizing a 100% renewable energy system in Macedonia by making use of the EnergyPLAN model. Analysis was conducted for two renewable scenarios designed for the years 2030 and 2050 [12,13]. First scenario considers realization of 50% renewable energy system, projected for the year 2030. This represents the first step towards a 100% renewable energy future for Macedonia. The second scenario has been designed for the 100% renewable energy system based only on the renewable energy sources (RES) by the year 2050. Authors give special attention to the design of these systems given the intermittent nature of RES and to energy storage technologies. The EnergyPLAN [13] model is the input/output model used for the annual analyses of regional and national energy systems in steps of 1 h [13].

Several authors have presented interesting work on HES design and configuration optimization, employing a variety of methods. Along this line of work, Milan et al. [14] present a cost optimization model for 100% renewable residential energy supply systems with important caveats, referring to higher installation costs compared to conventional systems and the need to account for the variability of the RES. These two caveats require an optimized design of the overall system, for which a new approach is needed which accounts for the interdependencies between the different supply technologies as well as consumption profiles of residents and on-site energy resource availability [14]. Various control strategies optimization have also been analyzed for stand-alone HRES (hybrid renewable energy systems) employing hydrogen storage. Thus, the work of Dufo-López et al. [15] aims to develop a model based on linear programming for the optimal design of 100% renewable supply systems in terms of the overall system costs, citing its successful application in a case study for the so called Net Zero Energy Building in Denmark with three technology options [15]. Another interesting work,by Alberg Østergaard et al. [16], focuses on how low-temperature geothermal heat may be utilized in DH (district heating) systems. Currently biomass resources are used to produce energy yet they are finite, so the two marginal energy resources in Aalborg are geothermal heat and wind power [16]. The analyses shown by authors prove that it is possible to meet Aalborg Municipality's energy needs through the use of locally available energy sources in combination with significant energy efficiency and energy savings of various kinds, along with reductions in industrial fuel use and fuel-substitutions in the transport sector [16]. In Ref. [17] a complete review of computer tools for analyzing the integration of RES into various energy systems is presented; wherein a variety of computer tools are described which can be used to analyze the integration of renewable energy. Thirty seven tools were included in the final analysis which was carried out in collaboration with the tool developers or recommended points of contact [17]. The results in the paper provide the necessary information to identify a suitable energy tool for particular needs warning that there is no energy tool that can address all issues related to integrating renewable energy. The tool to be chosen will depend first on the specific objectives that must be fulfilled [17] plus other important considerations. On a similar line Foley et al. [17] present a strategic review of electricity systems models, focusing on the changing role of electricity systems modeling over the years in a strategic manner. Particular focus is given to modeling responses to key developments, the move away from