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A Methodological Procedure for Sizing Hybrid Renewable Energy Systems in Off-grid Areas

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Abstract

This paper presents a methodological procedure for sizing Hybrid Renewable Energy (HRE) systems in off-grid areas. The HRE system to be analyzed in this paper is composed of photovoltaic plants, diesel plants and batteries, since they are the most common elements used in off-grid areas. The procedure is based on a bibliographic review and the experience of the authors. Firstly, the reviewed sizing methodologies are classified according to the objective function and the technique to be used to solve the optimization problem, also the most relevant aspects are highlighted. Then, the procedure sizing HRE is exhaustively described being presented as an organized methodology. Designers could easily follow the procedure reducing its design time; all main concepts to take into account in the design are described in this procedure.

Keywords*:* Hybrid Renewable Energy (HRE), photovoltaic plants, diesel plants, off-grid areas.

INTRODUCTION

Nowadays the access to electrical energy has become fundamental for the development of any region. Nonetheless, in developing countries there are still many communities without a proper access to this service. There are plenty of reasons that make difficult the electrification of rural areas, however Hybrid Renewable Energy (HRE) systems have become an attractive option to solve these problems and provide with energy rural areas. Among HRE systems, the solar-diesel is often employed because of the abundance of solar resource. Battery banks are also used since the low reliability of photovoltaic energy systems make necessary the storage of energy. In this work, HRE systems based on solar-diesel with batteries are considered which are commonly in off-grid areas.

Several reviews regarding HRE systems and optimization techniques used for their design can be found [1]-[3]. In [1], the authors made a review about different mathematical models proposed to optimize the design of HRE systems in function of economic and reliability aspects. First, the review presents the different models used to simulate HRE systems with and without Diesel Generators (DGs). Then, modeling and optimization techniques are summarized forming three groups: (1) Classical/conventional techniques, (2) Artificial Intelligent Techniques and (3) Hybrid techniques. Classical techniques are analytical in nature and use differential calculus to optimize the energy model. Artificial intelligent techniques use heuristic-based optimization algorithms to address the sizing problem of HRE systems. Examples of these techniques are: knowledge based system; Genetic Algorithms (GAs); Particle Swarm Optimization (PSO); Evolutionary Particle Swarm Optimization (EPSO) and Ant Colony Optimization (ACO), among others. These techniques are the most applied in optimization problems regarding the design of HRE systems.

Another review in [2] divides the sizing methodologies according to the optimization technique used. Methodologies are divided in four groups: (1) Probabilistic, (2) Analytical, (3) Iterative, and (4) Hybrid. Probabilistic Methods optimize one or two system performance indicators in order to size the components of the system; however, they are highly dependent of the data input used. In Analytical Methods, the HRE system is represented by computational models and the best configuration of the system is determined in accordance with one or more performance index indicators. This method does not offer an accurate solution in multi-objective problems. Iterative Methods use a recursive algorithm to reach the best configuration of the system according to the design specifications, being useful for multi-objective optimization. Hybrid methodologies combine two or more methodologies improving the convergence time in the optimization process. In the author's opinion, the iterative and hybrid methodologies are the best suited to solve a multi-objective sizing problem in a hybrid microgrid.

In [3], five optimization techniques for distributed generation systems are presented; these are classified as: (1) Analytical Techniques (2) Classical Optimization Techniques (3) Artificial Intelligent (Meta-heuristic) Techniques (4) Miscellaneous Techniques (5) Other Techniques for Future Use. This review also presents different methodologies according to the objective function. This author concludes that analytical and classical methods are not computationally efficient for large and complex systems. In contrast, meta-heuristic and hybrid methods reach a solution in a more efficiently way, including also conditions of uncertainties in the load profile and the meteorological data commonly found in off-grid areas.

Due to the stochastic nature of the variables associated to a HRE system and the lack of information and technical knowledge on off-grid areas, the design process of these systems could be difficult. For this reason, it is presented an assessment of sizing optimization techniques for HRE systems in off-grid areas. In this research, the authors propose a classification of HRE optimization techniques which are divided in two groups: (1) according to the objective function and, (2) according to the optimization method used.

HRE OPTIMIZATION TECNIQUES ACCORDING TO THE OBJETIVE FUNCTION

In [4], it is proposed a sizing methodology for off-grid PV system in developing countries where traditional sources of energy (ex. Batteries, small diesel generators) are already in use. The methodology introduces the concept of Levelized Cost of Supplied and Lost Energy (LCoSLE) which, in contrast of the traditional Levelized Cost of Energy, includes the Value of Loss of Energy related costs in the equation. The objective in this methodology is to minimize the LCoSLE. In this way, it is possible to optimize economically the sizing of the main component of the photovoltaic system in a rural zone using as input data the load profile of the target location. In the author's opinion, this methodology is more appropriated for sizing in rural areas of developing countries than traditional approaches that use as target the reliability of the system.

In [5], the author analyzes seven configurations using wind, solar and diesel as source of energy for three communities in Colombia. The software tool HOMER is used to perform a techno-economic feasibility of the proposed hybrid systems, taking into account Net Present Cost (NPC), Initial Capital Cost (ICC), and the Levelized Cost of Energy (LCOE) as economic indicators. Three locations are analyzed proving solar-diesel combination as preferred due to the environmental and economic benefits in the long run. Nevertheless, if the capital cost would be considered as the only criteria among the proposed configuration, the diesel based system would be selected as optimal. This methodology is limited by the restrictions imposed by the software HOMER. Also, the result may vary if the reliability of the system is considered on the model.

HRE OPTIMIZATION TECNIQUES ACCORDING TO THE OPTMIZATION METHOD USED

In [6], the author seeks for the optimal solution for electrification in rural areas using a hybrid system. Several renewable energy sources such as wind energy, solar photovoltaic, micro-hydro, also with diesel generator as backup, are considered. The solution yields an optimal combination with unit sizing of each component in the system to minimizing the Annual Operating Cost (AOC). The combination with lowest cost, minimal use of diesel generators and service reliability is selected as optimal. The optimization model is solved by a quasi-Newton algorithm, which is a numerical iterative algorithm with nonlinear constrains. This kind of algorithm could require a large amount of memory and could thus be disadvantageous in the cases of large complicated systems.

In [7], the authors compare the performance of seven evolutionary algorithms for optimum sizing of a PV/ WT/battery hybrid system to continuously satisfy the load demand with the minimal Total Annual Cost (TAC). The evaluated algorithms were: (1) Particle Swarm Optimization (PSO), Tabu Search (TS) and Simulated Annealing (SA), Improved Particle Swarm Optimization (IPSO), Improved Harmony Search (IHS), Improved Harmony Search-based Simulated Annealing (IHSBSA), and Artificial Bee Swarm Optimization (ABSO). The experimental data used in the comparison is from South of Iran, and Matlab software is used to code and execute the heuristic algorithms. As result, the author finds that ABSO yields better results than other algorithms in terms of TAC. Also, it is concluded that PV/Wind/Battery systems are the most cost-effective to supply 100% of the demand. If a Loss of Power Supply Probability (LPSP) of 5% is considered, the PV/Battery systems are the most effective system.

In [8], the authors show an optimal sizing methodology using a Multi-Objective Genetic Algorithm (MOGA) to guarantee a reliable energy supply, minimizing non served demand with lowest investment and minimizing TAC. The model is evaluated with and without uncertainties of the demand and meteorological data. These uncertainties are resolved using a Monte Carlo (MC) Technique. The analysis shows that these uncertainties affects significantly the value of investment. The results are showed using a Pareto Front in which a tradeoff between reliability and investment can be observed. The development performed in [8] is similar to the objective of our proposal; nonetheless, the economic model may vary in order to consider other variables as the government incentives and the optimization algorithm used to solve the problem could change with the intention of find more efficiently a solution for the problem.

A recent example of a hybrid optimization method is showed in [9]. A hybrid evolutionary method is used to determine the optimal number of modules, wind turbines and batteries for a specific region in Iran, minimizing the TAC of the system. This methodology uses a PSO algorithm combined with a MC technique to reach the solution. This methodology proves to be useful in areas where the meteorological and demand data is scarce.

In the last decade, it was shown that a numerous amount of optimization techniques has been used to obtain an optimal solution of the sizing of HRE systems. The results among the different approaches may vary depending on the characteristics of the model employed to simulate the behavior of the different elements of the system and the economic and reliability model used as base on the optimization process. In Table 1 the techniques for sizing HRE systems, according to the optimization method employed, are summarized.

Table 1. Summary of sizing methodologies in HRE systems.

#	Ref	Optimization Method	Parameter to optimize	Criteria	Observations
1	[4]	Numerical Method – Matlab	LCoSLE	Economic Reliability	It is used to optimize the sizing of the main components of the photovoltaic system in a rural zone using as input data the load profile of the target location.
2	[5]	HOMER	NPC ICC LCOE	Economic Environmental	Solar-diesel combination are preferred due to the environmental and economic benefits in the long run in three areas of Colombia. It is limited by the restrictions imposed by the software HOMER.
3	[6]	Analytical - Quasi-Newton algorithm	AOC	Economic Reliability	This algorithm requires a large amount of memory; thus it is disadvantageous for large system.
4	[7]	PSO ABSO TS IHSBSA SA HIS IPSO	TAC	Economic Reliability	ABSO yields better results than other algorithms in terms of TAC.
5	[8]	MOGA MC	TAC DNM	Economic Reliability	Uncertainties affects significantly the value of investment. Economic incentives provided by government are not considered.
6	[9]	PSO MC	TAC	Economic	Useful in areas where the meteorological and demand data are scarce.

METHODOLOGICAL PROCEDURE PROPOSED FOR SIZING HRE SYSTEMS

This section describes a methodological procedure proposed for the optimal sizing of HRE systems, that includes a sequence of five steps.

Step 1: Gather information on solar resource and temperature, costs of system elements (solar, diesel and batteries), average installation costs and energy demand in off-grid areas. For executing step 1, the following four activities should be carried out:

1) Build a model to generate a long-year hour resolution array of global irradiance over an arbitrary inclined surface from the daily average monthly global horizontal irradiation and the geographical location.
2) Estimate the load profile of the selected locations.
3) Build a table with the price of each element on the HRE System. Each element of the system based on Solar/diesel/battery should be described. The information should be collected from local distributors.
4) Estimate the installation and maintenance cost in an off-grid area. For this, renewable energies installations companies in each country should be consulted to obtain an average installation cost for HRE systems.

Step 2: Develop energy production models of diesel and photovoltaic systems, considering a system of power storage through a battery bank. For executing step 2, the following five activities should be carried out:

1) Describe the mathematical model of a photovoltaic system with battery backup.
2) Describe the mathematical model of diesel plant. In the same way, the equations and constrains that describe the production of energy should be described.
3) Describe the mathematical model of a Diesel/photovoltaic hybrid system without battery backup. Also describe the equations and constrains to be considered.
4) Describe the mathematical model of a diesel/photovoltaic hybrid system with battery backup. The equations and constrains to be considered in this scenario should also be described.
5) Describe the energy dispatch strategies used on HRE systems.

Step 3: Build a model that allows assessment of implementation, operation and maintenance costs of the system, considering the individual costs of each technology. For executing step 3, the following three activities should be carried out:

1) Describe the equations of the economic model of a photovoltaic system with battery backup for an off-

grid area. These equations should be obtained in function of the price of each element, installation and maintenance cost gathered on step one. Among the indicator to be considered on the model will be the LCOE and the Annualized cost of the system (ACS).

2) Describe the equations of the economic model of a Diesel generation system for an off-grid area. Installation and maintenance cost as well replacement costs should be considered.

3) Describe the equations of the economic model of a HRE system based on photovoltaic/diesel with battery storage in an off-grid area.

Step 4: Develop a mathematical model of multi-objective optimization for sizing hybrid power generation systems (solar-diesel) with batteries in off-grid areas. For executing step 4, the following five activities should be carried out:

1) Select a multi-objective optimization technique to maximize economic benefits and reliability.

2) Set the objective functions, parameters and constraints according the results on step 2 and 3 for a HRE system.

3) Develop an algorithm to find an optimal solution for the optimization problem.

4) Write the programming code and run the algorithm. The results must indicate the number of solar modules, batteries, diesel plants for each location, together with the economic and reliability indicators associated to the solution.

5) Analyze the results obtained for the location selected.

Step 5: Validate the applied methodology comparing the results obtained with those yielded by other computational design tools for hybrid power generation systems. For executing step 5, the following three activities should be carried out:

1) Select computational design tools for hybrid power generation systems to run the problem.

2) Use the data gather in step 1 as input for the selected tool and run the analysis.

3) Describe and compare the results obtained.

Figure 1 summarizes the methodological procedure proposed.

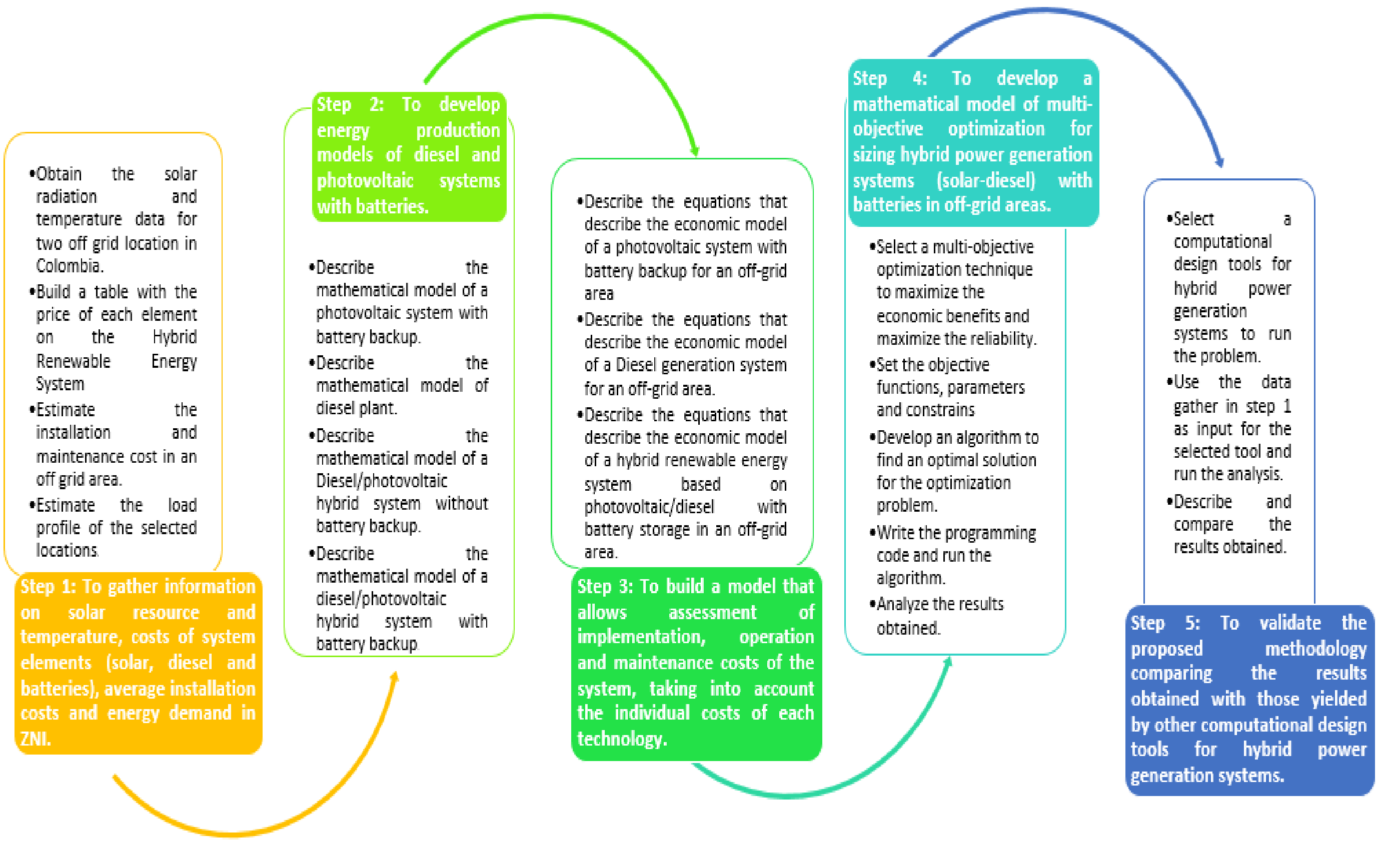

Figure 1. Proposed methodological procedure

CONCLUSIONS

This paper proposed a methodological procedure for sizing HRE systems which are composed of photovoltaic and diesel plants and also batteries. Optimization techniques were classified according to the objective function and the optimization method to be used, so designers can easily choose an option according to their necessities. Then, a methodological procedure was described in five steps with a series of activities within each step. Step 1 consists on gathering information about solar resource, temperature, costs of system elements (solar, diesel and batteries), average installation costs and energy demand in off-grid areas. Step 2 consists on developing energy production models of diesel and photovoltaic systems, considering a system of power storage through a battery bank. Step 3 consists on building a model that allows assessment of implementation, operation and maintenance costs of the system. Step 4 consists on to developing a mathematical model of multi-objective optimization for sizing hybrid power generation systems (solar-diesel) with batteries in off-grid areas. Step 5 consists on validating the proposed methodology comparing the results obtained with those yielded by other computational design tools for hybrid power generation systems.

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