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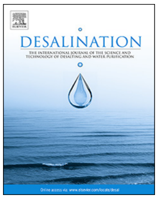

Sizing methodology based on design of experiments for freshwater and electricity production from multi-source renewable energy systems

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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

In remote areas, the vital need is production of drinking water and the provision of electrical energy for housing. Often the only sources of energy are based on renewable energies with storage to create a local micro-network. This paper investigates the optimal design of embodied energy for water treatment by reverse osmosis, coming from brackish water (6 g/l) and with a double storage that is done in a drinking water tank and in batteries for electricity. Taking account wind and photovoltaic potentials in such system for assessing its performance implies its simulation over long periods of time. This can drastically increase the CPU time cost related to the design step, especially if the system energy management and sizing are sequentially optimized into a two-level optimization process. In order to solve this problem and accelerate the system simulation, meta-models are used for representing the system constraints and objectives. These meta-models are built by the design of experiments method. From realistic data, the results of this paper show that the contribution of the meta-models divides by two or three the design time by obtaining values of the sizing parameters close to the dynamic simulator depicting the real operation of the whole system.

1. Introduction

Around the world, large-scale development of renewable energy technologies is giving new opportunities to regions that lack fresh water and electricity. Even regions rich in fossil energy are beginning to worry about energy efficiency, long-term sustainability and environmental friendliness [1]. Today, many papers deal with systems for generating electrical energy from renewable energies: development of structures and their optimal sizing based on environmental and/or economical considerations [2,3]. In this regard, it is necessary to select and configure the optimal life cycle calibration of all hybrid renewable energy systems to operate at minimum economic and energy costs (embodied energy) while maintaining reliability of the system. From electrical energy, often the reverse osmosis process is used, because the need is to supply booster pumps and to fill tanks [4,5]. But intermittent renewable sources require the establishment of storage elements and/or mixing several sources. Many papers have already been published in this context. A study in Australia shows, when the distribution network is present, adding a wind turbine, PV and not using batteries reduces the financial cost of water production [6]. Another in Iran, on a remote site not really favorable for the wind turbine, shows that it is more profitable to use only PV with batteries [7]. Thus, the context of the site is a very important factor in the choice of the structure of the freshwater production system.

Regarding the design, sizing and optimization of the power systems based on renewable energy sources, several approaches are proposed using different indicators and configurations. For hybrid wind-solar power systems, linear programming techniques [8,9], pattern search based on SMCS (Sequential Monte Carlo Simulation) [10], particle swarm optimization algorithm [11], bees algorithm [12] have been applied under economic and technical indicators. An optimal sizing using a linear programming of photovoltaic power plants based on the optimal participation in electricity markets has been developed in Ref. [13]. In Ref. [14], a method employs the genetic algorithm to reduce the total cost of an offshore wind farm by optimizing its architectural design. A recent paper compares several optimization approaches for reverse osmosis water desalination system with solar and wind hybrid energy [15]. A robust solution method proposed in Ref. [16] used DIgSILENT Power Factory software for optimally coordinating a mix of distributed energy resources in the presence of high wind penetration to

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Nomenclature

β	coefficient of the temperature of the PV cells (%)
Δt	sampling step (h)
η_r	polycrystalline solar PV efficiency (%)
η_{Cou}	Coulomb efficiency for charge-discharge (%)
η_{pc}	aging factor (%)
η_{sc}, η_g	static converter efficiency, generator efficiency (%)
ρ	air density (kg/m^3)
A_{WT}	wind turbine swept area (m^2)
C_n	nominal battery capacity (Ah)
$C_{p,opt}$	optimal wind turbine power coefficient (%)
CMD	RO size (cubic meters per day)
EE	embodied energy (MJ)
EE_{BAT}	battery embodied energy (MJ)
EE_{MP}	motor-pumps 1 and 2 embodied energy (MJ)
EE_{OI}	RO embodied energy (MJ)
EE_{PV}	PV embodied energy (MJ)
EE_{ST}	tanks 1 and 2 embodied energy (MJ)
EE_{WT}	wind turbine embodied energy (MJ)
I_{Bat}	battery current (A)
L_1, L_2	tank 1, tank 2 water level (m)
L_{2u}	intermediate water level in tank 2 (m)
$LPSP_E$	Loss of electric Power Supply Probability (%)
$LPSP_H$	Loss of hydraulic Power Supply Probability (%)
$\min(L_1) > 0$	minimum level in tank 1 (m)
$NOCT$	nominal operating cell temperature (°C)
P_1, P_2	motor-pumps 1, 2 electric power (W)
P_r	pump 1 pressure (bar)
P_{Bat}	battery power (W)
$P_{CV\ 1}$, $P_{CV\ 2}$	converter power of motor-pumps 1 and 2 (V.A)
P_{Diff}	$= P_{PV} + P_{WT} - P_{load-elec}$ (W)
$P_{load-elec}$	electric power consumed (W)
P_{PV}	optimal photovoltaic generator power (W)
P_{WT}	wind turbine power (W)
Q_1, Q_2	motor-pumps 1, 2 flow rate (m^3/h)
Q_{2p}	freshwater flow rate (m^3/h)
Q_{2r}	concentrate flow rate (m^3/h)
$Q_{load-hydrau}$	water consumed (m^3/h)
R_r	recovery rate (%)
S_1, S_2	tank 1, tank 2 surface area (m^2)
SOC	state of charge (%)
SOC_u	intermediate state of charge (%)
T_a	ambient temperature (°C)
T_c	temperature of the PV cells (°C)
V_{Bat}	voltage battery (V)
V_{wind}	wind speed (m/s)
DOE	design of experiments
PV	photovoltaic panel
RO	reverse osmosis membrane
WT	wind turbine

simultaneously minimize operating costs and maximize the utilization of wind turbine generation.

Many sizing optimization publications optimize life cycle cost [1-7,9-13] and take into account weather conditions (wind speed, solar radiation and temperature) for one year [5-7,12,17,18]. In this paper, modeling is done on the amount of embodied energy (*EE*) for the life cycle of each element of the system, from meteorological records (wind speed, solar radiation, and temperature) over a year and for isolated sites. Sizing optimization is always done using optimization algorithms that require a high CPU time for the implementation of the optimization algorithms that depends on the modeling used to represent the operation of the system. Some authors use a dynamic simulator including the physical equations of each element, weather data and load equations. The resolution is done with a computing step of several minutes or hours. Thus, one year data resolution represents several thousand computation loops for one parameter vector. So, global optimization can take a CPU time of several days if the system is a bit complex. The goal of this paper is to propose a new modeling based on meta-models that replaces the dynamic simulator with an equation vector that links the outputs with the parameter vector in the optimization process. The quality of the meta-models becomes a crucial point for the quality of the results and it is also important to minimize the time to establish these meta-models. Early experiments have shown that the Design Of Experiments (DOE) approach can give good results. The application of the DOE method in several areas has been discussed by many authors [19,20], but only a very few attempts have been made to integrate the DOE in systemic design. In a recent study, a modeling approach is presented by Ref. [17] to size an autonomous multi-source system with battery storage and a diesel generator. It is also used in Ref. [21] for a photovoltaic/wind/Battery energy system with storage to investigate a meta-model by hybrid spline interpolation. This study contributes to integrate a sizing methodology with DOE to optimize a freshwater and electricity production by multi-source renewable energy systems located in remote areas.

This paper gathers the papers already made in this area by the same authors by presenting the complete study with the results obtained and which integrates a new modeling of the reverse osmosis unit with its motor pump for a salinity of the water: 6 g/l (brackish water from southern Tunisia (see Appendix A)). This last model uses only one parameter, which is the cubic meter per day (CMD), to limit the number of parameters in order to reduce the complexity of the system. The paper is organized as follows: after the Introduction, Section 2 describes the system with its modeling, presents the methodology to realize the optimization by implementing a dynamic simulator or meta-models. Section 3 shows the results and discusses the results obtained. The paper ends with a conclusion, one appendix and the bibliographic references.

2. Description and methodology

2.1. System description

2.1.1. Architecture

The electricity acquired from photovoltaic panels (PV) wind turbines (WT) will be used to feed the motor-pumps of a hydraulic process (water pumping and reverse osmosis desalination unit) and other electrical house loads. The system has two types of storage: battery energy storage and hydraulic storage in water tanks (brackish water storage and freshwater storage). The global architecture of the system, shown in Fig. 1, corresponds to the application described for the isolated areas. The different subsystems are coupled to the DC bus with different converters (DC/DC, AC/DC or DC/AC).

The hydraulic loads are composed of a first motor-pump 1 used to pump brackish water from well and to store it in a first tank and a second motor-pump supplied by the brackish water (6 g/l (see Appendix A)) to the Reverse Osmosis (RO) desalination unit to produce freshwater. This freshwater is stored in a second tank without pumping.

2.1.2. Power and water flow models

This part is devoted to the power and water flow models of the investigated system. In the context of optimizing the size of the system, it is important to specify all energy models with significant expressions to reduce the running time of the optimization program. For all renewable energy generator, the maximum power is taken account in the