Energy Conversion and Management 177 (2018) 161–175

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Economic and ecological optimization of multi-source systems under the variability in the cost of fuel

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ARTICLE INFO

Keywords:
Stand-alone multi-source systems
Renewable energy
Diesel generator
Design of experiments
Meta-models
Multi-objective optimization
Single-objective optimization
Embodied energy
Lifecycle cost

ABSTRACT

Multi-Source Systems combining renewable energy sources with diesel generators have been widely adopted in isolated sites. The economic and ecological aspects are very important for analyzing and evaluating such systems. In this paper, an optimization approach that includes the former aspects has been proposed. This approach takes into account the changes in the fuel cost over a lifecycle and the minimization of the greenhouse gas emission. The proposed method is based on three main steps. At first, a fuel cost progression model over a period of 40 years has been developed. Second, due to the complexity of such systems and in order to simplify the modeling, meta-models have been extracted by using the Design of Experiments technique. Finally, Single-Objective and Multi-Objective Optimization of the system based on economic and ecological criteria have been performed. The obtained results show that, changes in fuel costs have a significant influence on the sizing of the system. Indeed, the increase in fuel cost can lead to an increase of 18% in the design cost. The best solution on Pareto's curve was found with a reduction rate in the fuel consumption between 30 and 35%. Furthermore, the optimization algorithm favors the introduction of renewable sources.

1. Introduction

Recently, electrification using Multi-Source Systems (MSS) has been widely exploited in various areas. Multi-Source Systems used in remote or connected areas are generally based on hybrid renewable systems. An adequate design of a Multi-Source System needs an in-depth study about the energy sources availability in site. So, the nature of energy sources in sites imposes possible hybrid electrification solutions. The stand-alone configurations which are based on a single renewable energy source such as solar (PV), or wind source (WT) without storage systems can be inefficient, inoperable, or prohibitively expensive. The challenges of single-technology systems can be remedied by hybridization between renewable energy systems and Systems of Storage (SS) such as batteries, or Hybrid Storage Systems (HSS) like a battery/super-capacitor configuration.

In recent years, the study of Multi-Source System configurations and their optimization have been treated as an interesting subject by a large number of researchers. The optimization represents an important tool to optimize the design and the operating costs of microgrids installed in isolated or connected areas. In general, the cost of the hybrid Multi-Source Systems can depend on different factors. Among them: the electricity demand, climatic characteristics of regions, installation and maintenance costs of energy sources, cost of storage systems, and other costs. The minimization of these costs needs new configurations between generators and/or storage systems.

In [1], a hybrid storage system combining batteries with super-capacitors have been proposed for an isolated renewable system. The authors demonstrated that, the association of super-capacitors with classical batteries under better management is a good structure for improving the lifetime of the battery bank, the performances, and minimization of the global cost of microgrid.

Others configurations of an autonomous systems have been used to provide electricity from different kinds of sources. The optimization of a new stand-alone configuration combining heating and power systems with a battery of storage was realized in [2]. The proposed configuration was used to satisfy an electrical and thermal load simultaneously.

In [3], a techno-economic optimization of a stand-alone system in an isolated area composed of a solar generator and a wind generator connected to a storage battery (PV/WT/Battery) has been realized. The authors have used the HOMER Software to optimize the system. The sizing optimization of the same stand-alone system has been presented, taking into account socio-demographic factors as new parameters in the

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https://doi.org/10.1016/j.enconman.2018.09.056
Received 23 March 2018; Received in revised form 13 September 2018; Accepted 16 September 2018

Nomenclature

AC_j	acquisition cost of component *j*
A_{pv}	photovoltaic panel area (m^2)
A_{wt}	wind turbine swept area (m^2)
Bat	battery bank
C_{Bat}	cost of battery bank (€)
CC	capital Cost (€)
C_{DG}	cost of diesel generator (€)
C_{FuelDG}	fuel cost (€)
C_n^{Bat}	battery bank capacity (Ah)
C_{pv}	cost of *PV* generator (€)
C_{wt}	cost of *WT* generator (€)
DG	diesel generator
DOE	design of experiments
DS	dynamic simulator
EE	embodied energy (MJ)
EE_{Bat}	embodied energy of battery bank (MJ)
EE_{DG}	embodied energy of DG (MJ)
EE_{pv}	embodied energy of PV generator (MJ)
EE_{wt}	embodied energy of WT generator (MJ)
E_{Gen}	energy provided by the energy sources (W)
E_{Load}	energy consumed by the load (W)
$Fuel_{DG}$	fuel consumed by DG (l/h)
I_r	irradiation (W/m^2)
j_g	the general annual expected inflation rate (%)
j_r	the annual interest rate (%)
l_f	lifetime of project (year)
LPSP	loss power supply probability (%)
MOGA	multi-objective genetic algorithm
MOO	multi-objective optimization
MOOP	multi-objective optimization problem
MSS	multi-source system
N	number of experiments (number)
$N_{Bat,s}$	number of batteries connected in series
NBIA	normal-boundary intersection algorithm
NPC	net present cost
OMC_j	operation & maintenance costs of component *j*
OT_{DG}	operating period of DG (h)
p	percentage change in fuel price per fifteen years (%)
P_{DG}	power provided by the DG (kW)
$P_G(t)$	total power delivered by all the generators (kW)
P_{Load}	electrical load profile (kW)
P_{NDG}	nominal power provided the by DG (kW)
P_{pv}	power provided by the solar generator (W)
PV	solar generator
P_{wt}	power provided by the wind generator (W)
R^2	quadratic factor (≥ 0 *and* ≤ 1)
R_a	rate of aging of battery bank (%/year)
RC_j	replacement cost of component *j* during the lifetime
SN_{DG}	number of diesel generator starts (number)
$SOCd_{Max}$	control threshold of DG (%)
SOO	single-objective optimization
SOOP	single-objective optimization problem
SS	storage system
SSE	error sum of squares
SSR	regression sum of squares
SST	total sum of squares
T_a	ambient temperature (°C)
T_G	global time of simulation (s)
T_{op}	time of optimization (s)
V_{bus}	the DC bus voltage
WG	wind generator
W_s	the wind speed (m/s)
$\bar{y}$	mean value of y_i for $N\psi$ experiments
y_i	individual response at experience *i*
$\hat{y}_i$	predicted response of the experience *i*
Δt	the sampling step
η_{Ba}	the charge-discharge efficiency of the battery
$\eta_{dcdc}, \eta_{dcac}, \eta_{acdc}$:	the efficiency of the converters
η_{pv}, η_{wg}	efficiency of PV generator and *WT* generator
ρ	the air density (kg/m^3)

dimensioning [4]. Performance analysis and dimensioning of MSS (PV/WT/Battery) in residential microgrids has been done in Ref. [5].

In the previous researches, the authors demonstrated that, the hybrid configurations are adequate solutions to minimize the disadvantages of single configurations. These solutions are ecologically clean, but sometimes in some cases become expensive, due to the significant aging of the battery banks during deep charge-discharge cycles at high temperatures. So, optimizing the cost of these configurations requires modeling the lifetime of the storage bank. Additionally, in some remote areas, the potential of renewable resources is poor and less profitable.

Furthermore, to improve the permanence of electrification by using stand-alone systems and minimizing the design cost, other solutions can be suggested. Among these solutions, is the hybridization between renewable, fossil energy sources, and storage systems such as (PV/DG/SS), (WT/DG/SS) and (PV/WT/DG/SS). A review of hybrid renewable energy systems and a comparison between different configurations in terms of costs and performances has been presented in [6]. In [7], a review study about stand-alone systems, a comparison between their configuration and the different sizing methods used have been presented. Therefore, several kinds of software used for dimensioning the stand-alone systems in general have been given. In [8], the authors have suggested a new scheduling algorithm for a remote microgrid. The operating cost of the power system minimization (PV/WT/DG-Batteries) was performed by increasing the lifetime of the battery bank and, reducing the consumption of fuel.

Ref. [9], among the first works which concern the integration of the diesel generator in microgrid systems with renewable sources in remote areas. So, the authors have developed more configurations of electrification comprising a diesel generator (PV/DG/SS). These configurations were practically used in Western Australia. In addition, a performance analysis about the feasibility of a diesel generator was also considered.

In many countries of the world, the majority of Multi-Source Systems in isolated regions use diesel generators as a second source of energy. In Bangladesh for example, forty percent of the population is not covered by the public electricity of the country. Instead, these underserved populations use a solar generator and a diesel generator as a backup source, and electrochemical batteries for storage (PV/DG/Batteries) [10]. In [11], the same system was developed in Malaysia to supply an isolated place. The study demonstrated that the economic performances of the system are very high. In Alaska, hybrid systems PV/Diesel increased in use dramatically in isolated areas following a survey performed by [12].

A techno-economic analysis of hybrid systems used to supply isolated residential areas in Urumqi, China has been developed [13]. The hybrid systems studied and analyzed are two PV/DG/battery and PV/Battery. The authors demonstrated that the hybrid power system (PV/DG/battery) was a more economical solution, where the diesel power system was very expensive in Urumqi. However, in terms of greenhouse gas emissions the hybrid power system without a diesel generator is considered cleaner.

In [14], the authors developed a hybrid electrification system to supply an isolated area located in Malaysia. The same configuration has