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Influence of actual component characteristics on the optimal energy mix of a photovoltaic-wind-diesel hybrid system for a remote off-grid application

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ABSTRACT

Hybrid energy systems are an interesting solution for the electrification of remote, off-grid users, which usually are obligated to satisfy their electricity demand by means of quite old technologies, like for example diesel generators. An energy mix including also renewable energy sources (such as wind and PV) would lead to a reduction of supply costs and is therefore being increasingly appreciated.

In the present study, a sizing strategy was developed based on a long-term energy production cost analysis, able to predict the optimum configuration of a hybrid PV-wind-diesel stand-alone system. With respect to conventional practical design approaches already available in the literature, a more realistic description of the problem was here provided, since the present analysis relies in the use of actual machines data, realistic system constraints and cost functions, which led to the identification of some trends that are usually neglected by the optimization processes using continuous variables for the power outputs of renewable energy sources.

The approach was tested on an isolated mountain chalet in Italian Alps. The hybrid system was optimized based on the maximum long-term saving with respect to a conventional diesel engine configuration. The results for this case study showed that the optimal solution was not that including the maximum allowed contribution from renewables, highlighting the existence of an optimized energy mix between the three sources. Accumulation batteries were also able to induce a reduction of both the fuel consumption and the engine transitory usage. According to the present results, a properly sized hybrid system could provide notable money and pollution savings for a remote consumer with respect to a diesel-only configuration.

1. Introduction

Renewable energy deployment in off-grid systems is continuously growing both in developed and developing countries. According to (International Renewable Energy Agency (IRENA), 2015), 1.16 billion people globally still have no access to the electricity grid. About 95% of these people live in the sub-Saharan Africa and South and East Asia, with the remainder spread almost equally across Middle East, Central Asia and South America (Bloomberg New Energy Finance, 2016). In spite of the average technological level, however, in 2009 there was still also a small part (about 0.5 million people) of the EU residents who had not direct access to a local utility network (Wind energy, 2009).

Even in case of developed countries there are areas where the it is not possible to be connected to the grid due to local electrical network scarcity in the area (e.g. remote areas) or due to the prohibitively high connection cost (e.g. 8000–11,000 €/km (Kaldellis, 2002)). Consequently, experiences of planned global rural electrification programs can be found in several countries (Narula and Bhattacharyya, 2017; Chowdhury et al., 2015), many of which include hybrid systems (e.g (Shezan et al., 2016)) integrating fossil fuels and renewable energies, managed following smart-grid approaches (Bigerna et al., 2016; Cardenas et al., 2014). In particular,

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Nomenclature

A	Total Area of Photovoltaic Panels [m^2]
A_{PV_S}	Area of a Single Photovoltaic Panel [m^2]
b	Parameter for the Electronic Devices Cost
c_f	Initial Oil Price [€]
CN	Long Term Cost [€]
E	Energy [kWh]
e_f	Oil Price Annual Escalation Rate
FC_n	Fixed Maintenance and Operation Cost [€]
G	Irradiance [W/m^2]
g_m	Annual Inflation Rate
GPS	Global Positioning System
h	Hours of Functioning [h]
i	Return on Investment Index
IC	Installation Cost [€]
$life$	Lifetime [h]
LTS	Long Term Savings [€]
m	Fixed O&M Costs Expressed as a Fraction of Initial Capital
M_f	Annual Fuel Consumption [l]
N_{PV}	Number of Photovoltaic Panels
PA	Pinch Analysis
PV	Photovoltaic Panels
P	Power [W]
P_{PVnom}	Power of Photovoltaic Panels [W]
P_{PV_S}	Nominal Power of a Single Photovoltaic Panel [W]
P_{Wnom}	Power of the Wind Turbine [W]
Q	Capacity of the Battery Bank [Ah]
T_m	Temperature of the Photovoltaic Panel [K]
VC_n	Variable Maintenance and Operation Cost [€]

Greek letters

α	Specific Installation Cost of PV Panels [€/kW]
γ	Specific Installation Cost of the Diesel Generator [€/kW]
ΔP	Power Lack/Surplus [W]
η_{nom}	Nominal Efficiency of Photovoltaic Panels
η_{rel}	Relative Efficiency of Photovoltaic Panels
λ	Parameter for the Electronic Devices Cost
ξ	Parameter for the Battery Bank Cost
τ	Parameter for the Electronic Devices Cost
ω	Parameter for the Battery Bank Cost

Subscripts

0	Initial Investment
BAT	Battery
DG	Diesel Generator
ELEC	Electronic Components
max	Maximum
min	Minimum
nom	Nominal
PV	Photovoltaic Panel
REN	Renewables
USER	User

the larger and larger penetration of distributed renewable energy sources in micro-grids is leading the research to develop new and more refined strategies for a correct management of the power coming from renewables, especially focusing on forecasting models, demand response programs, accumulation systems and power routing models (Boroojeni et al., 2016a, 2016b; Hadi Amini et al., 2017; Hadi Amini et al., 2013).

On the other hand, in many developing countries the population growth is far outpacing the extension of the grid. According to (International Energy Agency, 2014), the number of people living off the grid has grown by 114 million people on the African continent since 2000, with the absolute number that will continue to grow in the next decade. Off-grid renewable energy systems are then not only urgently needed to connect this vast number of people with a source of electricity, but also most appropriate to geographical constraints and cost for grid extension in many applications. At the same time, with declining cost and increasing performance for small hydro installations, solar photovoltaics (PV) and wind turbines, as well as declining costs and technological improvements in electricity storage and control systems, off-grid renewable energy systems could become an important growth market for the future deployment of renewables themselves. As discussed in (International Renewable Energy Agency (IRENA), 2015), in the short-to medium-term, the market for off-grid renewable energy systems is expected to increase through the hybridization of existing diesel grids with wind, solar PV, biomass gasification and small hydropower, especially on islands and in rural areas. Furthermore, renewables in combination with batteries allow stand-alone operations and batteries are now a standard component of solar PV lighting systems and solar home systems (e.g (Li and Yu, 2016; Hemmati, 2017)). To this purpose, increasing interest is being paid by researchers and industrial manufacturers in further analyzing and optimizing these systems.

The motivation of the present study is to contribute to the development of robust techniques for a further development of design strategies for off-grid hybrid systems including renewables, batteries for energy storage and fossil-fuel generators. In particular, as will be shown later on, the purpose of the study is to show the impact on the best design trends of the real characteristics of the selected components.

By looking first at the relevant technical literature on the general topic of sizing and management of micro-grids and/or off-grid hybrid systems, it is apparent that it is extremely vast. Among others, a great impulse to the study of hybrid renewable energy systems was given by the team of Prof. J.K. Kaldellis of TEI of Piraeus (Greece), who established a robust approach for the energy mix selection in small grids like those of Greek islands (Kaldellis et al., 2009a, 2012), as a function of many parameters like, for example, long term wind data (Kaldellis, 2002), wind potential classes (Kaldellis and Vlachos, 2006) or minimum long-term electricity production cost (Kaldellis et al., 2006).

Based on their experience, similar approaches have been replicated in the recent past by many researchers into different environments (e.g (Chua et al., 2014; Bekele and Tadesse, 2012; Ismail et al., 2013a; Omer et al., 2015; Proietti et al., 2015)). The use of proper mixes of renewable energy sources also has some very interesting prospects in even smaller applications, i.e. in satisfying the energy demand of remote buildings (Baghdadi et al., 2015) or residential complexes located in particular environments (Ismail et al., 2013b), far from the local electricity grid (Luo et al., 2014).

As correctly noticed by (Hemmati, 2017), from mathematical perspective, the sizing of a general hybrid energy system is “a constrained optimization problem that aims at minimizing an objective function subject to a set of constraints”. A first key element is then to identify the objective function to be optimized.