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Multi-objective optimization of batteries and hydrogen storage technologies for remote photovoltaic systems

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A B S T R A C T

Stand-alone photovoltaic (PV) systems comprise one of the promising electrification solutions to cover the demand of remote consumers, especially when it is coupled with a storage solution that would both increase the productivity of power plants and reduce the areas dedicated to energy production.

This paper presents a multi-objective design of weakly connected systems simultaneously minimizing the total levelized cost and the connection to the grid, while fulfilling a constraint of consumer satisfaction.

For this task, a multi-objective code based on particle swarm optimization has been used to find the best combination of different energy devices. Both short and mid terms based on forecasts assumptions have been investigated.

An application for the site of *La Nouvelle* in the French overseas island of *La Réunion* is proposed. It points up a strong cost advantage by using lead-acid (Pb-A) batteries in the short term and a mitigated solution for the mid term between Pb-A batteries and Gaseous hydrogen (GH2). These choices depend on the cost, the occupied area and the local pollution and, of course, legislation.

1. Introduction

Nowadays, how to satisfy the energy demand is a sensitive topic in the world, especially in island regions. In parallel, it is also necessary to limit fossil fuels consumption for both sustainability and energy self-sufficiency issues. Therefore, in the context of global warming, the development of intermittent renewable energy such as photovoltaic (PV) could partly respond to the long term prospects of an increasing energy demand. Such systems would be especially adapted when coupled with a storage solution that would both increase the productivity of power plants and reduce the areas dedicated to energy production. Thus, the European Commission has set a goal of 22% of electricity production from renewable energies in 2010 for the whole electricity consumption in Europe [1]. Likewise, in the particular case of the French island *La Réunion*, the PRERURE [2] plans an electrical autonomy in 2025.

To adhere to the above principles and improve the life-quality of several remote consumers, we would consider the implementation of autonomous renewable energy based stand-alone systems which would be able to increase the security of supply levels through distributed generation [3,4]. Towards this direction, PV driven stand-alone systems, such as PV-Battery configurations, suggest an off-the-shelf energy solution with a broad field of applications and a considerable research background [5–7]. Other storage like hydrogen (H2) have also been studied, but in a lesser extent [8].

The objective of the present paper is to study the technical and economic relevance of PV-Battery-H2 configurations to meet the energy needs identified for the short term (2012) and the medium term (2020). These evaluations are applied on a realistic case of a remote village called *La Nouvelle*, located in the cirque of *Mafate* in the island of *La Réunion*. This village is not connected to the electricity network by a transmission line and will probably never be connected to (or at least not shortly). However, the possibility of connecting this site to the grid is considered. The idea is to evaluate if such a connection could have a real value, keeping in mind that it is a considerable investment, particularly in this hilly place. The grid is represented by an infinite source and sink for energy, only limited by the transmission link. Thus, the minimization of both the cost and the areas dedicated to the electricity production and storage can be carried out.

Two kinds of batteries are simulated: lead-acid (Pb-A) and nickel–cadmium (Ni–Cd) batteries. For H2 storage, only gaseous storage at 200 bar is considered. The choice of gaseous hydrogen

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Nomenclature

A_ω	dimensional parameter for the charge efficiency
B_ω	dimensional parameter for the charge efficiency
c	indices of charge for a battery
$C_{bat,N}$	nominal capacity of the battery (A h)
C_i	cost of investment (€)
C_o	cost of overheads and maintenance (€/year)
d	indices of discharge for a battery
dod	depth of discharge of the battery (%)
G	coefficient which characterize $\Delta u = f(q_{bat})$
GH2	gaseous hydrogen
i	current (A)
ig	gassing current (A)
MOMuS	Modelling and Optimization of Multi-objective Storage code
$NOCT$	Nominal Operating Cell Temperature
Ni–Cd	nickel–cadmium
P	energy produced (W)
P^0_{max}	standard peak power of a module (W)
Pb-A	lead-acid
PEMFC	proton exchange membrane fuel cell
P_{PV}	electrical production of a PV panel (W)
PV	photovoltaic
q_{bat}	battery state of charge (A h)
q_{exc}	quantity of energy given or extracted from the battery (A h)
Qs	self-discharge of the battery (A h)
q_{self}	quantity of energy lost by the self-discharge of the battery (A h)
R_{int}	internal resistance of a battery (Ω)
S_{max}	maximum power of connection to the grid (W)
soc	state of charge of the battery (%)
t	integer that represents the year considered
TC	total levelized cost (€/kWh)
T_c	temperature of the cell (°C)
T_{Cref}	temperature of the cell in standard conditions (°C)
T_e	time of exploitation (year)
T_{ext}	outside temperature (°C)
T_i	time of investment (year)
u	voltage (V)
U_{co}	battery output voltage (V)

Greek letters

ξ	solar irradiance (W/m^2)
ξ_{ref}	solar irradiance in standard conditions (W/m^2)
$\mu_{P_{max}}$	temperature coefficient
τ	rate of discount (%)
χ	efficiency of the battery charge

(GH2) solution results from the immatureness of the solid H2 storage and the too high energy cost of the liquid H2 storage due to the liquefaction phase. The value of the pressure answers to two criteria. On the one hand, high pressure would increase the price too much since it requires expensive compressor and composite vessels. On the other hand, a sufficient pressure should be used in order to minimize the system size. Yet, a very low pressure could be an interesting pursue if the output pressure of the electrolyser is high enough to avoid the use of a compressor.

In addition to the minimization of the system cost, the concept of “customer satisfaction” is taken into account. It represents the granted risks [9] and the social acceptability. This concept requires to be clarified. Indeed many criteria such as the consumer habits, convictions, satisfaction, etc. may be involved in its definition. In this paper, we restrict this concept to the energy supply rate (ratio between delivered electricity and demanded electricity).

The techno-economic evaluations of these technologies will be made thanks to an in-house computer code performing multi-objective optimizations under constraints, the Modelling and Optimization of Multi-objective Storage (MOMuS) code developed at CEA. Thus, for a given satisfaction of the consumer, the solution that minimizes the cost of storage and the network connection is obtained.

After this introduction of the rationale of our study, the particular context of an isolated village is introduced. The statement of the corresponding techno-economic model is thus presented. Then, the principle of the numerical optimization is briefly explained. Finally, a general discussion based on well chosen simulations is proposed to discriminate the storage types regarding the time horizon (short or mid term).

2. Description of the studied system and statement of the techno-economic model

The site of *La Nouvelle* in the cirque of *Mafate* on the French island *La Réunion*, in the Indian Ocean, is only accessible on foot or by helicopter. The annual consumption of the 750 inhabitants is provided by ARER [10], presenting a maximal peak of electrical consumption of 140 kW. We assumed that it is weakly connected to the grid (at the present time, the electricity is produced by diesel generator). To reach the objective of energy independence at time horizon 2025, our goal is to satisfy the electricity demand of the consumer (load) by producing electricity thanks to PV panels only. Indeed, due to green energy pressure and the guiding rules predicted by the PRERURE [2], the fossil fuel are planned to vanish. Of course, PV electricity depends on the meteorological data of the site land. These fluctuating data are provided by ARER [10]. The load cannot be fully satisfied without storage technologies and we have evaluated the relevancy of a storage system based on a Pb-A or Ni–Cd batteries coupled with a H2 chain. This set up is made of an alkaline electrolyser, a H2 compressor, GH2 storage in bottles and a proton exchange membrane fuel cell (PEMFC), as visible in Fig. 1.

The bellow paragraphs detail the different models used for each entity of the system:

- The “economical data” subsection shows how the total levelized cost (*TC*) is calculated;
- The “meteorological data” subsection exhibits the required inputs to calculate the produced electricity;
- The “electrical production with PV panels” subsection presents the model and the data used to calculate the electricity production from PV panels;
- The “electrical load data” subsection explains the electricity consumption we want to satisfy;
- The “storage technologies” subsection contains the models and the data used for the batteries and for the H2 chain;
- The “connection to the grid” subsection details the prices for selling or purchasing some electricity to or from the grid;
- And finally the “management of the system energy” subsection aims at explaining which technology is prior to another one for the supply and demand of electricity.