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Short communication

Cost and surface optimization of a remote photovoltaic system for two kinds of panels' technologies

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ABSTRACT

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 short communication presents a multi-objective design of a remote PV system coupled to battery and hydrogen storages systems simultaneously minimizing the total levelized cost and the occupied area, 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 Heterojunction with Intrinsic Thin layer (HIT) rather than crystalline silicon (c-Si) cells for the short term. However, the discrimination between these two PV cell technologies is less obvious for the mid term: a strong constraint on the occupied area will promote HIT, whereas a strong constraint on the cost will promote c-Si.

1. Introduction

Satisfying the energy demand has now become a sensitive topic in the world, especially in insular areas, in addition to the need to limit fossil fuel consumption for both sustainability and energy self-sufficiency issues. 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*, an electrical autonomy in 2025 is planned [2]. Thus, we recently proposed a paper aiming at optimizing renewable electricity production coupled to storage technologies in the *La Nouvelle* village [3].

Stand alone photovoltaic (PV) systems are one of the promising electrification solutions to answer the demand of remote consumers, especially when these systems are coupled with a storage solution that would both increase the output of power plants and reduce the areas dedicated to energy production. In line with the above principles and to improve the standard of living of several remote consumers, the implementation of autonomous stand-alone renewable energy based systems which would be able to increase the security of supply through distributed generation has been considered [4,5]. To achieve that, 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 [6–8]. Other storages like hydrogen (H2) have also been considered in the literature, but to a lesser extent [9].

Our previous study [3] proposed 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 "end-user satisfaction" which represents the granted risks [10]. Using an in-house multi-objective code based on particle swarm optimization (MOMuS), we pointed 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) when coupled to c-Si PV panels.

The objective of this short communication is to extend this previous study by assessing the technical and economic relevance of PV–battery–H2 configurations to meet the energy needs identified for the short and the medium term, considering two kinds of PV panels (c-Si and HIT). The multi-objective design of the system is simultaneously minimizing the total discounted electricity cost and

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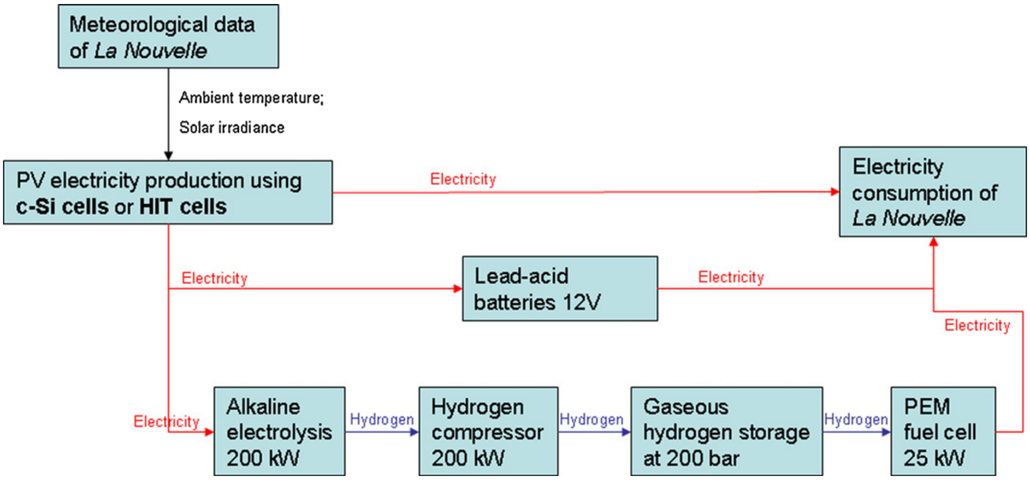

Fig. 1. The stand-alone isolated photovoltaic-storage system.

the area occupied by the whole energy system, while fulfilling a constraint of "end-user satisfaction".

After this introduction of the rationale of our study, the particular context of the isolated village of *La Nouvelle* is presented, as well as the corresponding techno-economic model. Then, the principle of the numerical optimization is briefly explained. Finally, a general discussion based on well chosen simulations is proposed to discriminate the PV panels' types according to the cost and surface criteria and regarding the time horizon (short or mid term).

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

The evaluations are carried out on a realistic case of a remote village, *La Nouvelle*, located in the cirque of *Mafate* in the French overseas island of *La Réunion*, in the Indian Ocean. The annual consumption of the 750 inhabitants is provided by the Regional Agency of Energy in *La Réunion* (ARER) [11], with an hourly precision and presenting a maximal peak of electrical consumption of 140 kW. To reach the objective of energy independence by 2025, our goal is to satisfy the electricity demand of the consumer by producing electricity thanks to PV panels only. Indeed, due to green energy pressure, the fossil fuels are planned to vanish. Of course, PV electricity production depends on the meteorological data of the site (solar irradiance and ambient temperature). These fluctuating data are provided by the ARER [11] with an hourly precision. The load cannot be fully satisfied without storage technologies and we proposed a storage system based on the results of our parent paper [3] (Pb-A batteries coupled with a hydrogen chain) as detailed in Fig. 1. This study is focussed on analysing two kinds of PV panels: c-Si and HIT cells.

In order to evaluate the system, we have to calculate the total electricity cost (TC). The detailed formula is given in [3]. In what follows, we have considered a discount rate of 8% and an operating time of the whole system of 20 years. We also calculate the total occupied surface, considering both the PV and storage devices.

The electrical production of a PV panel can be calculated knowing the temperature of the cell (at *t* time), the solar irradiance (at *t* time), the standard peak power of a module, and the temperature coefficient, as described in [3]. We studied both c-Si and HIT cells which are more efficient than c-Si but with a higher cost (for more details on these technologies see [12]). Technical data are chosen to be the same as the photowatt-PW6 panel [13] whereas costs are issued from an extensive literature review [14]. According to the advanced scenario of EPIA [15], we assumed an annual growth of installed peak power of 28% between 2011 and 2020, and we considered a learning factor of 22%, which leads the cell cost to decrease from 2€/W_p in 2012 to 0.64€/W_p in 2020 for c-Si; and from 2.4€/W_p in 2012 to 0.77€/W_p in 2020 for HIT respectively.

The storage is modelled as proposed in [3]. For the battery model, we used the Shepherd model [16] for our simulation. It predicts the charge–discharge phenomena for Pb-A batteries. The economic data mostly depend on the technologies. For this study, we considered a Pb-A battery of 100 A h with a tubular configuration which costs 100€ with about 500 cycles of life time. The hydrogen chain is composed of four elements: (i) a 200 kW alkaline electrolyser producing hydrogen from electricity; (ii) a 200 kW compressor compressing hydrogen from 30 bar to 200 bar; (iii) a storage system comprising several 50 L – cylinders with a maximum allowable working pressure of 200 bar; (iv) and 25 kW PEMFC systems delivering electricity from the stored hydrogen.

The management of the energy of the system is a crucial element of the simulation. Indeed, the priority between the components has a strong impact on the results. In the simulations below, we have considered the following management rules: (i) the consumer has the priority for consuming electricity; it takes it first from the PV production, then from the batteries and finally from the hydrogen system which delivers the most expensive electricity; (ii) an empty battery has the priority on another battery; thus limiting the risk of a too long discharge time, which could damage the storage system.

3. Multi-objective optimization method

Our goal is to minimize two objectives: TC and the occupied area. The two objectives conflict, since using a high number of PV panels instead of numerous storage technologies is cheaper but more space-consuming. So, solutions we are searching for are the compromise sets, as it is defined by Pareto. When a solution belongs to this set, you cannot find another one that will be better for all the objectives: if it is better for one objective, it will be worse for another one.

We also consider two constraints: one for the consumer satisfaction, and another one for a proper use of Pb-A batteries. Satisfaction needs to be upper than 97% in terms of amount of supplied energy compared to the demand. Pb-A batteries need to be frequently fully recharged otherwise they will suffer a loss of capacity due to the sulfation phenomena [17] (we assumed 20 days maximum between two fully recharged states).

Thus we are dealing with a problem of multi-objective optimization under constraints. Note that this optimization process

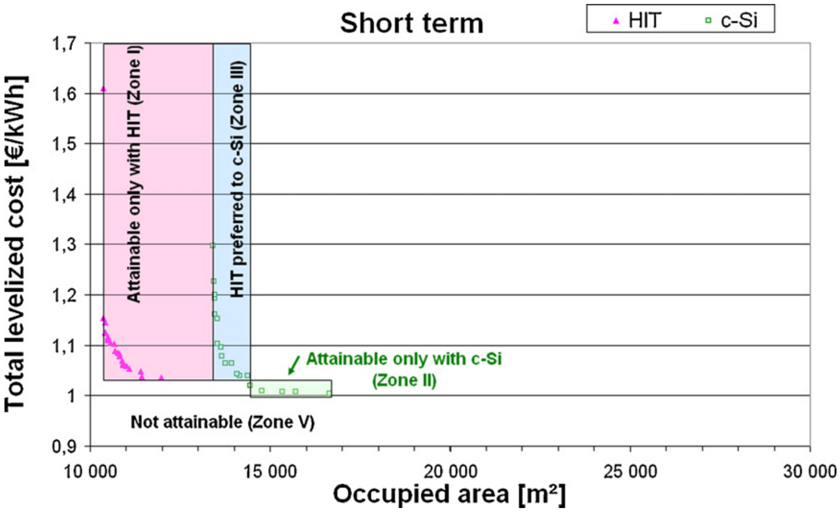

Fig. 2. Solutions that minimize both the total levelized cost and the occupied area for both c-Si and HIT technologies for the short term.

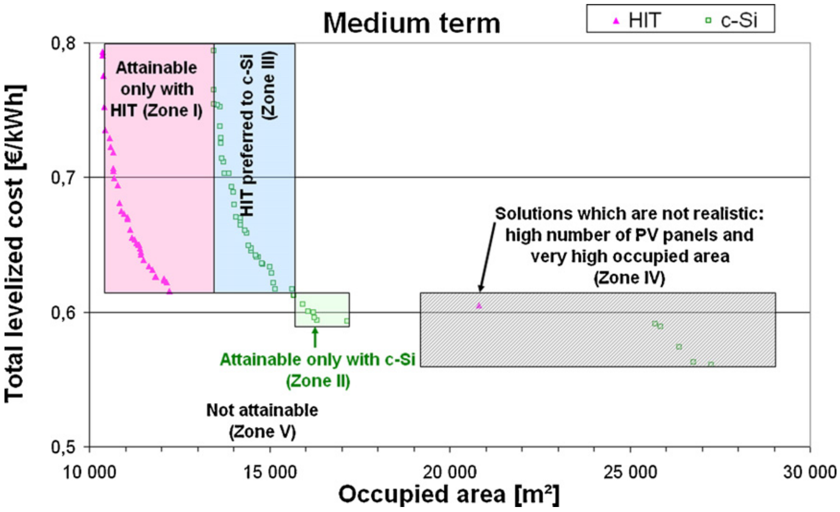

Fig. 3. Solutions that minimize both the total levelized cost and the occupied area for both c-Si and HIT technologies for the mid-term.

is simultaneously performed for all the objectives. Therefore, we have improved the MOMuS code (Modeling and Optimization of Multi-objective Storage) developed by the CEA [3], adding the occupied area as an optimization parameter. It includes the previously detailed model and an optimization algorithm based on particle swarms [18]. Such a method performs numerical optimization without explicating the gradient of the variables to be optimized. For a given scenario the MOMuS code modifies the arrangement of the system by changing the number of PV panels, batteries, electrolysers, hydrogen bottles and PEMFC systems, until reaching optimal solutions. We finally obtain the whole set of solutions that simultaneously minimizes TC and the area, while satisfying the two above constraints.

4. Results

The computational results are presented for the short and medium terms using the data presented in the paragraph 2 and distinguishing c-Si (squares) and HIT (triangles) technologies for the PV panels. Our objective is to minimize the cost and the occupied area.

Short term results and mid-term results are presented in Figs. 2 and 3. Each point represents an optimal solution (quantities of PV panels and storage devices) for a given cost and surface area. We can observe 5 zones:

- The first one (zone I, in rose), is the one attainable only with HIT cells. It corresponds to the minimum area attainable.
- The second one (zone II, in green), is the one attainable only with c-Si cells. It corresponds to the minimum total levelized cost but with a strong increase of the area occupied.
- The third one (zone III, in blue), is the one where HIT should be preferred to c-Si. Since for a similar cost in zone I, it offers a reduced occupied area.
- The fourth one (zone IV, in grey), is the one where solutions are not realistic due to the very high number of PV panels and as a consequence the very high occupied area. This zone only appears for the mid-term.
- Finally, the fifth zone is not attainable with these technologies (TC and area occupied are to low).

Concerning the storage technologies, it appears that the storage is principally performed through the Pb-A batteries for the two time frames, the hydrogen storage being considered as a seasonal storage [9]. The main difference between the short and mid term consists in the higher number of PV panels for the medium term (due to their lower cost) which reduces the number of storage technologies.

5. Discussion and conclusion

The aim of this study was to evaluate, for both the short and the medium terms, different configurations using c-Si or HIT PV cells and Pb-A batteries and hydrogen storage for remote systems for the precise site of *La Nouvelle* in the French overseas island of *La Réunion*. It was done using a multi-objective optimization methodology taking into account technological and economic criteria. The purpose was to simultaneously minimize two objectives: the cost and the occupied area.

This problem is very complex. Simulations enable to obtain the best solutions that simultaneously satisfy these two objectives and the two constraints (a minimum consumer satisfaction of 97% and a constraint on batteries recharge). Each solution is composed by a combination of physical components (PV panels, batteries, etc.).

In the precise case of *La Nouvelle*, it appears that:

- For the short term, there is a strong advantage to use HIT cells rather than c-Si (c-Si can be used to obtain the lowest cost, but with a very important area dedicated to the whole system);
- For the mid term, the discrimination between to the two kinds of PV cells is less obvious (c-Si would be preferred if we want to minimize the cost whereas HIT would be preferred if area is constrained which is the case in *La Nouvelle*);
- Coupled with Pb-A batteries, the hydrogen is used as a seasonal storage.

These results demonstrate the practical utility of the developed design method. It also has to be noticed that despite the fact that those simulations were based on the *La Nouvelle* specific case, the results can be extrapolated to many remote areas presenting the same constraints. However, a validation of the simulation results will be necessary, by comparing the conclusions to those obtained with other computational models as well as experimental results.

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Glossary

ARER: Regional Agency of Energy in *La Réunion*
c-Si: crystalline silicon
GH2: gaseous hydrogen
H2: hydrogen
HIT: Heterojunction with Intrinsic Thin layer
Pb-A: lead-acid battery
PV: photovoltaic
TC: total electricity cost [€/kWh]
W_p: Watt peak [W]