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Study of optimal sizing for various hybrid power plants including Hydrogen Vector as storage system. A case of study in Corsica Island.

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ABSTRACT

The present paper aims to determine the optimal configuration of several hybrid power plants composed of renewable electricity production and various storage systems such as hydrogen storage systems. The sizing optimization problem is solved by using a Multi-Objective Particle Swarm Optimization (MOPSO). The multi-objective function consists in the minimization of the Annual System Cost and the share of Imported Energy from the grid or other non-renewable sources. The results show that configurations including hybrid storage systems are more reliable and economic than the one with only hydrogen storage systems. A power station with only hydrogen storage is three times more expensive than one with two storages. In addition, the current costs of hydrogen equipment do not appear competitive compared to the battery storage system costs. To mitigate this effect, some economic forecasts such as national subsidies, allowing the decrease prices of hydrogen components have been added. Actually, if the prices of hydrogen components decrease from 50%, a power plant containing both electrochemical and chemical storages becomes viable. That suits well to the European Union's policy in this area of Hydrogen. Considering a configuration with 10% of imported energy from the grid and 60% of reduction costs on hydrogen storage system, with the addition of a 535 kW PEMEL and a 335kW PEMFC, the batteries bank decreases from 7MWh to 5.6 MWh.

KEYWORDS

Multi-objective Particle Swarm Optimization; hydrogen storage system; hybrid renewable energy plant

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INTRODUCTION

Nowadays, the electricity production in non-interconnected areas returns more and more expensive and harmful due to the important amount of imported fossil fuels. For instance, the production cost in Corsica Island is around [198.7 €/MWh in 2019](#) [1] and can easily climb to 390 €/MWh ; about three times higher than the one in continental France [2]. However the noticeable potential of renewable energy sources should be studied [3]. Because of the intermittence behaviour of those sources, the addition of one or several types of storage systems seems interesting to manage energy production and consumption. The battery storage system is attractive for short term. However, if a long-term storage capacity is needed, other alternatives such as chemical storage system may be exploited. Hydrogen is considered as a promising solution for energy independence and carbon neutrality in locations weakly-connected [4] such as islands. The researches led about the interest of hydrogen in insular territories are not numerous. Krajačić et al. [6] have conducted primary studies in Mljet Island (Croatia), proving the suitability of coupling hydrogen and renewables sources in remote locations and islands. Nevertheless, optimizations did not consider financial parameters. Another article, written by Lambert et al. [7] present a microgrid and its power management strategy located in Tahiti. In this article thermal and electrical load are considered. They highlighted the interest of an absorption cooling system for lifetime of the fuel cell and the electrolyzers. It increases the efficiency of the whole system as well. More generally, Kovač et al. [4] reviewed the different national strategies adopted to implement hydrogen storage solutions in various countries.

For better performances, hybrid power plants require a suitable energy management system and as well optimal sizing [8]. Indeed, a sub-optimal sizing may cause a considerable rise of the total system costs or an important loss of power supply. Mono and Multi-objective optimization problems are currently treated for energetic systems. Usually, multi-objective optimizations provide more sophisticated decision processes. The most commonly found objective functions found are: minimisation of costs (total, operation...), minimisation of greenhouse gas emissions, maximisation of power production...

The literature shows that optimization sizing problems have resorted to various algorithms such as Mixed-Integer-Linear-Programming (MILP) or Particle Swarm Optimization (PSO) [9]. Marocco et al. [10] propose the resolution of a problem using a single-layer MILP program. The stand-alone hybrid plant was dedicated to power an off-grid insular village. It is composed of a solar farm, hydrogen chains and batteries. The sizing function corresponds to the minimisation of the total annual cost of the plant. The results conclude that hydrogen storage system allows to reduce the sizing of the batteries. Sanchez et al. [11], look at a techno-economic optimization thanks to a PSO algorithm. It aims to determine the best configuration for a hybrid renewable energy source (HRES) composed of wind power, solar power and fuel cell. The objective function is the minimization of the costs (capital expenditure CAPEX and operational expenditure OPEX). PSO shows better results than an evolutionary algorithm (differential evolution i.e. DE) regarding the convergence speed. The PSO has a better ability compared to DE to solve the problem as well. Maleki et al. [12], studied an optimization problem, using two modified algorithms, coming from particle swarm optimization. The power plant supplies the thermal and the electric consumptions of a residential load. Furthermore, commercial software like Hybrid Optimization of Multiple Energy Resources (HOMER) allows for economic optimization sizing. Basu et al.[13] analyse three hybrid plant configurations composed of either solar plant, or wind turbine plant or both and a hydrogen storage system. HOMER software defines optimal sizes of the components and also gives economic parameters of the plant such as the Net Present Cost (NPC). However, it only treats

mono-objective optimisations problems and the fitness function is the minimisation of the actualized cost of the system [12]. Nevertheless, all these studies show that exploiting hydrogen storage system can have a positive impact on the viability of a hybrid renewable power plant.

In this techno-economic study, in order to obtain the optimal size of a hybrid power plant, a multi-objective particle swarm optimization (MOPSO) algorithm [14] is used. The method has already been applied in a wind, solar and battery micro-grid in Tilos Island [15]. Here, the following plant is composed of a photovoltaic farm and one or two kinds of storage systems: a battery module and/or a hydrogen storage system (electrolyser, gaseous storage tank and fuel cell). The hybridization of the storage systems increases performances and lifetimes of components as well. The hybrid power station is located in Ajaccio, the capital of Corsica Island. The first part explains the initialization of the algorithm and details the modelling of the power plant as well. Then the MOPSO algorithm, is succinctly presented. The last part analyses the obtained results. The main contribution focuses on the financial and technical competitiveness between various configurations and to propose some future improvements in comparison to the original algorithm.

Materials and Methods

This part describes the modelling of consumption and production. After that, the description and the parameters of the hybrid power plant are given.

Load and Production Profiles

The yearly global horizontal irradiance in Ajaccio is about 1605.8 kWh/m^2 [25]. In order to model solar production, meteorological weather data were collected in the Georges Peri Centre meteorological station located in Vignola, Ajaccio. Because of the geographical location, only one renewable source appears favourable for electricity production: the solar resource. Wind speed is not optimal for deployment of wind turbines [16]. The chosen load profile gathers two types of electrical consumptions: the first one of Ajaccio's cruise terminal and the other one of the active power called during the connection of a fast ferry onto the wharf. The ferry is connected three times a week, thus the other days only the consumption of the cruise terminal is considered. Figure (1.a), illustrates the yearly profile where the seasonal variabilities are represented while Figure (1.b) shows the weekly profile. There are two power peaks demands, during the ferry arrival and departure times. The load consumption is multiplied by 10 when the ferry is connected. For both profiles, an hour step-time is used. The profiles stay the same for all the duration of the study.

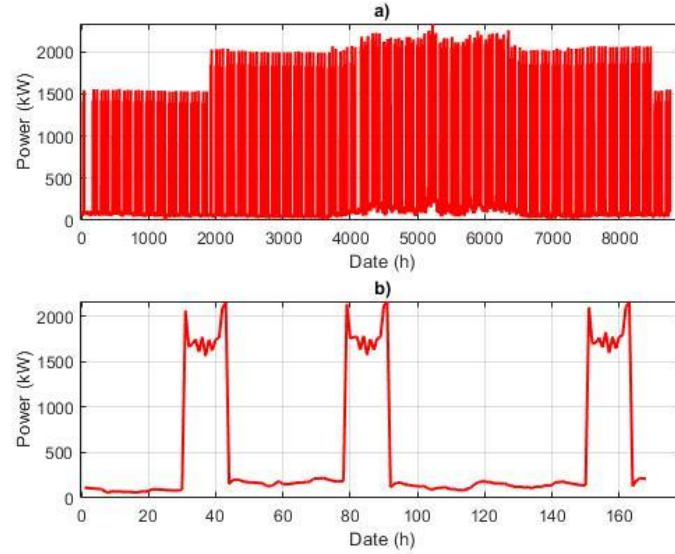


Figure 1.a) Yearly Load Consumption Profile. b) Weekly Load Consumption Profile.

Plant scheme and parameters

Plant configuration is mostly defined by the user. Figure (2) gives the schematic diagram of the power plant. As written previously only one renewable source is exploited. Thus, the second possible renewable source represented by transparent elements is not considered in our configuration. The solar farm produces DC power, converted to AC by a solar inverter. The load consumes the power directly and the surplus supplies the storage system after the DC converter. The modelling makes an analogy between the storage systems. The different converters correspond to either charge and discharge inverters of the batteries bank or proton exchange membrane electrolyser (PEMEL) and proton exchange membrane fuel cell (PEMFC) for production and consumption of hydrogen. The battery storage system rests on a Lithium-ion Batteries bank and a gaseous tank stores the hydrogen. The initial state of charge of both batteries bank and hydrogen tank are defined by the user. In our case, because of no transportation or distribution of the hydrogen, the pressure in the tank is the same as the output pressure of the electrolyser. The power produced by the fuel cell is converted to AC via an inverter. Finally, the hybrid plant is connected to the local grid or a diesel generator in case both renewable electricity production and storage systems are not sufficient for the load demand or for export.

To model the hybrid plant, financial and technical parameters for each component are needed: lifetime, yield or efficiency, cost investment, operation and maintenance costs. Table 1 presents the previous parameters. The French “Comission de Régulation de l’Energie” published in 2019 a report on the costs and the profitability of photovoltaic field where the solar panel cost has been extracted [17]. French manufacturers provide costs for hydrogen equipments. Then, the battery cost has been selected according to a technical report available on the National Renewable Energy Laboratory (NREL) website [18]. Because of their lack of maturity, prices for electrolyser and fuel cell are still high. Nevertheless, Yue et al. [19] propose a review about the current status of hydrogen exploitation worldwide. They conclude that capital cost of hydrogen systems is declining and thus large-scale deployments are in progress. Furthermore, the current policies focussing on green hydrogen [4], [20], allows us to add different subsidies on the costs of those ones. Thus, a range of reduction from 20% to 60% on the unit prices of all the hydrogen equipment have been applied. Their maintenance rates decrease from 3% to 2%. The duration of the study is set to 25 years. Project HyLES attempts to reach the neutral carbon

for non-interconnected areas on horizon 2050. As a result, expecting deployment of those hybrid renewable plants near 2030 may be interesting, in the economic point of view. Costs projecting for electrolyzers and fuel cells will decrease with the development of large-scale industries and advances in research and development.

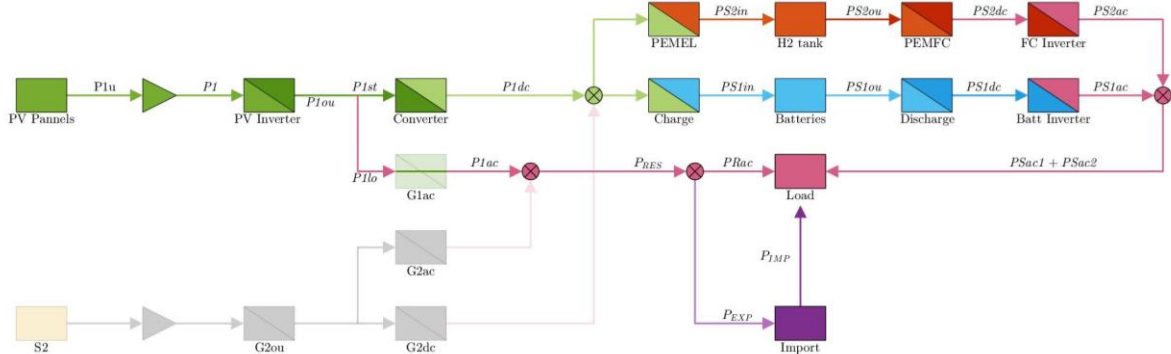


Figure 2. Schematic Representation of the Hybrid Power Plant's components and their power flows.

Table 1. Financial and Technical parameters used for the components

	PV Panel	Battery Li-ion	H2 Tank	PEMEL	PEMFC	Inverter
Yield	0.8	/	/	0.7	0.7	0.96
Unit Price (UP)	0.936 €/W	0.6 €/Wh	0.313 €/Wh	0.9282 €/W	2.5 €/W	0.063 €/W
UP with 20% Subsidies	0.936 €/W	0.6 €/Wh	0.25 €/Wh	0.7426 €/W	2 €/W	0.063 €/W
UP with 40% Subsidies	0.936 €/W	0.6 €/Wh	0.156 €/Wh	0.4641 €/W	1.25 €/W	0.063 €/W
UP with 60% Subsidies	0.936 €/W	0.6 €/Wh	0.125 €/Wh	0.3713 €/W	1 €/W	0.063 €/W
Lifespan (year)	25	15	20	7	7	15
O&M Rate (%)	2%	1%	1%	3%	3%	1%
Updating Rate (%)	5%	4%	3%	6%	6%	2%

Then it's possible to define the minimum and maximal sizes of each component or to size one with a constant value or depending on the size of another component. For instance, MOPSO algorithm will size the charge and discharge inverters of the batteries according to the batteries bank capacity. In one study, the maximum size of the batteries bank was limited.

Power flow management strategy

MOPSO is built to analyse lots of solutions in a short time, it is necessary to manage the power flow in a simple way. Thus, the power management flow is only based upon input and output powers of the components. For the storage, the state of charge and the capacity are used. Figure (3) summarizes the flow management.

Renewable electricity production firstly feeds the load and the surplus charges the electrolyser in order to produce hydrogen and store it. If the hydrogen tank is completely full and if there is

still renewable electricity production, it charges the battery bank. Otherwise if the batteries bank reaches the maximum state of charge, plant exports renewable electricity to the grid. When the renewable production is not able to supply the total load consumption, storage systems ensure the difference: fuel cell uses hydrogen produced to convert it into electricity and batteries discharge. In case both renewable production and storage systems are not sufficient (it means the batteries are at their minimum state-of-charge and the hydrogen tank is empty), the local grid or a diesel generator will supply the load. However, imported energy is not used to charge the batteries or to power electrolyser. Also, the storage systems are not connected directly to the grid. This flow management corresponds for a plant containing the two types of the storages. When only one electrochemical or chemical storage is present in the power plant, it uses a simpler management system. The surplus produced by the solar farm, heads toward one storage directly.

Others strategies of power flow management such as one depending on the state of charge of the storages or using various limited power rates can be developed.

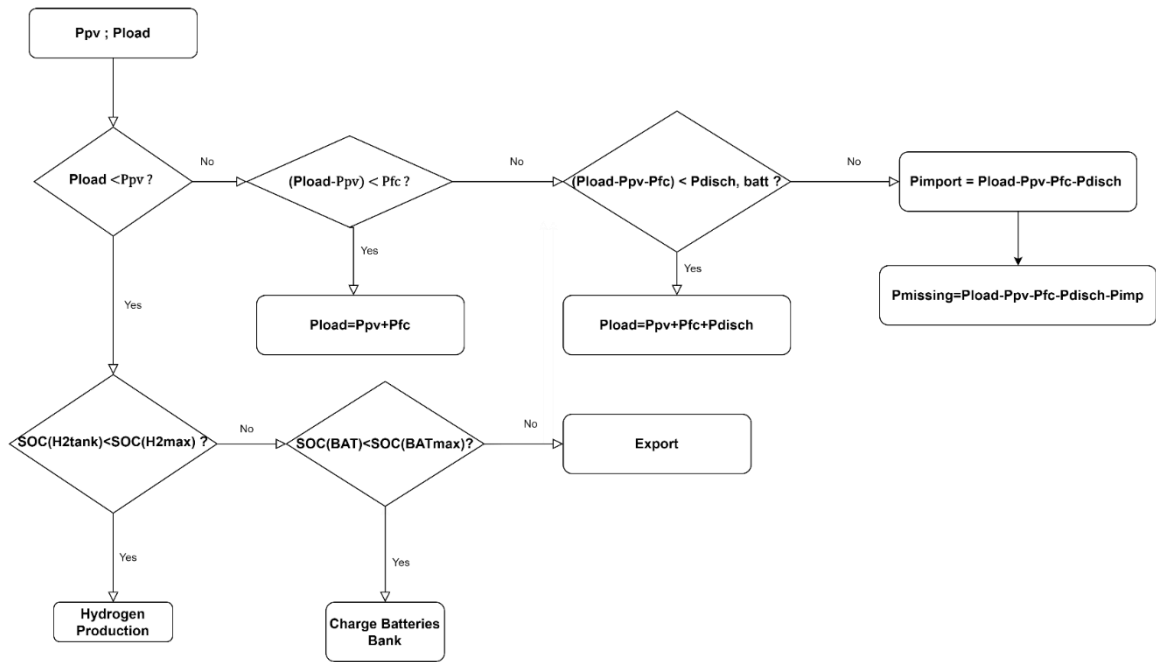


Figure 3. Power Flow Management Diagram

Optimization Sizing Method

Particle Swarm Optimization is a heuristic method to solve optimization problems, inspired by the behaviour of birds' swarms or of fish shoals. It was introduced in 1995 by R.Eberhart et J.Kennedy [21]. The particle swarm is made of several particles, moving in the searching space and one particle represents one solution. The whole particles are searching for the global optimum. Position and speed define each particle. The algorithm steps are the following: initialization of the population by choosing particles randomly in the search space. Particle's trajectories are adjusted to achieve the best positions and then the position of the whole swarm is saved. A Multi-Objective Particle Swarm Optimization (MOPSO) [22] solves the sizing optimisation. The algorithm is developed under MATLAB R2021b environment. Objective function consists in the minimization of the annual cost system (ACS) and the energy imported (E_{IA}) with the constraints of the Lost Power Supply Probability (LPSP) is equal to zero.

Mathematical formulation (1) of the problem is:

$$\begin{aligned} x = \operatorname{argmin}_{x \in X} [ACS(x), E_{IA}(x)] \\ LPSP(x) = 0 \end{aligned} \quad (1)$$

The Annual Cost of the global system (ACS) corresponds to the sum of the annualized cost of each component. It can be formulated as (2):

$$ACS = \sum_{i=1}^n C_{\text{buying}_i} + C_{\text{maintenance}_i} \quad \text{with } n = \text{number of the component} \quad (2)$$

The Imported Energy Percentage is the fraction between the Imported Energy (E_{IA}) and the Energy consumed by the load (E_{CA}). It's given by the following equation (3):

$$\%E_{IA} = \frac{E_{IA}}{E_{CA}} \quad (3)$$

In the case of multi-objective optimization, two approaches can be studied [21]. The first one comprises the combination of all the objective functions. On one hand, the weight of each function is evaluated or on the other hand, all the objective functions except one are treated as constraints. The second approach defined by Pareto Optimization. It allows to determine a set of solutions that are the best compromise between the objective functions. It corresponds to the method used for the sizing problem treated.

Results and Discussion

This ending part focuses on the presentation and short analyses of the results given after simulations. Then the limits of the work will be underlined and thus some potential enhancements will be suggested.

This section summarises the results obtained after the algorithm running. An important one is the Pareto Front highlighting all the Pareto Optimum. One solution corresponds to a configuration of hybrid power plant. The solutions give the best compromise between the two objective functions. In the same graph, the item sizes are drawn.

In our study, different optimisations have been led:

- Two optimisations include only one kind of storage (either batteries or hydrogen).
- The others treat the case with a coupling of the two storage. As mentioned previously, there was a case imposing a limit on the batteries bank capacity to 3MWh. Then the last simulations were conducted according to the various percentages of subsidies give previously.

Concerning the optimization with a limit applied on batteries bank size, the Pareto Front and items sizes are given in Figure (4). Between 0% and 23%, the system keeps the maximum batteries bank size, and replaces the remaining part with hydrogen storage. As from 23% of imported energy, it only conserves the battery storage system and no more hydrogen storage. When the imported energy exceeds more than 50%, hybrid plant only contains a PV farm and importations.

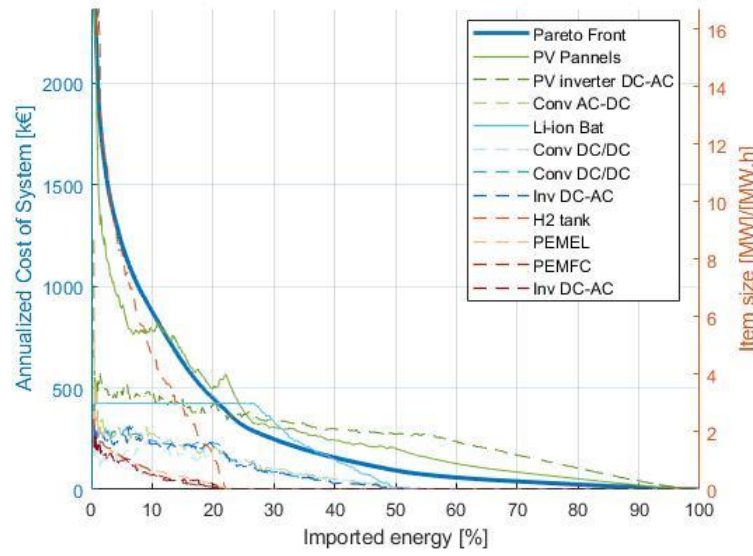


Figure 4. Pareto Front and sizes of components for optimization with batteries bank capacity limit

Table (2) presents the sizes of the PV array, the batteries bank, the electrolyser and fuel cell for a configuration of hybrid plant with 10% of imported energy and depending on the percentage of reductions applied on the hydrogen equipment. Even if, there is a slight decrease, the total annual cost stays in same order, around 530 k€. This concordance is valid, no matter the imported energy value. As a result, the identical Pareto Front appears on Figure (5). However, sizes of the components differ. With 20% of external subsidies, the results do not change compared to the study with basic costs. Even when both storages are added, the algorithm will choose preferentially the use of the batteries. If the subsidies bring 40% of cost reductions, the impact is still no noticeable. The algorithm will still favour the battery storage system. For values such as 20% or 40%, it opts for installation of an important batteries bank, about 7MWh. The important capacity of the battery module may be explained by the fact that, to supply correctly the load during the times solar production is not sufficient or non-existent, storages must ensure the load consumption. The configuration with only hydrogen as storage results in very expensive system. When the subsidies reach to 50%, the algorithm begins to include hydrogen storage system. Thus, deployment of hybridization between two storages including chemical storage becomes viable. It's consistent with the current policies that bring a help of 55% on CAPEX equipment in France [23].

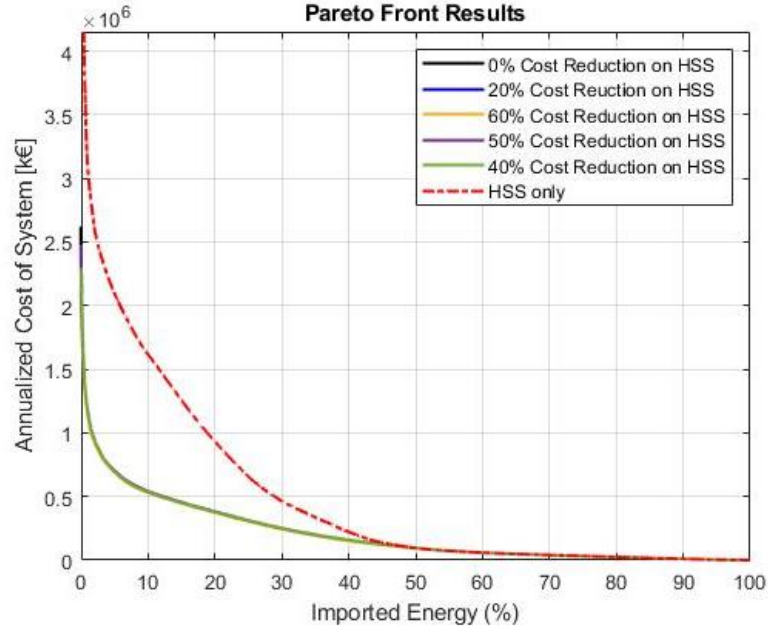


Figure 5. Pareto Fronts Obtained for various studies

Table 2. Comparison of the various configurations for 10% of Imported Energy according the percentage of reductions on hydrogen equipment

Reduction apply	0%	20%	40%	50%	60%
Annual Cost System	532.9 k€	532.5 k€	537.6 k€	531.7 k€	529.3 k€
PV Panels	2.65 MW	2.7 MW	2.70 MW	2.69 MW	2.57 MW
Batteries Bank	7.66 MWh	7.54 MWh	7.54 MWh	6.46 MWh	5.62 MWh
PEMFC	0 kW	0.78 kW	0.78 kW	297 kW	535 kW
PEMEL	0 kW	1.1 kW	1.1 kW	127 kW	335 kW

Possible Improvements

The present algorithm gives the ability to choose flexible configuration of power plant; however, in order to prove the competitiveness of hydrogen as storage system, some improvements described as follow can be brought:

- The consideration of some economic parameters including the cost of reducing greenhouse gas emissions. They may contribute to the diminution of the annual cost for innovative systems with the two storage or for one with hydrogen storage system [6]. Furthermore, reducing GHG is benefit for people's life conditions. Hydrogen vector may help to achieve the goals fixed by the National Plan of Reducing Atmospheric Pollutant [24].
- Other economic parameters should be considered: dismantling and recycling costs of the batteries.
- It can be relevant to consider the autonomous demand part of the system. Batteries bank has interest for short term whereas hydrogen storage system may be more profitable for medium and long term.

- The modelling and consequently the power flow management are quite simple, only based on output and input powers of the components. To simulate the real and reliable performances of the entire system, a modelling with more accurate degrees will be analysed. It will include for instance the auxiliary systems of electrolyser and fuel cell, others battery parameters.

Conclusion

This present framework aims to study various optimal configurations of power renewable energy plant coupled to one or two energy storage systems. Electrochemical Storage (battery) and Chemical Storage (hydrogen) are tested for the optimizations. The sizing problem uses a Multi-Objective Particle Swarm Optimization algorithm. The objective function corresponds to the minimization of two objectives: the annual cost of the entire system and the percentage of the imported energy from grid or other non-renewable sources electricity production. To conserve the rapidity of the algorithm, a simple power flow management is implemented. User define the financial and technical parameters. The first results of our study have showed that based on current costs of the components, using hydrogen storage system alone provides an expensive total cost for the plant. For the same percentage of imported energy, a power plant with only hydrogen storage system has a cost three times higher than a plant with both storages. With a percentage of imported energy equal to 10%, annual cost system rises from 530k€ with two storage systems to 1.6 M€ when only hydrogen storage system is present. Even if, two storages are present, the algorithm will favour installation of a batteries bank to minimize the annual cost system. However, to overcome the important costs of the hydrogen equipment, some assumptions about the subsidies were made. A range of grants between 20% and 60% were applied on the hydrogen equipment costs. Regarding an autonomy of 90% (it means 10% of imported energy), the same annual cost of the system (around 530 k€) is emphasized. For all the configuration, the PV array is near 2.7 MW, however the sizes of the storages differ. Below 50% of reduction, hybrid plant contains a battery module of 7 MWh whereas, once the subsidies reach more than 50%, the battery capacity decreases to 5MWh and a 535 kW PEMEL and a 335 kW PEMFC are installed. Thus, according to the different sizing optimizations realized, when the financial assists of up to 50%, viability for hybrid plants including hydrogen storage systems is proved. The ending part presents some limits detected in the algorithm, and proposes improvements for further works. Also, the obtained results for sizing have to be checked and validated on harder and more detailed modelling.

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Nomenclature

Symbol	Description
AC	Alternating current
ACS	Annual cost of the system
CAPEX	Capital expenditure
C_{buying}	Buying cost
$C_{\text{maintenance}}$	Maintenance cost
DE	Differential evolution

DC	Direct current
E_{CA}	Annual consumed energy
E_{IA}	Annual imported energy
GHG	Greenhouse gas
HRES	Hybrid renewable energy source
HOMER	Hybrid Optimization of Multiple Energy Resources
HyLES	Integration of hydrogen energy storage in weakly or non-interconnected grids
LPSP	Lost power supply probability
MILP	Mixed integer linear programming
MOPSO	Multi-objective particle swarm optimization
NREL	National Renewable Energy Laboratory
NPC	Net present cost
OPEX	Operational expenditure
PEMEL	Proton exchange membrane electrolyser
PEMFC	Proton exchange membrane fuel cell
PSO	Particle swarm optimization
PV	Photovoltaic

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