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Optimal sizing of Marine Current Energy Based Hybrid Microgrid

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Abstract. This paper presents an optimal sizing of a marine current energy-based hybrid microgrid. For this purpose, a particle swarm optimization (PSO) has been developed on Matlab Software. An energy management strategy that takes into account the availability of renewable energy and energy consumption at all times has been implemented to meet demand throughout the year. In order to test the performance of the PSO, the results were compared to those obtained by the genetic algorithm (GA). The standard household load profile is selected to model an island residential loads variation. The Alderney Race (Raz-Blanchard in French) site is chosen as a case study for our marine energy system because its currents are among the highest in the world.

Keywords. Microgrid, marine current energy, PSO, energy management strategy.

1. Introduction

With the rapid increase in energy consumption worldwide, renewable energies, such as solar and tidal, are proving to be an effective solution to replace fossils fuels, as the latter are non-renewable and unfriendly environmental nature. However, their unpredictable behavior and dependence on weather conditions make their integration into Microgrids very challenging. Therefore, Hybrid systems present a better option to increase the reliability of the electricity supply.

The sizing of system components is an essential step in designing a reliable and low-cost system with high penetration of renewables in the energy mix. Researchers have addressed this concern in several ways. HOMER has widely been used in different case studies [1]-[3]. Despite the fact that is a powerful tool facilitating the hybrid systems optimization with minimum net present cost, “Black box” code utilization doesn’t represent the source characteristics exactly [4]. Heuristic optimization algorithms, such as genetic algorithm (GA) and particle swarm optimization (PSO), have also been utilized, for grid-connected and isolated hybrid systems as well. The latter has become one of the favorite optimization methods due to its high-speed convergence for single-objective optimization. In [5], the authors have used PSO to determine the optimal sizing of a hybrid Microgrid system intended to supply the energy to the households. They have considered the lowest Cost of Electricity (COE) and the Loss of Power Supply Probability (LPSP) as an objective function to design a reliable and high-quality power supply with a competitive cost. Hakimi et al. [6] presented a sizing methodology for wind-fuel cell hybrid system, using PSO. Hydrogen is produced from municipal waste and stored for later use in the case of an energy deficit. The results showed that the hybridization of the system has led to greater reliability and better energy management while optimizing the total cost. In [7], an MPSO (modified PSO) based optimal configurations and sizing of a hybrid PV/wind/battery system was presented. The authors have implemented the code in Matlab software, whose purpose is to ensure a balance between energy supply and demand sides while minimizing the total investment cost of the system. Results showed that the proposed approach leads to a faster convergence speed and a shorter computational time than the conventional PSO. In [8], the authors proposed a new methodology for the design of a Multi-sources system integrated with real time energy management (EMS) based on GA. Feroldi et al. have concluded that the bioethanol-fuel cell system allows reducing the other components sizing while ensuring its performance. In [9], pigeon inspired optimization has been applied to optimize a standalone hybrid PV/wind energy system considering the Levelized Cost of Energy (LCE) as an objective function. The results proved that the PV/wind/battery system is more cost-effective than the wind/battery system and better meets the battery storage needs. Moreover, four well-known heuristic algorithms were applied by the authors of [10] for the hybrid water pumping system optimal sizing, namely; BAT Algorithm (BA), Cuckoo Search Algorithm (CS), Firefly Algorithm (FA) and Flower Pollination Algorithm (FP). Life Cycle

Cost (LCC) has been defined as an objective function. They have concluded that CS is more promising than the other algorithms in terms of the LCC. Other methods have been used to address this issue such as in [11]-[14].

In this paper, the optimal sizing of a standalone hybrid renewable energy system is introduced. For this purpose, particle swarm optimization (PSO) and genetic algorithm (GA) have been developed on MATLAB Software, considering Loss of Power Supply Probability (LPSP) and Equivalent Loss Factor (ELF) as reliability indices [5], [15].

Solar and tidal currents have been selected as the primary sources for feeding a residential island load, which is represented by the household profile as shown in Fig. 1. Although the place of solar energy remains minimal, it is now promised to grow vigorously worldwide [16]. Tidal energy has also gained popularity recently due to its high predictability [17]. The hydrogen system is chosen as the primary storage system to supply the load during fluctuations. The LiFePO$_4$ battery is selected as a backup system to smooth the fast dynamics of the energy [18].

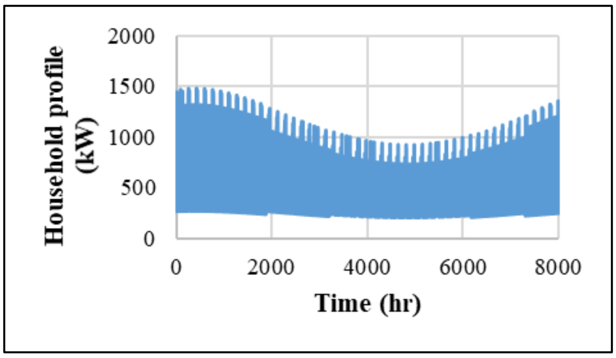

Fig. 1. Household annually load profile.

2. System description

As stated above, the hybrid system includes tidal turbines, PV panels, batteries, and hydrogen storage system. The latter is composed of an electrolyzer, a fuel cell, and a hydrogen tank. Fig. 2 illustrates the final architecture of our system.

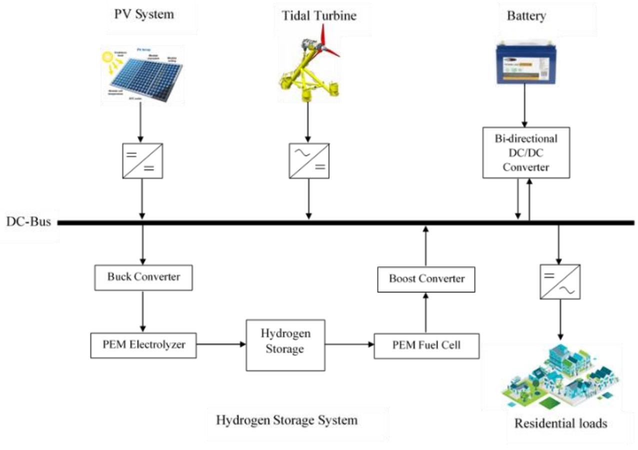

Fig. 2. Hybrid system architecture.

A. Photovoltaic

PV generator is a device that produces electricity from light [19]. The power generated from the PV panels is a function of solar radiation and temperature, it is given by (1) [20].

$$P_{PV} = N_{PV}.P_{r-PV}.\frac{G}{G_{ref}}.\left[1+K_t.\left(T_c - T_{ref}\right)\right] \tag{1}$$

Where N_{PV} is the number of PV arrays, P_{r-PV} is the rated power under standard test conditions (kW), G is the solar radiation (W/m^2), G_{ref} is 1000 W/m^2, K_t is -3,7.10^{-3}, T_{ref} is 25 °C and T_c is the cell temperature (°C). The latter is a function of the ambient temperature (T_a), the solar radiation (G) and the nominal operating cell temperature (NOCT). Its value can be calculated by (2).

$$T_c = T_a + G.\left(\frac{NOCT-20}{800}\right) \tag{2}$$

The annual solar radiation data from Cherbourg have been used in our study. For clarity, we present only daily data, as shown in Fig. 3. The photovoltaic array characteristics are presented in Table I.

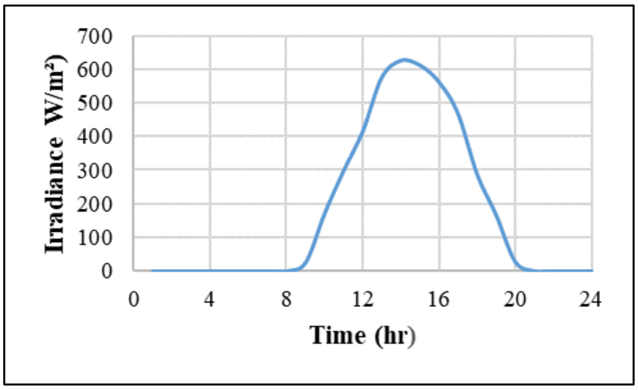

Fig. 3. Cherbourg daily solar radiation.

Table I. - Photovoltaic array characteristics.

PARAMETER	SYMBOL	VALUE
Rated power	P_{r-PV}	500 (kW)
Capital Cost	*CC*	2000 ($/kW)
Replacement Cost	*RC*	2000 ($/kW)
Operation & Maintenance Cost	*MC*	10 ($/kw)
Lifetime	*LF*	20

B. Tidal

Tidal energy can be defined as the energy extracted from tides and converted into electricity. Although it is still in its infancy, it is considered among the most predictable renewable energy sources, to within 98% accuracy [21]. The output power of tidal turbines is governed by (3).

$$P_t = \begin{cases} 0, & v_{tide} < v_{cut-in}, v_{tide} > v_{cut-out} \\ N_t 0.5\rho A C_p v_{tide}^3, & v_{cut-in} < v_{tide} < v_r \\ N_t P_{r-t}, & v_r < v_{tide} < v_{cut-out} \end{cases} \tag{3}$$

Where v_{tide}, v_{cut-in} , $v_{cut-out}$ and v_r represent the marine current velocity, the cut-in speed, the cut-out speed, and the rated speed, in m/s, respectively. N_t, ρ, A and C_p are the number of tidal turbines, the seawater density (1027 kg/m3), the turbine blades swept area (πR^2) and the power coefficient, respectively. In this study, C_p is 0.45, which falls within its defined range of 0.35-0.45 [15], [22]. The marine current speed profile in the Alderney Race is shown in Fig. 4. Table II presents the tidal turbine characteristics.

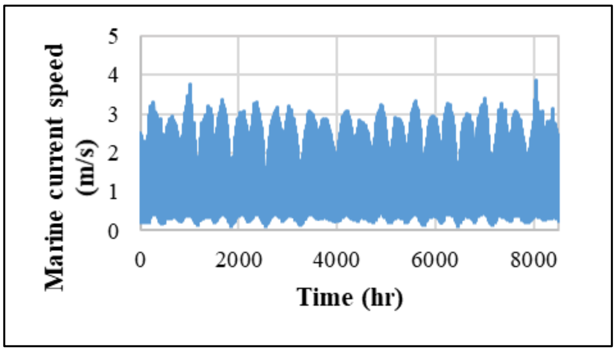

Fig. 4. Marine current speed profile for one year.

Table II. - The tidal turbine characteristics.

PARAMETER	SYMBOL	VALUE
Rated power	P_{r-tt}	1500 (kW)
Rated speed	v_r	3,2 (m/s)
Cut-in speed	v_{cut-in}	1 (m/s)
Cut-out speed	$v_{cut-out}$	3,8 (m/s)
Radius	R	8 (m)
Capital Cost	CC	5000 ($/kW)
Replacement Cost	RC	--
Operation & Maintenance Cost	MC	150 ($/kW)
Lifetime	LF	20

C. *Battery*

When the power generated by renewable systems is not sufficient to meet the demand for electricity, the battery is selected to make up the shortfall. The energy stored in the battery E_b can be calculated by (4) and (5) [23].

- During battery charging:

$$E_b(t) = E_{bat}(t-1)(1-\sigma) + \left[E_g(t) - \frac{E_L(t)}{\eta_{inv}}\right].\eta_b^{ch} \tag{4}$$

- During battery discharging:

$$E_b(t) = E_{bat}(t-1)(1-\sigma) - \left[\frac{E_L(t)}{\eta_{inv}} - E_g(t)\right]/\eta_b^{dch} \tag{5}$$

Where σ, E_L, η_{inv}, η_b^{ch} and η_b^{dch} are the hourly rate of battery self-discharge, the energy required by the load, the inverter efficiency, the battery charging efficiency and the battery discharging efficiency, respectively. E_g represents the energy produced by the renewables, it is given by (6).

$$E_g(t) = E_{pv}(t) + E_{tt}(t) \tag{6}$$

In this paper, the parameters of the considered LiFePO$_4$ battery are given in Table III.

Table III. - Battery characteristics.

PARAMETER	SYMBOL	VALUE
Rated energy	E_{r-b}	250 (kWh)
Charging efficiency	η_b^{ch}	0,8
Discharging efficiency	η_b^{dch}	0,8
Depth of Discharge	DOD	0,8
Capital Cost	CC	343 ($/kWh)
Replacement Cost	RC	343 ($/kWh)
Operation & Maintenance Cost	MC	0
Lifetime	LF	5

D. *Hydrogen storage system*

Hydrogen is environmentally friendly because neither its production nor its storage or transport emit noxious gases [24]. In order to have a highly reliable and economical system, our system uses both battery and hydrogen storage. Batteries are used for fast energy storage while the hydrogen system is used for long-term energy storage. When the battery is fully charged, the excess energy generated can be stored in tanks in the hydrogen form. To this end, the electrical energy produced will be fed to an electrolyzer responsible for the separation of water to generate hydrogen at the cathode and oxygen at the anode, under the electric current effect. The hydrogen chemical energy will be converted into electrical energy by the fuel cell when there is an energy deficit. The Fuel cell, electrolyzer, and tank characteristics are presented in Table IV.

Table IV. - Hydrogen system characteristics.

Component Parameter	FC	Electrolyzer	Tank
Rated power	1500 (kW)	1500 (kW)	1 (Kg)
Efficiency	η_{fc} =0.7	η_{elz} = 0.9	η_r =0.8
Lifetime	5	20	20
Capital Cost (CC)	3000 ($/kW)	2000 ($/kW)	660 ($/kg)
Replacement Cost	2500	1500	400
O&M Cost	0.02*CC	20 ($)	0.02*CC

The power of the electrolyzer and the fuel cell are given by (7) and (8), respectively.

$$P_{ELz} = N_{elz}.I_{elz}.V_{elz} \tag{7}$$

$$P_{fc} = N_{fc}.I_{fc}.V_{fc} \tag{8}$$

Where N_{ELz}, I_{ELz}, V_{ELz} are the number of electrolyzers, the electrolyzer current (A) and its voltage (V), respectively. N_{FC}, I_{FC}, V_{FC} are the number of fuel cells, the fuel cell output current (A) and its output voltage (V), respectively.

3. Optimization Strategy

In this section, the system optimal sizing is presented, in order to determine the best configuration (Number of tidal turbines, photovoltaic panels, batteries, fuel cells, electrolyzers, and tanks), from an economic and energetic point of view.

A. *Proposed objective function*

The objective function is to minimize the hybrid system cost by respecting certain reliability indices. The ones we used are loss of power supply probability (LPSP) and the equivalent loss factor (ELF).

In this paper, Net Present Cost (NPC) is considered, it includes the capital cost (CC), replacement cost (RC) and maintenance cost (MC) of each component. The objective function is defined as in (9) [15].

$$NPC= \sum_{j=1}^{L} N_j.P_j(CC_j+RC_j.\ K_j+MC_j.PWA(ir,\ R) \qquad (9)$$

Where L is the number of the hybrid system component (L=6), N_j is the optimization algorithm decision variable that stands for the number of each component (N_{tt},N_{pv}, N_b, N_{elz}, N_{fc}, N_h). N_{tt}, N_{elz}, N_{fc} are, respectively, the number of tidal turbines, electrolyzers and fuel cells with 1.5 MW rated power. N_{pv} is the number of PV arrays with 500 kW rated power and N_h is the number of 10 kg tanks. P_j is the rated power of each component. In order to convert the replacement cost of a component at the end of its lifetime to present, K_j is used; it can be calculated by (10).

$$K_j = \sum_{n=1}^{l1} \frac{1}{(1+ir)^{n*l2}} \qquad (10)$$

Where $l1$ represents the replacement frequency of a renewable source, $l2$ is its lifetime and ir is the interest rate (ir=0.06). it is worth noting that for sources with a lifetime equal to the project lifetime, K_j is equal to zero. $PWA(ir,\ R)$ is used to estimate the present value of maintenance and operation annual cost over the project lifetime, it is given by (11).

$$PWA(ir, R) = \frac{(1+ir)^R - 1}{ir(1+ir)^R} \qquad (11)$$

Where, R is the total lifetime of the project, which is 20 years.

B. *Reliability indices*

In this paper, LPSP and ELF have been selected as reliability indices. These indices allow us to determine the configuration that ensures a reliable power supply at the lowest cost. LPSP is a statistical parameter that indicates the probability of power supply loss either due to the renewable resource unavailability or to a technical failure [5]. LPSP and ELF can be calculated by (12) and (13), respectively.

$$LPSP = \frac{\sum_{t=1}^{T} E_{unmet}(t)}{\sum_{t=1}^{T} E_L(t)} \qquad (12)$$

$$ELF = \frac{1}{T} \sum_{t=1}^{T} \frac{P_{unmet}(t)}{P_L(t)} \qquad (13)$$

Where T represents the period during which the data were used, i.e. 8760 h. E_{unmet} represents the unmet load, it can be expressed by (14).

$$E_{unmet}(t) = E_L - \left(E_g(t) + E_{fc}(t) \ + \ (E_b(t) - E_{bmin})\right) \qquad (14)$$

C. *Constraints*

In order to size the system correctly, the following constraints are defined:

$$1 \le N_{tt} \le N_{ttmax} \qquad (15)$$

$$1 \le N_{pv} \le N_{pvmax} \qquad (16)$$

$$1 \le N_b \le N_{bmax} \qquad (17)$$

$$1 \le N_{elz} \le N_{elzmax} \qquad (18)$$

$$1 \le N_{fc} \le N_{fcmax} \qquad (19)$$

$$1 \le N_h \le N_{hmax} \qquad (20)$$

$$ELF \ \le ELF_{max} \qquad (21)$$

$$LPSP \ \le LPSP_{max} \qquad (23)$$

D. *Optimization algorithms*

An optimal sizing program was developed in Matlab software using metaheuristic optimization methods. These methods are Particle Swarm Optimization (PSO) and Genetic Algorithm (GA).

PSO is a method derived from stochastic descent, developed in 1995 by Kennedy and Eberhart. It is based on the behavior of birds to compute global optimization functions. Each partner in the swarm is called a particle. These particles are randomly placed in the search space of the objective function to be minimized. Each particle is characterized by its position $\overrightarrow{\boldsymbol{xi}}$ and velocity $\overrightarrow{\boldsymbol{vi}}$. At each iteration, these particles move towards their best position and therefore that of their neighborhood, which corresponds to the optimum position, by updating their velocity [15], [25]. Fig. 5 illustrates the flowchart of the proposed algorithm PSO in detail.

GA is a search heuristic that is inspired by Charles Darwin’s theory of natural evolution. The main operators of GA are the “selection”, the “crossover” and the “mutation”. These operators have an important role in the success of the optimization because they influence the evolution from the initial population to the final population. At each iteration, the best individuals are selected for reproduction, while maintaining a certain diversity to avoid premature convergence towards a local minimum [26].

The parameters of the PSO algorithm and those of GA considered in this study are shown in Table V.

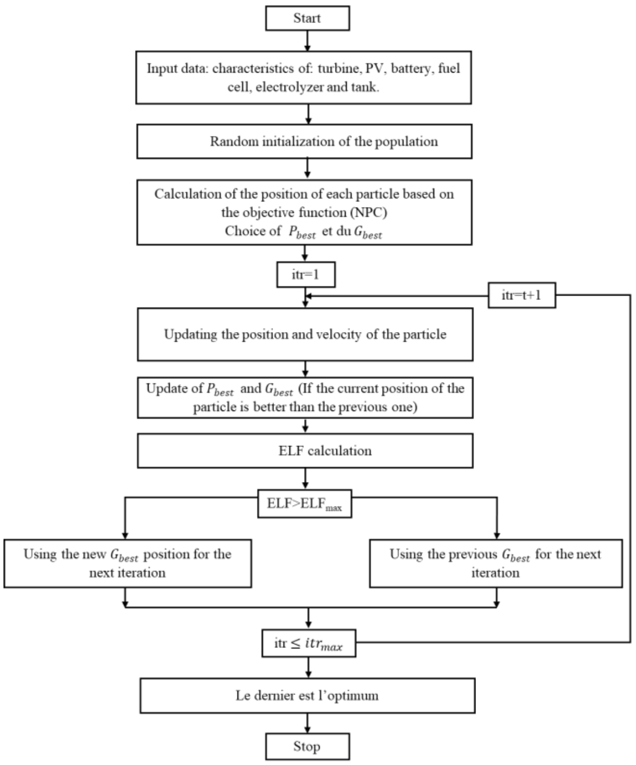

Fig. 5. Particle Swarm Optimization flowchart.

Table V. - GA and PSO Parameters.

	QUANTITY	VALUE
PSO parameters	Swarm size	50
	Max. number of iterations	100
	Personal acceleration coefficient	1,5
	Social acceleration coefficient	1,5
	Inertia coefficient	0,7298
	Inertia coefficient damping Ratio	1
GA parameters	Number of variables	23
	Population Size	100
	Max. number of iterations	200
	Crossover percentage	0,8
	Mutation rate	0,02
	Number of mutants	random

4. Simulation Results

The optimal sizing was applied to meet the energy consumption of the residential loads. To address the problem of intermittent renewable energies, energy management strategy is adopted. This strategy considers the availability of green energy and the load demand at all times. The optimization algorithms are intended to select the best configuration, considering the aforementioned constraints. In order to find the optimal solution to achieve the minimum cost, we ran the simulations several times based on one year's data. Table VI presents the results obtained by the two optimization methods with the minimum installation cost NPC (Net Present Cost).

Table VI. - The Optimization Results

OPTIMIZATION METHOD	PSO	GA
N_{tt}	1	1
N_{pv}	7	7
N_b	5	6
N_{elz}	1	1
N_{fc}	1	1
N_h	37	34
NPC ($)	4,590e+07	4,517e+07
ELF	0,0195	0,0196
LPSP	0.0473	0.0470

Convergence was achieved at the 39th and 31st iteration for PSO and GA, respectively. The optimal cost obtained by PSO is $45.9 MM, suggesting to use 1 tidal turbine, 7 photovoltaic arrays, 5 batteries, one electrolyzer, one fuel cell, and 37 hydrogen tanks (which represents a total capacity of 370 kg at pressure level of 30 bar), with an ELF equal to 1,95% and an LPSP equal to 4,73%. The results obtained by GA are similar to those obtained by PSO, except for the number of batteries that is 6 and the number of tanks that is 34 (a total capacity of 340 kg), the installation cost is $45,17 MM with an ELF equal to 1,96% and an LPSP equal to 4,7%. Compared with the PSO algorithm, the genetic algorithm reduces the NPC by 1,59%, which is not enormous. The results are consistent and almost similar, this allows us to validate the energy management we have developed on Matlab as well as the two optimization algorithms.

To better visualize the proposed optimal system, Fig. 6 illustrates the energy generated by the hybrid system and the energy consumed by the load during one week (168h). From this graph, we can see that the batteries and fuel cells cover the periods when the energy generated is not sufficient to supply the load, especially at night since there is no photovoltaic energy. Similarly, the batteries are charged and the electrolyzer produces hydrogen when the power generated is greater than that required. The electrolyzer and fuel cell do not operate simultaneously, avoiding the use of a hydrogen production system as an electrical storage system. The amount of hydrogen never goes below 74 kg (minimum allowed quantity), which means that the constraints imposed on the hydrogen system are satisfied, as shown in Fig. 7. Fig. 8 presents the contribution of each technology to the system's total cost. We can clearly notice that the fuel cell has the major share in the total cost, up to 26,13%, due to its high capital cost and replacement cost, which is why only one fuel cell is proposed, followed by the tank, the tidal turbine, the PV arrays, and the electrolyzer. Thus, a significant reduction in the cost of fuel cells and tidal turbines can lead to further savings. Batteries have a relatively low cost, hence their minor contribution to the NPC compared to the other components. It is worth noting that there is no replacement cost for tidal turbines, PV arrays, electrolyzers, and hydrogen tanks since their life span is equal to the system life span (20 years).

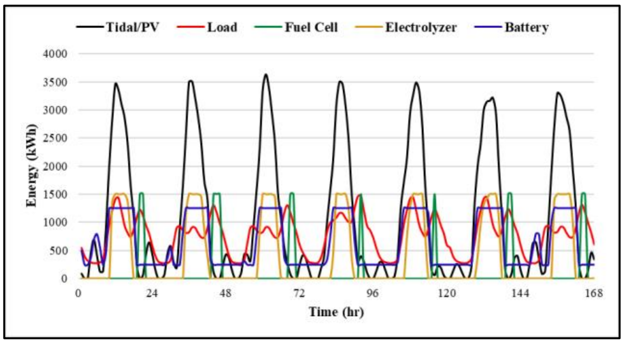

Fig. 6. The generated energy from the hybrid system and the demand energy for one week.

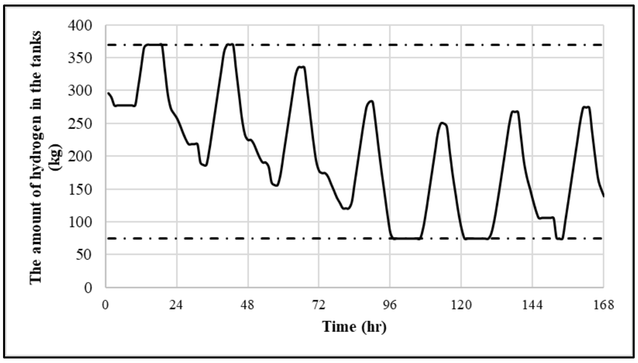

Fig. 7. The amount of hydrogen in the hydrogen tanks.

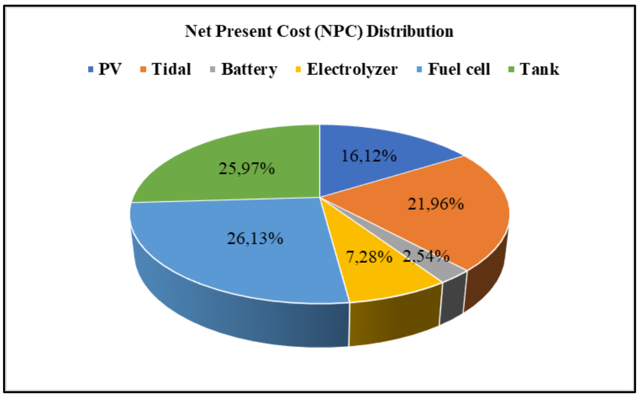

Fig. 8. The contribution of each component in NPC.

4. Conclusion

In this paper, the optimal sizing of new hybrid renewable sources is presented, using two algorithms called PSO and GA. In order to address the renewable sources intermittency, energy management strategy had been implemented to balance energy between production and consumption. Net Present Cost (NPC) has been selected as an objective function, considering LPSP and ELF as reliability indices. The results showed that GA is better compared to PSO, in terms of cost savings, with an NPC of $45,17 MM.

The proposed method can be applied to a wide variety of problems; it offers a compromise between the solution quality and the calculation time of the optimization problem. It can be used as a support tool to optimize the sizing of the power supply system for various loads such as data centers oriented towards solutions aimed at autonomy, economy, and ecology.

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