

Comparative Study on Storage Devices for Standalone Hybrid Energy Systems

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Abstract

Background/Objectives: The intermittency in the renewable sources is a great menace to the quality of the power delivered and to the lifetime of the components. In the process of straightening up the short coming storage devices come in handy. **Methods/Statistical Analysis:** Batteries and fuel cells are the commonly used storage devices for Photovoltaic system. Recently ultra-capacitors are introduced in combination with storage devices as it has a better power density as compared to batteries and fuel cells. Also, the ultra-capacitors can provide higher energy for a short period of time. This paper deals with comparison of different storage devices incorporated with the Photovoltaic panels. A combination of PV/battery, PV/fuel cell and PV/battery/ultra-capacitor are taken into consideration. **Findings:** The number of PV panels in parallel, number of batteries in parallel and the number of fuel cells are the variables that are considered for the minimization of cost and Expected Energy Not Served (EENS) using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) in MATLAB programming environment. The load profile and the solar irradiation data of Zaragoza (Spain) are considered for implementation. It is finally concluded that PV/battery/ultra-capacitor combination gives minimum cost and EENS as compared to the PV/battery and PV/fuel cell based systems. **Applications:** This can be applied as an optimization tool to bring out the conclusion in choosing an appropriate storage device, in combination with the renewable PV based standalone system.

Keywords: Expected Energy Not Served, Photovoltaic Panels, Proton Exchange Membrane Fuel Cell, State of Charge, Ultra-Capacitor

1. Introduction

The depleting nature of fossil fuel has led to the development of sustainable energies such as wind and solar. Broadly speaking, the standalone Photovoltaic systems are preferred in remote locations, due to the price and trouble involved in extending the national grid. As the renewable energy systems such as wind and solar are intermittent in nature, they need energy storage devices to balance the load demand. Storage devices in standalone solar PV systems guarantee energy supply during times when there is no sunlight or when it is available but not at the required intensity as on cloudy days. Storage is also so important to improve system reliability. Batteries and fuel cells are most commonly used storage devices. Combination of batteries and ultra-capacitors are also used as storage devices as this will improve battery life and reliability.

In Photovoltaic system which employs battery as the only storage device, the rapid load power variation reduces the lifetime of the battery due to high discharge current. Though this surge current has to be met only for a few seconds, it requires a large battery capacity to account for the increased current discharge. In comparison to commonly used battery storage, fuel cell is well suited for seasonal storage, because of its inbuilt high mass energy density and longevity of energy storage¹⁰. In such a hybrid system, electricity production in excess of demand is converted to hydrogen, using an electrolyzer and electricity requirement in excess of production is met by converting the stored hydrogen back to electricity using a fuel cell^{8,9}. Ultra-capacitors supply more energy over a shorter period of time, as it has better power density than batteries^{16,17}. On the contrary, the batteries have a higher energy density than the ultra-capacitors to supply the load power requirement. The ultra-capacitor when added

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with the batteries increases the lifetime of the battery, as the high fluctuating current discharge is taken care by the ultra-capacitors. This in turn reduces the system lifetime cost. In the hybrid system, the ultra-capacitor supplies the peak fluctuating currents while the battery supplies the average current. This utilizes the battery more efficiently and reduces the risk of premature loss of load¹⁸.

The economic advantages of the PV-hybrid system with respect to other energy sources and storage devices are analysed by many researchers¹. Among the different storage devices, it has been suggested that during load transition period, the super capacitor provides necessary energy balance at a faster rate². Different techniques were also proposed to solve the optimization of cost and reliability in standalone system. A technique was proposed to arrive at an optimal standalone hybrid PV/Wind/Diesel/battery bank using MOGA to minimize the leveled cost of energy and carbon di oxide emission³. A triple multi objective optimal design to reduce the total cost of the standalone hybrid power system was developed using MOPSO/NSGA-II⁴ by considering various inequality constraints. The sizing of the unit based on an economical operation and evaluation of a hybrid Wind/Fuel cell generation system using PSO was developed⁵. A sizing method was also proposed using GA for a hybrid solar-wind system employing a battery bank to optimize the configuration, by minimizing LPSP and annualized cost of the system⁶. The standalone PV system using different energy storage technologies are modeled and optimized and it also facilitates the estimation of storage capacity and calculation of the system efficiency⁷. A grid independent hybrid PV/Wind system optimization model which utilizes the iterative optimization technique was proposed and it followed the LPSP model, leveled unit electricity model for power system reliability and cost⁸. The two active hybrid fuel cell/battery power sources were proposed to enhance the power and its density based on its system control design⁹. An algorithm for optimal sizing of a standalone hybrid wind diesel electric power generation system in terms of minimum energy cost was reported and that system also exposes the optimum power electronic converter ratings which has a non-linear relationship¹⁰. To optimize the sizing of the hybrid power generation system employing a battery bank, Hybrid Solar Wind system optimization sizing model was developed¹¹. A generic fuel cell was modeled, to represent the behavior of the fuel cells fed

with hydrogen and air¹². The dynamic characteristic of a fuel cell model in conjunction with power electronic circuit was analysed¹³. An improved non-linear dynamic modeling and control of a PEM fuel cell stack¹⁴ power system for vehicle application was proposed and it has been simulated using MATLAB/Simulink^{15,16}. Energy management of multi power sources was projected as a solution for a hybrid energy system which uses solar cells, fuel cells and a super capacitor as an energy storage device¹⁷. The characteristic of the specific energy and power of the hybrid system were found by a hardwired parallel combination of state of the art rechargeable Lithium ion battery and super capacitor¹⁸. The super capacitor was used as a storage device in a standalone PV system and its characteristic was analyzed via PSIM simulation¹⁹.

In this paper comparison of different storage devices like battery, fuel cells and combination of batteries and ultra-capacitors is carried out in MATLAB programming using NSGA-II based on cost and EENS parameters. Comparative study is done for each storage device with PV system and also as a combination. The radiation data of Spain is used. This paper considers acquisition cost, operation and maintenance cost and replacement cost of storage devices and PV panels. The combinations PV/batteries, PV/fuel cells and PV/ultra-capacitor/batteries are analyzed based on cost and reliability.

2. Modelling

2.1 PV Model

The chosen PV panel provides the DC supply at 48 V. The output of the PV source is represented by current modeling¹. The power output of each PV panel at any time instant is given by:

$$P_{PV_i} = N_p \cdot N_s \cdot V_{PV} \cdot I_{PV_i} \quad (1)$$

Where N_p is the number of PV panels in parallel, N_s is the number of PV panels in series and V_{PV} is the PV panel's DC voltage. The PV panel's current at the i th hour is given by:

$$I_{PV_i} = G_i I_p \quad (2)$$

Where G_i is the irradiation of Zaragoza, Spain in hours and I_p is the peak current of the panel.

2.2 Battery Model

The battery bank is considered as a backup source. They are charged or discharged based on the dispatch strategy⁷. For given time step, the maximum current¹¹, the battery can provide is given by:

$$I_{bat\ max}(t + \Delta t) = \max \left[0, \min \left\{ I_{\max} \left(\frac{c}{\Delta t} SOC_{\max} - SOC(t) \right) + \left(SOC(t) - SOC_{\min} \right) \frac{1-c}{\Delta t} \right\} \right] \quad (3)$$

Where $I_{bat\ max}$, is the maximum charge current, SOC is the state of charge of battery banks at a time t , c is a binary variable defined as:

$$c = \begin{cases} 1 & \text{battery is charging} \\ 0 & \text{battery is discharging} \end{cases} \quad (4)$$

The minimum and maximum state of charge of the battery bank is given as SOC_{\min} and SOC_{\max} respectively:

$$SOC_{\min} = N_{bat_p} C_N (1 - DOD_{\max}) \quad (5)$$

$$SOC_{\max} = N_{bat_p} C_N \quad (6)$$

Where C_N is the nominal capacity in Ah, N_{bat_p} is the number of batteries connected in parallel, DOD_{\max} is the maximum depth of discharge.

For the next time step, the state of charge of the battery is given by:

$$SOC(t + \Delta t) = SOC(t) \cdot (1 - \delta) + I_{bat}(t) \cdot \Delta t \cdot \eta_{bat} \quad (7)$$

Where δ is the self-discharge coefficient and η_{bat} is the efficiency and I_{bat} is the previous time step's battery current.

2.3 Fuel Cell Model

A fuel cell, similar to battery converts chemical energy to electrical and thermal energy^{12,13}. From among the different types of fuel cells, Proton Exchange Membrane based Fuel Cell (PEMFC) has been considered for the study¹⁴. It can be operated at low temperature of about 80° K with high power density. Proton exchange membrane has high startup system and shadow system performance. These advantages have increased the interest of research on fuel cells in recent years, especially in stationary and mobile power generators and electric vehicles. Two factors that are responsible for proliferation of trade of fuel cell technology are high performance and low cost. Fuel cell performance has been influenced by operating

conditions, material properties and cell design.

Generally, two configurations are available for operating the fuel cell;

- A fuel cell which uses electrolyser to produce hydrogen (and stores H_2 in the tank).
- A fuel cell which uses external hydrogen and does not require electrolyser or tank.

This paper adopts configuration 1, where no external source of hydrogen is available but an electrolyzer is used to produce hydrogen.

Figure 1 indicates the amount of hydrogen needed to obtain the desired power output from a fuel cell. It is observed that it requires a minimum of 0.008 kg/hr of hydrogen mass flow rate to generate electricity.

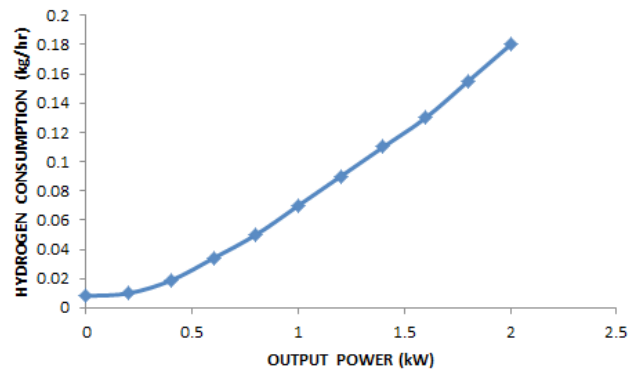


Figure 1. Efficiency and consumption of a particular fuel cell.

The fuel cell can be modelled as follows:

$$\text{If } P / P_{N\ FC} \leq P_{\max\ ef} (\%) \quad (8)$$

$$Cons_{FC} = B_{FC} P_{N\ FC} + A_{FC} P$$

$$\text{If } P / P_{N\ FC} > P_{\max\ ef} (\%)$$

$$Cons_{FC} = B_{FC} P_{N\ FC} + A_{FC} P \left(1 + F_{ef} \left(\frac{P}{P_{N\ FC}} - \frac{P_{\max\ ef} (\%)}{100} \right) \right) \quad (9)$$

Where $Cons_{FC}$ is the consumption of hydrogen, A_{FC} (kg/kWh), and B_{FC} (kg/kWh) are the power coefficients Consumption Parameters, $P_{\max\ ef}$ is the rated efficiency of the fuel cell at maximum efficiency, F_{ef} is Faraday's efficiency and $P_{N\ FC}$ is the nominal rating of the fuel cell.

2.4 Electrolyzer Model

Figure 2 shows the electrical input power for different hydrogen output flow. It can be seen that the electrolyzer requires 0.6 kW electric powers to begin generating hydrogen.

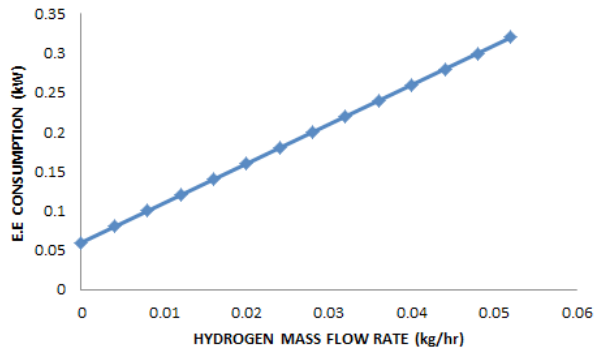


Figure 2. Efficiency and consumption of an electrolyzer.

2.5 Ultra-capacitor Model

The equivalent circuit of an ultra-capacitor is shown in Figure 3. The circuit consists of a capacitance C , an equivalent series resistance and parallel resistances R_{es} and R_{ep} respectively^{2,15}.

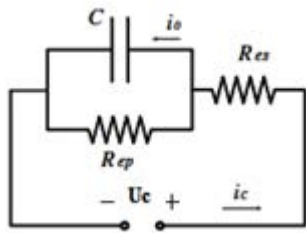


Figure 3. Equivalent circuit of ultra-capacitor.

During charging period, the current input I_c and voltage input U_c of the ultra-capacitor is expressed as:

$$I_c = I_0 + \frac{1}{R_{ep}C} \int I_0 dt \quad (10)$$

$$U_c = I_c * R_{es} + \frac{1}{C} \int I_0 dt \quad (11)$$

Where I_0 is the total current in the ultra-capacitor and C is the capacitance of the individual ultra-capacitor.

Based on the voltage and current rating, ultra-capacitor cells are connected in parallel and in series to form the ultra-capacitor banks. The total capacitance C_{tub} and resistance R_{tes} of the UB are calculated as:

$$C_{tub} = C \frac{n_p}{n_s} \quad (12)$$

$$R_{tes} = R_{es} \frac{n_s}{n_p} \quad (13)$$

Where n_p is the number of cells connected in parallel and n_s is the number of cells in series.

While discharging, the terminal current (I_{tub}) and the voltage (V_{tub}) of the ultra-capacitor bank, at any time instance is expressed as:

$$I_{tub} = C_{tub} \frac{dV_{tub}(t)}{dt} \quad (14)$$

$$V_{tub}(t) = V_{tub0} - \frac{1}{C_{tub}} \int_0^t I_{tub}(t) dt \quad (15)$$

Where V_{tub0} is the initial voltage of the ultra-capacitor.

The stored energy in an ultra-capacitor is given as:

$$W_{tub} = \frac{1}{2} C_{tub} (V_{tub_max}^2 - V_{tub_min}^2) = n_p * n_s * W_c \quad (16)$$

Where W_c is the stored energy in an ultra-capacitor cell.

The output voltage from the ultra-capacitor is given by:

$$V_{tub_out}(t) = V_{tub}(t) - I_{tub}(t) * R_{tes} \quad (17)$$

The power output from the ultra-capacitor is calculated as:

$$\begin{aligned} P_{tub_out}(t) &= V_{tub_out}(t) * I_{tub}(t) \\ &= I_{tub}(t) * (V_{tub}(t) - I_{tub}(t) * R_{tes}) \\ &= I_{tub}(t) * (V_{tub0} - \frac{1}{C_{tub}} \int_0^t I_{tub}(t) dt - I_{tub}(t) * R_{tes}) \end{aligned} \quad (18)$$

2.6 Cost Model

The generation system should ensure a continuous supply of power and should also be affordable. But, in order to increase the reliability of the system, the resources should also be increased, resulting in increased costs. The main objective of any generation system is to optimize the reliability and cost. The common methods adopted in the calculation of the cost functions³ are Annualized Cost of the System (ACS)^{4,6}, Net Present Value (NPV), etc. This paper adopts the Net Present Value of the system for cost calculation.

2.6.1 Net Present Value

The Net Present Value of the system components includes

acquisition cost, replacement cost, operation and maintenance cost which are computed for the life time of the system. Mathematically, the NPV value is given by:

$$NPV = C_{ACQ} + C_{OM} + C_{REP} \quad (19)$$

Where, C_{ACQ} is the acquisition cost, C_{OM} is the operation and maintenance cost and C_{REP} is the replacement cost.

2.6.2 Total Cost

The total cost of the hybrid energy system during the measured period is obtained by adding the Net Present Values of the individual components of the system.

$$Cost = NPV_{pv} + NPV_{bat} + NPV_{reg} + NPV_{uc} \quad (20)$$

Where NPV_{pv} , NPV_{bat} and NPV_{reg} are the Net Present Values of Photovoltaic panels, batteries and charge regulator respectively; NPV_{uc} is the total cost of ultra-capacitor.

3. Reliability Calculation

The Expected Energy Not Served (EENS) is estimated to assess the system reliability. At every hour, if the total energy from the renewable and backup source meets the load requirement, then the EENS for that hour is considered as 0. Otherwise the EENS for that hour will be the difference between the energy needed by the load and the energy provided by the source. EENS for every hour is summed up to find the EENS of a year. The EENS in percentage is expressed as:

$$EENS = \frac{\sum_{i=1}^{8760} EENS(i)}{E} \quad (21)$$

Where the $EENS(i)$ is the expected energy not served for i^{th} hour and E is the total energy demand of the system for 8760 hours.

4. Non-dominated Sorting Genetic Algorithm

NSGA is a non-domination based Genetic Algorithm for resolving multi-objective optimization problem. It is a very effective algorithm but has computational complexity, lack of elitism and an inbuilt difficulty in choosing the

optimal value for the sharing function. A modified version, the NSGA-II with better sorting algorithm was developed. This algorithm incorporates elitism and does not require prior selection of sharing parameter. The algorithm starts with the initialization of population and sorts the population based on non-domination into different fronts. The first front is the completely non-dominant set in the current population and the second front is dominated by the individuals in the first front, the front goes on. The individual fitness values in each of the front are assigned with ranking based on the front they belong to. Individuals in first front are given a value of 1 and individuals in second are assigned the fitness value as 2 and so on. Then, the crowding distance for each of the individual is calculated. The crowding distance is a measure of how close an individual is to its neighbours. Large crowding distance in the population results in better diversity. Based on the ranking assigned and the crowding distance the parents are selected using binary tournament selection. An individual is selected if the rank is lesser than the other or if crowding distance is greater than the other.

Based on non-domination, again the current population and offspring are sorted and the best N individuals are selected, where N is the population size. Figure 4 shows the flow chart of this algorithm.

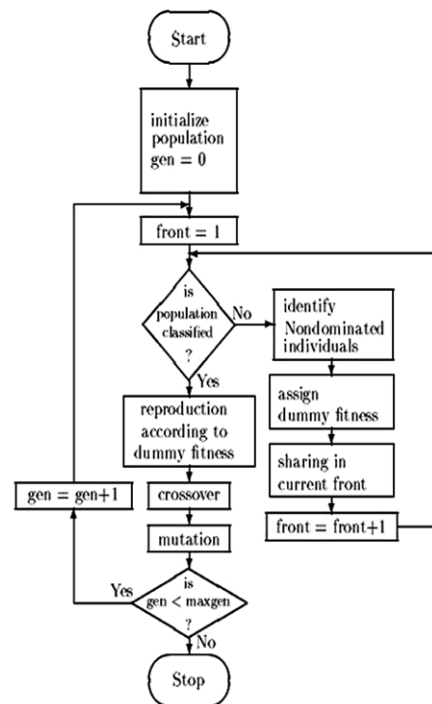


Figure 4. NSGA-II algorithm.

5. Results

Combinations of storage devices PV/battery, PV/fuel cell, PV/battery/ultra-capacitor to meet the given load are analyzed taking cost and Expected Energy Not Served (EENS) as the objectives. Finally, the best combination is arrived at from the results obtained.

5.1 System Data

The NSGA-II is used in the optimization of the cost and reliability (EENS). Tournament selection is utilized in the NSGA-II algorithm with the cross over rate of 0.8. The number of PV panels in parallel, number of batteries and the number of fuel cell are taken as variables. The maximum and minimum limits of the variables are given as [1, 100], [1, 20] and [1, 10] for PV panel, battery and fuel cell respectively.

The 24-hour sample load data considered for implementation is shown in Figure 5. This load profile is extended for 8760 hours.

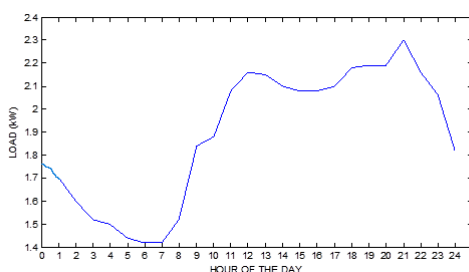


Figure 5. Load profile.

The radiation data for this design is that of Zaragoza in Spain. The monthly average solar irradiation data is taken

from the NASA metrological database which is converted to hourly data for 8760 hours using the i-HOGA software and it is plotted in Figure 6.

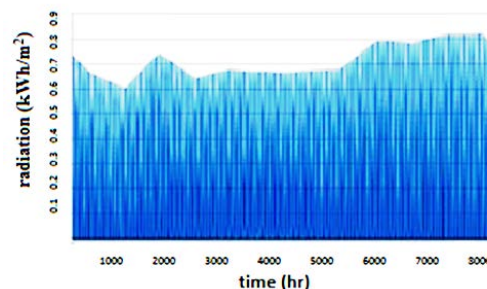


Figure 6. Radiation data.

Four PV panels, each of 12 V DC are connected in series to maintain a voltage of 48 V DC. The number of PV panels to be connected in parallel is considered as one of the variable out of the different types of PV panels available from different manufacturers, one of the PV panel type chosen from i-HOGA database is mentioned in Table 1.

Table 1. PV panel data

PV panel type	Current (A)	Acquisition cost (€)	O&M cost (€/year)	Lifespan (year)
1	1.32	109	1.09	25

The four batteries of 12 V each are connected in series to maintain a voltage of 48 V DC in the system. The number of batteries to be placed in parallel is considered as variable. The ten different types of batteries considered for analysis are tabulated in Table 2.

Table 2. Battery data

Type	Nominal capacity (Ah)	Acquisition cost (€)	O & M (€/hr)	Max current	DEL	Efficiency (%)	No. of cycles	Float life (years)
1	68	166	1.7	13.6	0.03	85	1110	15
2	78	254.9	2.55	15.6	0.02	85	1400	18
3	97	150	1.49	19.4	0.05	80	450	12
4	106	194.9	1.95	21.2	0.05	80	450	12
5	120	160	1.6	24	0.05	80	450	12
6	134	154	1.54	26.8	0.05	80	450	12
7	170	464	4.64	34	0.03	85	1110	15
8	189	174.9	1.75	37.8	0.05	80	450	12
9	190	562	5.61	38	0.02	85	1400	18
10	296	961	9.6	59.2	0.03	85	1110	15

Optimization of cost and EENS is done considering PV/batteries. If excess power is produced from the PV panel, it is used to charge the battery. If the power produced by the PV system is not enough to meet the demand, then the battery is discharged to meet the demand. There is a State of Charge (SOC) limits to which the battery can be charged and discharged.

Figure 7 shows the Pareto front plot of cost vs. EENS obtained from battery Type 3 for 8760 hours. In the system, the best compromised solution obtained from the knee point of the Pareto optimal front for cost and EENS are 20884.80 € and is 0.09600 respectively.

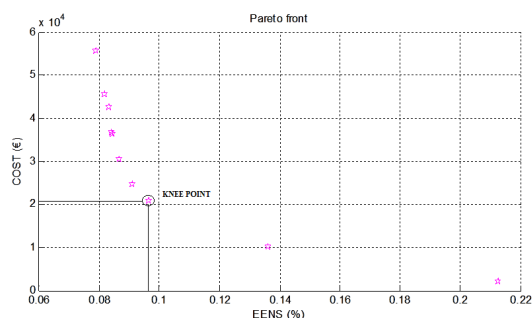


Figure 7. Pareto front of COST vs. EENS for PV/battery system.

Table 3 shows the best compromised solutions of cost and reliability for the ten different types of batteries.

Table 3. Cost and EENS values for PV/battery system

SL No.	EENS(%)	Cost(€)	No. of Batteries	No. of PV
1	0.081195	54730.04	8	91
2	0.083725	46515.35	4	77
3	0.096000	20884.82	3	32
4	0.078804	58230.27	5	99
5	0.082582	41779.62	3	73
6	0.082442	41004.92	3	72
7	0.081365	50926.15	3	82
8	0.088317	26574.12	3	44
9	0.079248	72010.77	8	91
10	0.085694	36785.11	1	53

PV with fuel cells is considered for optimization of

Table 4. Fuel cell data

Type	Power(kW)	Cost (€)	O & M (€/h)	Life time(h)	A (kg/ kWh)	B (kg/ kWh)	P min (%)	Pmax_eff(%Pn)	Fef
1	1	9100	0.26	15000	0.05	0.004	10	20	1
2	2	15600	0.26	15000	0.05	0.004	10	20	1
3	5	26000	0.39	15000	0.05	0.004	10	20	1

cost and EENS. Number of fuel cells and the number of PV panels in parallel are taken as variables. Three different types of fuel cells are considered as in the Table 4.

If excess power is available from the PV panel, then this power will be converted into hydrogen by electrolyzer and stored in the hydrogen tank. If the PV system is unable to meet the power demand, then the fuel cell converts the hydrogen stored in the hydrogen tank to electricity and uses it to meet the load demand.

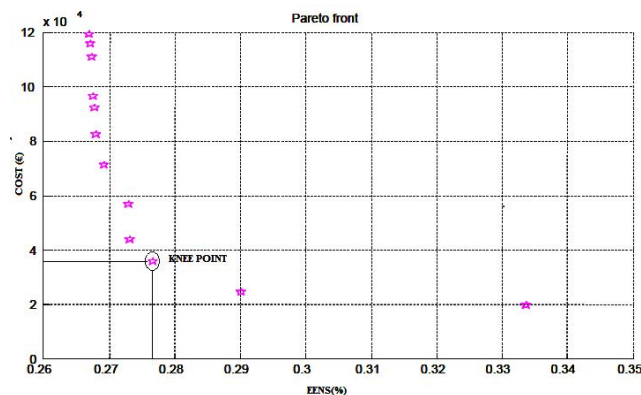


Figure 8. Pareto front of EENS vs. COST for type 2 fuel cell.

Figure 8 shows the Pareto front plot of cost vs. EENS obtained for 2nd type of fuel cell for 8760 hours. The best compromised solution is 35739.54€ for cost and 0.276649 for EENS from the Pareto front plot.

Table 5 shows the best compromised solution of cost and EENS obtained for the three different types of fuel cells.

Table 5. Cost and reliability of hybrid system with fuel cell

SL. No.	EENS(%)	Cost(€)	No. of fuel cells	No. of PV panels
1	0.268966	63542.63	1	99
2	0.276649	35739.54	1	32
3	0.267239	105799.8	1	143

Table 6 shows the type of ultra-capacitor chosen in this paper. Ultra-capacitor has high power density and battery

has high energy density. So ultra-capacitor is made to operate at high peak power demand and when constant power supply is needed then the battery is utilized.

Table 6. Ultra-capacitor data

Ultra-capacitor	Capacitance (F)	Voltage (V)	Weight (g)	Cost (€)	Volume (L)
Maxwell Model	450	2.5	190	46.81	0.15

Number of batteries and number of PV panels are taken as variables. The excess power from the PV system is utilized to charge the battery. After charging the battery and if still excess power is available then, ultra-capacitor is charged. If the power from the PV panel is not sufficient to meet the load, then the power is drawn from the ultra-capacitor first and then from the battery.

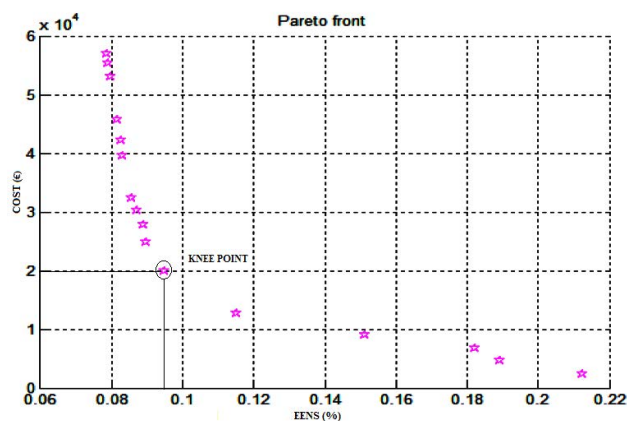


Figure 9. Pareto front of EENS vs. COST for PV battery with ultra-capacitor.

Figure 9 shows the Pareto front plot of cost vs. EENS obtained for a combination of battery and ultra-capacitor as storage devices for 8760 hours. The best compromised solution from the Pareto front for the cost of the system is 20000€ and EENS is 0.0930.

The comparison of different combination of storage devices that includes the PV/battery, PV/fuel cell, PV/battery/ultra-capacitor are done in two different ways. One is based on the minimum cost obtained from best compromised solution of the Pareto optimal front and the other is based on the fixed number of PV panels. Table 7 denotes the comparison based on the minimum cost of the combination. It is observed that the cost and EENS are minimum for the system with PV/battery/ultra-capacitor than for the system with battery or fuel cell individually.

Table 7. Comparison of different storage devices based on minimum cost

Battery as a storage device		Fuel cell as a storage device		Battery along with ultra-capacitor as storage device	
Cost(€)		EENS (%)		EENS (%)	
0.096	20884.82	0.27664	35739.54	0.093	20000

While using a combination of battery and ultra-capacitor, they complement each other and hence the performance of the hybrid system enhances. It is observed in a long run, the cost and reliability is better for combination of ultra-capacitors and batteries while comparing with individual storage devices like batteries and fuel cell.

Table 8 shows the comparison of different storage devices based on the fixed number of PV panels (99). From the results it is seen that while considering EENS and cost as parameters the combination of PV/battery/ultra-capacitor is most suitable for implementation.

Table 8. Comparison of different storage devices with fixed number of PV panels

Pv/battery as a storage device		Pv/fuelcell as a storage device		Battery along with ultra-capacitor as storage device	
Cost(€)		EENS (%)		EENS (%)	
0.079	55570.8	0.268966	63542.63	0.079728	53152.33

As already explained addition of ultra-capacitor with battery will reduce the strain on battery and hence the life cycle of battery will increase. Ultra-capacitor has long life span and hence the operation and maintenance cost and replacement cost will reduce for this combination. Hence in long run the cost will be minimum for combination of batteries and ultra-capacitor while comparing with batteries and fuel cells as storage devices.

6. Conclusion

In this paper storage device like batteries, fuel cells and batteries with ultra-capacitors are compared to arrive at the best combination with the PV system. The Non-

dominated Sorting Genetic Algorithm (NSGA-II) technique is employed to optimize the EENS and cost parameters of PV/battery, PV/fuel cell and PV/battery/ultra-capacitor combinations. The effect of including the ultra-capacitor in the Photovoltaic system is analyzed. The batteries and ultra-capacitors complement each other in terms of their power and energy densities. While using fuel cell the cost and the EENS of the system is not optimum on comparison with the battery and ultra-capacitor. The conclusion arrived at is unique for both the cases of the number of PV panels fixed as well as the minimization of cost of the combination. Adopting the NSGA-II technique it is concluded that for both the cases PV/battery/ultra-capacitor combination gives minimum cost and EENS when compared to the PV/battery and PV/fuel cell systems.

7. References

1. Dufo-Lopez R, Jose L, Agustín B. Design and control strategies of PV-diesel systems using Genetic Algorithms. Elsevier - Solar Energy. 2005; 79:33–46.
2. Lajnef W, Vinassa JM, Briat O, Azzopardi S, Woïrgard E. Characterization methods and modelling of ultra-capacitors for use as peak power sources. Journal of Power Sources. 2007; 168:553–60.
3. Ould Bilala B, Sambou V, FKebe CM, Ndiaye PA, Ndong M. Methodology to size an optimal standalone PV/wind/diesel/battery system minimizing the levelized cost of energy and the CO₂ emissions. Energy Procedia. 2012; 14:1636–47.
4. Farahat S, Yazdanpanah Jahromi MA, Barakati SM. Modeling and sizing optimization of standalone hybrid renewable energy systems. International Conference on Mechanical, Nanotechnology and Cryogenics Engineering (ICMNC'2012); 2012 Aug, p. 25–6.
5. Hakimi SM, Tafreshi SMM, Kashefi A. Unit sizing of a standalone hybrid power system using Particle Swarm Optimization (PSO). Proceedings of the IEEE International Conference on Automation and Logistics; 2007 Aug.
6. Yang H, Zhou W, Lu L, Fang Z. Optimal sizing method for standalone hybrid solar–wind system with LPSP technology by using Genetic Algorithm. Solar Energy. 2008; 82:354–67.
7. Li CH, Zhu XJ, Cao GY, Sui S, Hu MR. Dynamic modeling and sizing optimization of standalone Photovoltaic power systems using hybrid energy storage technology. Renewable Energy. 2009; 34:815–26.
8. Kaabeche A, Belhamel M, Ibtouen R. Sizing optimization of grid-independent hybrid Photovoltaic/wind power generation system. Energy. 2011; 36:1214–22.
9. Gao L, Jiang Z, Dougal RA. An actively controlled fuel cell/battery hybrid to meet pulsed power demands. Journal of Power Sources. 2004; 130:202–7.
10. Saha TK, Kastha D. Design optimization and dynamic performance analysis of a standalone hybrid wind–diesel electrical power generation system. IEEE Transactions on Energy Conversion. 2010 Dec; 25(4):1209–17.
11. Yang H, Lu L, Zhou W. A novel optimization sizing model for hybrid solar-wind power generation system. Solar Energy. 2007; 81:76–84.
12. Souleman NM, Tremblay O, Dessaint LA. A generic fuel cell model for the simulation of fuel cell power systems. IEEE Power and Energy Society General Meeting; 2009 Jul.
13. Xin K, Khambadkone AM. Dynamic modelling of fuel cell with power electronic. IEEE; 2003.
14. Somanath N, Seshi Reddy D. Efficient power management strategies for inter-grid connected PV-FC hybrid system. Indian Journal of Science and Technology. 2015 Sep; 8(22).
15. Yu Q, Srivastava AK, Choe SY, Gao W. Improved modeling and control of a PEM fuel cell power system for vehicles. IEEE Proceedings of the SoutheastCon; 2006.
16. Kim MJ, Peng H, Lin CC, Stamos E, Tran D. Testing, modeling and control of a fuel cell hybrid vehicle. American Control Conference; 2005 Jun. p. 3859–64.
17. Thounthong P, Chunkag V, Sethakul P, Sikkabut S, Pierfederici S, Davat B. Energy management of fuel cell/solar cell/super capacitor hybrid power source. Journal of Power Sources. 2011; 196:313–24.
18. Cericola D, Ruch PW, Kotz R, Novak P, Wokaun A. Simulation of a super capacitor/Li-ion battery hybrid for pulsed applications. Journal of Power Sources. 2010; 195:2731–6.
19. Li J, Chen Y, Liu Y. Research on a standalone Photovoltaic system with a super capacitor as the energy storage device. Energy Procedia. 2012; 16:1693–700.