Optimal Sizing of a PV/Wind Hybrid System using Pigeon Inspired Optimization

Aeidapu Mahesh
Electrical Engineering Department
NIT Kurukshetra
Email: mahesh.aeidapu@gmail.com

Kanwarjit Singh Sandhu
Electrical Engineering Department
NIT Kurukshetra
Email: kjssandhu@rediffmail.com

***Abstract*—This paper presents an optimal sizing study of a stand-alone hybrid PV/wind energy system (HPWES)with battery storage. The main objective of the optimization is minimization of the total system cost while satisfying the reliability constraint and maintaining the healthy charge on the battery. A relatively new optimization technique, pigeon inspired optimization (PIO) has been used to optimize the system. A break-even analysis has also been performed whether the wind/battery (WB) or a PV/wind/battery (PWB) system is more cost-competitive. The effectiveness of the proposed strategy has been verified through a case study and the results indicate that the PWB hybrid system is more economical when compared to the WB system.**

Keywords: Hybrid renewable energy systems; size optimization; pigeon inspired optimization

I. INTRODUCTION

The renewable energy sources such as solar and wind energy are certain to play a vital role in the future energy scenario due to the steep fall in the fossil fuel reserves, raising environmental concerns and the ever increasing load demand. Even though the renewable sources are freely and abundantly available in nature, the major issue in utilizing the renewable sources to full extent is the unpredictable nature, due to which the power generated will be always fluctuating. Due to this fluctuating nature, these sources when explored independently requires a storage. But, often these stand-alone PV or wind system requires a huge storage to satisfy the load demand which will reduce its economical benefits.

One of the unique feature of the PV and wind energy sources is their complementary nature, with which they support each other very well during all climatic conditions. By taking advantage of this feature a hybrid PV/wind energy system can be formed which will be more reliable. As atleast one of the sources is available all the time, which will reduce the storage requirement and the system will be more cost-effective [1], [2].

In order to get the actual benefits in terms of economic as well as reliability of the HPWES, the system must be properly sized for a particular location. The main aim of any optimal sizing is to minimize the cost of the system, while satisfying the reliability, area constraints. According to the available literature, several researchers have addressed this problem in different ways. Few authors have used graphic construction methods [3], [4] and others used iterative techniques [5]–[9]. But, the problem with the graphic construction technique is that it cannot be applied for more variable problems and the iterative techniques doesn't guarantee you the global optimum value. So, for solving these multi-objective optimization problems, the evolutionary algorithms have been widely utilized by the researchers. One of the main advantage of evolutionary algorithms is that these methods doesn't depend on the problem surface and they can search the entire search problem space effectively for the global optimum. The genetic algorithm(GA) has been the most used algorithm for optimal sizing studies [10]–[16] and the other include ant colony optimization [17], artificial bee swarm algorithm [18], Strength Pareto Algorithm [19] and simulated annealing [20]. This paper presents a optimal sizing study of a HPWES using a new optimization technique PIO. The PIO is also a swarm based optimization technique, but the convergence rate of this algorithm is very high when compared to it's counterparts GA and PSO. The case study presented in this work will demonstrate the effectiveness of the proposed strategy.

The paper is organized as follows, section 2 presents the mathematical modeling of the various system components, The economic modeling is presented in section 3, The PIO has been explained in detail in section 4, the proposed optimization strategy is given in section 5 and the case study & the results with detailed discussion are presented in section 6 along with the concluding remarks.

II. MATHEMATICAL MODELING OF THE HPWES

A. PV system modeling

The actual power output from the photovoltaic (PV) panel depends on the amount of solar radiation that falls on the panel G, temperature of the panel T and it is given by the equation,

$$P_{pv} = P_{pv_r} \frac{G}{G_n} \left[1 - \gamma_t . (T - T_n)\right] \tag{1}$$

where, the rated power of the PV panle is given by P_{pv_r}, T_n and G_n are the nominal temperature and irradiation respectively and γ_t is the temperature co-efficient of power. An extra multiplication factor can be used to represent the dust or the ice formation effect on the PV panel and generally it is taken as 0.8.

978-1-4673-8962-4/16/$31.00

B. Wind system

The output power of a wind system is dependent on three velocities namely the cut-in wind speed V_{ci}, cut-off wind speed V_{co} and the rated wind speed V_r, and the power output based on these velocities is given by the following equation

$$P_{WT} = \begin{cases} 0 & v(i) < V_{ci} \text{ or } v(i) > V_{co} \\ P_{r\_wt} \frac{v(i)-V_{ci}}{v_r - V_{ci}} & V_{ci} < v(i) < V_{cr} \\ P_{r\_wt} & V_{cr} < v(i) < V_{co} \end{cases} \tag{2}$$

where, P_{r_wt} is the maximum output power from a wind the wind turbine and $v(i)$ is the wind speed in (m/s) at any given instant.

C. Battery Modeling

To represent the non-linear capacity behavior of the batteries a simple analytic model is used in this work, which is called as the kinetic battery mode (KiBam). As shown in the Figure 1, this model assumes the battery as two charge tanks, one tank represents the available energy, which can be readily converted into the electrical energy when required and the other tank represents the energy called bound energy. This bound energy cannot be directly converted into the electrical energy, as it has to be first converted to available energy and then to electrical energy. The rate constant k acts like a valve between these two tanks and controls the rate of control of energy between two tanks. The capacity ratio c is the ratio of available energy to the bound energy. Whenever there is a height difference between two tanks the energy transfer takes place until the height difference is going to become zero. At each time step the available and the bound energy are calculated as,

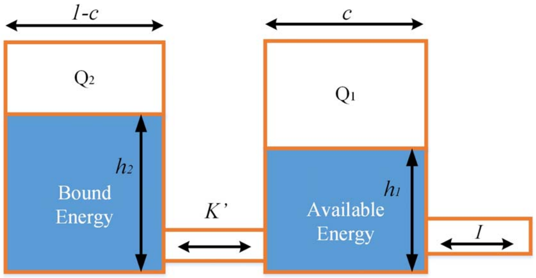

Fig. 1: Kinetic Battery Model

$$Q_1 = Q_{1_0} e^{-k(t-t_0)} + \frac{(Q_{1_0} kc - P_{bs}(t))(1 - e^{-k(t-t_0)})}{k} + \frac{cP_{bs}(t)(k(t-t_0) - 1 + e^{-k(t-t_0)})}{k} \tag{3}$$

$$Q_2 = Q_{2_0} e^{-k(t-t_0)} + Q_{2_0}(1-c)\left(1 - e^{-k(t-t_0)}\right) + \frac{P_{bs}(t)(c-1)(k(t-t_0) - 1 + e^{-k(t-t_0})}{k} \tag{4}$$

$$Q = Q_1 + Q_2 \tag{5}$$

where, $P_{bs}(t)$ is the charge or discharge power at a given instant $'t'$ based on its sign, the positive sign indicates the discharging process and the negative sign indicates the charging process. The state of charge (SOC) of the battery can be indicated by the height h_1 and when the height h_1 becomes zero, then the battery is considered to be fully discharged.

D. Energy Balance

When the system is working in stand-alone mode, in case if the power generated by the PV and wind sources combined together is more than load demand at that instant, then the surplus power will be given to the batteries for charging.

$$P_{bs\_ch}(t) = P_{pv}(t) + P_{wt}(t) - L(t) \tag{6}$$

On the other hand if the power generated is less than the load demand then the batteries will discharge to supply the load.

$$P_{bs\_dch}(t) = L(t) - P_{pv}(t) + P_{wt}(t) \tag{7}$$

III. ECONOMIC MODELING

The total cost of the system is generally divided into the following costs, i) investment cost ii) operation and maintenance cost iii) replacement cost. The investment cost C_{inv} is the initial cost one has to bear when the plant is being installed, this includes the cost of all of the equipment such as PV panels, wind turbines, batteries, converters/inverters and their installation costs. The operation and maintenance $C_{o\&m}$ in this case is the regular maintenance cost of various equipment as the fuel cost is virtually free. The replacement cost C_r is the cost, which is considered when the lifetime of the particular component is less than the plant lifetime. Along with these costs, there is a penalty cost associated with the reliability constraint, whenever the reliability of the plant falls below the acceptable limit β_L, then the penalty cost is calculated using the following equation

$$C_{pc} = C_{pc_1}(LPSP - \beta_L) \sum_{i=1}^{N} P_L(t_i) \text{ , if}(LPSP > \beta_L) \tag{8}$$

Where, C_{pc_1} is the penalty cost for the shortage of supply (\$/kWh).

So, the total annual cost of the entire system is given by,

$$C_{A\_total} = C_{inv} + C_{o\&m} + C_r + C_{pc} \tag{9}$$

The Levelized Cost of Energy (LCE) can be expressed as the total cost per unit of energy generated, given by

$$LCE = \frac{C_{A\_total}}{E_{total}} \tag{10}$$

IV. PIGEON INSPIRED OPTIMIZATION

The PIO is also a swarm based algorithm, which has been developed by Duan and Qiao [21] simulating the natural homing behavior of pigeons. Due to this special ability, these pigeons have been widely used in World War II for communication. The pigeons can track the way back home by depending on three factors; the sun, the magnetic field of earth and the landmarks in the way. This behavior has been modeled as an algorithm, which can be used to solve optimization problems. The main operator used int PIO are the map & compass operator and the landmark operator. Initially in a d-dimensional space, random pigeons are generated, each will have an initial velocity and the position. Then for each pigeon, the fitness value is calculated and the best of all is called as the G_{best}. By using the best pigeon velocity and position, the rest of pigeons are going to adjust their own map & compass operators, which is give by,

$$V_i(t) = V_i(t-1)e^{-Rt} + rand.(G_{best} - X_i(t-1)) \quad (11)$$

$$X_i(t) = X_i(t-1) + V_i(t) \quad (12)$$

where, R denotes the map & compass factor, $rand$ is a random number generated between 0 and 1. The strategy used in this PIO is almost similar to the PSO algorithm, but the PIO has been found to have very fast convergence rate, when compared to the other evolutionary algorithms. The Figure 2 shows the gradient plot of the three evolutionary algorithms when applied to a standard test function Ackley, within a search rage [(-5000,5000),(-5000,5000)]. From the figure, it can be seen that the PIO is able to converge very fast when compared to the GA and PSO. In recent times, the PIO has successfully been applied for various complex optimization problems such as path finding [21] and entry guidance of reentry vehicles [22] and all of them have shown the superiority of PIO over other evolutionary algorithms.

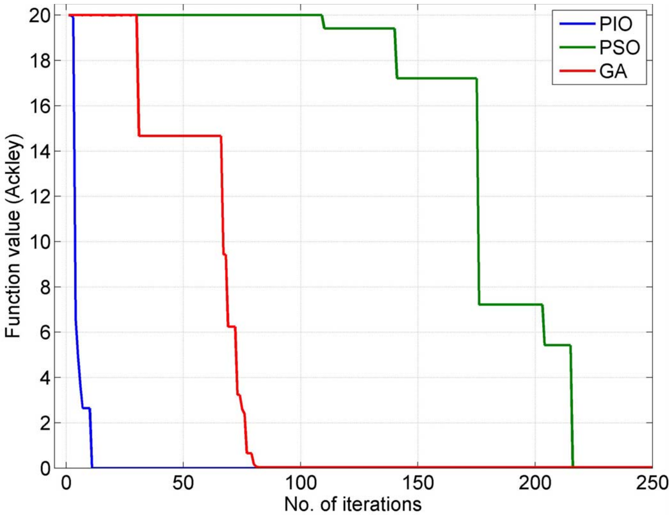

Fig. 2: Comparision of PIO with PSO and GA for Ackley test function

V. OPTIMIZATION STRATEGY

Any optimization study requires constraints which are going to determine the boundary for the solution. The constraints used for this optimization study are i) reliability constraints ii) Battery SOC constraints.

A. Constraints

In this work the system reliability is modeled by using a parameter called as the loss of power supply probability (LPSP). It is a widely used constraint to specify to which extent the renewable system is reliable. It can be defined as the ratio of the load which the HPWES is unable to supply to the total load on the system during the entire study period. It can be represented mathematically as,

$$LPSP = \sum_{i=1}^{N} \frac{P_L(t_i) - P_s(t_i)}{\sum_{i=1}^{N} P_L(t_i)} \quad (13)$$

where, $P_s(t_i)$ is the power supplied by the system and $P_L(t_i)$ is the load at an instant of time t_i and N is the total hours in a year.

The reliability constraint for this study is given by,

$$LPSP \leq \beta_L \quad (14)$$

where, β_L is the allowable limit of the reliability of the system, which is generally taken as 0.05.

To maintain the healthy charge on the battery, the state of charge SOC is supposed to be maintained within the minimum and maximum limits, so that the battery is never fully charged and fully discharged. This will reduce the number of charge/discharge cycles and improves the life time of the battery. So, the battery constraints is given by,

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (15)$$

Along with these constraints, area constraints are also be included as the available land is going to determine the maximum number of components to be installed at that location.

B. Objective function

The size optimization is a multi-objective problem and in order to solve this, only one of all objectives is treated as main objective function and rest are converted into the additional constraints. So, the final objective function is given by,

$$minf = min(LCE) \quad (16)$$

C. Strategy

The proposed optimization strategy is as shown in Figure 3. In the entire search space, the pigeons are generated randomly, for each of the pigeon, the objective function is evaluated for those pigeons which are satisfying the constraints given by the Equations (14) and (15), Then the pigeon with the highest fitness (i.e. minimum cost) is considered as the G_{best} found till now. Based on the value of G_{best}, the velocity and the position of the pigeons are updated for the next iteration. At the end of all iterations, the final optimal solution can be obtained with the minimum LCE.

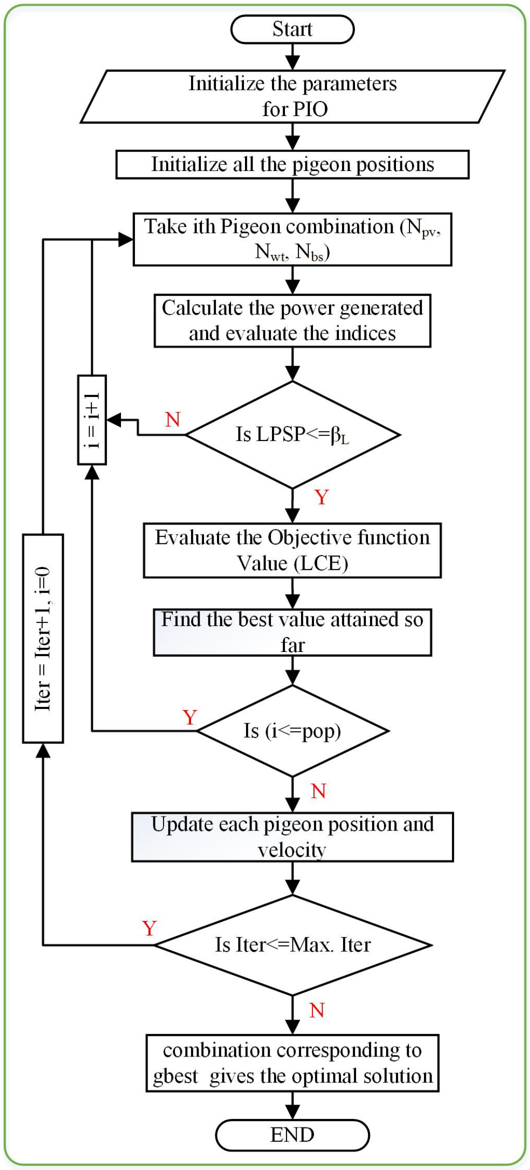

Fig. 3: Optimal sizing strategy

VI. CASE STUDY

To present the effectiveness of the proposed strategy, a case study has been considered for the location of University of Illinois, Champaign, IL, USA (40.1105^{0}N, 88.2284^{0}W). As the climatic conditions can greatly effect the final optimal solution, the typical meteorological year (TMY3) data has been used. The TMY3 data represents the local weather conditions effectively as it has been generated form the data of 15 years at that particular site. The Figure 4 shows the hourly solar irradiation, temperature and wind speed patterns for the duration of 1 year (8760 hours). Figure 5 shows the hourly load pattern for the selected site. The system componets used for the study are, i) PV Panel - 200 W (SANYO HIT Power 200) ii) Wind turbine - 35 kW (PGE 35 kW) and iii) Battery - 600Ah (Hoppecke 60PzS 600).

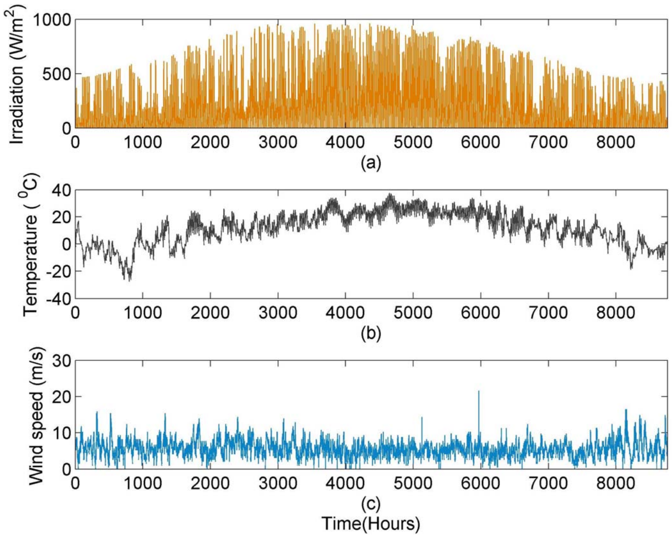

Fig. 4: Hourly meteorological data patterns (a) Solar irradiation (b) Temperature (c) Wind speed

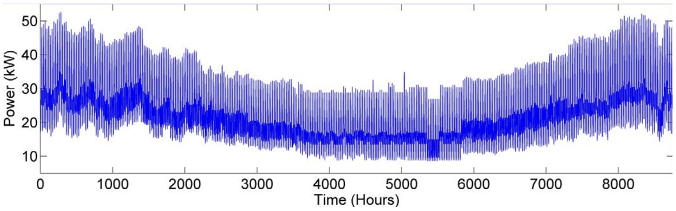

Fig. 5: Hourly load pattern

TABLE I: Results of the optimal sizing

Type	N_{pv}	N_{wt}	N_{bs}	LCE ($)	LPSP
PV/Wind/Battery	298	6	316	0.4981	0.0499
Wind/Battery	-	8	565	0.5966	0.05

In order to effectively represent the technical as well as the economical benefits of the PWB system, the simulation is performed in two cases, at first a hybrid system including the all three sources is considered and it has been compared with the wind/battery system. The results of both optimization studies is presented in Table I. From the results it can be seen that, the PWB system is more cost effective as the LCE is $0.4981, which is very less when compared to the other case. And also the WB system requires more battery storage which is not desirable from the cost and maintenance point of view.

The Figure 7 shows the scatter plot of the various combinations of the PV/wind/battery in the search space (within minimum and maximum values), The red color dots in the figure indicates the combinations which are satisfying the reliability criteria and the blue ones are not satisfying the same. The final optimal value is the one with the minimum cost value in the red combinations. The cost Vs iteration plot for the both the cases is as shown in the Figure 6. From the figure, it can be clearly seen that for both the cases the PIO algorithm is converging very fast (i.e. less than 20 iterations) and the final optimal value of cost is much less for the PWB system when compared to the WB system.

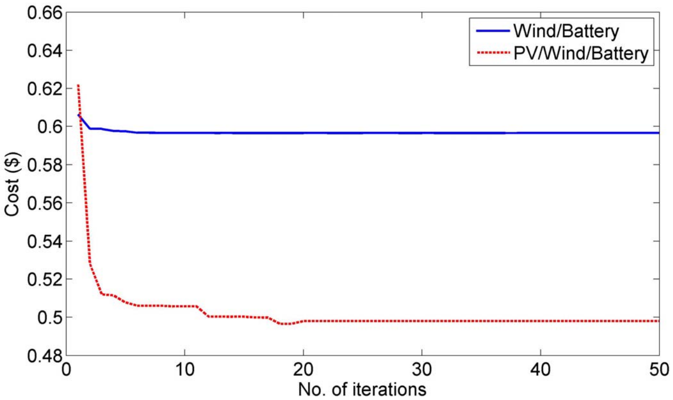

Fig. 6: Error gradient for optimization

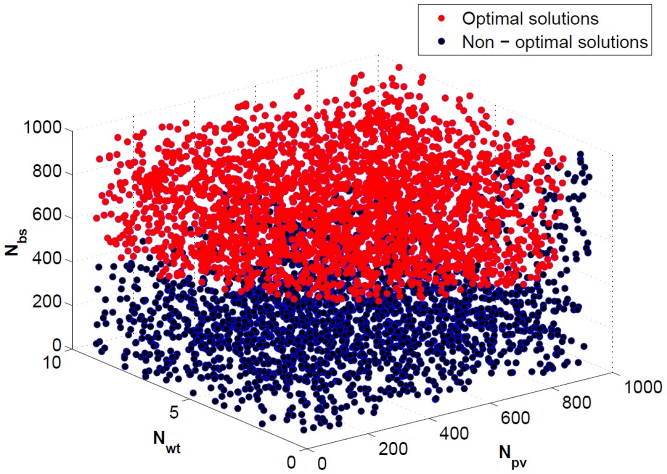

Fig. 7: Solutions in the search space for the PWB system optimization

Figure 8 shows the total power generated by the PWB system during the study period. Form the result is can be seen that both PV and wind are both complementing each other very well as at least one of the source is generating the power when the absence of the other so that the power generated is not zero. The battery SOC is shown in the Figure 9 and from the figure it can be seen that the battery state of charge is also very well maintained and for the very short duration only its value is below the minimum limit.

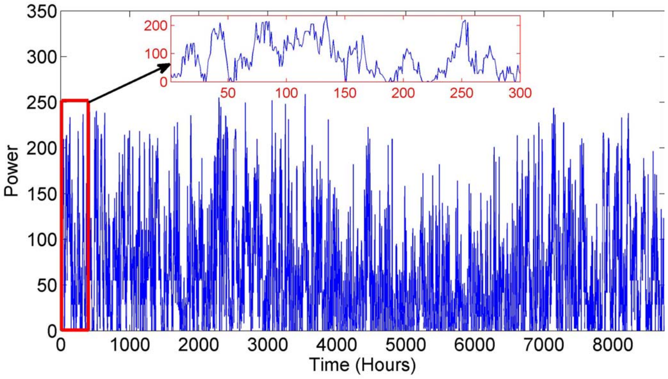

Fig. 8: Power generated by the PWB system

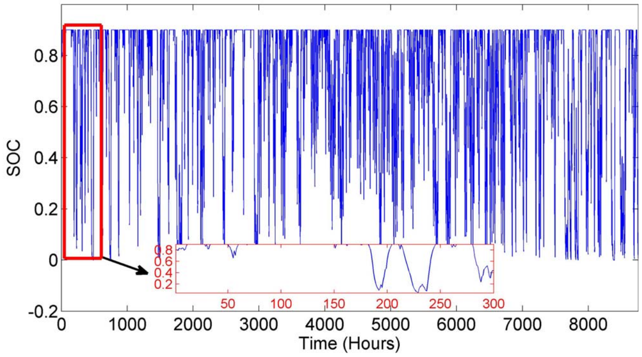

Fig. 9: Battery SOC

VII. CONCLUSION

An optimal sizing strategy for a PV/wind/battery hybrid system has been presented in this paper using pigeon inspired optimization. The detailed methodology and modeling of the components, constraints and the objectives have been presented clearly. It is observed that, the PIO algorithm is able to optimize the system very quickly and effectively while satisfying all the constraints. The results of the optimization of a PWB system are compared with the WB system, which indicates that the PWB system is clearly a better choice when compared to the other combination in terms of cost as well as the battery storage requirement. Thus, it can be concluded that the proposed strategy is able to effectively optimize the stand-alone HPWES with the given constrains.

REFERENCES

[1] A. Mahesh and K. S. Sandhu, "Hybrid wind/photovoltaic system developments: Critical review and findings," *Renewable and Sustainable Energy Reviews*, vol. 0, no. 0, p. Article in Press, 2015.

[2] K. S. Sandhu and A. Mahesh, "A new approach of sizing battery energy storage system for smoothing the power fluctuations of a pv/wind hybrid system," *International Journal of Energy Research*, vol. 40, no. 9, pp. 1221–1234.

[3] T. Markvart, "Sizing of hybrid photovoltaic-wind energy systems," *Solar Energy*, vol. 57, no. 4, pp. 277 – 281, 1996.

[4] B. Borowy and Z. Salameh, "Methodology for optimally sizing the combination of a battery bank and pv array in a wind/pv hybrid system," *IEEE Trans. on Ener. Conv.*, vol. 11, no. 2, pp. 367–375, Jun 1996.

[5] H. Belmili, M. Haddadi, S. Bacha, M. F. Almi, and B. Bendib, "Sizing stand-alone photovoltaicwind hybrid system: Techno-economic analysis and optimization," *Ren. and Sust. Ener. Rev.*, vol. 30, no. 0, pp. 821 – 832, 2014.

[6] C. E. C. Nogueira, M. L. Vidotto, R. K. Niedzialkoski, S. N. M. de Souza, L. I. Chaves, T. Edwiges, D. B. dos Santos, and I. Werncke, "Sizing and simulation of a photovoltaic-wind energy system using batteries, applied for a small rural property located in the south of brazil," *Ren. and Sust. Ener. Rev.*, vol. 29, no. 0, pp. 151 – 157, 2014.

[7] A. Madhlopa, D. Sparks, S. Keen, M. Moorlach, P. Krog, and T. Dlamini, "Optimization of a pvwind hybrid system under limited water resources," *Ren. and Sust. Ener. Rev.*, vol. 47, no. 0, pp. 324 – 331, 2015.

[8] W. Kellogg, M. Nehrir, G. Venkataramanan, and V. Gerez, "Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/pv systems," *IEEE Trans. on Ener. Conv.*, vol. 13, no. 1, pp. 70–75, Mar 1998.

[9] A. Kaabeche, M. Belhamel, and R. Ibtiouen, “Sizing optimization of grid-independent hybrid photovoltaic/wind power generation system,” *Energy*, vol. 36, no. 2, pp. 1214 – 1222, 2011.

[10] B. Zhao, X. Zhang, P. Li, K. Wang, M. Xue, and C. Wang, “Optimal sizing, operating strategy and operational experience of a stand-alone microgrid on dongfushan island,” *Appl. Ener.*, vol. 113, no. 0, pp. 1656 – 1666, 2014.

[11] W. Sheng, K. yan Liu, X. Meng, X. Ye, and Y. Liu, “Research and practice on typical modes and optimal allocation method for pv-wind-es in microgrid,” *Electric Power Systems Research*, vol. 120, no. 0, pp. 242 – 255, 2015.

[12] M. A. Y. Jahromi, S. Farahat, and S. M. Barakati, “Optimal size and cost analysis of stand-alone hybrid wind/photovoltaic power-generation systems,” *Civil Engg. and Envi. Systems*, vol. 31, no. 4, pp. 283–303, 2014.

[13] A. Arabali, M. Ghofrani, M. Etezadi-Amoli, M. Fadali, and Y. Baghzouz, “Genetic-algorithm-based optimization approach for energy management,” *IEEE Trans. on Pow. Del.*, vol. 28, no. 1, pp. 162–170, Jan 2013.

[14] M. Alsayed, M. Cacciato, G. Scarcella, and G. Scelba, “Multicriteria optimal sizing of photovoltaic-wind turbine grid connected systems,” *IEEE Trans. on Ener. Conv.*, vol. 28, no. 2, pp. 370–379, June 2013.

[15] D. Abbes, A. Martinez, and G. Champenois, “Eco-design optimisation of an autonomous hybrid wind photovoltaic system with battery storage,” *Renewable Power Generation, IET*, vol. 6, no. 5, pp. 358–371, Sept 2012.

[16] E. Koutroulis, D. Kolokotsa, A. Potirakis, and K. Kalaitzakis, “Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms,” *Solar Energy*, vol. 80, no. 9, pp. 1072 – 1088, 2006.

[17] A. Fetanat and E. Khorasaninejad, “Size optimization for hybrid photovoltaicwind energy system using ant colony optimization for continuous domains based integer programming,” *Applied Soft Computing*, vol. 31, no. 0, pp. 196 – 209, 2015.

[18] A. Maleki and A. Askarzadeh, “Artificial bee swarm optimization for optimum sizing of a stand-alone pv/wt/fc hybrid system considering lpsp concept,” *Solar Energy*, vol. 107, no. 0, pp. 227 – 235, 2014.

[19] S. Diaf, G. Notton, M. Belhamel, M. Haddadi, and A. Louche, “Design and techno-economical optimization for hybrid pv/wind system under various meteorological conditions,” *Appl. Ener.*, vol. 85, no. 10, pp. 968 – 987, 2008.

[20] O. Ekren and B. Y. Ekren, “Size optimization of a pv/wind hybrid energy conversion system with battery storage using simulated annealing,” *Appl. Ener.*, vol. 87, no. 2, pp. 592 – 598, 2010.

[21] H. Duan and P. Qiao, “Pigeon-inspired optimization: a new swarm intelligence optimizer for air robot path planning,” *International Journal of Intelligent Computing and Cybernetics*, vol. 7, no. 1, pp. 24–37, 2014.

[22] G. Sushnigdha and A. Joshi, “Evolutionary method based hybrid entry guidance strategy for reentry vehicles,” *IFAC-PapersOnLine*, vol. 49, no. 5, pp. 339 – 344, 2016.