cogent engineering

Taylor & Francis
Taylor & Francis Group

Cogent Engineering

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/oaen20

PV-wind hybrid system: A review with case study

Yashwant Sawle , S.C. Gupta & Aashish Kumar Bohre |

To cite this article: Yashwant Sawle , S.C. Gupta & Aashish Kumar Bohre | (2016) PV-wind hybrid system: A review with case study, Cogent Engineering, 3:1, 1189305, DOI: 10.1080/23311916.2016.1189305

To link to this article: https://doi.org/10.1080/23311916.2016.1189305

Published online: 07 Jun 2016.

Sawle et al., *Cogent Engineering* (2016), 3: 1189305
http://dx.doi.org/10.1080/23311916.2016.1189305

cogent engineering

ELECTRICAL & ELECTRONIC ENGINEERING | RESEARCH ARTICLE

PV-wind hybrid system: A review with case study

Yashwant Sawle[1]*, S.C. Gupta[1] and Aashish Kumar Bohre[1]

Received: 06 April 2016
Accepted: 17 April 2016
Published: 07 June 2016

*Corresponding author: Yashwant Sawle, Department Electrical Engineering, Maulana Azad Institute of Technology, Bhopal, India
E-mail: yashsawle@gmail.com

Reviewing editor:
Wei Meng, Wuhan University of Technology, China

Additional information is available at the end of the article

Abstract: Renewable energy systems are likely to become widespread in the future due to adverse environmental impacts and escalation in energy costs linked with the exercise of established energy sources. Solar and wind energy resources are alternative to each other which will have the actual potential to satisfy the load dilemma to some degree. However, such solutions any time researched independently are not entirely trustworthy because of their effect of unstable nature. In this context, autonomous photovoltaic and wind hybrid energy systems have been found to be more economically viable alternative to fulfill the energy demands of numerous isolated consumers worldwide. The aim of this paper is to give the idea of the hybrid system configuration, modeling, renewable energy sources, criteria for hybrid system optimization and control strategies, and software used for optimal sizing. A case study of comparative various standalone hybrid combinations for remote area Barwani, India also discussed and found PV–Wind–Battery–DG hybrid system is the most optimal solution regarding cost and emission among all various hybrid system combinations. This paper also features some of the near future improvements, which actually has the possibility to improve the actual monetary attraction connected with this sort of techniques and their endorsement by the consumer.

Subjects: Computer Science; Engineering & Technology; Urban Studies

Keywords: PV–wind-based hybrid systems; photovoltaic; wind turbine; modeling; optimization techniques

ABOUT THE AUTHORS

The key research area of authors is optimal sizing of renewable energy system.

This paper information is very helpful for pre-analysis of hybrid renewable energy system design. This work analyzed the different combinations of hybrid renewable energy source model and compared each other on the basis of emission, fuel consumption, cost, and component used in the system. This study gives the hybrid system consisting of PV/Wind/Battery/Generator which is a feasible solution. The total net present cost, cost of energy, operating cost, and emission are very less for the presented hybrid renewable energy combination compared to the other. This paper addresses the issues related to the feasibility of the system, combination of renewable source and cost function for pre-analysis of any hybrid practical system and wider projects.

PUBLIC INTEREST STATEMENT

The aim of the paper is to electrify those remote locations where the utility supply is not available. In all over the world many remote location areas where the electricity supply is so costly due to the higher transportation cost, transmission losses, etc. to sort out all these problems renewable energy is the better option. Solar and wind energy resources are freely available in atmosphere thus utilizing these renewable energy sources to power generation is easy and economic. This type of hybrid system can be modeled near to the consumer, which reduces the transmission cost, losses, and transportation cost. Hybrid renewable energy system is environment friendly because it does not produce harmful gasses such as carbon dioxide, unburned hydrocarbons, sulfur dioxide, and nitrogen oxides.

1. Introduction

Many remote communities around the world cannot be physically or economically connected to an electric power grid. The electricity demand in these areas is conventionally supplied by small isolated diesel generators. The operating costs associated with these diesel generators may be unacceptably high due to discounted fossil fuel costs together with difficulties in fuel delivery and maintenance of generators. In such situations, renewable energy sources, such as solar photovoltaic (PV) and wind turbine generator provide a realistic alternative to supplement engine-driven generators for electricity generation in off-grid areas. It has been demonstrated that hybrid energy systems can significantly reduce the total life cycle cost of standalone power supplies in many off-grid situations, while at the same time providing a reliable supply of electricity using a combination of energy sources. Numerous hybrid systems have been installed across the world, and the expanding renewable energy industry has now developed reliable and cost competitive systems using a variety of technologies. In a report, India's gross renewable energy potential (up to 2032) is estimated at 220 GW. It is likewise noted in the report that, with a renewable energy capacity of 14.8 GW (i.e. 9.7% of the total installed generation capacities of 150 GW as on 30 June 2009), India has barely scratched the surface of a huge opportunity. However, in the last couple of years itself, the share of renewable energy in installed capacity has grown from 5 to 9.7% (The Economic Times, 2009). This implies an enormous potential in energy generation, which can achieve several hundred GW with current renewable energy technologies. As the cost of building solar PV–wind capacity continues to fall over the next five to ten years; a significant scale-up of renewable generation is a very realistic possibility in the developing world. Thousands of villages across the globe are still being exiled from electricity and energizing these villages by extended grids or by diesel generators alone will be uneconomical. Moreover, with the current resource crunch with government, these villages receive low priority for grid extension because of lower economic return potential. Standalone solar PV–wind hybrid energy systems can provide economically viable and reliable electricity to such local needs. Solar and wind energy are non-depletable, site dependent, non-polluting, and possible sources of alternative energy choices. Many countries with an average wind speed in the range of 5–10 m/s and average solar insolation level in the range of 3–6 KWh/m^2 are pursuing the option of wind and PV system to minimize their dependence on fossil-based non-renewable fuels (Bellarmine & Urquhart, 1996; Nayar, Thomas, Phillips, & James, 1991). Autonomous wind systems (in spite of the maturity of state-of-the-art) do not produce usable energy for a considerable portion of time during the year. This is primarily due to relatively high cut-in wind speeds (the velocity at which wind turbine starts produces usable energy) which ranges from 3.5 to 4.5 m/s. In decree to overcome this downtime, the utilization of solar PV and wind hybrid system is urged. Such systems are usually equipped with diesel generators to meet the peak load during the short periods when there is a deficit of available energy to cover the load demand. Diesel generator sets, while being relatively inexpensive to purchase, are generally expensive to operate and maintain, especially at low load levels (Nayar, Phillips, James, Pryor, & Remmer, 1993). In general, the variation of solar and wind energy does not match the time distribution of the demand. Thus, power generation system dictates the association of battery bank storage facilities to overcome/smoothen the time distribution-mismatch between the load and renewable (solar PV and wind) energy generation (Borowy & Salameh, 1996). A drawback common to wind and solar system is their unpredictable nature and dependence on weather and climatic change. Both of these (if used independently) would have to be oversized to make them completely reliable, resulting in an even higher total cost. However, a merging of solar and wind energy into a hybrid generating system can attenuate their individual fluctuations, increase overall energy output, and reduce energy storage requirement significantly. It has been shown that because of this arrangement, the overall expense for the autonomous renewable system may be reduced drastically (Bagul & Salameh, 1996). Nowadays, the integration of PV and wind system with battery storage and diesel backup system is becoming a viable, cost-effective approach for remote area electrification. Wind and solar systems are expandable, additional capacity may be added as the need arises. Moreover, the combination of wind and solar PV system shrinks the battery bank requirement and further reduces diesel consumption. The prospects of derivation of power from hybrid energy systems are proving to be very promising worldwide (Beyer & Langer, 1996; Erhard & Dieter, 1991; Seeling-Hochmuth, 1997). The use of hybrid energy systems also reduces combustion of fossil fuels and consequent CO_2 emission which

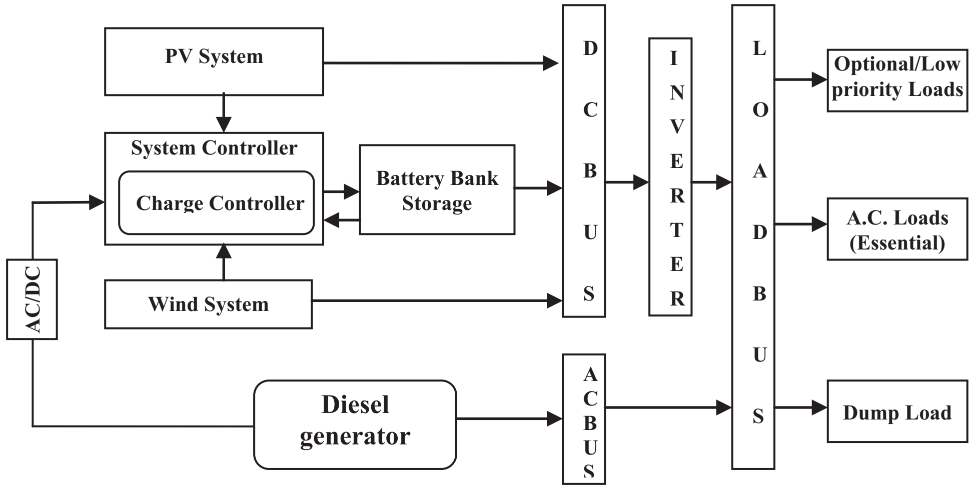


Figure 1. Block diagram of a typical PV–wind hybrid system is depicted.

is the principle cause of greenhouse effect/global warming. The global warming is an international environmental concern which has become a decisive factor in energy planning. In wake of this problem and as a remedial measure, strong support is expected from renewables such as solar and winds (Diaf, Notton, Belhamel, Haddadi, & Louche, 2008). The smart grid readying is associate optimum resolution to the present-day power sector issues like environmental pollution caused by typical power generation, grid losses, as well as poor reliableness and accessibility of power in rural areas (Zaheeruddin & Manas, 2015). The PV–wind hybrid energy system using battery bank and a diesel generator as a back-up can be provided to electrify the remotely located communities (that need an independent source of electrical power) where it is uneconomical to extend the conventional utility grid. All possible advantages of a hybrid energy system can be achieved only when the system is designed and operated appropriately (Gupta, Kumar, & Agnihotri, 2011). In these systems, sizing, control setting, and operating strategies are interdependent. In addition, some of the system components have non-trivial behavior characteristics. Thus, the task of assessing different design possibilities to plan a hybrid system for a specific location becomes quite difficult. The block diagram of a typical PV–wind hybrid system is depicted in Figure 1

The paper is organized as follows: Section 2 description of hybrid renewable energy systems; Section 3 depicts a discussion on hybrid PV/wind energy system modeling; Section 4 provides criteria for PV–wind hybrid system optimization; Section 5 discusses control strategies; Section 6 provides an overview of software tool used for optimal sizing; Section 7 case study of standalone hybrid system; and Section 8 highlights the challenges and future scope and also discussed with a conclusion.

2. Description of hybrid renewable energy schemes

A hybrid renewable PV–wind energy system is a combination of solar PV, wind turbine, inverter, battery, and other addition components. A number of models are available in the literature of PV–wind combination as a PV hybrid system, wind hybrid system, and PV–wind hybrid system, which are employed to satisfy the load demand. Once the power resources (solar and wind flow energy) are sufficient excess generated power is fed to the battery until it is fully charged. Thus, the battery comes into play when the renewable energy sources (PV–wind) power is not able to satisfy the load demand until the storage is depleted. The operation of hybrid PV–wind system depends on the individual element. In order to evaluate the maximum output from each component, first the single component is modeled, thereafter which their combination can be evaluated to meet the require dependability. If the electric power production, though this type of individual element, is satisfactory the actual hybrid system will offer electrical power at the very least charge.

2.1. Hybrid photovoltaic system

Solar energy is one of the non-depletable, site-dependent, non-polluting energy sources, and is available in abundance. It is a potential source of alternative/renewable energy and utilization of solar radiation for power generation reduces the dependence on fossil fuel (Douglas, 1997; Erhard & Dieter, 1991; Mahmoud, 1990; Post & Thomas, 1988; Richard, 1989; Traca De Almeida, Martins, & Jesus, 1983). Solar PV power generation unit consists of PV generator, diesel generator, and inverter and battery system shown in Figure 2. For improved performance and better control, the role of battery storage is very important (Shaahid & Elhadidy, 2003, 2004a). The necessary condition for the design of the hybrid PV systems for maximum output power is hot climate. This type of system is cost effective and reliable, especially for those locations where the power supplies though the grid is not suitable and the cost of the transmission line is very high such as remote and isolated areas (Valente & de Almeida, 1998). Table 1 shows the summary of subjects based on PV hybrid system. In literature a number of methods are used to evaluate performance of the hybrid PV system as a combination of PV with battery, diesel generator, and PV without battery. Muselli, Notton, Poggi, and Louche (2000) in the hybrid system modeling of battery with respect to the state of charge and best possible sizing of the system can also be achieved. El-Hefnawi (1998) developed a technique for minimizing the PV area and evaluate of least number of storage days in a PV hybrid system. Syafaruddin, Narimatsu, and Miyauchi (2015) designed the real-time output power, PV system for calculating the accumulative energy and capacity factor. This information is used for evaluating the energy production model based on the capacity factor. Designed a system for computing production cost associated with hybrid PV battery method in which the size associated with PV method is calculated on such basis as electrical requirements not attained (Abouzahr & Ramakumar, 1991). For standalone hybrid PV system, analysis of reliability is determined in the term of loss of load (LOL) probability. A number of numerical and analytical models are employed for measuring the LOL probability (Egido & Lorenzo, 1992). Execution of hybrid PV system is assessed on the premise of the reliability of the power supply under broadly differing conditions (Marwali, Shahidehpour, & Daneshdoost, 1997).

2.2. Hybrid wind energy system

For the design of a reliable and economical hybrid wind system a location with a better wind energy potential must be chosen (Mathew, Pandey, & Anil Kumar, 2002). In addition, analysis has to be conducted for the feasibility, economic viability, and capacity meeting of the demands (Elhadidy & Shaahid, 2004; Nfaoui, Buret, & Sayigh, 1996; Nfaoui, Buret, Sayigh, & Dunn, 1994; Papadopoulos & Dermentzoglou, 2002; Rehman, Halawani, & Mohandes, 2003). The algorithm for calculating the size of wind turbines and optimal location of distributed energy system has to be developed by using a hybrid configuration of ant colony optimization (ACO), artificial bee colony (ABC) (Kefayat, Lashkar Ara, & Nabavi Niaki, 2015). Optimal sizing of a hybrid wind system and forecasting of a hybrid system based on regression analysis, neural network, Monte Carlo simulation technique, and genetic algorithm were described in the literature (Feijoo, Cidras, & Dornelas, 1999; Li, Wunsch, O'Hair, &

Figure 2. Architecture of PV hybrid system.

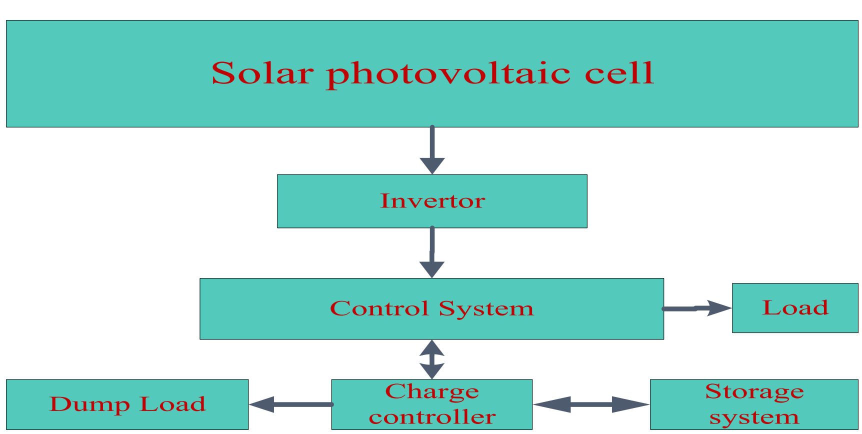
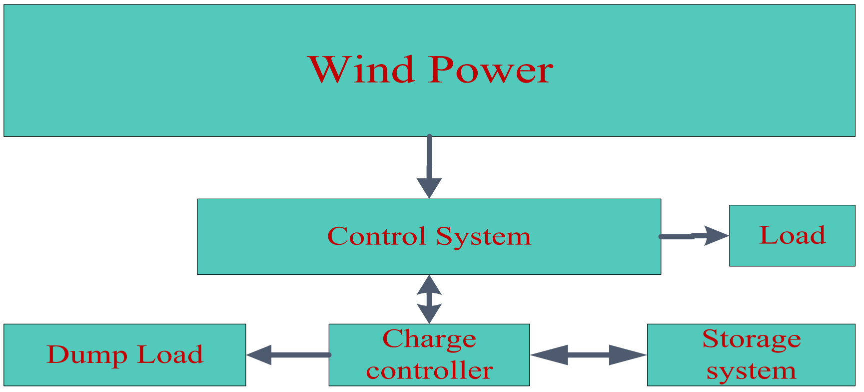


Table 1. Summary of studies based on PV hybrid system

Author	Indicator optimized	SA/GC	Location	Load type	Outcome	Algorithm used
Mahmoud (1990)	Reliability and economic feasibility study	SA	Jordan	Water pumping motor	The report exemplifies the invention and testing of water pumping systems powered by PV generators	Matlab
Post and Thomas (1988)	Cost	SA/GC		–	Study on PV systems for present and upcoming relevancies	–
Richard (1989)	Systems with a fixed tilt array, product or energy storage	SA	US	–	Built up the correlations for optimal sizing which give storage capacity and array size as a function of horizontal insolation and the long-term loss-of-load probability, respectively	LLP
Traca De Almeida et al. (1983)	Reliability	GC	Portugal	Grid connected	Design an optimal hybrid system which reduce system cost and give higher reliability	Monte Carlo simulation
Shaahid and Elhadidy (2003)	Potential of utilizing hybrid system	SA	Dhahran, Saudi Arabia	Residential buildings	An attempt has been made to address monthly average daily energy generated by the PV systems or different situations while meeting the load allocation	Matlab
S. M. Shaahid et al. (2004)	Feasibility of hybrid system	SA	Saudi Arabia	Commercial	1. System load can be satisfied in the optimal way	Matlab
					2. Diesel efficiency can be maximized	
					3. Diesel maintenance can be minimized	
					4. A reduction in the capacities of diesel and battery can occur	
L. Carlos et al. (1998)	Costs and the reliability	SA	Northern, Brazil	Residential	1. Software has been developed to optimize the generation cost starting from a given load curve	Matlab
					2. The PV/diesel option is more reliable and economical than the diesel system	
M. Muselli et al. (2000)	Lower kilowatt-hour cost	SA	Corsica island	Residential	The design hybrid system for remote location to fulfill load requirement	–
Tahrir Street et al. (1998)	Minimum number of storage days and the minimum PV array area	SA	Egyptian Eastern Desert	Farm	1. The sized hybrid system is reliable and can absorb any load disturbances	A program has been designed using FORTRAN language
					2. The hybrid system is more economic than the standalone system	
R. Ramakumar et al. (1991)	Energy storage and the loss of power supply probability	SA	–	Residential	Evaluate relationships between the amount of energy storage and the loss of power supply probability under various operating conditions can be investigated using the results	LPSP
M. Egido et. al. (1992)	Reliability	SA	Spain	Residential	Developed a new model which is more accurate and simple as compare to analytical and numerical models	LLP
M. K. C. Marwali et al. (1997)	Production cost	GC	–	Utility systems	Examine valuable method for generation expectation, production assessment and EENS in a PV-utility with battery storage	Probabilistic approach

Giesselmann, 2001; Papaefthymiou & Stavros, 2014). Salameh and Safari (1995) propose a methodology for identifying the wind turbine generator parameters as capacity factor which relates to identically rated available wind turbine and capacity factor calculated on the basis of wind speed data at different hours of the day of many years. Hybrid wind system installation planning for a particular site and system control strategies have also been reported by researchers (Chedid, Karaki, & El-Chamali, 2000; Jangamshetti & Ran, 2001). For calculating the monthly performance of wind energy system without hourly wind data, a Weibull function is needed (Celik, 2003a). Hybrid wind system performance, reliability, and reduction in the cost of energy (COE) can be obtained by using a

Figure 3. Architecture of wind hybrid system.



battery backup system. When the hybrid system generated power is in surplus, this power is used for loading the batteries for backup security and this charge battery power is used when the load requirement is not supplied by design hybrid system (Elhadidy & Shaahid, 2000). Figure 3 shows the architecture of wind hybrid energy system and Table 2 shows the summary of studies based on wind hybrid system.

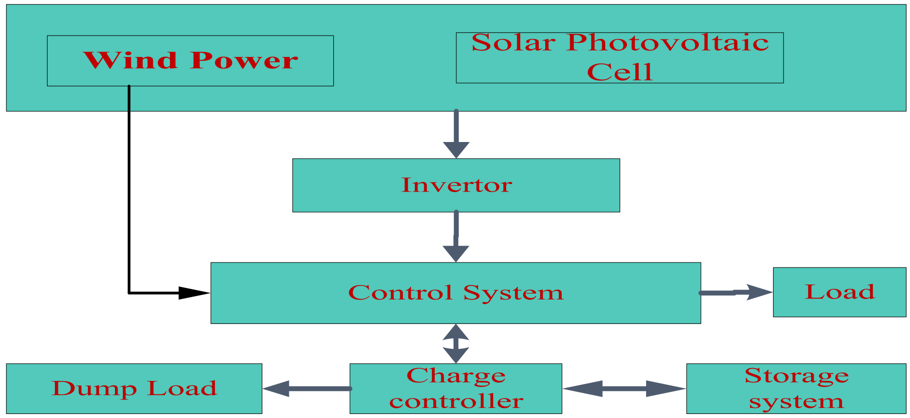
2.3. Hybrid photovoltaic/wind energy system

PV and wind system, both depending on weather condition, individual hybrid PV and hybrid wind system does not produce usable energy throughout the year. For better performance of the standalone individual PV combination or wind combination need battery backup unit and diesel generator set, which increase the hybrid system cost (Elhadidy & Shaahid, 2004; Giraud & Salameh, 2001; McGowan, Manwell, Avelar, & Warner, 1996) for proper operation and better reliability, and lower cost of the system, studies are reported by researchers regarding the combination of hybrid PV–wind system. The current report offers a new strategy determined by the iterative approach, to accomplish the suitable sizing of any standalone hybrid PV/wind/hydrogen method, supplying a desalination unit which feeds the area's inhabitants with fresh water (Smaoui, Abdelkafi, & Krichen, 2015). Gupta, Kumar, and Agnihotri (2011) designed a Matlab software tool for evaluating the economic cost and loss of power supply probability (LPSP) technique is used as a key system constraint to assess the reliability and net present cost (NPC) of the system. González, Riba, Rius, and Puig (2015) suggested a system which is able to seek the sizing leading into a minimum life cycle cost of the system while matching the electrical supply with the local requirement. In the present post, the system is examined through a case study that precise by the hour electrical energy store and also current market rates are actually implemented for getting practical estimations of life cycle costs and also benefits. Design an off-grid hybrid PV–wind battery system with high reliability and minimum production cost of the system. The main objective of the design is to obtain a cost-effective solution (Cano, Jurado, Sánchez, Fernández, & Castañeda, 2014; Sawle & Gupta, 2014, 2015). Maleki and Askarzadeh (2014) use different artificial techniques for the optimal size of the hybrid system to minimize total annual cost. For this aspire sizing is formulated in four different techniques such as particle swarm optimization (PSO), tabu search (TS), simulated annealing (SA), and harmony search (HS). Shang, Srinivasan, and Reindl (2016) this specific paper will take the actual dispatch-coupled sizing approach through adding the actual battery to the procedure on the generation unit inside a process, and formulates this particular program issue employing optimum control. A couple of renewable energy sources––PV panels and wind turbines––are viewed as, together with traditional diesel generators. Shin, Koo, Kim, Jung, and Kim (2015) in order to optimally design ability as well as functioning, preparing of the hybrid system, per hour electricity demand data should be applied more than 8,760 h of 12 months. An optimization that matches hourly supply and demand problem had been resolved to have sparse matrices and also the linear programming algorithm. Lingfeng Wang and Singh (2009) study on techno-economic and environmental for hybrid system PV–wind, and battery banks and optimized for total cost, energy index of reliability, and pollutant emissions (PEs) and evaluate. A set of trade-off solution is obtained using multi-criteria meta-heuristic method

Table 2. Summary of studies based on wind hybrid system

Author	Indicator optimized	SA/GC	Location	Load typ0065	Outcome	Algorithm used
Mathew et al. (2002)	Distribution of wind velocity	SA	Kerala, India	Water pumping	A method to calculate the energy potential of a wind regime is suggested	Matlab
Rehman et al. (2003)	Cost calculation of three different wind turbine capacities	SA	Saudi Arabia	Residential	The wind duration curves have been formulated in addition to employed to estimate the cost every kWh involving power created coming from several decided on the wind machines	Matlab
Nfaoui et al. (1996)	Cost of electricity generated and fuel saving	SA	Morocco	Residential	Develop an optimum hybrid system which reduces the cost energy generation	–
Elhadidy and Shaahid (2004b)	Role of hybrid power systems		Saudi Arabia	Commercial	Design an optimal system which capable to minimize maintains, the cost of generation and maximized the efficiency	Matlab
Papadopoulos and Dermentzoglou (2002)	Economic viability	GC	Greece	Utility system	Developed software which analysis the economic viability for two different cases in this study	Software developed
Kefayat et al. (2015)	Optimal location and sizing of distributed energy resources (DERs) on distribution systems	GC	–	Utility system	In this study found to minimize power loss, emission, cost of energy and increase the voltage stability	Hybrid ACO-ABC
Papaefthymiou and Stavros (2014)	Two alternative perspectives regarding the optimization targets: 1. The investor's perspective, profit 2. The system perspective	SA	Greece	Residential	Enhance the penetration of green power technique plus decrease in levelized price of energy	Genetic algorithms
Li et al. (2001)	Compares regression and artificial neural network models	GC	Fort Davis, Texas	Utility system	The neural network model is found to own far better effectiveness than the regression model pertaining to wind generator energy curve evaluation within challenging have an effect on components.	Regression and artificial neural
Feijoo et al. (1999)	Optimization based on two methods 1. Wind speed distribution, assumed to be Rayleigh 2. Application of the simulation to the wind speed series	GC	–	–	Two methods have been proposed to calculate the probability of occurrence of wind speed in several wind farms simultaneously	Monte Carlo simulation
Salameh and Safari (1995)	Finding the capacity factors (CF)	–	Irbid-Jordan	–	Time calculation and selection of windmill is done capacity factor.	–
Chedid et al. (2000)	To generate fuzzy membership functions and control rules for the controller.	GC	–	Motor load	Develop a adaptive fuzzy control for wind-diesel weak power systems	Fuzzy logy
Celik (2003a)	Estimate the monthly performance of autonomous hybrid system with battery storage	SA	Athens		Design a model for estimating the monthly performance of autonomous wind energy systems	ARES
Elhadidy and Shaahid (2000)	Identified the viability of hybrid system in Dhahran	SA	Saudi Arabia	Commercial	Parametric study of hybrid generating systems	Matlab

Figure 4. Architecture of PV–wind hybrid system.



that offers many design alternatives to decision-maker. Bilal, Sambou, Ndiaye, Kébé, and Ndongo (2013) developed a methodology to size and to optimize a hybrid PV–wind system minimizing the levelized COE and the carbon emission using a multi-objective genetic algorithm approach. Kamel and Dahl (2005) study on standalone hybrid PV–wind–diesel generate-battery system for economic analysis and evaluated annualized cost LPSP optimization results show that hybrid systems are less costly than diesel generation from a NPC perspective. Dufo-López, Bernal-Agustín, and Mendoza (2009) design a grid connected hybrid PV–wind system, taking constraints of land surface acquired by system and initial installation cost and evaluated that system is economical if the selling price of the electric energy is roughly 10 €/kg. Katsigiannis, Georgilakis, and Karapidakis (2010) work on economic and environmental study of a standalone hybrid system, the main aim of the work is to calculate the greenhouse gas emission based on life cycle cost of each component of the hybrid system. Bernal-Agustín, Dufo-López, and Rivas-Ascaso (2006) design is posed as a possible optimization problem whose solution allows having the configuration of the system as well as the control strategy that simultaneously minimizes the total cost through the particular useful life of system plus the PEs. Tina and Gagliano (2010) study on the probabilistic method for standalone hybrid system on the basis of the energy index of the reliability, internal rate of return and expected energy not supplied, evaluate the inform at the design of a pre-processing stage for the input of an algorithm that probabilistically optimized the design of hybrid power systems. In literature various types of method are used for most feasible solution, high reliability, and minimizing the COE such as (Yang, Lu, & Burnett, 2003) probabilistic method (Diaf, Notton, et al., 2008; Dufo-López et al., 2009; Kamel & Dahl, 2005), analytical method (Khatod, Pant, & Sharma, 2010), iterative method (Ekren & Ekren, 2009; Yang, Wei, & Chengzhi, 2009), hybrid method (Bernal-Agustín et al., 2006; Katsigiannis et al., 2010; Lingfeng Wang & Singh, 2009). Figure 4 shows the architecture of PV–wind hybrid energy system and Table 3 shows the summary of studies based on PV–wind hybrid system.

3. Modeling of hybrid renewable energy system components

Different modeling techniques are suggested by researches for modeling the component of a hybrid renewable energy system. The modeling of hybrid system component is discussed below.

3.1. Modeling of photovoltaic system

The outputs of the PV fully depend on solar radiation. Hourly solar radiation on a fixed inclined surface (I_T) can be evaluated as (Onar, Uzunoglu, & Alam, 2006).

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \quad (1)$$

where I_T = solar radiation on an incident surface; I_b = direct normal and diffuse; I_d = solar radiations; R_b = the tilt factors for the beam; R_d = the tilt factors for the diffuse; and R_r = reflected part of the solar radiations.

PV power output with respect to area is calculated by

Table 3. Summary of studies based on PV–wind hybrid system

Author	Indicator optimized	SA/GC	Location	Load type	Outcome	Algorithm used
McGowan et al. (1996)	Life cycle cost	SA	Brazil	Telecom	The major performance parameters for the design and sizing of renewable energy systems can be set up	HYBRID 2 and SOME
Francois Giraud et al. (2001)	Reliability, power quality, loss of supply	GC	England	Residential	Evaluate performance of hybrid system regarding cost, reliability	LPSP
Elhadidy et al. (2004)	Load distribution and power generation	GC	Saudi Arabia	Commercial	Investigate the potential of utilizing hybrid energy conversion systems to meet the load requirements	Matlab
Mariem Smaoui et al. (2015)	Economic	SA	South of Tunisia	Residential	Evaluate a hybrid system, which is designed to supply sea water desalination	Iterative technique
Arnau González et al. (2015)	Minimum life cycle cost	GC	Catalonia Spain	Residential	Design a hybrid system to meet the load demand at minimum life cycle cost on the basis of net present cost	GA and PSO
Antonio Cano et al. (2014)	Unit-sizing and the total net present cost	SA	Malaga Spain.	Residential	Investigate a hybrid system by dissimilar methods and examine hybrid off-grid system is more reliable and cost effective	HOMER, HOGA, MATLAB
Akbar Maleki et al. (2014)	Annual cost	SA	-	Residential	Evaluate an optimal system by using PSO tool which result at minimum cost while comparing to other artificial intelligence techniques	PSO, HS, TS, SA
Ce Shang et al. (2016)	Economic, levelized cost	SA	Singapore	Residential	The author describes the sizing optimization in the dispatch-coupled way, and derives the optimal size of battery for systems with different penetration levels of renewable	PSO
Younggy Shin et al. (2015)	Capacity design and operation planning	SA	South Korea	Building load	It observes the hybrid renewable energy system is more reliable as compare to diesel generator system for island location.	Pareto optimal front
Lingfeng Wang et al. (2009)	Cost, reliability, and emissions	GC	-	Utility system	A set of trade-off clarifications is obtained by way of the multi-criteria meta-heuristic scheme that provides numerous design substitutes to the decision-maker	PSO
Ould. Bilal et al. (2013)	Levelized cost of energy (LCE) and the CO_2 emission	SA	North-western of Senegal	Three different loads	Author takes variation of three dissimilar load profile for hybrid system and minimized LCE and the CO_2 emission	Genetic Algorithm
Sami Kamel et al. (2005)	Economic	SA	Egypt	Agricultural load	Hybrid renewable energy system is more cost valuable and environmentally pleasant as compare to diesel generator scheme	HOMER
Rodolfo Dufo-López et al. (2009)	Net present value	GC	Spain	Utility system	Design in addition to cost-effective analysis connected with hybrid techniques connected to the grid for the irregular generation connected with hydrogen	GRHYSO
Banu Y. Ekren et al. (2009)	Economic	SA	Urla, Turkey	Institute load	Evaluate optimal sizing at different loads and auxiliary energy positions and output shown by loss of load probability and autonomy analysis	ARENA
Katsigiannis et al. (2009)	Cost of energy and greenhouse gas (GHG) emissions	SA	Crete, Greece	Residential	The main uniqueness of the anticipated methodology is the thought of LCA results for the estimate of CO_2 emissions	Genetic Algorithm
Yang Hongxing et al. (2010)	Economic	SA	China	Telecommunication station	Design an optimal hybrid system which annualized cost is least while load demand is satisfied on the basis of loss of power supply probability	Genetic algorithm
Bernal-Agustín et al. (2006)	Pollutant emissions, cost	SA	–	Farm Load	Developed a software tool which objective is to reduce cost of energy and co_2 emission	Pareto Evolutionary
Yang et al. (2003)	Reliability, and probability of power supply	SA	Hong Kong	Telecommunication	Study on weather data and probability analysis of hybrid power generation systems	Matlab
Khatod et al. (2010)	Well-being assessment and production cost	SA	Gujarat, India	–	Design a technique which has high accuracy and taking less calculating time as compare to Monte Carlo method	Monte Carlo simulation
Tina et al. (2010)	Probability distribution function	–	Italy	–	Developed a algorithm which results gives information about more reliable and optimal configurations for design of hybrid system	Matlab

$$P = I_T A_{PV} \eta_{PV} \tag{2}$$

A_{PV} and η_{PV} are PV system area and PV system efficiency, respectively.

The PV system efficiency is defined as

$$\eta_{PV} = \eta_M \, \eta_{PC} \left[1 - \beta\left(T_C - T_R\right)\right] \tag{3}$$

where η_M = module efficiency; η_{PC} = power conditioning efficiency; T_C = monthly average cell temperature; T_R = reference temperature; and β = array efficiency temperature coefficient.

In the ideal equivalent circuit of PV cell a current source is connected in parallel with diode. Onar et al. (2006) connected PV cell with load, voltage, and current equation of cell which is calculated by

$$I_{PV} = I_{PH} - I\left(e^{QV_{PV}/KT} - 1\right) \tag{4}$$

where I_{PV} = is the PV current (A); I = the diode reverse saturation current (A); Q = the electron charge = 1.6 _ 10_19 (C); k = the Boltzman Constant = 1.38 _ 10_23 (J/K); and T = the cell temperature (K).

3.2. Modeling of wind energy system

The actual mathematical modeling of wind energy conversion process comprises wind turbine dynamics as well as generator modeling. Borowy and Salameh (1997) took a three blade, horizontal axis and repair free wind generator is installed for modeling. Power generation through the wind turbine can be calculated by wind power equation. The turbine is characterized by non-dimensional performance as a function of tip the speed quantitative relation. Bhave (1999) estimates the generated output power and torque by the wind turbine by giving the formula.

$$P_T = \left(\frac{C_P \lambda_\rho A V^3}{2}\right) \tag{5}$$

Torque developed by wind turbine given as

$$T_T = \frac{P_T}{\omega M} \tag{6}$$

$$\lambda = \frac{\omega R}{V} \tag{7}$$

where P_T = output power; T_T = the torque developed by wind turbine; C_P = the power co-efficient; λ = the tip speed ratio; ρ = the air density in kg/mg^3; A = the frontal area of wind turbine; and V = the wind speed.

Many researchers work on different mathematical modeling for wind energy conversion. Arifujjaman, Iqbal, Quaicoe, and Khan (2005) has worked on small wind turbine by controlling horizontal furling scheme. This furling scheme is used to control aerodynamic, power extraction through the wind. The system is designed in Matlab/Simulink for evaluating appropriate control approach. Two controllers are designed and simulated. For the first scheme, a controller uses rotor speed and wind speed information and controls the load in order to operate the wind turbine at optimal tip speed ratio. In the second scheme, controller compares the output power of the turbine with the previous power and based on this comparison it controls the load.

3.3. Modeling of diesel generator

Hybrid PV–wind system's operation and power generation depends on weather conditions. If poor sunshine and low wind speeds then hybrid PV–wind system's operation and efficiency are affected and the load requirement is not satisfied by either hybrid system or by batteries. All this issue can be resolved by using a diesel generator in hybrid PV–wind system. The application of diesel generator depends on the type and nature of load demand. Notton, Muselli, and Louche (1996) present two essential conditions for calculating the rated capacity of the generator to be installed. The first condition, if the diesel generator is directly connected to the load then the rated capacity of the generator must be at least equal to the maximum load. Second condition, if the diesel generator is used as a battery charger then the current produced by the generator should not be greater than CAh/5 A, where CAh is the ampere-hour capacity of the battery. The efficiency of a diesel generator is specified by the formula (Kaldellis & Th, 2005; Nag, 2001).

$$\eta_{\mathrm{T}} = \eta_{\mathrm{B}} + \eta_{\mathrm{G}} \tag{8}$$

where η_{T} total efficiency and η_{B}, η_{G} are the thermal and generator efficiency. In hybrid system, a generator is used to maintain the reliability and load requirement. To obtain the lowest cost of system generator should work between the ranges of 70–90% of full load (El-Hefnawi, 1998; Valenciaga & Puleston, 2005). Generator fulfills the load demand and battery charging if peak load is not available.

3.4. Modeling of battery system

Sinha (2015) mentions that battery is used to store surplus generated energy, regulate system voltage and supply load in case of insufficient power generation from the hybrid system. Battery sizing depends on the maximum depth of discharge (*DD*), temperature, and battery life. A battery's state of charge (S_{C}) is expressed as follows:

During charging process

$$S_{\mathrm{C}}(t+1) = S_{\mathrm{C}}(t)\left[1-\sigma(t)\right] + \left[I_{\mathrm{B}}(t)\Delta t.\eta_{\mathrm{C}}(t)/C_{\mathrm{B}}\right] \tag{9}$$

During discharging process

$$S_{\mathrm{C}}(t+1) = S_{\mathrm{C}}(t)\left[1-\sigma(t)\right] - \left[I_{\mathrm{B}}(t).\Delta t.\eta_{\mathrm{D}}(t)/C_{\mathrm{B}}\right] \tag{10}$$

where S_{C} = state of charge; $\sigma(t)$ = hourly self-discharge rate depending on the battery; I_{B} = battery current; C_{B} = nominal capacity of the battery (Ah); η_{C} = charge efficiency (depends on the S_{C} and the charging current and has a value between 0.65 and 0.85); and η_{D} = discharge efficiency (generally taken equal to one)

and

$$\left[1-DD\right] \leq S_{\mathrm{C}}(t) \leq 1 \tag{11}$$

where *DD* = depth of discharge.

4. Criteria for PV–wind hybrid system optimization

In literature, optimal and reliable solutions of hybrid PV–wind system, different techniques are employed such as battery to load ratio, non-availability of energy, and energy to load ratio. The two main criteria for any hybrid system design are reliability and cost of the system. The different methods used for these criteria are given below.

4.1. Reliability analysis

Hybrid PV–wind system performance, production, and reliability depend on weather conditions. Hybrid system is said to be reliable if it fulfills the electrical load demand. A power reliability study is important for hybrid system design and optimization process. In literature, several methods are used to determine the reliability of the hybrid system. Al-Ashwal (1997) has developed, LOL risk method for reliability analysis. LOL risk evaluation is performed using a probabilistic model. LOLR is defined as the probability of the generating system failure to meet the daily electrical energy demand due to the deficient energy of the renewable energy sources used (Planning & installing PV system: A guide for installers, architects & engineers, 2005) LOLR can be represented as $LOLR = 1-P$ or $LORL = Q$, where P is the cumulative probability of meteorological status which corresponds to electrical energy generation and Q is the probability of failure. Maghraby, Shwehdi, and Al-Bassam (2002) worked on system performance level. System performance level is defined as the probability of unsatisfied load. Shrestha and Goel's Shrestha & Goel, (1998) reliability calculated on the basis of LOL hours. LOL hours is the summation of LOL expectation in hours over a specified time (usually one year) that the power system is unable to meet load requirements due to lack of power at an instant excluding the effects of component breakdown or maintenance time. *LA* is defined as one minus the ratio between the total number of hours in which LOL occurs and the total hours of operation (Celik, 2003b).

$$LA = 1 - H_{\mathrm{LOL}}/H_{\mathrm{TOT}} \tag{12}$$

where H_{LOL} hours which LOL occurs (h) and H_{TOT} total hours operation system (h). Kaldellis (2010) uses different methods for analysis of hybrid system reliability as LPSP, LOL probability (LOLP), unmet load (UL). LPSP is the most widely used method on condition when power supplies do not fulfill the required load demand. LPSP is the ratio of power supply deficits to the electric load demand during a certain period. As for the LOL probability (LLP), it is defined as the power failure time period divided by the total working time of the hybrid system. Lastly, UL can be defined as the load which cannot be served divided by a total load of a time period (normally one year).

4.2. Cost analysis

NPC or net present worth (NPW) is defined as the total present cost of a time series of cash flows. It is a standard method for using the time value of money to appraise long-term projects. The basis of NPC analysis is to be an ability to express a series of yearly costs in constant currency taking into account the changing value of money as well as cost escalation due to inflation (Dufo-López et al., 2009; Gupta et al., 2011). Therefore, the NPC means the present value of the cost of installing and operating the hybrid system over the lifetime of the project. It is calculated as follows:

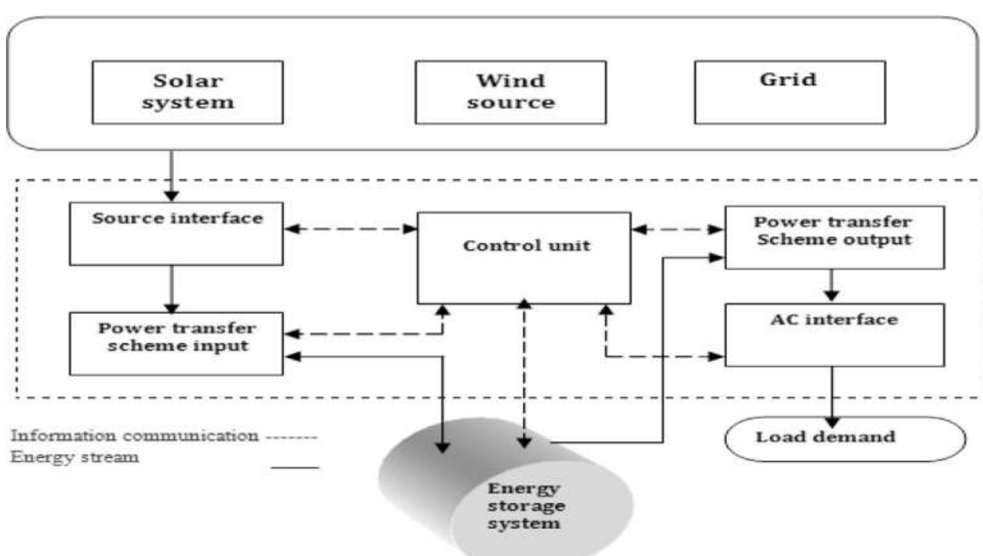
$$NPC = C_{\mathrm{ANN}}/CRF\left(i, T_{\mathrm{PLT}}\right) \tag{12}$$

where C_{ANN} = total annualized cost; CRF = capital recovery factor; i = interest rate; and T_{PLT} = project lifetime. Life cycle costs (LCC) are the sum of all the hybrid system component costs and discounted operational costs arising during the project until the end of the project horizon, which is usually set between 20 and 30 years (Bhuiyan, Asgar, Mazumder, & Hussain, 2000). The component costs are the capital cost incurred at the beginning of hybrid system project; operational costs include system running costs, maintenance, and replacement costs. The COE reflects the cost of energy or electricity generation and is expressed as the ratio of total annualized cost of the system to the annual electricity delivered by the system. Total annualized cost includes all the costs over the system's lifetime from initial investment and capital costs to operations and maintenance (e.g. fuel) and financing costs (Zhou, Lou, Li, Lu, & Yang, 2010).

5. Control strategies

As the hybrid renewable energy system is the combination of different renewable energy sources, diesel generator–conventional sources, and energy storage system it is very difficult to get output at maximum efficiency and reliability without applying any proper control strategy (Dimeas & Hatziargyriou, 2005). In hybrid renewable energy system, for a variable, monitoring and power supply load for the requirement is done by the controller. Controller also keeps the output voltage, frequency and determines the active and reactive power from different energy sources. Different types of controller are applied in a hybrid renewable energy system according to the requirement of different energy sources, output power, and control strategy. Controller, predominantly are of four types as centralized, distributed, hybrid (combination of centralized and distributed) control, and multiple control system. In each one of the cases, every source is expected to have its own controller that can focus on ideal operation of the relating unit taking into account current data. In the centralized control arrangement, the entire energy source's signals and storage system are controlled by centralized (master controller) arrangement. Multi-objective energy unit framework can accomplish global optimization in view of all accessible data (Abido, 2003; Azmy & Erlich, 2005; Lagorse, Simoes, & Miraoui, 2009; Miettinen, 1998; Sawle & Gupta, 2014). The disadvantage of this centralized unit is that it suffers from heavy computation load and is subjected to single-point failures. The second control unit is the distributed control unit; in this, unit single energy source is connected to individual to local control unit and thus control units are connected to each other for communicating measurement signals and take a suitable assessment for global optimization. This control unit more advantageous as compared to the centralized control unit because it calls for a minimum computational load without any failure (Hajizadeh & Golkar, 2009; Huang, Cartes, & Srivastava, 2007; Kelash, Faheem, & Amoon, 2007; Ko & Jatskevich, 2007; Lagorse et al., 2009; Nagata & Sasaki, 2002; Nehrir et al., 2011; Toroczckai & Eubank, 2005; Weiss, 1999; Yang et al., 2006). Withal, this control structure has the shortcoming of multi-faceted communication systems among local controllers. This problem of distributed control unit can be solved by artificial algorithm techniques. Multi-agent system is a standout among the most encouraging methodologies for a distributed control unit. The third control arrangement is a hybrid control unit (Ko & Jatskevich, 2007; Torreglosa, García, Fernández, & Jurado, 2014; Torres-Hernandez, 2007). Hybrid control unit is the arrangement of centralized and distributed control units. In hybrid control unit, renewable sources are assembled within the integrated system. In this hybrid control unit, local optimization in a group and global optimization with different groups are obtained by centralized control unit and distributed control unit, respectively. This hybrid control unit is more advantageous and suitability over other control units because it takes less computation burden which reduces the failure problem of the system. The main drawback of the system is the potential complexity of its communication system. The fourth control is a multi-level control unit. The working operation of this control unit is almost the same as the hybrid control unit but the advantage is it has supervisor control which takes care about real-time operation of each energy unit on the basis of control objective within millisecond range. It also facilitates with the two-way communication existing among diverse levels to execute choices (Torreglosa et al., 2014; Upadhyay & Sharma, 2014). The drawback of this control unit is the potential complexity of its communication system. Figure 5 shows the energy flow and data communication information.

Figure 5. The energy flow and data communication information.



6. Software based on optimization of hybrid system

There are many software tools that are capable to assess the renewable energy system performance for pre-defined system configurations. These include HYBRID 2, PVSYST, INSEL, SOLSIM, WATSUN-PV, PV-DESIGNPRO, RAPSIM, PHOTO, SOMES, HOMER, RAPSYS, RETScreen, ARES, and PVF-chart. Out of all these software tools only two (SOMES and HOMER) are exactly relevant to this investigation, because these two software are capable of providing optimal design of hybrid system. A brief description of each tool is given below sections.

6.1. Software tools for pre-defined system configurations

6.1.1. HYBRID 2

HYBRID 2 (http://www.ceere.org/rerl/projects/software/ hybrid2/index) is a simulation tool that aims to provide a versatile model for the technical and economical analysis of renewable hybrid energy system. The tool was developed in NREL, Canada in the year 1993. This programming model utilizes both the time series and a statistical approach to evaluate the operation of renewable hybrid system. This allows the model to determine long-term performance while still taking into account the effect of short-term variability of solar and wind data. A range of system components, control and dispatch option can be modeled with users specified time steps. HYBRID 2 comprises all kinds of energy dispatch strategies researched by Barley (1995). HYBRID 2 is an extensively validated model. Though the technical accuracy of the model is very high but the model is incapable to optimize the energy system. The HYBRID 2 code employs a user-friendly graphical user interface (GUI) and a glossary of terms commonly associated with hybrid power systems. HYBRID 2 is also packaged with a library of equipment to assist the user in designing hybrid power systems. Each piece of equipment is commercially available and uses the manufacturer's specifications. In addition the library includes sample power systems and projects that the user can use as a template. Two levels of output are provided, a summary and a detailed time step by time step description of power flows. A graphical results interface (GRI) allows for easy and in-depth review of the detailed simulation results.

6.1.2. PVSYST

PVSYS 4.35 (2009) developed by Geneva University in Switzerland is a software package for the study sizing, simulation, and data analysis of complete PV systems. It allows determination of PV size and battery capacity, given a user's load profile and the acceptable duration that load cannot be satisfied. The software offers a large database of PV components, metrological sites, an expert system, and a 3-D tool for near shading detailed studies. This software is oriented toward architects, engineers, and researchers, and holds very helpful tools for education. It includes an extensive contextual help, which explains in detail the procedures and the models used. Tool performs the database meteo and components management. It provides also a wide choice of general solar tools (solar geometry, meteo on tilted planes, etc.), as well as a powerful mean of importing real data measured on existing PV systems for close comparisons with simulated values.

6.1.3. INSEL

Integrated simulation environment and a graphical performing language (INSEL) is software developed by University of Oldenburg, Germany, in which simulation models can be created from existing blocks in the graphic editor HP VEE with a few mouse clicks (Swift & Holder, 1988). The simulation of systems like on-grid PV generators with MPP tracker and inverter, for instance, becomes practically a drawing exercise. This software supports the designer with database for PV modules, inverters, thermal collectors, and meteorological parameters. Even more, INSEL offers a programming interface for the extension of the block library. The main advantage of this model is the flexibility in creating system model and configuration compared to simulation tools with fixed layouts. A disadvantage is that INSEL does not perform system optimization, though it completes or even replaces the experimental laboratory for renewable energy system, since components can be interconnected like in reality.

6.1.4. SOLSIM
Simulation and optimization model for renewable Energy Systems (SOLSIM) (Schaffrin, 1998) is developed at Fachhochschule Konstanz, Germany. SOLSIM is a simulation tool that enables users to design, analyze, and optimize off-grid, grid connected hybrid solar energy systems. It has detailed technical models for PV, wind turbine, diesel generator, and battery components as well as for biogas and biomass modeling. SOLSIM software package consists of different tools: the main simulation program called SOLSIM; the unit to optimize the tilting angle of PV module called SolOpti; the unit to calculate life cycle cost called SolCal; and the unit to simulate wind generators called SolWind. This program is also incapable to find the optimal size of hybrid system for any location on techno-economical ground.

6.1.5. WATSUN-PV
WATSUN-PV 6.0 (Tiba & Barbosa, 2002) developed by University of Waterloo, Canada, is a program intended for hourly simulation of various PV systems: standalone battery back-up, PV/diesel hybrid, utility grid-connected system, and PV water pumping system simulations. The modules standalone battery back-up and PV/diesel hybrid system simulation modules are very complete; on the other hand, the module that deals with PV water pumping systems only allows the analysis of configurations using DC electric motors, which is not a configuration very frequently used nowadays. The modeling systems for solar radiation, PV arrangement, and the battery are quite detailed and updated. The model used for DC motors is a simple relationship between the voltage and current supplied by the array and the torque and angular speed of the motor. WATSUN-PV 6.0 has a library containing information on PV modules, batteries, inverters, and diesel and gasoline generators. The database does not include information on motors or pumps.

6.1.6. PV-DESIGN PRO
The PV-design pro simulation program (Planning & installing PV system: A guide for installers, architects & engineers, 2005) comprises three variants for simulating standalone system, grid-connected system, and PV pump system. For standalone systems, a reserve generator and a wind generator can be integrated into the PV system, and a shading analysis can be carried out. The system can be optimized by varying the individual parameters. Detailed calculations are performed for operating data and characteristics curves. The module and climate database are very comprehensive. This program is recommended for the PV systems that have battery storage. Simulation is carried out on hourly basis. An advantage of PV-design pro is that its database already includes most information needed for PV system design.

6.1.7. RAPSIM
RAPSIM (Pryor, Gray, & Cheok, 1999) or remote area power supply simulator is a computer modeling program developed at the Murdoch University Energy Research Institute, Australia. It is designed to simulate alternative power supply options, including PV, wind turbine, battery, and diesel system. The user selects a system and operating strategy from a few pre-defined options and optimization is sought by varying component sizes and by experimenting with the control variables that determine on-off cycles of the diesel generator. Battery aging effect is not considered in this model.

6.1.8. RETScreen
RETScreen is developed and maintained by the Government of Canada through Natural Resources Canada's Canmet Energy research centre in 1996. RETScreen software is capable to calculate the energy efficiency, renewable energy, and risk for various types of renewable-energy, energy-efficient technologies and also analyze the cost function of the design system and hybrid system feasibility (RETScreen, 2009). RETScreen working is based on Microsoft excel software tool. The main characteristics of this software are to minimize the green house gas emission, life cycle cost, and energy generation (Sinha & Chandel, 2014).

6.1.9. PHOTO

The computer code PHOTO (Manninen, Lund, & Vikkula, 1990) developed at the Helsinki University of Technology in Finland simulates the performance of renewable energy system, including PV–wind hybrid configuration. A back up diesel generator can also be included in the system configuration. The dynamic method developed uses accurate system component models accounting for component interactions and losses in wiring and diodes. The PV array can operate in a maximum power mode with the other subsystems. Various control strategies can also be considered. Individual subsystem models can be verified against real measurements. The model can be used to simulate various system configurations accurately and evaluate system performance, such as energy flows and power losses in PV array, wind generator, backup generator, wiring, diodes, and maximum power point tracking device, inverter, and battery. A cost analysis can be carried out by PHOTO. This code has facility to create a stochastic weather generation database in the cases where hourly data are not available. The simulation results compare well with the measured performance of a PV test plant.

6.1.10. SOMES

The computer model SOMES (simulation and optimization model for renewable energy systems) developed at University of Utrecht Netherlands (RETScreen, 2009) can simulate the performance of renewable energy systems. The energy system can comprise renewable energy sources (PV arrays, wind turbines), diesel generator, a grid, battery storage, and several types of converters. An analysis of the results gives technical and economical performance of the system and the reliability of power supply. The simulation is carried out on hourly basis for the simulation period of, for example, one year. Hourly average electricity produced by solar and wind system is determined. Hourly results are accumulated for simulation period. The accumulated values are used to evaluate technical and economical performance of system. The model contains an optimization routine to search for the system with lowest electricity cost, given the customer's desired reliability level.

6.1.11. HOMER

HOMER (https://analysis.nrel.gov/homer/includes/downloads/HOMERBrochure_English.pdf) is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, standalone, and distributed generation (DG) applications. HOMER is developed by the National Renewable Energy Laboratory (NREL, USA), HOMER's optimization and sensitivity analysis algorithms allow us to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER models both conventional and renewable energy technologies: such as PV, wind turbine, run-of-river hydropower, diesel or biogas generator, fuel cell, utility grid, battery bank, micro turbine, and hydrogen storage. HOMER performs simulation for all of the possible system configurations to determine whether a configuration is feasible. Then, HOMER estimates the cost of installing and operating cost of the system, and displays a list of configurations sorted by their life cycle cost. This tool offers a powerful user interface and accurate sizing with detail analysis of the system.

6.1.12. RAPSYS

RAPSYS (version 1.3) was developed in the University of New South Wales, Australia in the year 1987 (RAPSYS, www.upress.uni-kassel.de/online/frei/978-3-933146-19-9). This software can simulate a wide range of renewable system components that may be included in a hybrid system configuration. The software can be used only by those who are experts in remote area power supply system. RAPSYS does not optimize the size of components. The user is required to pre-define the system configuration. The simulation recommends the switch ON and OFF timings of diesel generator. RAPSYS does not calculate the life cycle COE system, though it is capable to provide detailed information about the operating cost of the system.

6.1.13. ARES
A refined simulation program for sizing and optimization of autonomous hybrid energy systems (ARES) developed at University of Cardiff, UK determines whether a system meets the desired reliability level while meeting the project budget based on user specified cost data (Morgan, Marshall, & Brink worth, 1995; Morgan, Marshall, & Brinkworth, 1997). This program, unlike the majority of other hybrid simulation program, predicts the battery state of voltage (SOV) rather than its state of charge (SOC). LOL occurs when the battery voltage drops below the low voltage cut-off limit. Given the load and weather profiles, ARES is able to predict the occurrence of LOL thus giving a direct measure of the system autonomy. The model predicts electrical quantities measured at the terminals of battery bank and do not describe the electro-chemical phenomena occurring within the individual cells. The simulation code has been validated by comparison with measured data obtained form a 200 W wind and PV system. Accurate prediction of battery voltage requires a fairly extensive knowledge of the descriptive parameters of system components. These details are rarely found in manufacturing data sheets. The lack of data concerning charge characteristics and temperature effects is even more blatant. It would be advantageous if a data bank with such parameters were to be made available. The battery aging and its effects on system performance has not been addressed as part of this program. The precision and reliability of the simulation results obtained by this software depend mostly on the accuracy of the descriptive parameters.

6.1.14. PVF-CHART
The computer program PVF-chart (Klein & Beckman, 1993; Planning & installing PV system: A guide for installers, architects & engineers, 2005) developed by F-chart software is suitable for prediction of long-term average performance of PV utility interface system, battery storage system, and system without interface or battery storage. It is a comprehensive PV system analysis and design program. The program provides monthly-average performance estimates for each hour of the day. The calculations are based upon methods developed at the University of Wisconsin which use solar radiation utilizability to account for statistical variation of radiation and the load. The PVF-Chart method consists of combination of correlation and fundamental expression for hourly calculation of solar radiation at given location.

6.2. Search methodology based on optimization of hybrid system
In addition to the software tool stated above, other search methods for the design of hybrid energy system are described in various technical publications. These methods, which are described below, include amp-hour (AH) method, knowledge-based approach, simulation approach, trade-off method, probability method, analytical method, linear programming, goal programming, dynamic programming, and non-linear programming.

6.2.1. AH method
AH method is the most straightforward method to size PV-battery–diesel hybrid system. This method detailed out in a handbook of PV design practices by Sandia National Laboratory (SANDIA, 1995). The storage capacity is determined by number of autonomous days (number of continuous days that the battery can cover the load without sunshine), which is arbitrary selected by designer (typically 3–7 days). The size of diesel generator is selected to cover peak demand. This method does not take into account the relationship between the output of PV, generator sets, and storage capacity. Unless the very accurate data are used to select the value for autonomous days, this can easily lead to the specification of oversized components and suboptimal results. This method is used in Bhuiyan and Ali Asgar (2003), Ming, Buping, and Zhegen (1995), Protogeropulos, Brinkworth, and Marshall (1997) to size the standalone PV systems.

6.2.2. Trade-off method
The trade-off method is introduced by Gavanidou and Bakirtzis (1993) for multi-objective planning under uncertainty. The idea is intended for use in the design of standalone systems with renewable energy sources. This is done first by developing a database that contains all possible combinations of PV plants, wind generator, and battery, given ranges and steps of component sizes. Next, all

possible planes are simulated over all possible futures, i.e. ±1 m/s variation in the wind velocity, ±10% variation in the global solar insolation. The author then creates a trade-off curve by plotting investment cost and LOL probability (LOLP) for all possible scenarios, eliminating options with LOLP greater than 10%, and identifying the knee-sets. Robust plans are then identified by the frequency of the occurrence of discrete option values in the conditional decision set. This method yield a small set of robust designs that are expected to work well under most foreseeable conditions. The final decision for the selection of the unique design is left to the decision-makers.

6.2.3. Probability method using LPSP technique

The concept of LPSP was introduced (Ofry & Braunstein, 1983) to design standalone PV systems. This technique enables the determination of the minimum sizes of the PV system and storage capacity, and yet assures a reliable power supply to load. The reliability of power supply is measured by total number of hours per year for which the consumer's power demand is greater than PV supply. The study is performed during a period of one year to collect the state of charge (SOC) of battery as function of time. The cumulative distribution function of the battery SOC is derived. The LPSP is then determined by calculating the value [1 − {cumulative proportion of the time where battery SOC is higher than the SOC min.}]. Similar work is done including wind generators in Borowy and Salameh (1996), Ghali, El Aziz, & Syam. (1997) and Ali, Yang, Shen, and Liao (2003), then adopted this concept to find the optimum size of the battery bank storage coupled with a hybrid PV–wind autonomous system. Long-term data of wind speed and insolation recorded for every hour of the day are deduced to produce the probability density function of combined generation. For the load distribution being considered, the probability density function of the storage is obtained. Finally, the battery size is calculated to give the relevant level of the system reliability using the LPSP technique.

6.2.4. Analytical method with LPSP technique

A closed form solution approach to the evaluation of LPSP of standalone PV system with energy storage, as well as standalone wind electric conversion system, is presented in Abouzahr and Ramakumar (1990). Similar to Borowy and Salameh (1996), in this paper also, authors have defined the LPSP as probability of encountering the state of charge (SOC) of battery bank falling below a certain specified minimum value. However, instead of using long-term historical data to determine LPSP, LPSP is determined by integrating the probability density function of power input to the storage. In addition to the above publications, there are several other publications that analyze and estimate reliability of a standalone PV system, using LOL probability (LOLP). These publications include Diaf, Belhamel, Haddadi, and Louche (2008), Diaf, Notton, et al. (2008), Klein and Beckman (1987), Yang, Lu, and Zhou (2007), Diaf, Diaf, Belhamel, and Haddadi (2007).

6.2.5. Knowledge-based approach

A knowledge-based design approach that minimizes the total capital cost at a pre-selected reliability level is introduced in Ramkumar, Abouzahr, and Ashenayi (1992) and Ramkumar, Abouzahr, Krishnan, and Ashenayi (1995). The overall design approach is as follows: first, a year is divided into as many times sections as needed. For each section the rating of energy converter and the sizes of energy storage system that satisfy the energy needs at the desired reliability level at the minimum capital cost are determined. Then, a search algorithm is used to search for feasible configurations. Since the final design is selected based on the seasonal designs, the user must decide whether to select the worst or best case designs or the designs in between.

6.2.6. Simulation approach

In this approach, design of hybrid renewable energy system comprising PV/wind/battery systems is carried out using the same concept as used in HOMER (https://analysis.nrel.gov/homer/includes/downloads/HOMERBrochure_English.pdf). Initially, simulation is performed using a time step of usually one hour (though not necessary) to identify all possible combinations that satisfy the desired level of reliability of user. An optimal combination is then extracted from these combinations on the basis of economic parameters. The reliability level is calculated by total number of load unmet hours divided by the total number of hours in simulation period. The similar approach is used by Ali et al.

(2003), Bernal-Agustín et al. (2006), Celik (2002) to find the optimal configurations. The simulations are done by varying fraction of wind and PV energy from zero to one, at the battery-to-load ratio (the number of days that the battery is able to supply the load while fully charged) of 1.25, 1.5, and 2.0, and various energy-to-load ratios (the ratio of the energy produced by renewable component to energy demand).

6.2.7. Linear programming method

This is a well-known popular method used by number of researchers to find the optimum size of renewable energy systems. A very good explanation and insights into how linear programming (LP) method can be applied to find the size of wind turbine and PV system in a PV–wind hybrid energy system is detailed out in Markvast (1997). The method employs a simple graphical construction to determine the optimum configuration of the two renewable energy generators that satisfies the energy demand of the user throughout the year. It is essential to note that method does not include battery bank storage and diesel generator. LP method was used in Swift and Holder (1988) to size PV–wind system, considering reliability of power supply system. The reliability index used is defined as the ratio of total energy deficit to total energy load. Other applications of this method are available in Chedid and Rahman (1997) and Ramakumar, Shetty, and Ashenayi (1986).

6.2.8. Non-linear programming method

The basic approach used in this method aims to take the interdependency between sizing and system operation strategy into account. Thus, it can simultaneously determine the optimal sizing and operation control for renewable hybrid energy system. This method has been used in Seeling-Hochmuth (1997) to determine the optimum size of hybrid system configuration.

6.2.9. Genetic algorithm method

Genetic algorithms are an adequate search technique for solving complex problems when other techniques are not able to obtain an acceptable solution. This method has been applied in Tomonobu, Hayashi, and Urasaki (2006), Dufo-Lopez and Bernal-Augustin (2005), and Shadmand and Balog (2014). The works reported in these papers use the hourly average metrological and load data over a few years for simulation. In reality, the weather conditions are not the same every day and in every hours of the day. Therefore, under varying every hour and every day weather conditions, the optimum number of facilities to use the hourly average data may not be able to be supplied without outages over a year. In such situations, the use of genetic algorithm method has been found most suitable.

6.2.10. Particle swarm optimization

The particle swarm algorithm was first presented by Kennedy and Eberhart (1995) as an optimization method to solve non-linear optimization problems. This procedure is inspired by certain social behavior. For a brief introduction to this method, consider a swarm of p particles, where each particle's position represents a possible solution point in the design problem space D. Every single particle is denoted by its position and speed; in an iterative process, each particle continuously records the best solution thus far during its flight. As an example of optimal sizing of hybrid energy systems by means of PSO, refers to Hakimi and Moghaddas-Tafreshi (2009) and Haghi, Hakimi, and Tafreshi (2010).

6.3. Outcomes

Above literature review leads to following conclusion:

(1) There are different software packages existing with varying degree in user friendliness, validation of simulation models, accuracy of system models, and possible configuration to simulate.

(2) Most of these software tools simulate a given and predefined hybrid system based on a mathematical description of component characteristic operation and system energy flow. But, the

Table 4. Software based on optimization of hybrid system

Software	Developed by	Advantages	Disadvantages	Ref.	Year	Availability
HYBRID 2	NREL; Canada	Technical accuracy of the model is very high	Model is incapable to optimize the energy system	HYBRID 2 (http://www.ceere.org/rerl/projects/software/hybrid2/index), Barley (1995)	1993	http://www.ceere.org/rerl/rerl_hybridpower.html
PVSYS	Geneva University in Switzerland	It allows determination of PV size and battery capacity	Limitation for renewable energy sources	PVSYST 4.35 (2009)	1992	Not free www.pvsyst.com
INSEL	University of Oldenburg, Germany	Flexibility in creating system model and configuration	Does not perform system optimization	Planning and installing PV system (2005)	1996	Not free www.insel.eu
SOLSIM	Fachhochschule Konstanz, Germany	The unit to calculate life cycle cost	In capable to find the optimal size of hybrid system	Schaffrin (1998)	1987	NOT Free
WATSUN-PV	University of Waterloo, Canada	The model used for DC motors is a simple relationship between the voltage and current supplied by the array and the torque and angular speed of the motor	The database does not include information of motors or pumps	Tiba and Barbosa (2002)	–	NOT FREE
PV-DESIGN PRO	–	Database already includes most information needed for PV system design	The module and climate database are very comprehensive	Planning and installing PV system (2005)	–	–
RAPSIM	Murdoch University Energy Research Institute, Australia	The control variables that determine on-off cycles of the diesel generator	Battery aging effect is not considered in this model	Pryor et al. (1999)	1997	Unknown, after 1997 any change are not accounted
RETScreen	Government of Canada through Natural Resources Canada's Canmet ENERGY research centre	This software is to minimized the green house gas emission, life cycle cost, energy generation	1. Does not support calculation of more advanced statistics/analysis 2. Limited search and retrieval features 3. Limited visualization features 4. Data sharing problems 5. Data validation 6. Difficult to relate different data-sets, hence need for duplication	RETScreen (2009), Sinha and Chandel (2014)	1996	Free http://www.retscreen.net/
PHOTO	The Helsinki University	Various control strategies can also be considered	High computational time	Manninen et al. (1990)	1990	Unknown
SOMES	University of Utrecht Netherlands	The model contains an optimization routine to search for the system with lowest electricity cost	SOMES does not give optimal operating strategy	SOME (http://www.web.co.bw/sib/somes_3_2_description.pdf)	1987	Not free http://www.uu.nl/EN/Pages/default.aspx
HOMER	National Renewable Energy Laboratory (NREL, USA),	This tool offers a powerful user interface and accurate sizing with detail analysis of the system	Technical accuracy of HOMER is low because its components mathematical models are linear and do not include many correction factors	HOMER (https://analysis.nrel.gov/homer/includes/downloads/HOMER-Brochure_English.pdf)	1993	Not Free www.homerenergy.com
RAPSYS	University of New South Wales, Australia	This software can simulate a wide range of renewable system components that may be included in a hybrid system configuration	It does not optimize the size of components	RAPSYS (www.upress.uni-kassel.de/online/frei/978-3-933146-19-9)	1987	www.upress.uni-kassel.de/online/frei/978–3-933146–19-9

(*Continued*)

Table 4. (*Continued*)

Software	Developed by	Advantages	Disadvantages	Ref.	Year	Availability
ARES	University of Cardiff, UK	ARES is able to predict the occurrence of loss of load thus giving a direct measure of the system autonomy	The battery aging and its effects on system performance has not been addressed as part of this program.	Morgan et al. (1995, 1997)	–	Not found
PV F-chart	F-chart software	It suitable for prediction of long-term average performance. Extremely fast execution	Tracking options fixed	Planning and installing PV system (2005), Klein and Beckman (1993)	1993	Not free www.fchart.com

mathematical models used for characterizing system components are unknown due to commercial reasons.

(3) Some of these software tools (such as HYBRID 2, RAPSIM), though incorporate financial costing but incapable of determining optimal hybrid system configuration.

(4) For the optimal hybrid system design problem so far only two software tools (HOMER and SOMES) exist, using simplified linear system components mathematical models but varying the design randomly within a chosen range of component sizes.

(5) Technical accuracy of HOMER is low because its components mathematical models are linear and do not include many correction factors. SOMES does not give optimal operating strategy and not freely available to the designer/users.

(6) Majority of the software packages require the user to come up with a pre-design system. Therefore, a better system performance with lower cost could be achieved in many of these designs only if the system configuration could be optimized.

(7) With reference to search methodology-based optimization of hybrid systems, several previous works have certain limitations: some gives oversized components; some leave many design configurations for user to select; some do not consider the important parameters/correction factors in the design; and some are very lengthy and time consuming.

(8) Many papers are available for sizing by using artificial intelligent techniques, such as GA and PSO, etc. these new artificial intelligent techniques which can also be considered while sizing of hybrid renewable energy system. These artificial intelligent techniques provide best possible solution as compared to other software tools, but they face a crisis in the form of poor performance when a number of hybrid system components are increased such as PV, wind, generator, batteries, etc.

7. Case studies

A routine of software tools are used to design hybrid system which are discussed in Section 6. Among all these software GA, PSO, and HOMER found to be more suitable for evaluating optimal sizing of hybrid renewable solution. In this case study design of optimal sizing of different combinations of PV/wind hybrid energy-based power system for rural electrification in the key area by using HOMER software tool is presented.

Figure 6. Daily load profile.

Table 5. Summary of search methodology for design hybrid system

Ref.	Software	SA/GC	Parameters optimized	Load type	Highlights
Ghali et al. (1997), Bhuiyan and Ali Asgar (2003), Ming et al. (1995), Protogeropulos et al. (1997)	AH method	SA	PV, battery	Residential	To operate the estimated load reliably in the month of minimum insolation taking into account different types of power losses
Gavanidou and Bakirtzis (1993)	Trade-off method	SA	PV, wind battery	Residential	Design that is a reasonable compromise between the conflicting design objectives under most foreseeable conditions
Ghali et al. (1997), Borowy and Salameh (1996), Ali et al. (2003), Ofry and Braunstein (1983)	Probability method using LPSP technique	SA	PV, battery	Residential	Determine the minimum (and thus the economical) sizes of the solar cell array and storage system capacity
Abouzahr and Ramakumar (1990), Klein and Beckman (1987), Yang et al. (2007), Diaf et al. (2007), Diaf, Notton, et al. 2008), Diaf, Belhamel, et al., 2008; Borowy and Salameh (1996)	Analytical method with LPSP technique	SA	Wind battery	Industrial	To evaluate the relationship between the amount of energy storage and the loss of power supply probability under various operating conditions
Ramkumar et al. (1992, 1995)	Knowledge-based approach	SA	PV, wind biogas, battery	Residential	A knowledge-based design approach that minimizes the total capital cost at a pre-selected reliability level
Ali et al. (2003), Bernal-Agustín et al. (2006), Celik (2002)	Simulation approach	SA	PV, Wind Battery	Residential	An optimum combination of the hybrid PV–wind energy system provides higher system performance than either of the single systems for the same system cost for every battery storage capacity
Chedid and Rahman (1997), Markvast (1997), Ramakumar et al. (1986), Swift and Holder (1988)	Linear programming (LP) method	GA	PV, wind battery	Residential	1. Linear programming techniques to minimize the average production cost of electricity while meeting the load requirement in a reliable manner
					2. A controller that monitors the operation of the autonomous grid -linked system is designed
8	Non-linear programming method	SA	PV, wind battery	Residential	A general method has been developed to jointly determine the sizing and operation control of hybrid-PV systems
Dufo-Lopez and Bernal-Augustin (2005), Shadmand and Balog 2014), Tomonobu et al. (2006)	Genetic algorithm method	GA	PV, wind battery	Residential	The proposed methodology employs a techno-economic approach to determine the system design optimized by considering multiple criteria including size, cost, and availability
Haghi et al. (2010), Hakimi and Moghaddas-Tafreshi (2009), Kennedy and Eberhart (1995)	Particle swarm optimization	SA	Wind fuel cells, hydrogen tanks	–	Minimize the total costs of the system in view of wind power uncertainty to secure the demand

7.1. Renewable energy resources

A Jamny Ven village Barwani (latitude 22.71 and longitude 75.85) Madhya Pradesh, India site renewable energy resource is an important factor for developing hybrid systems. According to IMD wind and solar energy are available in many parts of India in large quantities (http:/homepage.mac.com/unarte/solar_radiatio n.html). These energy sources are discontinuous and naturally obtainable; because of these issues our primary preference to power the village base power station is renewable energy sources like wind and solar. Climate data for particular site renewable hybrid energy systems are important factors to study the possibility of the former the confidential information, wind and solar energy resources data for the village are taken from NASA (Lilienthal & Flowers, 1995).

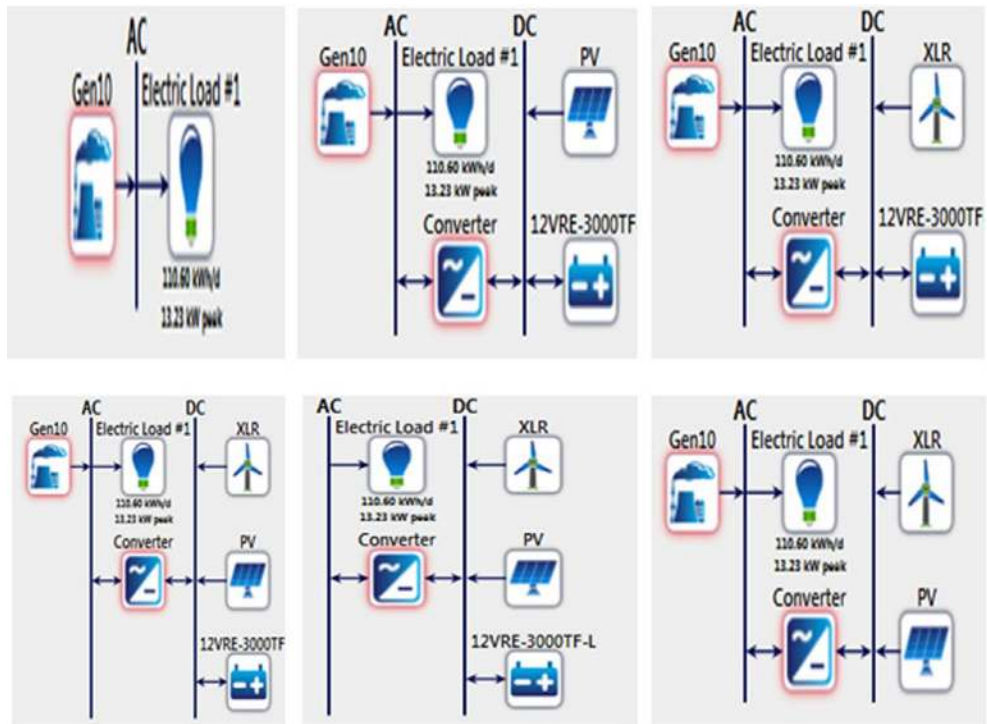


Figure 7. Architecture of hybrid renewable energy system with (i) DG, (ii) PV–Battery–DG, (iii) Wind–Battery–DG, (iv) PV–Wind–DG, (v) PV–Wind–Battery,(vi) PV–Wind–Battery–DG.

7.2. Solar energy resource

Hourly solar emission information was collected from the environment Barwani Jamny village. Long-term average annual resource scaling (5.531). Solar power is higher in summer season when compared to the winter season. Here solar insolation and clearance index data are shown in Table 4.

7.3. Wind energy resource

Confidential information may be an occurrence that is associated with the connection of air, plenty caused mainly by the degree of difference star heating of the Earth's surface. Seasonal and position variations within the energy arriving from the Sun have an effect on the strength and manner of the wind. Power from the wind depends upon the swept space of the rotary engine blades and, therefore,

Table 6. Resource of PV–Wind data

S. No	Months	Insolation (KWh/m^2/d)	Clearance index	Wind speed (m/s)
1	January	4.810	0.684	4.794
2	February	5.650	0.697	5.702
3	March	6.350	0.675	3.338
4	April	6.990	0.668	4.121
5	May	7.210	0.656	4.062
6	June	6.080	0.546	2.664
7	July	4.770	0.432	3.572
8	August	4.170	0.393	3.630
9	September	5.190	0.533	3.594
10	October	5.790	0.684	4.823
11	November	4.900	0.675	6.587
12	December	4.510	0.675	7.195
13	Average	5.531	0.598	4.500

Table 7. Input parameters used hybrid system

S. No	Items cost($)			Other parameters	Life span
1	Wind turbine			Hub height: 30 m Rotor diameter 1.75 m	20 year
	Initial: 23220	Replacement: 1775	O&M: 480		
2	PV			Derating factor: 80% Ground reflectance: 20%	20 year
	Initial: 1590	Replacement: 750	O&M: 2		
3	Inverter			Efficiency: 90%	15 year
	Initial: 2400	Replacement: 2350	O&M: 1		
4	Battery			Capacity: 240 Ahvoltage: 12 V	3550 h
	Initial: 250	Replacement: 250	O&M: 10		
5	Generator			Minimum load ratio: 30	15000 h
	Initial: 15300	Replacement: 1450	O&M: 0.2		

the cube of the wind speed, wind energy has been considered as potential toward meeting the continually increasing demand for energy. The wind sources of energy the alteration processes are pollution-free, and it is freely available. Periodical regular wind information for Jamny Ven village was together beginning environmental of Barwani climate. The scaled annual average wind speed is 4.5 the highest value of monthly average wind speed is observed during the month of December with a maximum of 7.195 m/s and the lowest value is observed during June with 2.664 m/s monthly average wind speed. Resource data are shown in Table 4 (Lilienthal & Flowers, 1995).

7.4. Electrical load data

The average estimation of daily energy consumption is 110.6 (kWh/day), peak load is found to be13.23 KW, and average is 4.61 KW. The information was computed for the entire hour basis daily electrical load condition of a demand for a village of Barwani district. The daily load profile with respective 24 h of day is shown in Figure 6.

7.5. Cost of hybrid system components

The cost of input components which are used to design optimal combination solution is given in Table 5.

7.6. Result and discussion

The study is to design of optimal sizing of different combinations of PV/wind hybrid energy-based power system for rural electrification in the key area (Jamny Ven Barwani) Madhya Pradesh, India where utility supply cost is really high due to limited consumer higher transmission and higher transportation cost. The chosen case study presents a power demand 110.6 kWh/d. The system is designed and optimized as hybrid energy base power system in parliamentary procedure to meet the existing user's power require at a minimum price of energy. The simulation-based optimization generates the best-optimized sizing of different combinations of wind and PV array with diesel generators for a rural hybrid base power system. Optimal sizing of various combinations such as DG (diesel generator), PV–Battery–DG, Wind–Battery–DG and PV–Wind–DG, PV–Wind–Battery and PV–Wind–Battery–DG are shown in Figure 7. Simulation and optimization result calculated by using HOMER software and analysis on the base of sensitive parameters of PV, wind resources data, and variation in diesel price. Among all six hybrid combinations only two hybrid system Wind-DG and PV–Wind–Battery–DG are more cost-effective, reliable and environmentally friendly solution. Emission and levelized COE of the both hybrid systems are nearly equal, but the total NPC and operating cost of the PV–Wind–Battery–DG is less as compared to Wind-DG hybrid system. As the penetration of solar, wind system will increase; the surplus energy is multiplied. It can be saved and used by foreseeable

Table 8. Comparative examination of different hybrid system configurations

S.No	Description	DG	PV/Battery/DG	Wind/Battery/DG	PV/Wind/DG	PV/Wind/Battery	PV/Wind/Battery/DG
1	Emission						
	Carbon dioxide (kg/yr)	62,204.00	36,334.00	28,394.00	61,517.00	0	29,201.00
	Carbon monoxide (kg/yr)	153.54	89.69	70.09	151.85	0	72.08
	Unburned hydrocarbons (kg/yr)	17.01	9.93	7.76	16.82	0	7.98
	Particulate matter (kg/yr)	11.58	6.76	5.28	11.45	0	5.43
	Sulfur dioxide (kg/yr)	124.92	72.97	57.02	123.54	0	58.64
	Nitrogen oxides (kg/yr)	1,370.10	800.27	625.39	1,354.90	0	643.17
2	Production						
	Excess electricity (KWh/yr)	5,471.00	0	14,785.00	6,087.40	63,747.00	7,701.90
	Unmet electric load (KWh/yr)	0	11.6	10	0	22.3	9.2
	Capacity shortage (KWh/yr)	0	40.2	38	0	35	37.3
	Renewable fraction	0	33.8	47.2	0	100	46.5
	Max. renew. penetration	0	496.8	2,180.70	49.7	3,634.60	1,453.80
3	Cost						
	Total net present cost ($)	3,20,873	3,44,576	3,30,844	4,08,347	6,27,750	3,24,178
	Levelized cost ($)	0.6149	0.6605	0.6341	0.7825	1.2	0.6213
	Operating cost ($)	24,465.94	21,355	19,297	30,607.03	23,909	19,261
4	Fuel						
	Total fuel consumed (L)	23,622.00	13,798.00	10,783.00	23,361.00		11,089.00
	Avg fuel per day (L/day)	64.73	37.81	29.55	64.01		30.38
	Avg fuel per hour (L/hour)	2.7	1.58	1.23	2.67		1.27
5	Battery						
	Energy input (KWh/yr)		6,953.90	6,897.10		13,415.00	6,433.50
	Energy out (KWh/yr)		5,965.00	5,862.60		11,403.00	5,468.70
	Storage depletion (KWh/yr)		49.8	−8.9		−35.96	−8.7
	Losses (KWh/yr)		939.05	1,043.40		2,048.20	973.47
	Annual throughput (KWh/yr)		6,470.00	6,358.90		12,368.00	5,931.70
	Expected life (yr)		13.72	13.96		18	14.96
6	Efficiency						
	Mean electrical efficiency	19.72	19.69	20.10	19.55		19.81
7	Components						
	Generic flat plate PV	×	✓	×	✓	✓	✓
	BWC Excel-R			✓	✓	✓	✓
	10 kW genset	✓	✓	✓	✓		✓
	Discover 12VRE-3000TF-L	×	✓	✓	×	✓	✓
	Converter	×	✓	✓	✓	✓	✓

future objective by making use of battery bank. The comparative analysis of all optimal combination is shown in Table 6.

8. Conclusion

For hybrid renewable energy system design number of new technologies are discussed in the literature, but due to some new problems like parameters of renewable source material and design, constraints of load, generator, battery, converter, and cost function, the system performance has

Table 9. Suggestion for hybrid system implementation		
Number	**Issue**	**Comments**
1	Converters losses	The loss involved with electrical power converters are actually reduced to some sufficient stage; on the other hand, it should be guaranteed that there's minimal quantity of electrical power reduction within these converters
2	Life-cycle	The life-cycle associated with storage units, such as batteries along with UCs, should be improved upon by means of innovative systems
3	Disposal of storage equipment	The convenience connected with storage space products, like power packs and also other storages, is among the significant problems for producers
4	Renewable energy sources	Photovoltaic and other renewable energy options require break-through systems for removing much more quantity of use full strength. The poor effectiveness involving a solar PV is often an important barrier inside stimulating its use
5	Control unit	With the entire supplement associated with unique turbines inside developing a hybrid renewable energy system raises the strain about power alteration devices. Any possible hybrid renewable energy system requires the feasible associated with right keeping track of design system that will record important info to its productive functioning. Each time almost any mismatch inside the power generation in addition to desire exists the system may open the circuit breakers with regard to much better safety in addition to functioning
6	Grid control	For controlling different generators which are linked to the hybrid renewable energy system, to the function of saving power and carry through the load demand a development of a small grid system required
7	Manufacturing cost	This making price tag of renewable energy sources needs a significant lessening considering that the higher capital price tag causes an elevated payback time. cost lessening will supply a motivation on the marketplace to be able to apply like devices
8	Load management	The particular renewable resources tend to be independent of the load variations and as such suitable energy management should be designed, in order that the prolonged existence on the hybrid renewable energy system can be increased. Big deviation inside the load could even result in a whole system fall
9	Stability	Hybrid renewable energy system depends on weather conditions so that theirs is needed to carry out transient analysis of the system for varying constraint like solar radiation, wind velocity, load demand
10	Government support	For reducing the cost of components, production costs of generation and wide deployment of Hybrid renewable energy system network, it is essential to give subsidy on renewable energy goods from central to the state government

decreased. These kinds of issues have to be attended properly, to resolve these shorted out. Table 7 presents some important suggestion and also scope with regard to potential research. This paper explains several hybrid system combinations for PV and wind turbine, modeling parameters of hybrid system component, software tools for sizing, criteria for PV–wind hybrid system optimization, and control schemes for energy flow management. In this paper for the sizing purpose of the hybrid system, 25 different types of computational software tools are discussed. Among all these software tools, HOMER and GA, PSO gives more feasible result for hybrid system design. Another technique for sizing of hybrid scheme which presents more promising result, such as genetic algorithm and PSO. At least to obtain the operational efficiency, highest system reliability and proper energy flow management, control strategies are suggested in this paper. Controller work as monitoring whole hybrid system and maintain the requirement of load demand while keeping system frequency and output voltage. Additionally, it is been located in which wide range of research work in the community associated with hybrid renewable energy system has been completed. A case study of various standalone hybrid system combinations for a remote location in India by using HOMER and evaluate best optimal hybrid system configuration such as PV–Wind–Battery–DG with respective total NPC, operating cost, COE, and also emission. The optimal hybrid system has following advantages (Table s 8 and 9).

- This non-conventional power PV–Wind–Battery–DG hybrid energy method is available to be technically achievable, emission much less along with less expensive with years to come.
- Its environment-friendly dynamics helps it be a nice-looking substitute for complementing the energy present inside countryside regions.
- Load demand is fulfilled in an optimal way.

On the other hand much more research along with the work usually is needed to increase battery's strength along with effectiveness with giving attention to decreasing the cost. Hybrid system performance depends on weather condition so as to minimize the issue related to the system reliability and operation there is a need to carry out transient analysis of the system for varying constraint like solar radiation, wind velocity, load demand. The COE sources used in hybrid system are very high so that there is needed to provide subsidy from central and state government to minimize initial cost of the system and also reduced the COE.

Funding
The authors received no direct funding for this research.

Author details
Yashwant Sawle[1]
E-mail: yashsawle@gmail.com
S.C. Gupta[1]
E-mail: scg.nit.09@gmail.com
Aashish Kumar Bohre[1]
E-mail: aashu371984@gmail.com
[1] Department Electrical Engineering, Maulana Azad Institute of Technology, Bhopal, India.

Citation information
Cite this article as: PV-wind hybrid system: A review with case study, Yashwant Sawle, S.C. Gupta & Aashish Kumar Bohre, *Cogent Engineering* (2016), 3: 1189305.

References

Abido, M. A. (2003). Environmental/economic power dispatch using multiobjective evolutionary algorithms. *IEEE Transactions on Power Systems, 18*, 1529–1537. http://dx.doi.org/10.1109/TPWRS.2003.818693

Abouzahr, I., & Ramakumar, R. (1990). Loss of power supply probability of stand-alone wind electric conversion systems: A closed form solution approach. *IEEE Transactions on Energy Conversion, 5*, 445–452. http://dx.doi.org/10.1109/60.105267

Abouzahr, I., & Ramakumar, R. (1991). Loss of power supply probability of stand-alone photovoltaic systems: A closed form solution approach. *IEEE Transactions on Energy Conversion, 6*, 1–11. http://dx.doi.org/10.1109/60.73783

Al-Ashwal, A. M. (1997). Proportion assessment of combined PV-wind generating systems. *Renewable Energy, 10*, 43–51. http://dx.doi.org/10.1016/0960-1481(96)00011-0

Ali, B., Yang, H., Shen, H., & Liao, X. (2003). Computer aided design of PV/wind hybrid system. *Renewable Energy, 28*, 1491–1512.

Arifujjaman, M., Iqbal, M. T., Quaicoe, J. E., & Khan. M. J. (2005). Modeling and control of a small wind turbine. *IEEE Transactions on Electrical and Computer Engineering,*, 778–781.

Azmy, A. M., & Erlich, I. (2005). Online optimal management of PEM fuel cells using neural networks. *IEEE Transactions on Power Delivery, 20*, 1051–1058. http://dx.doi.org/10.1109/TPWRD.2004.833893

Bagul, A. D., & Salameh, Z. M. (1996). Sizing of a stand-alone hybrid wind-photovoltaic system using a three-event probability density approximation. *Solar Energy,56*, 323–335. http://dx.doi.org/10.1016/0038-092X(95)00116-9

Barley, C. D. (1995). Optimal control of remote hybrid power system, Part I: Simplified model. In *Proceedings of Wind Power 95*. Washington, DC.

Bellarmine, G. T., & Urquhart, J. (1996). Wind energy for the 1990s and beyond. *Energy Conversion Management, 37*, 1741–1752. http://dx.doi.org/10.1016/0196-8904(96)00009-X

Bernal-Agustín, J. L., Dufo-López, R., & Rivas-Ascaso, D. M. (2006). Design of isolated hybrid systems minimizing costs and pollutant emissions. *Renewable Energy, 31*, 2227–2244. http://dx.doi.org/10.1016/j.renene.2005.11.002

Beyer, H. G., & Langer, C. (1996). A method for the identification of configurations of PV/wind hybrid systems for the reliable supply of small loads. *Solar Energy, 57*, 381–391. http://dx.doi.org/10.1016/S0038-092X(96)00118-1

Bhave, A. G. (1999). Hybrid solar–wind domestic power generating system—case study Renew. *Energy, 17*, 355–358.

Bhuiyan, M. M. H., & Ali Asgar, M. (2003). Sizing of a stand-alone photovoltaic power system at Dhaka. *Renewable Energy, 28*, 929–938. http://dx.doi.org/10.1016/S0960-1481(02)00154-4

Bhuiyan, M. M. H., Asgar, M., Mazumder, R. K., & Hussain, M. (2000). Economic evaluation of a stand-alone residential photovoltaic power system in Bangladesh. *Renewable Energy, 21*, 403–410. http://dx.doi.org/10.1016/S0960-1481(00)00041-0

Bilal, B. O., Sambou, V., Ndiaye, P. A., Kébé, C. M. F., & Ndongo, M. (2013). Study of the influence of load profile variation on the optimal sizing of a standalone hybrid PV/Wind/Battery/Diesel system. *Energy Procedia, 36*, 1265–1275. http://dx.doi.org/10.1016/j.egypro.2013.07.143

Borowy, B. S., & Salameh, Z. M. (1996). Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. *IEEE Transactions on Energy Conversion, 11*, 367–375. http://dx.doi.org/10.1109/60.507648

Borowy, B. S., & Salameh, Z. M. (1997). Dynamic response of a stand-alone wind energy conversion system with battery energy storage to a wind gust. *IEEE Transactions on Energy Conversion, 12*, 73–78. http://dx.doi.org/10.1109/60.577283

Cano, A., Jurado, F., Sánchez, H., Fernández, L. M., & Castañeda, M. (2014). Optimal sizing of stand-alone hybrid systems based on PV/WT/FC by using several methodologies. *Journal of the Energy Institute, 87*, 330–340. http://dx.doi.org/10.1016/j.joei.2014.03.028

Celik, A. N. (2002, January). Optimization and techno-economic analysis of autonomous photovoltaic-wind hybrid energy systems in comparison to single

photovoltaic and wind system. *Energy Conversion and Management, 43*, 2453–2468.
Celik, A. N. (2003a). A simplified model for estimating the monthly performance of autonomous wind energy systems with battery storage. *Renewable Energy, 28*, 561–572. http://dx.doi.org/10.1016/S0960-1481(02)00067-8
Celik, A. N. (2003b). Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods. *Energy Conversion and Management, 44*, 1951–1968. http://dx.doi.org/10.1016/S0196-8904(02)00223-6
Chedid, R., & Rahman, S. (1997). Unit sizing and control of hybrid wind-solar power systems. *IEEE Transactions on Energy Conversion, 12*, 79–85. http://dx.doi.org/10.1109/60.577284
Chedid, R. B., Karaki, S. H., & El-Chamali, C. (2000). Adaptive fuzzy control for wind-diesel weak power systems. *IEEE Transactions on Energy Conversion, 15*, 71–78. http://dx.doi.org/10.1109/60.849119
Diaf, S., Belhamel, M., Haddadi, M., & Louche, A. (2008). Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island. *Energy Policy, 36*, 743–754. http://dx.doi.org/10.1016/j.enpol.2007.10.028
Diaf, S., Diaf, D., Belhamel, M., & Haddadi, M. (2007). A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy, 35*, 5708–5718. http://dx.doi.org/10.1016/j.enpol.2007.06.020
Diaf, S., Notton, G., Belhamel, M., Haddadi, M., & Louche, A. (2008). Design and techno-economical optimization for hybrid PV/wind system under various meteorological conditions. *Applied Energy, 85*, 968–987. http://dx.doi.org/10.1016/j.apenergy.2008.02.012
Dimeas, A. L., & Hatziargyriou, N. D. (2005). Operation of a multiagent system for microgrid control. *IEEE Transactions on Power Systems, 20*, 1447–1455. http://dx.doi.org/10.1109/TPWRS.2005.852060
Douglas, B. (1997, May/June). The essence way renewable energy system. *Solar Today, 5*, 16–19.
Dufo-Lopez, R., & Bernal-Augustin, J. L. (2005). Design and control strategies of PV-diesel using genetic algorithm. *Solar Energy, 79*, 33–46.
Dufo-López, R., Bernal-Agustín, J. L., & Mendoza, F. (2009). Design and economical analysis of hybrid PV–wind systems connected to the grid for the intermittent production of hydrogen. *Energy Policy, 37*, 3082–3095. http://dx.doi.org/10.1016/j.enpol.2009.03.059
Egido, M., & Lorenzo, E. (1992). The sizing of stand alone PV-system: A review and a proposed new method. *Solar Energy Materials and Solar Cells, 26*, 51–69. http://dx.doi.org/10.1016/0927-0248(92)90125-9
Ekren, B. Y., & Ekren, O. (2009). Simulation based size optimization of a PV/wind hybrid energy conversion system with battery storage under various load and auxiliary energy conditions. *Applied Energy, 86*, 1387–1394. http://dx.doi.org/10.1016/j.apenergy.2008.12.015
Elhadidy, M. A., & Shaahid, S. M. (2000). Parametric study of hybrid (wind+solar+diesel) power generating systems. *Renewable Energy, 21*, 129–139.
Elhadidy, M. A., & Shaahid, S. M. (2004a). Promoting applications of hybrid (wind+photovoltaic+diesel+battery) power systems in hot regions. *Renewable Energy, 29*, 517–528. http://dx.doi.org/10.1016/j.renene.2003.08.001
Elhadidy, M. A., & Shaahid, S. M. (2004b). Role of hybrid (wind+diesel) power systems in meeting commercial loads. *Renewable Energy, 29*, 109–118. http://dx.doi.org/10.1016/S0960-1481(03)00067-3
El-Hefnawi, S. H. (1998). Photovoltaic diesel–generator hybrid power system sizing. *Renewable Energy, 13*, 33–40. http://dx.doi.org/10.1016/S0960-1481(97)00074-8
Erhard, K., & Dieter, M. (1991). Sewage plant powered by combination of photovoltaic, wind and bio-gas on the Island of Fehmarl, Germany. *Renewable Energy, 1*, 745–748.
Feijoo, A. E., Cidras, J., & Dornelas, J. L. G. (1999). Wind speed simulation in wind farms for steady-state security assessment of electrical power systems. *IEEE Transactions on Energy Conversion, 14*, 1582–1588. http://dx.doi.org/10.1109/60.815109
Gavanidou, E. S., & Bakirtzis, A. G. (1993). Design of a standalone system with renewable energy sources using trade-off methods. *IEEE Transactions on Energy Conversion, 7*, 42–48.
Ghali, F. M. A., El Aziz, M. M. A., & Syam, F. A (1997, August 3–6). Simulation and analysis of hybrid systems using probabilistic techniques. In *Proceedings of the Power Conversion Conference* (Vol. 2, pp. 831–835). Nagaoka. http://dx.doi.org/10.1109/PCCON.1997.638338
Giraud, F., & Salameh, Z. M. (2001). Steady-state performance of a grid-connected rooftop hybrid wind–photovoltaic power system with battery storage. *IEEE Transactions on Energy Conversion, 16*, 1–7. http://dx.doi.org/10.1109/60.911395
González, A., Riba, J. R., Rius, A., & Puig, R. (2015). Optimal sizing of a hybrid grid-connected photovoltaic and wind power system. *Applied Energy, 154*, 752–762. http://dx.doi.org/10.1016/j.apenergy.2015.04.105
Gupta, S. C., Kumar, Y., & Agnihotri, G. (2011). Design of an autonomous renewable hybrid power system. *International Journal of Renewable Energy Technology, 2*, 86–104. http://dx.doi.org/10.1504/IJRET.2011.037983
Haghi, H. V., Hakimi, S. M., & Tafreshi, S. M. M. (2010, June 14–17). Optimal sizing of a hybrid power system considering wind power uncertainty using PSO-embedded stochastic simulation. In *IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)* (pp. 722–727). Singapore.
Hajizadeh, A., & Golkar, M. A. (2009). Fuzzy neural control of a hybrid fuel cell/battery distributed power generation system. *IET Renewable Power Generation, 3*, 402–414. http://dx.doi.org/10.1049/iet-rpg.2008.0027
Hakimi, S. M., & Moghaddas-Tafreshi, S. M. (2009). Optimal sizing of a stand-alone hybrid power system via particle swarm optimization for Kahnouj area in south-east of Iran. *Renewable Energy, 34*, 1855–1862. http://dx.doi.org/10.1016/j.renene.2008.11.022
Huang, K., Cartes, D. A., & Srivastava, S. K. (2007). A multiagent-based algorithm for ring-structured shipboard power system reconfiguration. *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews), 37*, 1016–1021. http://dx.doi.org/10.1109/TSMCC.2007.900643
Jangamshetti, S. H., & Ran, V. G. (2001). Optimum siting of wind turbine generators. *IEEE Transactions on Energy Conversion, 16*, 8–13. http://dx.doi.org/10.1109/60.911396
Kaldellis, J. K. (2010). *Stand-alone and hybrid wind energy systems*. Tigaday of island of El Hierro: Woodhead Publishing Limited and CRC Press LLC. http://dx.doi.org/10.1533/9781845699628
Kaldellis, J. K., & Th, G. (2005). Vlachos Optimum sizing of an autonomous wind–diesel hybrid system for various representative wind-potential cases. *Applied Energy, 83*, 113–132.
Kamel, S., & Dahl, C. (2005). The economics of hybrid power systems for sustainable desert agriculture in Egypt. *Energy, 30*, 1271–1281. http://dx.doi.org/10.1016/j.energy.2004.02.004
Katsigiannis, Y. A., Georgilakis, P. S., & Karapidakis, E. S. (2010). Multiobjective genetic algorithm solution to the

optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables. *IET Renewable Power Generation, 4*, 404–419. http://dx.doi.org/10.1049/iet-rpg.2009.0076

Kefayat, M., Lashkar Ara, A., & Nabavi Niaki, S. A. (2015). A hybrid of ant colony optimization and artificial bee colony algorithm for probabilistic optimal placement and sizing of distributed energy resources. *Energy Conversion and Management, 92*, 149–161. http://dx.doi.org/10.1016/j.enconman.2014.12.037

Kelash, H. M., Faheem, H. M., & Amoon, M. (2007). It takes a multiagent system to manage distributed systems. *IEEE Potentials, 26*, 39–45. http://dx.doi.org/10.1109/MP.2007.343026

Kennedy, J., & Eberhart, R. C. (1995). Particle swarm optimization. In *Proceedings of IEEE International Conference on Neural Network IV*. Piscataway, NJ. http://dx.doi.org/10.1109/ICNN.1995.488968

Khatod, D. Kumar, Pant, V., & Sharma, J. (2010). Analytical approach for well-being assessment of small autonomous power systems with solar and wind energy sources. *IEEE Transactions on Energy Conversion, 25*, 535–545. http://dx.doi.org/10.1109/TEC.2009.2033881

Klein, S. A., & Beckman, W. A. (1987). Loss-of-load probability for stand-alone photovoltaic systems. *Solar Energy, 39*, 449–512.

Klein, S. A., & Beckman, W. A. (1993). *PVF-chart user's manual window version*. Middleton, WI. Retrieved from F-Chart Software: www.fchart.com

Ko, H., & Jatskevich, J. (2007). Power quality control of wind-hybrid power generation system using fuzzy-LQR controller. *IEEE Transactions on Energy Conversion, 22*, 516–527. http://dx.doi.org/10.1109/TEC.2005.858092

Lagorse, J., Simoes, M. G., & Miraoui, A. (2009). A multiagent fuzzy-logic-based energy management of hybrid systems. *IEEE Transactions on Industry Applications, 45*, 2123–2129. http://dx.doi.org/10.1109/TIA.2009.2031786

Li, S., Wunsch, D. C., O'Hair, E., & Giesselmann, M. G. (2001). Comparative analysis of regression and artificial neural network models for wind turbine power curve estimation. *Journal of Solar Energy Engineering, 123*, 327–332. http://dx.doi.org/10.1115/1.1413216

Lilienthal, P., & Flowers, L. (1995). HOMER: The hybrid optimization model for electrical renewable. In *Proceedings of WindPower 95* (pp. 475–480). Washington, DC: American Wind Energy Associations.

Lingfeng Wang, L., & Singh, C. (2009). Multicriteria design of hybrid power generation systems based on a modified particle swarm optimization algorithm. *IEEE Transactions on Energy Conversion, 24*, 163–172. http://dx.doi.org/10.1109/TEC.2008.2005280

Maghraby, H. A. M., Shwehdi, M. H., & Al-Bassam, G. K. (2002). Probabilistic assessment of photovoltaic (PV) generation systems. *IEEE Transactions on Power Systems, 17*, 205–208. http://dx.doi.org/10.1109/59.982215

Mahmoud, M. (1990). Experience results and techno-economic feasibility of using photovoltaic generators instead of diesel motors for water pumping from rural desert wells in Jordan. *IEE Proceedings C, 37*, 391–394.

Maleki, A., & Askarzadeh, A. (2014). Comparative study of artificial intelligence techniques for sizing of a hydrogen-based stand-alone photovoltaic/wind hybrid system. *International Journal of Hydrogen Energy, 39*, 9973–9984. http://dx.doi.org/10.1016/j.ijhydene.2014.04.147

Manninen, M., Lund, P. D. & Vikkula, A. (1990). *PHOTO-A computer simulation program for photovoltaic and hybrid energy systems* (Report TKK-F-A-670). Espoo: Helsinki University of Technology. ISBN 951-22-04657.

Markvast, T. (1997). Sizing of hybrid photovoltaic-wind energy systems. *Solar Energy, 57*, 277–281.

Marwali, M. K. C., Shahidehpour, S. M., & Daneshdoost, M. (1997). Probabilistic production costing for photovoltaics-utility systems with battery storage. *IEEE Transactions on Energy Conversion, 12*, 175–180. http://dx.doi.org/10.1109/60.629700

Mathew, S., Pandey, K. P., & Anil Kumar, V. (2002). Analysis of wind regimes for energy estimation. *Renewable Energy, 25*, 381–399. http://dx.doi.org/10.1016/S0960-1481(01)00063-5

McGowan, J. G., Manwell, J. F., Avelar, C., & Warner, C. L. (1996). Hybrid wind/PV/diesel hybrid power systems modeling and South American applications. *Renewable Energy, 9*, 836–847. http://dx.doi.org/10.1016/0960-1481(96)88412-6

Miettinen, K. (1998). *Nonlinear multiobjective optimization*. Boston, MA: Kluwer. http://dx.doi.org/10.1007/978-1-4615-5563-6

Ming, J., Buping, L., & Zhegen, C. (1995). Small scale solar PV generating system-the household electricity supply used in remote area. *Renewable Energy, 6*, 501–505.

Morgan, T. R., Marshall, R. H., & Brink worth, B. J. (1995). SEU-ARES––A refined simulation program for sizing and optimization of autonomous hybrid energy system. In *Proceedings of the annual meeting of the International Solar Energy Society*. Harare.

Morgan, T. R., Marshall, R. H., & Brinkworth, B. J. (1997). 'ARES'—A refined simulation program for the sizing and optimisation of autonomous hybrid energy systems. *Solar Energy, 59*, 205–215. http://dx.doi.org/10.1016/S0038-092X(96)00151-X

Muselli, M., Notton, G., Poggi, P., & Louche, A. (2000). PV–hybrid power systems sizing incorporating battery storage: An analysis via simulation calculations. *Renewable Energy, 20*, 1–7. http://dx.doi.org/10.1016/S0960-1481(99)00094-4

Nag, P. K. (2001). *Power plant engineering* (2nd ed.). New Delhi: Tata McGraw-Hill.

Nagata, T., & Sasaki, H. (2002). A multi-agent approach to power system restoration. *IEEE Transactions on Power Systems, 17*, 457–462. http://dx.doi.org/10.1109/TPWRS.2002.1007918

Nayar, C. V., Phillips, S. J., James, W. L., Pryor, T. L., & Remmer, D. (1993). Novel wind/diesel/battery hybrid energy system. *Solar Energy, 51*, 65–78. http://dx.doi.org/10.1016/0038-092X(93)90043-N

Nayar, C. V., Thomas, F. P., Phillips, S. J., & James, W. L. (1991). Design considerations for appropriate wind energy systems in developing countries. *Renewable Energy, 1*, 713–722. http://dx.doi.org/10.1016/0960-1481(91)90018-K

Nehrir, M. H., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., ... Salameh, Z. (2011). A review of hybrid renewable/alternative energy systems for electric power generation: Configurations, control, and applications. *IEEE Transactions on Sustainable Energy, 2*, 392–403. http://dx.doi.org/10.1109/TSTE.2011.2157540

Nfaoui, H., Buret, J., & Sayigh, A. A. M. (1996). Cost of electricity generated and fuel saving of an optimized wind-diesel electricity supply for village in Tangier-area (Morocco). *Renewable Energy, 9*, 831–835. http://dx.doi.org/10.1016/0960-1481(96)88411-4

Nfaoui, H., Buret, J., Sayigh, A. M. M., & Dunn, P. D. (1994). Modelling of a wind/diesel system with battery storage for Tangiers, Morocco. *Renewable Energy, 4*, 155–167. http://dx.doi.org/10.1016/0960-1481(94)90001-9

Notton, G., Muselli, M., & Louche, A. (1996). Autonomous hybrid photovoltaic power plant using a back-up generator: A case study in a Mediterranean Island. *Renewable Energy, 7*, 371–391.

Ofry, E., & Braunstein, A. (1983). The loss of power supply probability as a technique for designing stand-alone solar electric photovoltaic system. *IEEE Transaction on Power Apparatus and System, PAS-102*, 1171–1175.

Onar, O. C., Uzunoglu, M., & Alam, M. S. (2006). Dynamic modeling, design and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system. *Journal of Power Sources, 161*, 707–722. http://dx.doi.org/10.1016/j.jpowsour.2006.03.055

Papadopoulos, D. P., & Dermentzoglou, J. C. (2002). Economic viability analysis of planned WEC system installations for electrical power production. *Renewable Energy, 25*, 199–217. http://dx.doi.org/10.1016/S0960-1481(01)00012-X

Papaefthymiou, S. V., & Stavros, A. (2014, April). Optimum sizing of wind-pumped-storage hybrid power stations in island systems. *Renewable Energy, 64*, 187–196.

Planning and installing PV system: A guide for installers, architects and engineers. (2005). (pp. 18–24). James & James. ISBN: 1-84407-131-6.

Post, H. N., & Thomas, M. G. (1988). Photovoltaic systems for current and future applications. *Solar Energy, 41*, 465–473. http://dx.doi.org/10.1016/0038-092X(88)90020-5

Protogeropulos, C., Brinkworth, B. J., & Marshall, R. H. (1997). Sizing and techno-economical optimization for hybrid solar photovoltaic/wind power systems with battery storage. *International Journal of Energy Research, 21*, 465–479. http://dx.doi.org/10.1002/(ISSN)1099-114X

Pryor, T., Gray, E., & Cheok, K. (1999, February). *How good are RAPS simulation program?-A comparison of RAPSIM & HYBRID 2*. World Renewable Energy Congress.

PVSYST 4.35. (2009, March). Retrieved 2008, from www.pvsyst.com

Ramkumar, R., Abouzahr, I., & Ashenayi, K. 1992. A knowledge-based approach to the design of integrated renewable energy systems. *IEEE Transaction on Energy Conversion, 7*, 648–659.

Ramkumar, R., Abouzahr, I., Krishnan, K., & Ashenayi, K. (1995). Design scenarios for integrated renewable energy system. *IEEE Transaction on Energy Conversion, 10*, 736–746.

Ramakumar, R., Shetty, P., & Ashenayi, K. (1986). A linear programming approach to the design of integrated renewable energy systems for developing countries. *IEEE Transactions on Energy Conversion, EC-1*, 18–24. http://dx.doi.org/10.1109/TEC.1986.4765768

Rehman, S., Halawani, T. O., & Mohandes, M. (2003). Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia. *Renewable Energy, 28*, 573–583. http://dx.doi.org/10.1016/S0960-1481(02)00063-0

RETScreen. (2009, April 26). *International National Resources Canada*. Retrieved from http://www.retscreen.net/

Richard, N. C. (1989). Development of sizing nomograms for stand-alone photovoltaic/storage systems. *Solar Energy, 43*, 71–76.

Salameh, Z. M., & Safari, I. (1995). The effect of the windmill's parameters on the capacity factor. *IEEE Transactions on Energy Conversion, 10*, 747–751. http://dx.doi.org/10.1109/60.475848

SANDIA. (1995). *Stand-alone photovoltaic systems: A handbook of recommended design practice'SAND87-7023*. Las Cruces, NM: Author.

Sawle, Y., & Gupta, S. C. (2014). Optimal sizing of photo voltaic/wind hybrid energy system for rural electrification. In *2014 6th IEEE Power India International Conference (PIICON)* (pp. 1–4). Delhi. http://dx.doi.org/10.1109/POWERI.2014.7117758

Sawle, Y., & Gupta, S. C. (2015). A novel system optimization of a grid independent hybrid renewable energy system for telecom base station. *International Journal of Soft Computing, Mathematics and Control, 4*, 49–57. http://dx.doi.org/10.14810/ijscmc

Schaffrin, C. (1998, September). SolSim and hybrid designer: Self optimizing software tool for simulation of solar hybrid applications. In *Proceedings of EuroSun'98*. Portooz.

Seeling-Hochmuth, G. C. (1997). A combined optimisation concet for the design and operation strategy of hybrid-PV energy systems. *Solar Energy, 61*, 77–87. http://dx.doi.org/10.1016/S0038-092X(97)00028-5

Shaahid, S. M., & Elhadidy, M. A. (2003). Opportunities for utilization of stand-alone hybrid (photovoltaic+diesel+battery) power systems in hot climates. *Renewable Energy, 28*, 1741–1753. http://dx.doi.org/10.1016/S0960-1481(03)00013-2

Shaahid, S. M., & Elhadidy, M. A. (2004a). Prospects of autonomous/stand-alone hybrid (photo-voltaic+diesel+battery) power systems in commercial applications in hot regions. *Renewable Energy, 29*, 165–177. http://dx.doi.org/10.1016/S0960-1481(03)00194-0

Shadmand, M. B., & Balog, R. S. (2014, September). Multi-objective optimization and design of photovoltaic-wind hybrid system for community smart DC microgrid. *IEEE Transactions on Smart Grid, 5*, 2635–2643. http://dx.doi.org/10.1109/TSG.2014.2315043

Shang, C., Srinivasan, D., & Reindl, T. (2016). An improved particle swarm optimisation algorithm applied to battery sizing for stand-alone hybrid power systems. *International Journal of Electrical Power & Energy Systems, 74*, 104–117.

Shin, Y., Koo, W. Y., Kim, T. H., Jung, S., & Kim, H. (2015). Capacity design and operation planning of a hybrid PV–wind–battery–diesel power generation system in the case of Deokjeok Island. *Applied Thermal Engineering, 89*, 514–525. http://dx.doi.org/10.1016/j.applthermaleng.2015.06.043

Shrestha, G. B., & Goel, L. (1998). A study on optimal sizing of stand-alone photovoltaic stations. *IEEE Transactions on Energy Conversion, 13*, 373–378. http://dx.doi.org/10.1109/60.736323

Sinha, S. S. (2015) Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems. *Renewable and Sustainable Energy Reviews, 50*, 755–769. ISSN 1364-0321. http://dx.doi.org/10.1016/j.rser.2015.05.040

Sinha, S., & Chandel, S. S. (2014). Review of software tools for hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews, 32*, 192–205. http://dx.doi.org/10.1016/j.rser.2014.01.035

Smaoui, M., Abdelkafi, A., & Krichen, L. (2015). Optimal sizing of stand-alone photovoltaic/wind/hydrogen hybrid system supplying a desalination unit. *Solar Energy, 120*, 263–276. http://dx.doi.org/10.1016/j.solener.2015.07.032

Swift, A. H. P., & Holder, M. R. (1988). Design of hybrid energy systems. In *Proceedings of the Seventh ASME Wind Energy Symposium* (pp. 175–181). New Orleans, LA.

Syafaruddin, Narimatsu, H., & Miyauchi, H. (2015). Optimal energy utilization of photovoltaic systems using the non-binary genetic algorithm. *Energy Technology & Policy, 2*, 10–18.

Tiba, C., & Barbosa, E. M. de. S. (2002). Software's for designating, simulating or providing diagnosis of photovoltaic water-pumping systems. *Renewable Energy, 25*, 101–113.

Tina, G., & Gagliano, S. (2010). Probabilistic analysis of weather data for a hybrid solar/wind energy system. *International Journal of Energy Research, 35*, 221–232.

Tomonobu, S., Hayashi, D., & Urasaki, N. (2006). Optimum configuration for renewable generating system in residence using genetic algorithm. *IEEE Transaction on Energy Conversion, 21*, 459–466.

Toroczckai, Z., & Eubank, S. (2005). *Agent-based modeling as a decision making tool* (Vol. 35, pp. 22–27). The Bridge, Publication of the National Engineering Academy.

Torreglosa, J. P., García, P., Fernández, L. M., & Jurado, F. (2014). Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control. *Energy Conversion and Management, 77*, 514–526. http://dx.doi.org/10.1016/j.enconman.2013.10.031

Torres-Hernandez, M. E. (2007). *Hierarchical control of hybrid power systems* (PhD dissertation). University of Puerto Rico, Mayaguez.

Traca De Almeida, A., Martins, A., & Jesus, H. (1983). Source reliability in a combined wind-solar-hydro system. *IEEE Transactions on Power Apparatus and Systems, PAS-102*, 1515–1520. http://dx.doi.org/10.1109/TPAS.1983.317879

Upadhyay, S., & Sharma, M. P. (2014). A review on configurations, control and sizing methodologies of hybrid energy systems. *Renewable and Sustainable Energy Reviews, 38*, 47–63. http://dx.doi.org/10.1016/j.rser.2014.05.057

Valenciaga, F., & Puleston, P. F. (2005). Supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy. *IEEE Transactions on Energy Conversion, 20*, 398–405. http://dx.doi.org/10.1109/TEC.2005.845524

Valente, L. C. G., & de Almeida, S. C. A. (1998). Economic analysis of a diesel/photovoltaic hybrid system for decentralized power generation in northern Brazil. *Energy, 23*, 317–323. http://dx.doi.org/10.1016/S0360-5442(97)00094-7

Weiss, G. (Ed.). (1999). *Learning in multi-agent systems*. Cambridge, MA: MIT Press.

The Economic Times. (2009, October 26).

Yang, H. X., Lu, L., & Burnett, J. (2003). Weather data and probability analysis of hybrid photovoltaic-wind power generation systems in Hong Kong. *Renewable Energy, 28*, 1813–1824. http://dx.doi.org/10.1016/S0960-1481(03)00015-6

Yang, H., Lu, L., & Zhou, W. (2007). A novel optimization sizing model for hybrid solar-wind power generation system. *Solar Energy, 81*, 76–84. http://dx.doi.org/10.1016/j.solener.2006.06.010

Yang, Z., Ma, C., Feng, J. Q., Wu, Q. H., Mann, S., & Fitch, J. (2006). A multi-agent framework for power system automation. *International Journal of Innovations in Energy Systems and Power, 1*, 39–45.

Yang, H., Wei, Z., & Chengzhi, L. (2009). Optimal design and techno-economic analysis of a hybrid solar–wind power generation system. *Applied Energy, 86*, 163–169. http://dx.doi.org/10.1016/j.apenergy.2008.03.008

Zaheeruddin, & Manas, M. (2015). Analysis of design of technologies, tariff structures, and regulatory policies for sustainable growth of the smart grid. *Energy Technology & Policy, 2*, 28–38.

Zhou, W., Lou, C., Li, Z., Lu, L., & Yang, H. (2010). Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems. *Applied Energy, 87*, 380–389. http://dx.doi.org/10.1016/j.apenergy.2009.08.012