Hindawi Publishing Corporation
Journal of Renewable Energy
Volume 2015, Article ID 856075, 18 pages
http://dx.doi.org/10.1155/2015/856075

Review Article

Decentralized Autonomous Hybrid Renewable Power Generation

Prakash Kumar and Dheeraj Kumar Palwalia

Department of Electrical Engineering, Rajasthan Technical University Kota, Rajasthan 324010, India

Correspondence should be addressed to Prakash Kumar; prakash.ucertu@gmail.com

Received 24 June 2015; Accepted 10 September 2015

Academic Editor: Jing Shi

Power extension of grid to isolated regions is associated with technical and economical issues. It has encouraged exploration and exploitation of decentralized power generation using renewable energy sources (RES). RES based power generation involves uncertain availability of power source round the clock. This problem has been overcome to certain extent by installing appropriate integrated energy storage unit (ESU). This paper presents technical review of hybrid wind and photovoltaic (PV) generation in standalone mode. Associated components like converters, storage unit, controllers, and optimization techniques affect overall generation. Wind and PV energy are readily available, omnipresent, and expected to contribute major future energy market. It can serve to overcome global warming problem arising due to emissions in fossil fuel based thermal generation units. This paper includes the study of progressive development of standalone renewable generation units based on wind and PV microgrids.

1. Introduction

Development of innovative power solution, capable of minimizing environmental concerns, has been key point of interest for power system researchers. These sources have gained attention since the oil crisis faced in early 1970. Depleting fossil fuel reserves need to be replaced by alternate economic and environment friendly power generation sources. Wind energy conversion system (WECS) and PV generation have proven to be potential power generation sources but its nonpromising nature has been of major concern. As these sources are climate and environment dependent, it may not efficiently meet load demand for specified time duration. Overall delivery cost of centralized electricity generation and grid distribution counts up to four times the cost of generation by stand-alone and minigrid options for "minimum threshold" demand scenario.

Most common sources of energy currently utilized worldwide for generating electricity include coal (39.3%), petroleum (0.7%), natural gas (27.6%), nuclear power (19.5%), hydro power (6.7%), wind (4.2%), and other renewable power (2.1%) that covers mainly geothermal, biomass, and PV energy [1]. PV generation has been found more promising than wind generation for small scale generation [2] but it is sure to remain unavailable during night time. So, in wind rich regions, standalone minigrid WECS is preferred more than PV generation. WECS-PV integrated storage unit causes accountable power loss in conversion equipment during conversion process [3–7]. Complementary characteristics of PV and wind reduce overall requirement of storage unit. In specific locations, hybrid wind-PV generation with storage unit can provide highly reliable power [8] to isolated loads like satellite earth station, broadcasting stations, hill top load stations, and so forth. Overall power reliability depends on optimal sizing of conversion equipment, optimization techniques, meteorological data, and load forecast. RES involves efficiency and economical issues. Among reported solutions, ensuring spinning reserve [9–12] and suitable storage unit facilities [13–16] have been considered as the most effective ones.

Due to variable nature of PV and wind round the clock and throughout the year, it becomes a herculean task to obtain regulated power supply [17]. Generation gets affected by weather and climatic condition. Tsoutsos et al. discussed impact of environment on PV generation and proposed necessary measures for proper project designing so as to ensure public acceptance [18]. Haruni et al. proposed a novel operation and control strategy for hybrid wind-fuel cell-electrolyzer-battery and a set of loads as standalone unit. Overall control strategy is based on a two-level structure, namely, energy management and power regulation system, to avoid system blackout. Depending on reference dynamic operating points of individual subsystems, local controllers control wind turbine, fuel cell, electrolyzer, and battery storage units [19]. Zhou et al. proposed an autonomous unified var controller to address system voltage issues and unintentional islanding problems associated with distributed PV generation systems. The controller consisted of features of both voltage regulation (VR) and islanding detection (ID) functions in a PV inverter based on reactive power control to ensure (1) fast VR due to autonomous control, (2) enhanced system reliability because of capability to distinguish between temporary grid disturbances and islanding events, (3) negligible nondetection zone (NDZ) and no adverse impact on system power quality for ID, and (4) no interferences among multiple PV systems during ID [20]. Hong et al. proposed a novel multiobjective nonlinear programming to determine shed loads of UFLS 81L relays in a hybrid wind-PV-gas turbine microgrid. Method incorporates GA to ensure decrease in load shed [21]. Koutroulis and Kolokotsa presented a methodology for optimal sizing of hybrid wind-PV power generation as standalone unit. He suggested a list of commercially available system devices, optimal number, and type of units ensuring that total system cost for about 20 years is minimized subject to constraint that load energy requirements are completely covered, resulting in zero load rejection implementing cost (objective) function minimization using gas [22]. Eftekharnejad et al. investigated impact of increased penetration of PV systems on static performance and transient stability of large power system. Advantages and problems associated with utility scale and residential rooftop PVs have also been identified for steady state stability and transient stability performance [23]. Kadda et al. discussed optimal sizing issue of a hybrid wind-PV-battery as standalone unit along with diesel generator, located at Oujda/Angad, in order to minimize overall generation cost [24]. Lund evaluated problems, associated with hybrid wind-PV-tidal power generation as standalone unit, in terms of excess or scarce electricity production due to fluctuating RES [25]. Kim et al. presented hybrid wind-PV-SMES (superconducting magnetic energy storage) system to operate under abnormal conditions, such as reactive power or current fluctuations. SMES can significantly enhance dynamic security of such distributed power systems due to its high energy density and quick response characteristics during fault or surge conditions [26].

PV power industry has gained attention due to its easy installation at domestic and commercial level. Associated problems have been minimized to great extent in consequent researches, yet a lot more problems need to be shorted out [27–30].

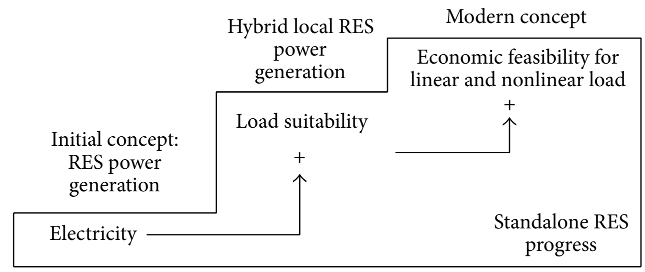

Figure 1: Progressive load demand dependent step by step RES standalone system development.

2. Decentralized Power Generation

Decentralized mode of power generation or distributed generation that depends on locally available resources, mostly RES, is either in standalone mode or connected to utility grid. This paper investigates standalone mode of power generation. The concept of standalone or grid isolated system has been revised from time to time, as shown in Figure 1. Initially RES based power generation only aimed to obtain an alternate source of electrical energy; but with increasing load demand, hybrid RES power generation gained attention to satisfy load suitability and ensure regulated electrical power. Presently, researchers have been trying to obtain regulated power from hybrid RES-ESU and meet liner as well as nonlinear load demand economically.

2.1. Decentralized WECS. Wind energy is supposed to be a major contributor in future world energy scenario and continues to be one of the fastest growing energy resources round the globe. Major challenge associated with WECS is uneven distribution of wind energy. Fluctuating wind brings voltage and frequency regulation problem. These problems can be dealt by dividing wind study into three time frames, namely, regulation, load following, and unit commitment [31]. The regulation time frame includes the period during which generation automatically compensates minute-by-minute deviations in load. Load following time frame is generally longer than regulation and refers to time required to obtain different set points of capacity to cope up with the load. Dedicated peak load generating units either have ready to use power or can be started quickly. Load following time frame generally ranges from 10 minutes to a few hours, depending upon time required to move generating unit to different set points of capacity and involved cost constraints. Unit commitment ranges from several hours to several days depending on scheduling dedicated generation to meet required electric demand.

At present, standalone wind system is more economical than standalone PV system for off-grid regions due to continuous ongoing research. Main components required for wind power generation is turbine, gearbox, generator, step-up transformer, nacelle, and tower. Santoso et al. described design and construction of wind power in terms of steady-state and dynamic operation of induction machines (IMs), speed of alternator, and modeling of aerodynamic, mechanical, and electrical components [32].

For WECS commonly employed alternators include self-exited induction generators, doubly fed induction generator (DFIG), permanent magnet (PM) brushless generators [33], PM synchronous generator (PMSG), switched reluctance generators, and doubly salient PM generators [34]. These alternators are not concerned with maximum power generation. Liu et al. proposed doubly excited PM brushless generator to tap maximum wind energy using online flux control [35].

Abu-Elhaija and Muetze discussed effects of fluctuating wind speed on minimum capacitance requirement to self-excite single phase self-excited reluctance generators by analyzing overall system damping and amplifying the components of Eigen values with lower and upper natural frequencies [36]. Singh and Sharma presented design, development, and analysis of voltage and frequency controllers (VFCs) for standalone WECS. An isolated asynchronous generator, a synchronous generator (SG), and a PMSG are used with these WECS [37]. These VFCs are developed with three-phase generators driven through a wind turbine to feed three-phase and single-phase loads. A battery energy storage system is used invariably with each system configuration to facilitate load leveling during change in wind speeds and/or consumer loads [38]. Performance of VFCs has been demonstrated to validate their operation as a load leveler, load balancer, phase balancer, neutral current compensator and an active filter along with a VFC.

2.2. Decentralized PV Generation. In 1839, French physicist named Edmund Bacquerel discovered PV effect [39]. Modern PV module consists of PV cells, mounting structure, MPPT mechanism, converters, storage unit, and electrical and mechanical connections to regulate and utilize electrical output [40]. Electrical power output of PV module depends on electrical, thermal, PV spectral, and optical property of PV cell array, PV angle, and irradiance [41]. Technical aspects and environmental factors affect optimal PV generation [42]. Zhao et al. discussed PV energy conversion standards and processes involved [4]. Main role player countries like Germany, Italy, Japan, Spain, USA, and South Korea contribute to about 30 to 50 percent of PV annual growth rate [43, 44]. Technical problems such as islanding detection, harmonic distortion, electromagnetic interference, and low efficiency of PV cells are major bottleneck for widespread application of PV systems [45].

Conventionally, PV cell designs are based on band gap energy (eV). Low band gap energy has high current ($I = eNA$) but low voltage ($V = E_g/e$), and vice versa. Here, e is electron charge, N is number of photons, E_g is energy gap, and A is surface area of solar cell. It is preferred to use materials with energy gap between 1 and 1.8 eV like crystal silicon (1.12 eV), amorphous silicon (1.75 eV), copper indium diselenide (1.05 eV), cadmium telluride (1.45 eV), gallium arsenide (1.42 eV), and indium phosphate (1.34 eV) [46–48]. These modules are rated in terms of peak kilowatts (kWp), that is, amount of expected electrical power output when sun is directly overhead on a clear day. Kosten et al. improved efficiency of silicon PV cell by restricting light escape angle. Restricting light escape angle to 2.767° in silicon PV cell of 3 μm thickness improved light trapping and efficiency by 3% [49].

There has been progressive growth in PV cell material [50–54]. Adamian et al. investigated possibility of porous silicon layers application as antireflection coating in common silicon PV cells (ZnS) [50]. Hanoka discussed a silicon ribbon growth method by comparing string Ribbon with two other vertical ribbon technologies and discussed characteristics of this ribbon, specially dislocation distribution, and explained growth progress of 100 m ribbon [51]. Yang et al. explored amorphous-Si PV technology and achieved an AM 1.5, 13% stable cell efficiency for splitting triple-junction spectrum made with roll-to-roll continuous deposition process [52]. Fave et al. compared epitaxial growth of silicon thin film on double porous sacrificial layers obtained by liquid or vapor phase epitaxy and found that mobility and diffusion length are slightly higher with vapor phase epitaxy compared to liquid phase epitaxy. Fabricating PV cells using a detached film obtained with vapor phase epitaxy and without any surface passivation treatment or antireflective coating gives an efficiency of 4.2% with a fill factor of 0.69 [53]. Dobrzański and Drygała explored laser texturization for PV cells made of multicrystalline silicon to improve interaction between laser light and test PV cell [54].

2.3. Decentralized Hybrid WECS-PV Generation. Wind and PV are complement to a certain extent. Due to individual merits and demerits of PV and WECS, hybrid PV-wind generation system with storage backup unit has proved to be reliable power source [55, 56] to feed electrical loads that need high reliability [57] and uninterrupted power supply [58]. Hybrid generation has been considered preferred choice for remote systems like radio telecommunication, satellite earth stations, or sites isolated from conventional power system [59, 60].

Hybrid system has also been an optimal choice for locations where grid connection has been farfetched idea due to economical and technical reasons [61–63]. Daniel and Gounden presented an isolated hybrid system consisting of a three-phase square wave inverter integrated with PV array and a wind-driven induction generator. They developed mathematical model for hybrid scheme consisting of variables in terms of synchronous reference frame [64]. Chen et al. proposed a multi-input inverter for hybrid PV-wind power system to obtain regulated supply and reduce overall power cost. Multi-input inverter consisted of a buck-boost fused multi-input dc–dc converter and a full bridge dc–ac inverter [65]. Kim et al. discussed power-control strategies for hybrid PV-wind generation with versatile power transfer. Hybrid system consisted of PV array, wind turbine, and battery storage connected to a common dc bus. Versatile power transfer has been defined as multimode operation, including normal operation without use of battery, power dispatching, and power averaging, which enables grid- or user-friendly operation [66]. Further Chiang et al. presented a hybrid regenerative power system consisting of PV-WECS hybrid generation with grid-tie system and uninterruptible power supply (UPS) for critical load applications. System included six-arm converter topology with three arms for rectifier-inverter, one arm each for battery charging/discharging and third arm for power conversion of the PV module and WECS alternator [58]. Liu et al. discussed PV-wind hybrid generation in standalone mode employing doubly excited PM brushless machine used for maximum electrical power extraction by using online flux control [35].

3. Maximum Power Point Tracking (MPPT) Strategies

Maximum power extraction, commonly known as maximum power point tracking (MPPT), includes maximum mechanical and electrical power extraction from wind. Mechanical power extraction is obtained by regulating tip speed ratio of the wind turbine, whereas electrical power extraction is associated with voltage and frequency regulation. In order to track maximum power, suitable control strategy, depending on site, needs to be implanted. MPPT's estimated usable efficiency (EUE) should be as high as possible. Table 1 shows some commonly used control strategies for WECS-MPPT and EUE obtained.

In order to track maximum power, useful MPPT techniques for PV applications have been developed and applied [67]. Commonly used methods for MPPT includes perturb and observe (PO), power matching, incremental conductance, fractional open-circuit voltage/short-circuit current, power differential feedback control, curve fitting, dc-link capacitor droop control, intelligent control, and some other special control methods [68, 69]. Due to simplicity and robust nature, PO and curve fitting techniques are widely used. MPPT techniques and algorithms have gained attention of power system researchers [70–87] due to its dominant advantages over conventional techniques. Table 2 shows some commonly used control strategies for PV-MPPT and EUE obtained.

4. Modeling of Hybrid Generation

Optimal sizing of conversion equipment is necessary to meet load demand. A number of useful simulations and optimization techniques have been used to evaluate performance of hybrid PV-wind systems [88, 89]. Commonly employed software tools include hybrid optimization model for electric renewables (HOMER), HYBRID2, hybrid optimization by GA (HOGA), HYBRIDS, hydrogen energy models (HYDROGEMS), transient systems simulation program (TRNSYS), village power optimization for renewable (ViPOR), Dymola, and matrix laboratory (MATLAB) simulink tool, which are employed for cost and performance analysis [90, 91]. These optimization tools have helped in optimizing simulation configuration in terms of production cost and reliability. Table 3 shows year of development, developer, merits, and demerits of some commonly used optimization tools used to simulate hybrid RES generation.

HOMER is public domain software used for hourly simulations to obtain optimum target. It is a time-step simulator using hourly load and environmental data inputs for RES assessment; it facilitates optimization of RES based on net present cost for a given set of constraints and sensitivity variables. HOMER has been used extensively in previous renewable energy system case studies [92, 93] and in renewable energy system validation tests [94]. Although simulations can take a long time, depending on number of variables used, their operation is simple and straightforward. Program's limitation is that it does not enable user to intuitively select appropriate components for a system, as algorithms and calculations are not visible or accessible. HYBRID2 is hybrid system simulation software with precise simulation, as it can define time intervals from 10 min to 1 h. NREL recommends optimizing system with HOMER and then once optimum system is obtained, designing is improved by using HYBRID2. HOGA is a hybrid system optimization program. Optimization is carried out by means of GA and can be single objective or multiobjective. Simulation is carried out using 1 h intervals, during which all of the parameters remained constant. Control strategies can also be optimized using GA. HYBRIDS assesses technical potential of RES for a given configuration to determine potential renewable fraction and evaluate economic viability based on net present cost. HYBRIDS is a Microsoft Excel spreadsheet based RES assessment application and design tool, requiring daily average load and environmental data estimated for each month of the year. Unlike HOMER, HYBRIDS can only simulate one configuration at a time and is not designed to provide an optimized configuration. HYBRIDS is comprehensive in terms of RES variables, level of detail required, and need of higher level of knowledge of RES configurations as compared to HOMER. It is designed so as to improve renewable energy system design skills through its application.

5. Energy Storage Technology

Renewable hybrid generation is incorporated with ESU to ensure better reliability and meet energy gap between generation and load demand.

Depending on application, classification of ESU technology has been shown in Figure 2. It can be classified as electrochemical [dry batteries: lithium ion (LI), nickel metal hydride (NMH), metal air (MA), nickel cadmium (NiCd), polysulphide bromide (PSB), and electrochemical capacitor (EC); wet batteries: lead acid (LA), valve regulated lead acid (VRLA), sodium sulphur (NaS), all-vanadium redox (AVR), zinc bromine (ZnBr), vanadium bromide redox (VBR), and zero emission battery research activity (ZEBRA); flow batteries (FB)], chemical [fuel cell (FC), electrolyzer (EZ), and synthetic natural gas (SNG)], electromagnetic [capacitors, super capacitor (SC), superconducting magnetic energy storage (SMES), and super conducting coil (SCC)], mechanical [flywheel energy storage (FES), pumped storage arrangement (PSA), and compressed air storage (CAS)], thermal [cryogenic energy storage (CES), electric thermal heaters (ETH), ice based technology (IBT), and pumped heat storage (PHS)] energy storage.

In large-scale nonregulated hybrid renewable electricity networks, energy storage (mostly bulk systems) is required to absorb the shock of energy overproduction and compensate

Table 1: Some MPPT technique literatures for standalone WECS.

Author	EUE (%)	Control strategy	Content	References
Pan and Juan	about 90.2	ACC	Presents reduced harmonics, reliable, and cost effective adaptive compensation control (ACC) based MPPT for a microscale WECS. ACC improves dynamic response and more wind energy can be extracted during variable wind speed.	[154]
Nishida et al.	>95	PWM converter	Discusses cost effective, reliable, and wide speed range variable-speed wind-turbine MPPT controller using PWM inverter cascaded in series with a series-type 12-pulse rectifier for interior PMSG based WECS. The system has reduced voltage and current (V&I) harmonics and total losses in WECS is minimized.	[155]
Lo et al.	>90	OTC, PCM, CVM, DCM, and CCM	Investigates buck-type power converter based MPPT controller using pulsating-current battery charger for small-size PM wind turbine in standalone mode to obtain improved charging efficiency. Battery charger operates in discontinuous conduction mode (DCM) with constant on-time control (OTC) to achieve the desired pulsating current mode (PCM) operation. At the end of battery charging state, charger operates in the constant voltage mode (CVM) to prevent battery overcharging. Over speed protection of the wind turbine can be naturally obtained when the charger enters continuous conduction mode (CCM) operation.	[156]
Mendis et al.	>97	Power curve, vector control	Proposes tip speed ratio and pitch angle based MPPT for PMSG and DFIG based hybrid WECS-battery storage as standalone unit. Different control strategies have been developed and proposed for system module to achieve AC voltage and frequency regulation, DC-link voltage stability, and maximum power extraction in proposed standalone unit.	[157]
Zou et al.	>95	Characteristic power curve, DSP kit	Investigates power-curve based MPPT algorithm to obtain robust and cost effective control method for wind turbine systems. Conditions for stable MPPT operation have been determined based on the small-signal model. The transfer function for variation of wind speed to generator speed is determined to be of the first order. The simulation and experimental results confirm validity of proposed transfer function. Dynamic behavior of generator speed is independent of instantaneous wind speed but dependent on dynamics of the wind speed.	[158]
Cirrincione et al.	>90	GNG algorithm, FOC, VOC, DS1103, and DSP TMS320F240	Presents growing natural gas (GNG) based MPPT for variable-pitch WECS with IMs to meet need of maximum power range and constant power range. To cope up with constant power region, the blade pitch angle has been controlled on the basis of closed-loop control of mechanical power absorbed by the IM. MPPT technique included field-oriented control (FOC) for induction generator and voltage oriented control (VOC) for grid-connected inverter.	[159]
Dalala et al.	>90	PO algorithm	Discusses perturb and observe (PO) based MPPT algorithm for small scale WECS, using DC-side current as perturbing variable. Algorithm is best suited for both slow and high wind speed fluctuation, attaining enhanced stability as well as fast tracking capability.	[160]
Urtasun et al.	About 99.7	V&I control during PCM, CVM, DCM, and CCM modes	Evaluates robustness and power loss in a sensorless MPPT, for PMSG based small WECS incorporating a diode bridge, as compared to conventional curve based MPPT techniques. Due to fluctuating source, it is difficult to obtain optimum power curve and precise relation between dc current and the dc voltage, thus causing power loss.	[161]

energy gap during low generation or blackouts [95]. This is also applicable renewable energy based distributed generation system (either isolated or connected to any distribution network), to deal with power quality issues and efficient power flow management [96, 97]. Optimal sizing of storage unit is important to obtain reliable power generation [98, 99].

In domestic and microgrid renewable generation, energy storage units are employed for satisfaction of electricity needs [100–104]. Maclay et al. presented a PV–hydrogen powered model for both standalone and grid-connected operation employing Matlab/Simulink tool to access computability of a regenerative fuel cell (RFC) as energy storage device with PV electrical generation and discussed issues like battery sizing, charge/discharge rates, and state of charge limitations [101]. Xu et al. proposed an improved optimal sizing method for wind-PV-battery hybrid power system for standalone

Table 2: Some MPPT technique literatures for standalone PV.

Author	EUE (%)	Control strategy	Content	References
Rub et al.	94–100	flyback dc-dc converter	Discusses parallel dc-dc converter based current compensated DMPPT for partially shaded series connection of PV modules. Current compensation schemes are either too complex or inaccurate. In this DMPPT scheme, current compensation has been simplified with accurate compensation to assure MPPT by special arrangement of shunt-connected flyback dc–dc converter.	[70]
Gules et al.	>98	neurofuzzy inference	Proposes neurofuzzy inference based artificial intelligent (AI) MPPT for PV generation in standalone operation. It incorporated quasi-Z-source (qZS) inverter to regulate duty ratio and the modulation index to ensure required voltage, current, and frequency.	[71]
Elgendy et al.	>95	PO, voltage perturbation, and direct duty ratio perturbation	Presents incremental conductance MPPT algorithm for standalone PV pumping system using 1080 Wp PV array connected to a 1 kW PM dc motor-centrifugal pump set. System has been investigated for fluctuating weather conditions using comparative study with PO algorithm. Results exhibited better stability for slow transient response and worse performance at rapidly changing irradiance, using direct duty ratio control.	[72]
Elgendy et al.	97–99	Reference voltage and direct duty ratio perturbation based PO MPPT algorithms	Evaluates reference voltage and direct duty ratio perturbation based PO MPPT algorithms. Reference voltage perturbation provides better response to rapidly changing irradiance and temperature transients but exhibits poor stability. Direct duty ratio perturbation provides better stability and energy utilization at a slower transient response but poor performance for rapidly changing irradiance. Algorithms have been justified on the basis of system stability, performance characteristics, and energy utilization for standalone PV pumping systems (1080 Wp PV array connected to a 1 kW PM dc motor-centrifugal pump set) in variable weather conditions.	[73]
Cristaldi et al.	98–100	PO, CVM, and MPPT	Proposes model based (MB) MPPT for single-series-diode model of PV module. This MPPT method has been found suitable and better alternative to traditional module integrated converter (MICs) topologies in terms of cost, robustness, and accuracy. Traditional PO or incremental conductance MPPT algorithms have low efficiency for rapidly changing weather conditions, whereas MB-MPPT offers better dynamic performance. This model can estimate solar radiation with adequate accuracy and does not need radiometer or dedicated cell, as required in conventional MB-MPPT techniques.	[74]
Lian et al.	Approx. 99	PO, PSO	Presents hybrid PO-PSO based MPPT for standalone PV generation. PO is cheap, robust, and good at exploration but not at exploitation; that is, it only tracks first local maximum point and stops progressing to next maximum. PSO works good to obtain global maximum point (GMP) but needs long time for convergence. Thus hybrid PO-PSO works as complement and provides optimized MPPT.	[75]
Konstantopoulos and Koutroulis	Approx. 99	HCPSO	Investigates hybrid chaotic-PSO (HCPSO) algorithm based global MPPT technique for flexible PV modules using effect of geometrical installation parameters like bending angle, tilt angle, orientation, and power-voltage characteristics. Application of proposed HCPSO algorithm minimizes power loss and maximizes energy production of the flexible PV module during global MPPT process.	[76]
Al Nabulsi and Dhaouadi	97–100	Fuzzy logic, PO	Evaluates fuzzy logic and a dual MPPT controller based digital MPPT control scheme for standalone PV system. Duel MPPT controller consisted of an astronomical two-axis sun tracker to track maximum solar radiation, power converter to control power flow between the PV panel and the load. This proposed technique reduces steady state oscillations and enhances the operating point convergence speed.	[77]
Alajmi et al.	98–100	Fuzzified hill climbing algorithm	Investigates fuzzy-logic based MPPT controller for PV systems under fluctuating weather conditions. Hill climbing MPPT has been improved by fuzzifying its rules. This provides less oscillations and fast convergence.	[78]

Table 2: Continued.

Author	EUE (%)	Control strategy	Content	References
Sundareswaran et al.	99.2–99.8	ABC	Proposes ABC algorithm based MPPT for partially shaded PV generation. ABC algorithm has been compared with other genetic algorithms (GA) and found ABC as superior solution.	[79]
Zhang et al.	>95	Duty cycle control	Investigates adaptive PO MPPT based on duty cycle modulation, to balance the tracking speed and oscillation requirements of resonant converters. Resonant converters, especially the LLC converter with soft switching, have high gain range and wide load and input voltage range for microinverter applications.	[80]
Badawy et al.	93.6–100	Duty ratio, RBB converter	Presents converter topology based MPPT technique for standalone battery charging PV module. Battery charging system included reversed buck-boost (RBB) converter enabled parallel power processing topology.	[81]
Balasubramanian et al.	>95.8	Boost converter	Addresses boost converter based MPPT for partially shaded PV generation. Boost converter has been designed to operate with high efficiency at MPPT voltage of the array by assuming a single peak power point on the PV characteristics.	[82]
Ghaffari et al.	98–100	Newton-based ES algorithm, dc-dc converter	Evaluates extremum seeking (ES) in dc-dc microconverter based MPPT for partially shaded standalone PV generation, where each PV module is coupled with its own dc/dc converter. PV generation dependents on variable parameter like irradiance and temperature, thus obtaining nonuniform transients in convergence to MPPT. This method uses Newton-based ES algorithm to estimate instantaneous irradiance and temperature variation for MPPT, thereby improving overall performance and reducing cost of power extraction.	[83]
Olalla et al.	90–98	Sub-MIC	Discusses distributed MPPT (DMPPT) architecture for partially shaded PV module in terms of conversion efficiencies and power constraints. DMPPT solutions based on submodule integrated converters (sub-MIC) offer 6.9–11.1% improvement in annual energy yield compared to baseline centralized MPPT scenario. Sub-MIC architecture eliminates insertion loss and provides higher granularity to DMPPT to track more power.	[84]
Singh et al.	>97	ILST, VSC	Investigates voltage source converter (VSC) based MPPT for PV distributed generation. A linear sinusoidal tracer (ILST) based control algorithm has been used for control of VSC and a variable dc link voltage is used for MPPT. This improved overall power quality and VSC utilization.	[85]
Raj and Jeyakumar	99.76–100	Power triangle	Evaluates power triangle based low cost MPPT in standalone operation of PV generation. A background online sweeping technique has been used in power region of I-V characteristic without disturbing actual PV module. This method offers robust control, with almost no divergence, upon change in irradiation and has no oscillations at steady state.	[86]
Boztepe et al.	97–99.33	GVS, POT, and VW	Presents global voltage step (GVS), power operating triangle (POT), and voltage window (VW) based global MPPT (GMPPT) algorithm for string PV system with shaded cells. Such GMPPT algorithms need to scan wide voltage ranges of PV array (nearly zero to open circuit voltage), which needs more scanning time and, in turn, more energy loss. Proposed GMPPT algorithm needs narrow VW search space and thus lower scanning time.	[87]

and grid-connected operation to ensure (a) high power supply reliability; (b) full utilization of complementary characteristics of wind and PV; (c) small fluctuation of power injected into the grid; (d) optimization of battery's charge and discharge state; (e) minimization of total cost of system [102]. Whittingham discussed evaluation of energy storage systems for gigawatt pumped hydro to smallest watt-hour battery and future predictions. Energy storage system can reduce peak power demands and intermittent nature of PV and wind power [103]. Trifkovic et al. presented system integration and controller design for power management of a standalone renewable energy hybrid system consisting of five main

Table 3: Optimization tools for hybrid RES study.

Tool	Year	Developer	Merits	Demerits	References
HOMER	2000	National Renewable Energy Laboratory (NREL)	Allows comparison between DC and AC coupled systems	Cannot enable user to intuitively select appropriate system components	[162]
HYBRID2	1996	Renewable Energy Research Laboratory (RERL)	Allows very detailed analysis for energy sources, system architectures, and dispatch strategies	Does not consider short term system fluctuation due to system dynamics or component transients, not suitable for economic and multiobjective optimization	[163]
HOGA	2005	Electrical Engineering Department (University of Zaragoza, Spain)	Carried out by gas; can be single or multi objective; can evaluate all possible combinations for components and control variable strategies	Not suitable for economic optimization	[164]
HYDROGEMS	1995	Institute for Energy Technology, (Norwegian University of Science and Technology, Trondheim)	Used to analyze performance of hydrogen energy systems; simulate hydrogen mass flows; and estimate electrical power flow in standalone and hybrid generation system	Now merged with TRANSYS	[165]
HYBRIDS	—	Solaris Homes	Comprehensive in terms of optimization variables; require higher level of knowledge of system configurations	Only simulates one configuration at a time	[166]
RETScreen	1997	Canadian Government (Ministry of Natural Resources)	Supports basic dimensioning calculations for PV-diesel off-grid systems preliminary feasibility study and general dimensioning	Limits available options for energy sources, system architectures, and dispatch strategies	[167]
PV-SPS	2001	Australian Business Council for Sustainable Energy (BCSE)	Consumption and power generation give a good general impression of system performance over course of the year	Layout of generator input form is not always optimal in terms of clarity, even after feeding PV irradiation, temperature, generator size, values of shiny and cloudy months, annual mean value, and so forth	[167]
PV*SOL	1998	Energy Software, Berlin, Germany	Time step simulation program for off-grid and grid coupled solar generation systems; capable of performing energy calculations, analysis of economic efficiency, and analysis of influences of shadowing	Limits available options for energy sources, system architectures, and dispatch strategies	[167]
TRNSYS	1975	University of Wisconsin-Solar Energy Laboratory	Provides customized performance simulation by splitting entire energy system into individual components	Does not include nuclear, wave, tidal, and hydro power. It includes BES as only electrical energy storage.	[168]
MATLAB/Simulink	1970	MathWorks	Allows much more flexibility in defining energy sources, system architectures, and dispatch strategies	More effort to learn software and develop models	[169]
Dymola	1978	Lund Institute of Technology (Lund University)	Allows much more flexibility in defining energy sources, system architectures, and dispatch strategies	More effort to learn software and develop models	[170]
PVsyst	1994	University of Geneva, Switzerland	Provides dimensioning proposals for standalone installations (PV and battery size) and warns user if chosen component combinations are not technically feasible	No inverter models for off-grid system simulation; only DC modeling is possible	[171]

Table 3: Continued.

Tool	Year	Developer	Merits	Demerits	References
ViPOR		NREL	Can decide power supply distribution layout for loads such as houses and minigrid	Able to access local loads and needs skilled labors.	[167]
PV-DesignPro	1998	Maui Solar Energy Software Corporation in Hawaii, USA	Designed to simulate both grid coupled and off-grid systems with PV and wind generators	Additional generator (e.g., diesel generator) is used to match the shortfalls; that is, realistic additional generator cannot be modeled	[167]

Other reported tools are Jpelect, PV-DesignPro, PowerSim, Off Grid Pro, Power Factory, Off Grid Sizer, Sunny Island Design, TALCO, INSEL, ARES, RAPSIM, SOMES, SOLSIM, Simplorer, Solar Pro, and HSWSO (Hybrid Solar-Wind System Optimization Sizing).

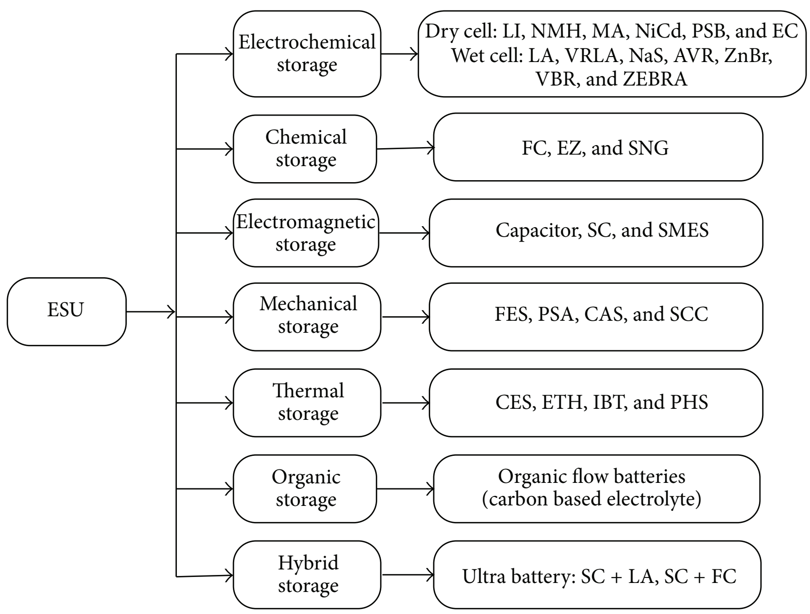

Figure 2: Electrical storage unit classifications.

components, namely, PV arrays, wind turbine, electrolyzer, hydrogen storage tanks, and fuel cell. They considered a two-level control system consisting of a supervisory controller to ensure power balance between intermittent renewable generation, energy storage, and dynamic load demand, as well as local controllers for PV, wind, electrolyzer, and fuel cell unit [104].

Therefore depending upon the storage need of respective RES, suitable storage technology is put into application. While considering suitable storage technology, optimal size, economical, and technical specifications are the dominant factors. The specifications and data enlisted in Tables 4 and 5 are among the key specifications which can be considered for different RES integration with suitable storage unit.

6. Barriers and Market Challenges

Due to high investment and low efficiency of renewable energy resources, generation unit should generate sufficiently high enough power to ensure economic power generation. This can be assured by using optimization techniques in hybrid generation system [105]. Optimization techniques include optimization scenario based on different meteorological data [106], graphic construction method [107], probabilistic approach [108], iterative technique [109], AI methods [110, 111], genetic algorithm [112], system control for energy flow and management [113–115], and multiobjective design [116–118] to obtain optimum size of generation unit to guarantee lowest investment with full use of system component. In order to obtain reliable optimum system configurations quickly and accurately, feasible optimization technique should be incorporated [119].

Nishioka et al. discussed variation in electrical characteristics due to temperature in InGaP/InGaAs/Ge triple junction PV cells under concentration and found that conversion efficiency decreases with increase in temperature and increased with increase in concentration ratio resulting in an increase in open-circuit voltage for these PV cells [106]. Hernández et al. presented a systematic algorithm to determine optimal allocation and sizing of PV grid-connected systems in feeders. It could efficiently compromise technical and economical aspect of multiobjective optimization approach and is robust

Table 4: Storage technology capital cost, advantages, disadvantages, and applications [172, 173].

Technology	Capital cost			Advantages	Disadvantages	Application	
	$/kW	$/kWh	kWh/cycle			Energy	Power
PSA	600–2000	5–200	0.1–2	High capacity, low cost	Special site requirement	Fully capable and reasonable	Not feasible or economical
MA	2800–5000	500–950	90–100	Very high energy density	Electric charging is difficult	Fully capable and reasonable	Not feasible or economical
FB	400–2900	110–2000	6–90	High capacity, independent power and energy ratings	Low energy density	Fully capable and reasonable	Reasonable for this application
NaS	1000–3000	300–950	8–50	High power and energy densities, high efficiency	High production costs and safety concerns	Fully capable and reasonable	Fully capable and reasonable
LA	300–900	200–1500	20–100	Low capital cost	Limited cycle life when deeply discharged	Feasible but not quite practical or economical	Fully capable and reasonable
NiCd	500–1500	800–3000	20–100	High power and energy densities, high efficiency	High production cost requires special charging circuit	Reasonable for this application	Fully capable and reasonable
LI	1200–4000	600–5000	15–100	High power and energy densities, high efficiency	High production cost requires special charging circuit	Feasible but not quite practical or economical	Fully capable and reasonable
FES	250–800	1000–7000	3–40	High power	Low energy density	Feasible but not quite practical or economical	Fully capable and reasonable
FC	10000+		6000–20000	High efficiency, fuel flexibility,and solid electrolyte reduce corrosion and management problems, quick start-up	High temperature enhances corrosion and breakdown of cell components	Fully capable and reasonable	Fully capable and reasonable
ZnBr	700–2500	150–1000	5–80	High capacity, independent power and energy ratings	Low energy density	Fully capable and reasonable	Reasonable for this application
AVR	600–1500	150–1000	5–80	High capacity, independent power and energy ratings	Low energy density	Fully capable and reasonable	Reasonable for this application
SC	100–700	100–2000	2–40	Long cycle life, high efficiency	Low energy density	Reasonable for this application	Fully capable and reasonable
SMES	200–300	1000–850000	350–489	Useful for power regulation on smaller, highly critical equipment such as computer systems	Very short timescales (<10 s), not for bulk power storage	Reasonable for this application	Fully capable and reasonable
CAS	400–1000	2–110	2–6	High capacity, low cost	Special site requirement needs gas fuel	Fully capable and reasonable	Not feasible or economical

Table 5: Storage technology ratings.

Technology	Power		Volume energy density (kWh/m^3)	Efficiency (%)	Time		Self-discharge/day (%)	Lifetime	
	Rating (MW)	Density (kW/m^3)			Discharge	Response		80% DoD (cycles)	Years
PSA	100–1000	0.1–0.2	0.2–2	70–85	1–24 h+	min	Negligible	15000–50000	50+
CAS	5–1000	0.2–0.6	2–6	41–79	1–24 h+	min	Small	9000–30000	25+
MA	0.001–0.01		20–30	40–50				100–300	
FB	0.01–100		20–30	72–85	min–10 h+	<s	0.1–0.8	2000–14000	
NaS	0.05–10	120–160	15–300	70–90	s–h+	<s	0.5–20	2100–4500	10–15
LA	0.001–20	90–700	20–80	72–90	min–h+	<s	0.1–0.5	200–1500	3–15
NiCd	0.001–40	75–700	15–80	60–80	s–h+	<s	0.2–0.6	1000–4000	5–20
LI	0.001–1.1	1300–10000	200–450	65–98	min–h+	<s	0.1–0.3	600–7000	5–100
FES	0.001–0.25	5000	10–80	80–97	s–h+	<s	50–100	1000–60000	15–25
FC	0.001–50	0.2–20	600	30–60	s–24 h+	s–min+	Negligible	250–2000	10–30
ZnBr	0.05–2	1–25	65	65–75	s–10 h+	<s	Small	1000–4000	5–10
AVR	0.001–5	0.5–2	20–70	60–75	s–10 h+	s	Small	>8000	5–20
SC	0.005–0.5	40000–120000	10–30	85–99	ms–h+	<s	20–40	1000–100000	4–12
SMES	0.1–10	2600	6	75–90	ms–s+	<s	10–15	500–10000	

with moderate computer requirements [120]. Shatter et al. investigated a hybrid generation system consisting of PV, wind, and fuel cells incorporating fuzzy based controller to ensure maximum power tracking for both PV and wind energies in order to obtain maximum power at fixed dc voltage bus [121]. Koutroulis and Kolokotsa proposed methodology to obtain optimum number of commercially available system devices and units so that overall system cost is minimized using GA with constraint like load energy requirements causing zero load rejection [122].

7. Policy Development

Consumers prefer low cost and reliable electricity irrespective of environmental concerns. Policy should ensure basic needs of users and reduce burden of fossil fuel based energy sources. Therefore respective policy should foot higher subsidy on renewable energy generating equipment to encourage common users to use green energy. Furthermore, large subsidies need to be offered to rural users to meet their economy. Rural users use very low efficient fuel like kerosene (about 6%), causing loss of a large amount of kerosene. Renewable energy is not only cost saving but also reduces carbon emission. Chaurey and Kandpal estimated in rural household of India that 373 kg carbon dioxide emission per year can be avoided by installing PV panels of 20–53 W [123]. For promoting decentralized rural electrification projects, India has provided capital subsidy up to a 90% for installation of new plants in some regions.

Power system researchers have continuously been working to make electricity market user friendly. Jia et al. evaluated a joint schedule problem for PV power, wind power, combined cooling, heating, power generation, high temperature chiller, liquid desiccant fresh air unit, battery, and power grid in order to satisfy electricity load in buildings with minimal expected cost. They concluded with two important results; that is, (1) simulation-based policy improvement (SBPI) methods are developed to improve from given base policies and (2) performance of these methods is systematically analyzed through numerical experiments. For sufficient computing budget, SBPI methods improve given base policies [124]. Shaahid and Elhadidy assessed technoeconomic feasibility of hybrid PV-diesel-battery power systems for a typical residential building at Dhahran (East-Coast, KSA) and evaluated that hybrid PV-diesel model configuration with battery storage decreases overall cost of diesel with increase in PV capacity [125]. Sarkar and Ajjarapu studied a stochastic planning approach for assessing MW resource of three wind and PV hybrid models by fixing varying penetration ratio level at 10%, 20%, and 30%. Method found applicability for different parameters such as cut-in speed, rated speed, furling speed, power rating of wind turbines, efficiencies of heat exchanger, steam turbine and electric generator, and maximum load [126]. Sun et al. studied a joint schedule problem to schedule PV power, wind power, combined cooling, heating, power generation, high temperature chiller, liquid desiccant fresh air unit, battery, and power grid in order to satisfy electricity load, sensible heat load, and latent heat load in buildings with minimal expected cost. Two major contributions have been presented; that is, three simulation-based policy improvement methods are developed to improve from given base policies and performance of these methods is systematically analyzed through numerical experiments [127].

Algorithm based policy approach has helped in maximizing efficiency and reducing cost function [128–131]. Arabali et al. proposed strategy to meet controllable heating, ventilation, and air conditioning (HVAC) load with a hybrid-renewable generation and energy storage system. GA based optimization approach is incorporated with a two-point estimate method to minimize cost and increase efficiency. Minimized cost function ensured minimum PV and wind generation installation as well as storage capacity selection to supply HVAC load [128]. Lannoye et al. proposed insufficient ramping resource expectation (IRRE) metrics to measure power system flexibility for long-term planning and derive adequacy metrics from traditional generation. A flexibility metrics can identify time intervals over which a system is most likely to face a shortage of flexible resources and can measure relative impact of changing operational policies and addition of flexible resources [129]. Mei et al. proposed game approaches for hybrid power system planning to model planning of a grid-connected hybrid power system consisting of wind turbines, PV panels, and storage batteries [130]. El-Tamaly and Mohammed investigated a fuzzy logic technique to calculate and study reliability index of PV-wind hybrid power system to determine impact of interconnecting system with utility grid [131].

8. Financial Approaches

Several economic criteria exist in providing useful power to utility grid. The costing structure should be simple so as to make user understand it when levied upon them. Until overall cost is user friendly, users may not prefer to adopt the system. Marí and Nabona splitted wind-PV hybrid generation cost into five parts, namely, initial investment cost, operating and maintenance cost, replacement cost of equipment, cost of power exchange between hybrid power generation unit and grid, and regulation cost of utility grid [107]. Different approaches have been made to encourage dependence on renewable energy and reduce fossil fuel based energy dependence [132–134]. Tezuka et al. suggested method to reduce amount of CO_2 emission by imposing carbon-tax revenue and give subsidy on PV-system installations and concluded that amount of CO_2 emission reduces by advertising PV system with subsidy policy even under the same tax-rate and CO_2 payback time [135]. Nelson et al. discussed unit sizing and made an economical evaluation of hybrid wind-PV-fuel cell generation system. They obtained a clear economic advantage of hybrid wind-PV-fuel cell-electrolyzer system over traditional hybrid wind-PV-battery system for a typical home in US Pacific Northwest [136]. Bilal et al. proposed a methodology of optimal sizing of hybrid systems PV/wind/battery in order to minimize annual cost system (ACS) and loss of power supply probability (LPSP) using multiobjective GA. The obtained results show that cost of optimal configuration strongly depends on LPSP. For example, cost of optimal configuration decreases by 25% when LPSP grows to 1% from 0% [116].

9. Microgrid and Equipment

9.1. Converters. In order to obtain regulated power supply from fluctuating power supply, converters need to be designed to meet frequency and voltage standards. Commonly employed converters include AC/DC (rectifiers), DC/DC (choppers), and DC/AC (inverters). Inverters are commonly employed at point of common coupling and need to be designed optimally. Depending upon output waveform, inverters are classified as square wave, modified square wave (quasi square wave or modified sin wave), and multilevel (multistep) and sin wave (high frequency PWM) inverters. Daniel and Gounden proposed three-phase square wave inverter for an isolated wind-PV hybrid scheme for the first time. They presented a dynamic mathematical model of the hybrid scheme in terms of synchronous reference frame and verified it for transient load conditions [64]. But this converter had high harmonic components and was not fully controlled. Park et al. presented five-level PWM inverter employing dead beat control for minimizing harmonic components of output voltage and load current [137]. Park et al. described an assembly of multilevel PWM inverter and cascaded transformer scheme for standalone generation to obtain high quality output voltage waveform. They validated the proposed system for 11-level and 29-level PWM output [137]. Nasrudin A. Rahim et al. presented five-level and seven-level single-phase multilevel PWM scheme for fluctuating reference input. They employed fluctuating output voltage as reference and compared it with triangular carrier signal to generate desired PWM signals for the switches of converter [138, 139]. Kumaravel and Ashok studied a diode-clamped multilevel inverter using bidirectional buck-boost choppers using single-pulse, multipulse, and hysteresis band current control schemes. Single-pulse scheme involves slow switching actions but needs high current rated chopper devices whereas multipulse scheme involves faster switching actions and low current rated chopper devices but has slower response. The hysteresis band current control scheme has faster switching action and lower current rating of the chopper devices and can nullify the initial voltage imbalance as well [16]. Further Gautam and Gupta discussed cascaded H-bridge multilevel PWM Inverter using multiband hysteresis modulation employing current control scheme [140]. Liu et al. proposed control scheme for ZS and qZS cascaded multilevel inverter (CMI). A multilevel space vector modulation integrated with shoot through states for single-phase qZS-CMI synthesizes staircase type multilevel voltage waveforms having low harmonic contents [141]. Fatu et al. discussed a variable-speed motion sensorless duel converter PI current controlled control scheme PM synchronous generator for WECS. They presented a voltage control scheme with selective harmonic compensation for standalone mode operation [142].

9.2. Power Flow Controllers (PFCs). PFCs are essential for promising reliable and economical power supply to connected load in microgrid for standalone operation [32]. Fluctuating variation in source causes stability and power quality problems in terms of voltage and frequency regulation. Situation becomes worse for reactive power demand due to limitation of reactive capability of wind generating system. Mendis et al. proposed a standalone hybrid system consisting of a PMSG, hybrid energy storage (battery storage and a supercapacitor), a dump load and a mains load for obtaining voltage and frequency regulation. Energy management algorithm has been used to improve performance of battery storage and active-reactive power flows [143].

Therefore, an efficient and intelligent PFC is necessary to ensure balance between load and source of generation. This can be assured by forecasting load demand and scheduling regulated power [144]. Depending on power flow, Chauhan and Saini divided PFCs into three categories: centralized control arrangement, distributed control arrangement, and hybrid control arrangement [145]. In centralized control arrangement, system consists of one master controller (centralized controller) and several slave controllers for various individual power sources and energy storage unit. Master controller operates in close coordination with all sources and slave controllers. In distributed control arrangement, each power source sends measurement signals to its local controller. Local controllers communicate with one another to take appropriate decision for global optimal solution [146, 147]. Hybrid control arrangement is combination centralized and distributed control schemes. In hybrid control scheme, RES are grouped within integrated system [148, 149]. Centralized control scheme is applied within each group and distributed control scheme is used to coordinate each group. In such hybrid control scheme, local optimization is achieved through centralized control within group and global optimization among different groups of energy sources is achieved by distributed control [145]. In this quest, Santoso et al. proposed a hierarchical control including a master and slave controllers for hybrid generation. Master controller selects power generation source and slave controller maintained constant DC bus voltage regulating duty cycle of DC/DC converters [32]. Zeng et al. presented a reduced switch count multiport dc–dc converter for standalone PV-wind hybrid generation. Converter has been applied for simultaneous MPPT control of a wind/PV hybrid generation system consisting of one wind turbine generator (WTG) and two different PV panels [150]. Botterón et al. proposed a high reliability DC/DC converter and a single-phase PWM inverter for standalone microgrids. It aims at designing two different controllers for two converters for reliable operation of microgrid and results have been validated for a 5kVA PWM modulated single-phase inverter, fully controlled by DSP TMS320F2407 [151].

10. Conclusion

In order to meet pollution-free future power demands, dependence on renewable energy should be encouraged by providing subsidy on installation products. Energy policy-makers need to encourage RES based usage and research to facilitate latest technology for power extraction. Narula et al. investigated probability of achieving 100% electricity demand in South Asia region by year 2030 by increasing dependence on RES based distributed generation [152]. Timilsina et al. estimated to achieve 1845 GW, 1330 GW, and 2033 GW power from PV by year 2030, 2040, and 2050, respectively [153]. More research activity needs to be carried out to improve reduced generation cost, improve storage unit facility, and load forecasting and efficiency of conversion equipment. By increasing dependence on DC microgrids, conversion losses can be minimized and exploitation of power could be optimized.

Hybrid PV-wind integrated with storage unit has been a feasible solution to meet off-grid load demand. A comprehensive review of PV-WECS standalone generation, converter topologies, storage facility options, hybrid simulation tools, and challenges associated with RES generation has been investigated in this paper. It has been found that hybrid generation is supposed to be major contributor in electrification of isolated regions to feed loads which need reliable power source. Suitable optimization techniques using GA and AI can optimize global optimal generation.

High cost of installation has been major issue in widespread RES based power generation. Hence power policy needs to be made liberal to encourage power dependence on RES. More research work needs to be carried out to improve overall durability and performance of storage facility and power conversion equipment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] "'Total energy', U.S. Energy Informatio Administration," http://www.eia.gov/totalenergy/data/monthly/#electricity.

[2] Z. Jiang and H. Rahimi-Eichi, "Design, modeling and simulation of a green building energy system," in *Proceedings of the IEEE Power & Energy Society General Meeting (PES '09)*, pp. 1–7, IEEE, Calgary, Canada, July 2009.

[3] R. Sternberger and D. Jovcic, "Theoretical framework for minimizing converter losses and harmonics in a multilevel STATCOM," *IEEE Transactions on Power Delivery*, vol. 23, no. 4, pp. 2376–2384, 2008.

[4] G. G. Oggier, G. O. GarcÍa, and A. R. Oliva, "Switching control strategy to minimize dual active bridge converter losses," *IEEE Transactions on Power Electronics*, vol. 24, no. 7, pp. 1826–1838, 2009.

[5] S. Ben-Yaakov, "On the influence of switch resistances on switched-capacitor converter losses," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 1, pp. 638–640, 2012.

[6] L. Schwager, A. Tuysuz, C. Zwyssig, and J. W. Kolar, "Modeling and comparison of machine and converter losses for PWM and PAM in high-speed drives," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 995–1006, 2014.

[7] A. Vidal, A. G. Yepes, F. D. Freijedo, J. Malvar, Ó. López, and J. Doval-Gandoy, "A technique to estimate the equivalent loss resistance of grid-tied converters for current control analysis and design," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1747–1761, 2014.

[8] H. X. Yang, W. Zhou, and C. Z. Lou, "Optimal design and techno-economic analysis of a hybrid solar-wind power generation system," *Applied Energy*, vol. 86, no. 2, pp. 163–169, 2009.

[9] S. S. Reddy, B. K. Panigrahi, R. Kundu, R. Mukherjee, and S. Debchoudhury, "Energy and spinning reserve scheduling for a wind-thermal power system using CMA-ES with mean learning technique," *International Journal of Electrical Power and Energy Systems*, vol. 53, no. 1, pp. 113–122, 2013.

[10] R. Ghaffari and B. Venkatesh, "Options based reserve procurement strategy for wind generators—using binomial trees," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1063–1072, 2013.

[11] M. A. Delucchi and M. Z. Jacobson, "Providing all global energy with wind, water, and solar power. Part II. Reliability, system

and transmission costs, and policies," *Energy Policy*, vol. 39, no. 3, pp. 1170–1190, 2011.

[12] A. A. Khatir and R. Cherkaoui, "A probabilistic spinning reserve market model considering DisCo' different value of lost loads," *Electric Power Systems Research*, vol. 81, no. 4, pp. 862–872, 2011.

[13] B. W. Jones and R. Powell, "Evaluation of distributed building thermal energy storage in conjunction with wind and solar electric power generation," *Renewable Energy*, vol. 74, pp. 699–707, 2015.

[14] M. Parastegari, R.-A. Hooshmand, A. Khodabakhshian, and A.-H. Zare, "Joint operation of wind farm, photovoltaic, pump-storage and energy storage devices in energy and reserve markets," *International Journal of Electrical Power and Energy Systems*, vol. 64, pp. 275–284, 2015.

[15] K. Wu, H. Zhou, S. An, and T. Huang, "Optimal coordinate operation control for wind–photovoltaic–battery storage power-generation units," *Energy Conversion and Management*, vol. 90, pp. 466–475, 2015.

[16] S. Kumaravel and S. Ashok, "Optimal power management controller for a stand-alone solar PV/wind/battery hybrid energy system," *Energy Sources*, vol. 37, no. 4, pp. 407–415, 2015.

[17] G. Delille, B. François, and G. Malarange, "Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 931–939, 2012.

[18] T. Tsoutsos, N. Frantzeskaki, and V. Gekas, "Environmental impacts from the solar energy technologies," *Energy Policy*, vol. 33, no. 3, pp. 289–296, 2005.

[19] A. M. O. Haruni, M. Negnevitsky, M. E. Haque, and A. Gargoom, "A novel operation and control strategy for a standalone hybrid renewable power system," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 402–413, 2013.

[20] Y. Zhou, H. Li, and L. Liu, "Integrated autonomous voltage regulation and islanding detection for high penetration PV applications," *IEEE Transactions on Power Electronics*, vol. 28, no. 6, pp. 2826–2841, 2013.

[21] Y.-Y. Hong, M.-C. Hsiao, Y.-R. Chang, Y.-D. Lee, and H.-C. Huang, "Multiscenario underfrequency load shedding in m Microgrid consisting of intermittent renewables," *IEEE Transactions on Power Delivery*, vol. 28, no. 3, pp. 1610–1617, 2013.

[22] E. Koutroulis and D. Kolokotsa, "Design optimization of desalination systems power-supplied by PV and W/G energy sources," *Desalination*, vol. 258, no. 1, pp. 171–181, 2010.

[23] S. Eftekharnejad, V. Vittal, G. T. Heydt, B. Keel, and J. Loehr, "Impact of increased penetration of photovoltaic generation on power systems," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 893–901, 2013.

[24] F. Z. Kadda, S. Zouggar, and M. L. Elhafyani, "Optimal sizing of an autonomous hybrid system," in *Proceedings of the International Renewable and Sustainable Energy Conference (IRSEC '13)*, pp. 269–274, IEEE, Ouarzazate, Morocco, March 2013.

[25] H. Lund, "Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply," *Renewable Energy*, vol. 31, no. 4, pp. 503–515, 2006.

[26] S.-T. Kim, B.-K. Kang, S.-H. Bae, and J.-W. Park, "Application of SMES and grid code compliance to wind/photovoltaic generation system," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, Article ID 5000804, 2013.

[27] S. Pacca, D. Sivaraman, and G. A. Keoleian, "Parameters affecting the life cycle performance of PV technologies and systems," *Energy Policy*, vol. 35, no. 6, pp. 3316–3326, 2007.

[28] V. H. M. Quezada, J. R. Abbad, and T. G. S. Román, "Assessment of energy distribution losses for increasing penetration of distributed generation," *IEEE Transactions on Power Systems*, vol. 21, no. 2, pp. 533–540, 2006.

[29] L. H. Stember, "Reliability considerations in the design of solar photovoltaic power systems," *Solar Cells*, vol. 3, no. 3, pp. 269–285, 1981.

[30] J. Schmidt, B. Lim, D. Walter et al., "Impurity-related limitations of next-generation industrial silicon solar cells," *IEEE Journal of Photovoltaics*, vol. 3, no. 1, pp. 114–118, 2013.

[31] J. DeCesaro and K. Porter, "Wind energy and power system operations: a review of wind integration studies to date," Subcontract Report NREL/SR-550-47256, National Renewable Energy Laboratory, 2009.

[32] S. Santoso, M. Lwin, J. Ramos, M. Singh, E. Muljadi, and J. Jonkman, "Designing and integrating wind power laboratory experiments in power and energy systems courses," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1944–1951, 2014.

[33] S. Niu, K. T. Chau, J. Z. Jiang, and C. Liu, "Design and control of a new double-stator cup-rotor permanent-magnet machine for wind power generation," *IEEE Transactions on Magnetics*, vol. 43, no. 6, pp. 2501–2503, 2007.

[34] Y. Fan, K. T. Chau, and M. Cheng, "A new three-phase doubly salient permanent magnet machine for wind power generation," *IEEE Transactions on Industry Applications*, vol. 42, no. 1, pp. 53–60, 2006.

[35] C. Liu, K. T. Chau, and X. Zhang, "An efficient wind-photovoltaic hybrid generation system using doubly excited permanent-magnet brushless machine," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 3, pp. 831–839, 2010.

[36] W. S. Abu-Elhaija and A. Muetze, "Self-excitation and stability at speed transients of self-excited single-phase reluctance generators," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 136–144, 2013.

[37] B. Singh and S. Sharma, "Voltage and frequency controllers for standalone wind energy conversion systems," *IET Renewable Power Generation*, vol. 8, no. 6, pp. 707–721, 2014.

[38] S. Sharma and B. Singh, "Asynchronous generator with battery storage for standalone wind energy conversion system," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2760–2767, 2014.

[39] A. F. Zobaa and R. C. Bansal, *Handbook of Renewable Energy Technology*, National Renewable Energy Laboratory, Golden, Colo, USA, 1996.

[40] M. M. El-Wakil, *Power Plant Technology*, McGraw-Hill, New York, NY, USA, 1984.

[41] D. L. King, W. E. Boyson, and J. A. Kratochavil, "Photovoltaic array performance model," Tech. Rep., Sandia National Laboratory, 2004.

[42] M. Hosenuzzaman, N. A. Rahim, J. Selvaraj, M. Hasanuzzaman, A. B. M. A. Malek, and A. Nahar, "Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 284–297, 2014.

[43] G. Zhao, H. Kozuka, H. Lin, and T. Yoko, "Solar energy conversion," in *Willy Encylopedia of Electrical and Electronics Engineering*, pp. 638–649, John Willy & Sons, New York, NY, USA, 1999.

[44] REN21, *Renewable Global Status Report: 2009 Update*, REN21 Secretariat, Paris, France, 2009.

[45] T. Ishikawa, “Grid-connected photovoltaic power systems: survey of inverter and related protection equipments,” Report of International Energy Agency, International Energy Agency, Paris, France, 2002, http://www.iea-pvps.org.

[46] Solarbuzz, “Solar cell technologies,” 2010, http://www.solarbuzz.com/technologies.htm.

[47] R. Menzies, “Designing a solar power systems,” in *Proceedings of the Solar Photovoltaic Energy Workshop*, Monash University, Caulfield, Australia, July 1998.

[48] Bright Green Energy, “What type of solar PV panels are available?” 2009, http://www.wirefreedirect.com/Types_Solar_PV_Panels.asp.

[49] E. D. Kosten, B. K. Newman, J. V. Lloyd, A. Polman, and H. A. Atwater, “Limiting light escape angle in silicon photovoltaics: ideal and realistic cells,” *IEEE Journal of Photovoltaics*, vol. 5, no. 1, pp. 61–69, 2015.

[50] Z. N. Adamian, A. P. Hakhoyan, V. M. Aroutiounian, R. S. Barseghian, and K. Touryan, “Investigations of solar cells with porous silicon as antireflection layer,” *Solar Energy Materials & Solar Cells*, vol. 64, no. 4, pp. 347–351, 2000.

[51] J. I. Hanoka, “Overview of silicon ribbon growth technology,” *Solar Energy Materials and Solar Cells*, vol. 65, no. 1, pp. 231–237, 2001.

[52] J. Yang, A. Banerjee, and S. Guha, “Amorphous silicon based photovoltaics—from earth to the ‘final frontier’,” *Solar Energy Materials & Solar Cells*, vol. 78, no. 1–4, pp. 597–612, 2003.

[53] A. Fave, S. Quoizola, J. Kraiem, A. Kaminski, M. Lemiti, and A. Laugier, “Comparative study of LPE and VPE silicon thin film on porous sacrificial layer,” *Thin Solid Films*, vol. 451-452, pp. 308–311, 2004.

[54] L. A. Dobrzański and A. Drygała, “Laser processing of multicrystalline silicon for texturization of solar cells,” *Journal of Materials Processing Technology*, vol. 191, no. 1–3, pp. 228–231, 2007.

[55] P. Jiang, H. Zhang, L. Xu, X. Li, P. Zhao, and S. Zhang, “Research on a novel hybrid power system,” in *Proceedings of the 9th IEEE International Conference on Mechatronics and Automation (ICMA ’12)*, pp. 2494–2498, IEEE, Chengdu, China, August 2012.

[56] A. R. Prasad and E. Natarajan, “Optimization of integrated photovoltaic–wind power generation systems with battery storage,” *Energy*, vol. 31, no. 12, pp. 1943–1954, 2006.

[57] A. Safdarian, M. Fotuhi-Firuzabad, and F. Aminifar, “Compromising wind and solar energies from the power system adequacy viewpoint,” *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2368–2376, 2012.

[58] H. C. Chiang, T. T. Ma, Y. H. Cheng, J. M. Chang, and W. N. Chang, “Design and implementation of a hybrid regenerative power system combining grid-tie and uninterruptible power supply functions,” *IET Renewable Power Generation*, vol. 4, no. 1, pp. 85–99, 2010.

[59] Z. Zheng, L. X. Cai, R. Zhang, and X. S. Shen, “RNP-SA: joint relay placement and sub-carrier allocation in wireless communication networks with sustainable energy,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 10, pp. 3818–3828, 2012.

[60] F. F. Nerini, R. Dargaville, M. Howells, and M. Bazilian, “Estimating the cost of energy access: the case of the village of Suro Craic in Timor Leste,” *Energy*, vol. 79, pp. 385–397, 2015.

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

[62] G. C. Bakos and N. F. Tsagas, “Technoeconomic assessment of a hybrid solar/wind installation for electrical energy saving,” *Energy and Buildings*, vol. 35, no. 2, pp. 139–145, 2003.

[63] S. Diaf, M. Belhamel, M. Haddadi, and A. Louche, “Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island,” *Energy Policy*, vol. 36, no. 2, pp. 743–754, 2008.

[64] S. A. Daniel and N. A. Gounden, “A novel hybrid isolated generating system based on PV fed inverter-assisted wind-driven induction generators,” *IEEE Transactions on Energy Conversion*, vol. 19, no. 2, pp. 416–422, 2004.

[65] Y.-M. Chen, Y.-C. Liu, S.-C. Hung, and C.-S. Cheng, “Multi-input inverter for grid-connected hybrid PV/wind power system,” *IEEE Transactions on Power Electronics*, vol. 22, no. 3, pp. 1070–1077, 2007.

[66] S.-K. Kim, J.-H. Jeon, C.-H. Cho, J.-B. Ahn, and S.-H. Kwon, “Dynamic modeling and control of a grid-connected hybrid generation system with versatile power transfer,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 4, pp. 1677–1688, 2008.

[67] A. R. Reisi, M. H. Moradi, and S. Jamasb, “Classification and comparison of maximum power point tracking techniques for photovoltaic system: a review,” *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 433–443, 2013.

[68] K. Ishaque and Z. Salam, “A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition,” *IEEE Transactions on Industrial Electronics*, vol. 60, no. 8, pp. 3195–3206, 2013.

[69] P. Sharma and V. Agarwal, “Exact maximum power point tracking of grid-connected partially shaded PV source using current compensation concept,” *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4684–4692, 2014.

[70] H. A. Rub, A. Iqbal, S. M. Ahmed, F. Z. Peng, Y. Li, and G. Baoming, “Quasi-Z-source inverter-based photovoltaic generation system with maximum power tracking control using ANFIS,” *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 11–20, 2013.

[71] R. Gules, J. D. P. Pacheco, H. L. Hey, and J. Imhoff, “A maximum power point tracking system with parallel connection for PV stand-alone applications,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 7, pp. 2674–2683, 2008.

[72] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, “Assessment of the incremental conductance maximum power point tracking algorithm,” *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 108–117, 2013.

[73] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, “Assessment of perturb and observe MPPT algorithm implementation techniques for PV pumping applications,” *IEEE Transactions on Sustainable Energy*, vol. 3, no. 1, pp. 21–33, 2012.

[74] L. Cristaldi, M. Faifer, M. Rossi, and S. Toscani, “An improved model-based maximum power point tracker for photovoltaic panels,” *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 1, pp. 63–71, 2014.

[75] K. L. Lian, J. H. Jhang, and I. S. Tian, “A maximum power point tracking method based on perturb-and-observe combined with particle swarm optimization,” *IEEE Journal of Photovoltaics*, vol. 4, no. 2, pp. 626–633, 2014.

[76] C. Konstantopoulos and E. Koutroulis, “Global maximum power point tracking of flexible photovoltaic modules,” *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2817–2828, 2014.

[77] A. Al Nabulsi and R. Dhaouadi, "Efficiency optimization of a dsp-based standalone PV system using fuzzy logic and dual-MPPT control," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 3, pp. 573–584, 2012.

[78] B. N. Alajmi, K. H. Ahmed, S. J. Finney, and B. W. Williams, "Fuzzy-logic-control approach of a modified hill-climbing method for maximum power point in microgrid standalone photovoltaic system," *IEEE Transactions on Power Electronics*, vol. 26, no. 4, pp. 1022–1030, 2011.

[79] K. Sundareswaran, P. Sankar, P. S. R. Nayak, S. P. Simon, and S. Palani, "Enhanced energy output from a PV system under partial shaded conditions through artificial bee colony," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 1, pp. 198–209, 2015.

[80] Q. Zhang, C. Hu, L. Chen et al., "A center point iteration MPPT Method with application on the frequency-modulated LLC microinverter," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1262–1274, 2014.

[81] M. O. Badawy, A. S. Yilmaz, Y. Sozer, and I. Husain, "Parallel power processing topology for solar PV applications," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1245–1255, 2014.

[82] I. R. Balasubramanian, S. I. Ganesan, and N. Chilakapati, "Impact of partial shading on the output power of PV systems under partial shading conditions," *IET Power Electronics*, vol. 7, no. 3, pp. 657–666, 2014.

[83] A. Ghaffari, M. Krstić, and S. Seshagiri, "Power optimization for photovoltaic microconverters using multivariable newton-based extremum seeking," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 6, pp. 2141–2149, 2014.

[84] C. Olalla, C. Deline, and D. Maksimovic, "Performance of mismatched PV systems with submodule integrated converters," *IEEE Journal of Photovoltaics*, vol. 4, no. 1, pp. 396–404, 2014.

[85] B. Singh, C. Jain, and S. Goel, "ILST control algorithm of single-stage dual purpose grid connected solar PV system," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5347–5357, 2014.

[86] J. S. C. M. Raj and A. E. Jeyakumar, "A novel maximum power point tracking technique for photovoltaic module based on power plane analysis of $I-V$ characteristics," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 9, pp. 4734–4745, 2014.

[87] M. Boztepe, F. Guinjoan, G. V. Velasco-Quesada, S. Silvestre, A. Chouder, and E. Karatepe, "Global MPPT scheme for photovoltaic string inverters based on restricted voltage window search algorithm," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 7, pp. 3302–3312, 2014.

[88] M. Bansal, R. P. Saini, and D. K. Khatod, "An off-grid hybrid system scheduling for a remote area," in *Proceedings of the IEEE Students' Conference on Electrical, Electronics and Computer Science (SCEECS '12)*, pp. 1–4, IEEE, Bhopal, India, March 2012.

[89] K. Kimura and T. Kimura, "Neural networks approach for wind-solar energy system with complex networks," in *Proceedings of the IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS '13)*, pp. 1–5, IEEE, Kitakyushu, Japan, April 2013.

[90] E. I. B. Gould, "Hybrid2: the hybrid system simulation model version 1.0," User Manual, National Renewable Energy Laboratory, 1996, http://www.nrel.gov/docs/legosti/old/21272.pdf.

[91] pp. 17–24, 2012, http://www.iea-pvps.org/fileadmin/dam/public/report/technical/rep11_01.pdf.

[92] E. S. Sreeraj, K. Chatterjee, and S. Bandyopadhyay, "One-cycle-controlled single-stage single-phase voltage-sensorless grid-connected PV system," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 3, pp. 1216–1224, 2013.

[93] E. Mamarelis, G. Petrone, and G. Spagnuolo, "An hybrid digital-analog sliding mode controller for photovoltaic applications," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 2, pp. 1094–1103, 2013.

[94] T. Senjyu, D. Hayashi, N. Urasaki, and T. Funabashi, "Optimum configuration for renewable generating systems in residence using genetic algorithm," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 459–467, 2006.

[95] X. Li, D. Hui, and X. Lai, "Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 2, pp. 464–473, 2013.

[96] D. Weisser and R. S. Garcia, "Instantaneous wind energy penetration in isolated electricity grids: concepts and review," *Renewable Energy*, vol. 30, no. 8, pp. 1299–1308, 2005.

[97] G. E. Ahmad and E. T. El Shenawy, "Optimized photovoltiac system for hydrogen production," *Renewable Energy*, vol. 31, no. 7, pp. 1043–1054, 2006.

[98] Q. Xie, Y. Wang, Y. Kim, M. Pedram, and N. Chang, "Charge allocation in hybrid electrical energy storage systems," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, vol. 32, no. 7, pp. 1003–1016, 2013.

[99] Y. V. Makarov, P. Du, M. C. W. K. Meyer, C. Jin, and H. F. Illian, "Sizing energy storage to accommodate high penetration of variable energy resources," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 1, pp. 34–40, 2012.

[100] P. Nema, R. K. Nema, and S. Rangnekar, "A current and future state of art development of hybrid energy system using wind and PV-solar: a review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2096–2103, 2009.

[101] J. D. Maclay, J. Brouwer, and G. Scott Samuelsen, "Dynamic analyses of regenerative fuel cell power for potential use in renewable residential applications," *International Journal of Hydrogen Energy*, vol. 31, no. 8, pp. 994–1009, 2006.

[102] L. Xu, X. Ruan, C. Mao, B. Zhang, and Y. Luo, "An improved optimal sizing method for wind-solar-battery hybrid power system," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 3, pp. 774–785, 2013.

[103] M. S. Whittingham, "History, evolution, and future status of energy storage," *Proceedings of the IEEE Special Centennial Issue*, vol. 100, pp. 1518–1534, 2012.

[104] M. Trifkovic, M. Sheikhzadeh, K. Nigim, and P. Daoutidis, "Modeling and control of a renewable hybrid energy system with hydrogen storage," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 1, pp. 169–179, 2014.

[105] W. Zhou, C. Lou, Z. Li, L. Lu, and H. Yang, "Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems," *Applied Energy*, vol. 87, no. 2, pp. 380–389, 2010.

[106] K. Nishioka, T. Takamoto, T. Agui, M. Kaneiwa, Y. Uraoka, and T. Fuyuki, "Annual output estimation of concentrator photovoltaic systems using high-efficiency InGaP/InGaAs/Ge triple-junction solar cells based on experimental solar cell's characteristics and field-test meteorological data," *Solar Energy Materials and Solar Cells*, vol. 90, no. 1, pp. 57–67, 2006.

[107] L. Marí and N. Nabona, "Renewable energies in medium-term power planning," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 88–97, 2015.

[108] G. Tina, S. Gagliano, and S. Raiti, "Hybrid solar/wind power system probabilistic modelling for long-term performance assessment," *Solar Energy*, vol. 80, no. 5, pp. 578–588, 2006.

[109] H. Yang, L. Lu, and W. Zhou, "A novel optimization sizing model for hybrid solar-wind power generation system," *Solar Energy*, vol. 81, no. 1, pp. 76–84, 2007.

[110] H. X. Yang, W. Zhou, L. Lu, and Z. Fang, "Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm," *Solar Energy*, vol. 82, no. 4, pp. 354–367, 2008.

[111] A. Mellit, S. A. Kalogirou, L. Hontoria, and S. Shaari, "Artificial intelligence techniques for sizing photovoltaic systems: a review," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, pp. 406–419, 2009.

[112] S. A. Kalogirou, "Optimization of solar systems using artificial neural-networks and genetic algorithms," *Applied Energy*, vol. 77, no. 4, pp. 383–405, 2004.

[113] R. Siddique, A. A. Faisal, M. A. H. Raihan et al., "A theoretical analysis of controlling the speed of wind turbine and assemblage of solar system in the wind energy conversion system," in *Proceedings of the IEEE International Conference on Power, Energy and Control (ICPEC '13)*, Dindigul, India, February 2013.

[114] Y. Bae, T.-K. Vu, and R.-Y. Kim, "Implemental control strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low-to-medium voltage network," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 619–631, 2013.

[115] P. Malysz, S. Sirouspour, and A. Emadi, "An optimal energy storage control strategy for grid-connected microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 4, pp. 1785–1796, 2014.

[116] B. O. Bilal, V. Sambou, P. A. Ndiaye, C. M. F. Kebe, and M. Ndongo, "Multi-objective design of PV-wind-batteries hybrid systems by minimizing the annualized cost system and the loss of power supply probability (LPSP)," in *Proceedings of the IEEE International Conference on Industrial Technology (ICIT '13)*, vol. 2, pp. 861–868, Cape Town, South Africa, February 2013.

[117] R. Dufo-López and J. L. Bernal-Agustín, "Multi-objective design of PV-wind-diesel-hydrogen-battery systems," *Renewable Energy*, vol. 33, no. 12, pp. 2559–2572, 2008.

[118] X. Pelet, D. Favrat, and G. Leyland, "Multiobjective optimisation of integrated energy systems for remote communities considering economics and CO_2 emissions," *International Journal of Thermal Sciences*, vol. 44, no. 12, pp. 1180–1189, 2005.

[119] J. P. Torreglosa, P. García, L. M. Fernández, and F. Jurado, "Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control," *Energy Conversion and Management*, vol. 77, pp. 514–526, 2014.

[120] J. C. Hernández, A. Medina, and F. Jurado, "Optimal allocation and sizing for profitability and voltage enhancement of PV systems on feeders," *Renewable Energy*, vol. 32, no. 10, pp. 1768–1789, 2007.

[121] T. F. El-Shatter, M. N. Eskander, and M. T. El-Hagry, "Energy flow and management of a hybrid wind/PV/fuel cell generation system," *Energy Conversion and Management*, vol. 47, no. 9-10, pp. 1264–1280, 2006.

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

[123] A. Chaurey and T. C. Kandpal, "Carbon abatement potential of solar home systems in India and their cost reduction due to carbon finance," *Energy Policy*, vol. 37, no. 1, pp. 115–125, 2009.

[124] Q.-S. Jia, J.-X. Shen, Z.-B. Xu, and X.-H. Guan, "Simulation-based policy improvement for energy management in commercial office buildings," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2211–2223, 2012.

[125] S. M. Shaahid and M. A. Elhadidy, "Economic analysis of hybrid photovoltaic–diesel–battery power systems for residential loads in hot regions—a step to clean future," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 2, pp. 488–503, 2008.

[126] S. Sarkar and V. Ajjarapu, "MW resource assessment model for a hybrid energy conversion system with wind and solar resources," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 4, pp. 383–391, 2011.

[127] B. Sun, P. B. Luh, Q.-S. Jia, Z. Jiang, F. Wang, and C. Song, "Building energy management: integrated control of active and passive heating, cooling, lighting, shading, and ventilation systems," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 3, pp. 588–602, 2013.

[128] A. Arabali, M. Ghofrani, M. Etezadi-Amoli, M. S. Fadali, and Y. Baghzouz, "Genetic-algorithm-based optimization approach for energy management," *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 162–170, 2013.

[129] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of power system flexibility," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 922–931, 2012.

[130] S. Mei, Y. Wang, F. Liu, X. Zhang, and Z. Sun, "Game approaches for hybrid power system planning," *IEEE Transactions on Sustainable Energy*, vol. 3, no. 3, pp. 506–517, 2012.

[131] H. H. El-Tamaly and A. A. E. Mohammed, "Impact of interconnection photovoltaic/wind system with utility on their reliability using a fuzzy scheme," *Renewable Energy*, vol. 31, no. 15, pp. 2475–2491, 2006.

[132] J. V. Paatero and P. D. Lund, "Effects of large-scale photovoltaic power integration on electricity distribution networks," *Renewable Energy*, vol. 32, no. 2, pp. 216–234, 2007.

[133] X. Xu and S. V. Dessel, "Evaluation of a prototype active building envelope window-system," *Energy and Buildings*, vol. 40, no. 2, pp. 168–174, 2008.

[134] V. Quaschning, "Technical and economical system comparison of photovoltaic and concentrating solar thermal power systems depending on annual global irradiation," *Solar Energy*, vol. 77, no. 2, pp. 171–178, 2004.

[135] T. Tezuka, K. Okushima, and T. Sawa, "Carbon tax for subsidizing photovoltaic power generation systems and its effect on carbon dioxide emissions," *Applied Energy*, vol. 72, no. 3-4, pp. 677–688, 2002.

[136] D. B. Nelson, M. H. Nehrir, and C. Wang, "Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems," *Renewable Energy*, vol. 31, no. 10, pp. 1641–1656, 2006.

[137] S.-J. Park, F.-S. Kang, M. H. Lee, and C.-U. Kim, "A new single-phase five-level PWM inverter employing a deadbeat control scheme," *IEEE Transactions on Power Electronics*, vol. 18, no. 3, pp. 831–843, 2003.

[138] N. A. Rahim and J. Selvaraj, "Multistring five-level inverter with novel PWM control scheme for PV application," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 6, pp. 2111–2123, 2009.

[139] N. A. Rahim, K. Chaniago, and J. Selvaraj, "Single-phase seven-level grid-connected inverter for photovoltaic system," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 6, pp. 2435–2443, 2011.

[140] S. Gautam and R. Gupta, "Switching frequency derivation for the cascaded multilevel inverter operating in current control mode using multiband hysteresis modulation," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1480–1489, 2014.

[141] Y. Liu, B. Ge, H. Abu-Rub, and F. Z. Peng, "An effective control method for quasi-Z-source cascade multilevel inverter-based grid-tie single-phase photovoltaic power system," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 1, pp. 399–407, 2014.

[142] M. Fatu, F. Blaabjerg, and I. Boldea, "Grid to standalone transition motion-sensorless dual-inverter control of PMSG with asymmetrical grid voltage sags and harmonics filtering," *IEEE Transactions on Power Electronics*, vol. 29, no. 7, pp. 3463–3472, 2014.

[143] N. Mendis, K. M. Muttaqi, and S. Perera, "Management of battery-supercapacitor hybrid energy storage and synchronous condenser for isolated operation of PMSG based variable-speed wind turbine generating systems," *IEEE Transactions on Smart Grid*, vol. 5, no. 2, pp. 944–953, 2014.

[144] H. Quan, D. Srinivasan, and A. Khosravi, "Short-term load and wind power forecasting using neural network-based prediction intervals," *IEEE Transactions on Neural Networks and Learning Systems*, vol. 25, no. 2, pp. 303–315, 2014.

[145] A. Chauhan and R. P. Saini, "A review on integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 99–120, 2014.

[146] M. Alsayed, M. Cacciato, G. Scarcella, and G. Scelba, "Multicriteria optimal sizing of photovoltaic-wind turbine grid connected systems," *IEEE Transactions on Energy Conversion*, vol. 28, no. 2, pp. 370–379, 2013.

[147] T. Zhou and W. Sun, "Optimization of battery-supercapacitor hybrid energy storage station in wind/solar generation system," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 2, pp. 408–415, 2014.

[148] H.-S. Ko and J. Jatskevich, "Power quality control of wind-hybrid power generation system using fuzzy-LQR controller," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 516–527, 2007.

[149] Z. Jiang and R. Dougal, "Hierarchical microgrid paradigm for integration of distributed energy resources," in *Proceedings of the IEEE International Conference on Power Engineering Society General Meeting (PES '08)*, pp. 20–24, Pittsburgh, Pa, USA, July 2008.

[150] J. Zeng, W. Qiao, and L. Qu, "An isolated multiport DC-DC converter for simultaneous power management of multiple renewable energy sources," in *Proceedings of the 4th Annual IEEE Energy Conversion Congress and Exposition (ECCE '12)*, pp. 3741–3748, Raleigh, NC, USA, September 2012.

[151] F. Botterón, R. Carballo, R. Núñez, A. Quintana, and G. Fernandez, "High reliability and performance PWM inverter for standalone microgrids," *IEEE Latin America Transactions*, vol. 11, no. 1, pp. 505–511, 2013.

[152] K. Narula, Y. Nagai, and S. Pachauri, "The role of decentralized distributed generation in achieving universal rural electrification in South Asia by 2030," *Energy Policy*, vol. 47, pp. 345–357, 2012.

[153] G. R. Timilsina, L. Kurdgelashvili, and P. A. Narbel, "Solar energy: markets, economics and policies," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 449–465, 2012.

[154] C.-T. Pan and Y.-L. Juan, "A novel sensorless MPPT controller for a high-efficiency microscale wind power generation system," *IEEE Transactions on Energy Conversion*, vol. 25, no. 1, pp. 207–216, 2010.

[155] K. Nishida, T. Ahmed, and M. Nakaoka, "A cost-effective high-efficiency power conditioner with simple MPPT control algorithm for wind-power grid integration," *IEEE Transactions on Industry Applications*, vol. 47, no. 2, pp. 893–900, 2011.

[156] K.-Y. Lo, Y.-M. Chen, and Y.-R. Chang, "MPPT battery charger for stand-alone wind power system," *IEEE Transactions on Power Electronics*, vol. 26, no. 6, pp. 1631–1638, 2011.

[157] N. Mendis, K. M. Muttaqi, S. Sayeef, and S. Perera, "Standalone operation of wind turbine-based variable speed generators with maximum power extraction capability," *IEEE Transactions on Energy Conversion*, vol. 27, no. 4, pp. 822–834, 2012.

[158] Y. Zou, M. E. Elbuluk, and Y. Sozer, "Stability analysis of maximum power point tracking (MPPT) method in wind power systems," *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1129–1136, 2013.

[159] M. Cirrincione, M. Pucci, and G. Vitale, "Neural MPPT of variable-pitch wind generators with induction machines in a wide wind speed range," *IEEE Transactions on Industry Applications*, vol. 49, no. 2, pp. 942–953, 2013.

[160] Z. M. Dalala, Z. U. Zahid, W. Yu, Y. Cho, and J.-S. Lai, "Design and analysis of an MPPT technique for small-scale wind energy conversion systems," *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 756–767, 2013.

[161] A. Urtasun, P. Sanchis, and L. Marroyo, "Small wind turbine sensorless MPPT: robustness analysis and lossless approach," *IEEE Transactions on Industry Applications*, vol. 50, no. 6, pp. 4113–4121, 2014.

[162] http://www.homerenergy.com/HOMER_pro.html.

[163] E. L. B. Gould, *Hybrid2: The Hybrid System Simulation Model*, User Manual, National Renewable Energy Laboratory, Golden, Colo, USA, 1996, http://www.nrel.gov/docs/legosti/old/21272.pdf.

[164] http://hoga-renewable.es.tl/.

[165] Ulleberg, *Standalone power systems for the future: optimal design, operation & control of solar-hydrogen energy systems [Ph.D. thesis]*, Department of Thermal Energy and Hydropower, Norwegian University of Science and Technology, Trondheim, Norway, 1998.

[166] F. Farret and M. Simões, *Micropower System Modeling with Homer*, Wiley-IEEE Press, 2006.

[167] http://www.retscreen.net/ang/centre.php.

[168] http://www.energyplan.eu/trnsys/.

[169] http://in.mathworks.com/academia/student_center/tutorials/?s_tid=acmain_st-pop-tut_gw_bod.

[170] H. Elmqvist, *Dymola: environment for object-oriented modeling of physical systems [Ph.D. thesis]*, 2009.

[171] Pvsyst contextual help, Users Guide, pp 2–13, http://files.pvsyst.com/pvsyst5.pdf.

[172] M. R. Patel, *Wind and Solar Power System*, CRC Press, New York, NY, USA, 1999.

[173] J. K. Kaldellis, *Stand-Alone and Hybrid Wind Energy Systems*, CRC Press Woodhead Publishing Series in Energy, CRC Press, 2010.