

State of the Art in Research on Optimum Design, Reliability and Control of Renewable Energy Microgrids

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Abstract: This paper has presented a comprehensive review in the area of microgrid from the design to implementation. The aim is to evaluate the current status, problems and research efforts toward realising functional microgrids in the power system. The expectations about microgrid are many; therefore the study is divided into three main sections. Recent advancements in the wind energy, solar energy and their future prediction are summarised. States of arts in optimum design of renewable energy microgrid are also investigated. In addition, critical literature review in the reliability analysis of microgrids consisting of renewable energy sources is also reported. Control of microgrids consisting renewable energy sources have been presented. Some examples of existing microgrids across the globe are critically reviewed. The work therefore recommends that energy planners and all stakeholders should consider environmental and regional difference in microgrids planning. Finally, future research areas and directions in these areas are highlighted.

Keywords: Microgrids, Wind, Solar, Reliability, Control.

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1. INTRODUCTION

Statistics of the World Energy Council (WEC) has shown that nearly 1.5 billion people have no access to electricity. These forced nearly three billion people to use wood for their daily energy needs [1]. Further analysis has revealed that a greater percentage of them are from Sub-Saharan Africa, India and South Asia [2]. Most of these people live in rural areas where extending the grid may be challenging. Furthermore, isolated area/loads are still in search of cost-effective means of power generation. Future forecasts by the WEC has shown that if all the stakeholders are not committed, there could still be about 880 million people by 2030 and 530 million people by 2050 without electricity, thereby, defeating the Sustainable Development Goals (SDGs). In order to achieve higher penetrations of electricity across the globe, more commitments from various stakeholders are necessary, leading to the declaration of 2014-2024 by the United Nations general assembly as the decade of sustainable energy for all [3]. Moreover, investigations have also revealed that, global energy demand is increasing along with the world population. The majority of people without access to electricity are in rural and isolated areas which are characterised with high rates of poverty, low income, lack of supporting infrastructure and extreme terrain features.

These challenges make extension of electric grid a difficult task.

Ordinarily, the cost of supplying grid-based electricity to these locations, should be less when compared to alternative off-grid options, however, the distances of these remote locations to the nearby transmission and distribution lines are beyond what could be sustained. These therefore, make the cost of grid extensions unattainable and, as such, standalone renewable energy microgrids become viable option. Among these options, wind and solar energy are the most widely proposed renewable energy sources. Thus, there is a need to evaluate the current status, problems and research efforts toward realising functional microgrids in the power system for sustainable development. This paper presents a comprehensive review in the area of microgrid from the design to implementation perspectives. In addition, the recent advancements in the wind energy, solar energy and their future prediction are provided. The states of arts in optimum design of renewable energy microgrid are also investigated. Extensive review in the reliability analysis of microgrids consisting of renewable energy sources is also reported.

2. THE GLOBAL OUTLOOK OF RENEWABLE ENERGY SOURCES

This section provides the recent advancements, deployments in the wind energy, solar energy and their future prediction as they are the most widely proposed renewable energy sources.

2.1 Solar energy

The global installed capacity for solar power electricity has seen an exponential growth in the last decade. In 2014, the Photovoltaic (PV) systems increased by 47 GW with a year-on-year growth rate of 24% as shown in Figure 1 [3]. Germany has sustained her leading role in PV installation over the decade; followed by China, Japan, Italy and United States. These countries have generated around 227 GW of electricity from solar energy at the end of 2015. With addition of 75 GW in the 2016 increasing the global power generating capacity to about 302 GW. In 2016, about 75 GW of new installation was added making the global power generating capacity to about 302 GW. In the same way, about two-third of the growth is from China recorded (34.5 GW) and USA (14.5 GW) combined together. In the same year, Japan provides 8.6 GW additional. In terms of cumulative installed capacity China maintained the lead (78.1 GW) making about more than one quarter of world total. Japan is second (42.8 GW) followed by Germany (41.3 GW) and USA (40.3 GW) behind Germany as shown in the Figure 1. The actual output of the PV system shows that, solar power generation has witnessed rapid increased in 2016 with about 26.6 % increased.

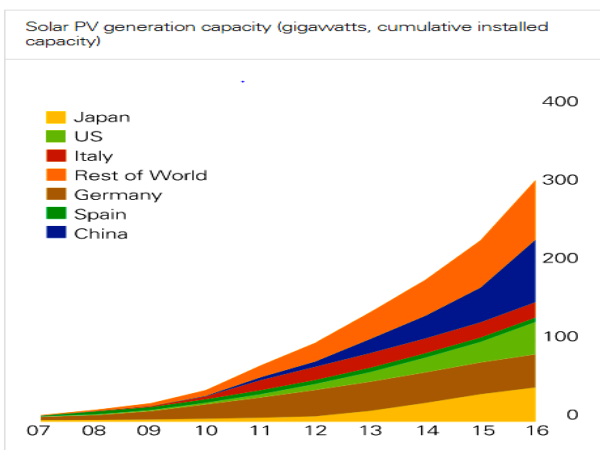


Figure 1. World solar energy [3]

This breakthrough makes it to have a noticeable impact in global power growth, contributing to more than 20% of the global power growth in 2016. Some of the factors responsible for higher penetration include a decrease in the cost of the solar panels, feed-in-tariffs, investment tax credits, subsidies, renewable energy portfolio, financial facilitation, public investment, net metering, lower lifetime costs and government policies that actually contribute to the business feeling comfortable [4]. It is unfortunate to note that the major installation of solar system has been in regions with less solar energy resources (China and Europe). On the other hand, tropical regions with high solar energy sources such as African and some parts of Middle East remain underutilised. However, the cost of solar system are falling in many countries while, the market of solar system are opening in emerging and developing nations. Recent investments in this area have

exceeded those in the conventional power based systems. Figure 2 shows recent trend in solar power investment, this represents a huge investment in solar energy technology. The trend shows that irrespective of the scenario, solar power in the next five years will still be between low and high scenarios. Presently, Asia continent is dominating about 60% of the market share with the trend to continue for next five years. The same region is expected to absorb about half of the new installation of solar power by 2020. Critical look at the figure indicates rapid solar power spread across the continent for the period under review. However, the top four countries China, US, India and Japan each is expected to add at least 20 GW by 2020. Also, in the high scenario; China is the only country that could exceed 100 GW level. This could be achieved with help of optimum supply of installation component and technology to mention just a few. Recent technological advancement has shown that the efficiency for solar cells has reached 46%. In order to take care of environment, there is need for strict and consistent regulations on the entire life cycle of the solar system.

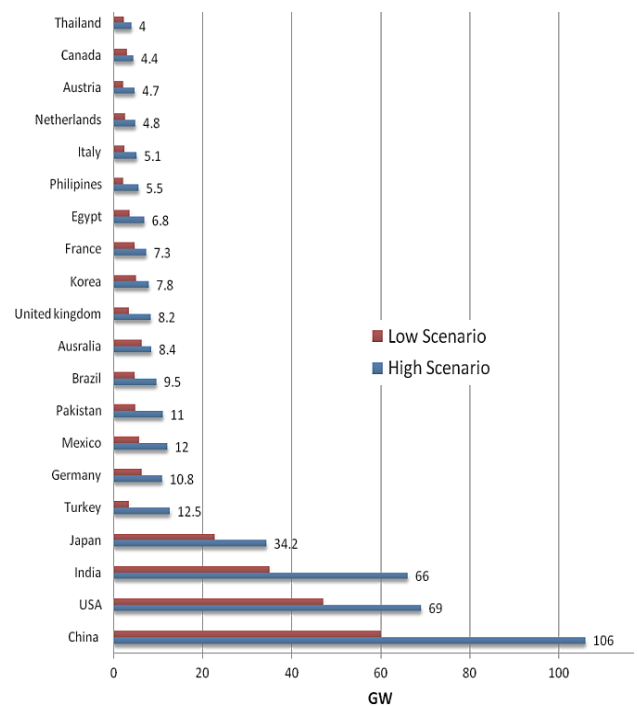


Figure 2. Figure 2. Markets Solar PV additions for High and Low Scenarios 2016-2020 [5]

2.2 Wind energy

An increase in wind energy penetration that was equal to about half of global electricity growth was witnessed in 2015, in fact about 60GW was installed this year. It has been noted by the World Wind Energy Association (WWEA), the last record set was in 2014, when nearly 50 GW of wind energy was added to the global capacity [8]. Moreover, as depicted in Table 1, there was an increase in the market volume of wind energy by about 40% in 2014 more than 2013 and significantly larger than 2012 when 44.6 GW was added. A total of 953 MW was added to the wind energy capacity by Africa and Middle East continents. This brings the cumulative installed capacity from these regions up to 3489 MW. Latin America and the Caribbean on the other hand saw an increase of 3652 MW with Brazil taking the lead. In Europe, Germany account for about 50% of the EU wind installation with about 6013

MW out of 13805 MW wind energy installation. Furthermore, 8598 MW worth of wind energy was added by the US out of 10817 MW supplied from North America. Finally, about 33.9 GW of wind energy was added from Asia region with China generating about 90% of this value.

After 2014 records, the wind power has surprise the world with another breaking in 2015 recording annual growth of about 22%. The big story behind this record was China by installing 308 GW as against the backdrop in a slowing economy and nearly flat demand. In addition, US, Mexico, Europe, Canada and other new markets emanating from different part of the world. The wind energy market will continue to grow due three main drivers. These

includes climate, cratering prices and US market stability. Figure 3 provides the regional scores of wind energy capacity.

Figure 4 shows that for the period under consideration, Asia will continue to dominate the wind energy market. This represents at least 50% of the global market with China still maintained the lead. In the same way, Brazil will continue to drive the market of Latin America. However, South Africa, Egypt and Morocco in a short time will dominate the market in Africa and Middle East with Kenya and Ethiopia coming stronger. On the other hand, policy stability will determine the growth in Pacific region within the same period.

Table 1: Global Installed Wind energy Capacity (MW) (Data Source: GWEC-2015) [6]

Country	End of 2014	End of 2015	Total End of 2015	Country	End of 2014	End of 2015	Total End of 2015	Country	End of 2014	End of 2015	Total End of 2015
AFRICA & MIDDLE EAST				EUROPE				LATIN AMERICA & CARIBBEAN			
South Africa	570	483	1,053	Germany	39,128	6,013	44,947	Brazil	5,962	2,754	8,715
Morocco	787	-	787	Spain	23,025	-	23,025	Chile	764	169	933
Egypt	610	200	810	UK	12,633	975	13,603	Uruguay	529	316	845
Tunisia	245	-	245	France	9,285	1,073	10,358	Argentina	271	8	279
Ethiopia	171	153	324	Italy	8,663	295	8,958	Panama	35	235	270
Jordan	2	117	119	Sweden	5,425	615	6,025	Costa Rica	198	70	268
Other1	151	-	151	Poland	3,834	1,266	5,100	Honduras	126	50	176
Total	2,536	953	3,489	Portugal	4,947	132	5,079	Peru	148	-	148
ASIA				Denmark	4,881	217	5,063	Guatemala	-	50	50
PR China	114,609	30,753	145,362	Turkey	3,738	956	4,694	Caribbean	250	-	250
India	22,465	2,623	25,088	Netherlands	2,865	586	3,431	Others	285	-	285
Japan	2,794	245	3,038	Romania	2,953	23	2,976	Total	8,568	3,652	12,220
South Korea	610	225	835	Ireland	2,262	224	2,486	NORTH AMERICA			
Taiwan	633	14	647	Austria	2,089	323	2,411	USA	65,877	8,598	74,471
Pakistan	256	-	256	Belgium	1,959	274	2,229	Canada	9,699	1,506	11,205
Thailand	223	-	223	Rest of Europe	6,564	833	7,387	Mexico	2,359	714	3,073
Philippines	216	-	216	Total Europe	134,251	13,805	147,771	Total	77,935	10,817	88,749
Other	167	-	167	of which EU-28	129,060	12,800	141,578				
Total	141,973	33,859	175,831								
PACIFIC REGION											
Australia	3,807	380	4,187								
New Zealand	623	-	623								
Pacific Islands	12	0,6	13								
Total	4,442	380,6	4,823								
World Total	369,705	63,467	432,883								

Table 2: More Examples of Microgrids

Location	Technical specification	Remark and type of control	Reference
Boston Bar-BC Hydro	Radial microgrid driven by two hydro plants with peak of 3MW	Radial/Controlled by autonomous controller.	[7]
Borex planned islanding Hydro Qubec	It facilitates replacement of 40 km feeder serving 3000 customers with peak of 7MW	controlled autonomously	[8]
The CERTS test bed-United Sates	Mesh type microgrid	Mesh/Controlled by autonomous controller.	[7]
UW microgrid-United State	Radial microgrid driven by PV and diesel generator	Radial/controlled autonomously using active power-frequency droop and voltage control.	[7]
Bronsbergen Holiday Park microgrid – Netherland:	Mesh type microgrid driven by several PV DGs with central energy storage. Peak generation capacity is 315kW	Centrally controlled.	
Microgrid of Am Steinweg in Stutensee – German:	Mesh driven microgrid driven by PV, DGs, CHP and lead acid battery of 880 Ah.	Mesh/Controlled Agent based control.	[9]
CESI RICERCA DER test microgrid – Italy:	LV driven by 14kW, PV DG, 10 kW solar thermal DG, 10 kW biomass CHP DG, 100kW micro turbine CHP DG and battery storage	Agent based control	[10]
Kythnos island microgrid – Greece:	Centrally controlled Radial microgrid driven by 12kW PV DG, 53kWh battery bank, and 5 kW diesel DG	Radial/Centrally controlled	[10]
Microgrid system at National Technical University of Athens (NTUA) – Greece	Laboratory scale microgrid driven by two PV generators, one wind turbine, and battery energy storage	Agent based control	[11]
DeMoTec test microgrid system – German	Two battery units and two diesel generators and a wind turbine	Agent based control	[12]
University of Manchester microgrid/flywheel energy storage laboratory prototype – UK:	20kVA radial laboratory microgrid prototype driven by a synchronous generator coupled to an induction motor	SCADA controlled	[12]
Aichi microgrid project – Central Japan airport city	The system is driven by seven fuel cells rated 1.4 MW, 330 kW PV and Nas battery storage	Radial	[12]
Kyoto eco-energy project (Kyotango project) – Japan	400kW, Gas turbine , 350kW of fuel cells, two PV systems and a 50kW small wind turbine	Mesh/centrally controlled system	[13]
Hachinohe project – Japan	5 PV units 130kW in all, 4 wind turbines 20kW in all, and 3 diesel generators rated at 170kW each.	Radial/centrally controlled system	[14]
Akagi-Central Research Institute of Electric Power Industry (CRIEPI) – Japan	PV generation derived through three 100kW inverters and a 200kVA dummy load	A Centrally controlled test system	[7]
Sendai project – Japan:	two 350kW gas engine generators, one 250kW fuel cell, 50kW PV and battery storage system	Radial/centrally controlled system	[15]
Microgrid testbed in Hefei University of Technology (HFUT) – China	PV generators, 3-phase wind generation simulators, fuel cell, battery bank, ultra capacitor bank, conventional generators used to simulate small hydro and fossil generators.	Mesh network/agent based controller.	[14]
KERI, Korea microgrid pilot plant	120kW microgrid driven by PV, PV and wind hybrid, two diesel generators, and a battery storage system.	Radial network	[16]

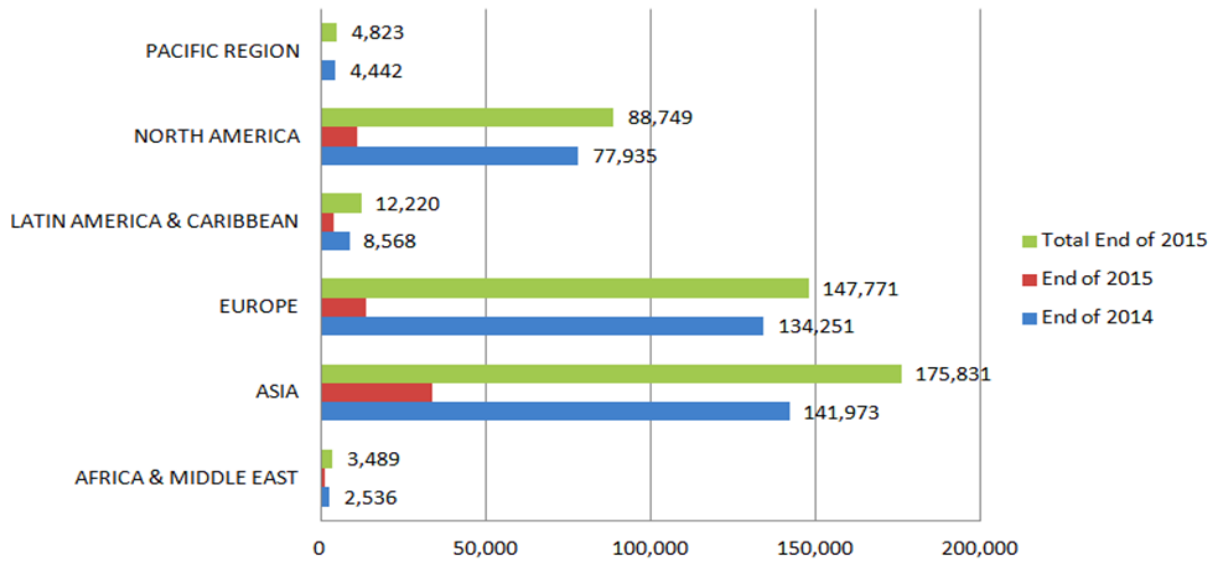


Figure 3. Regional installed wind energy capacity (MW)

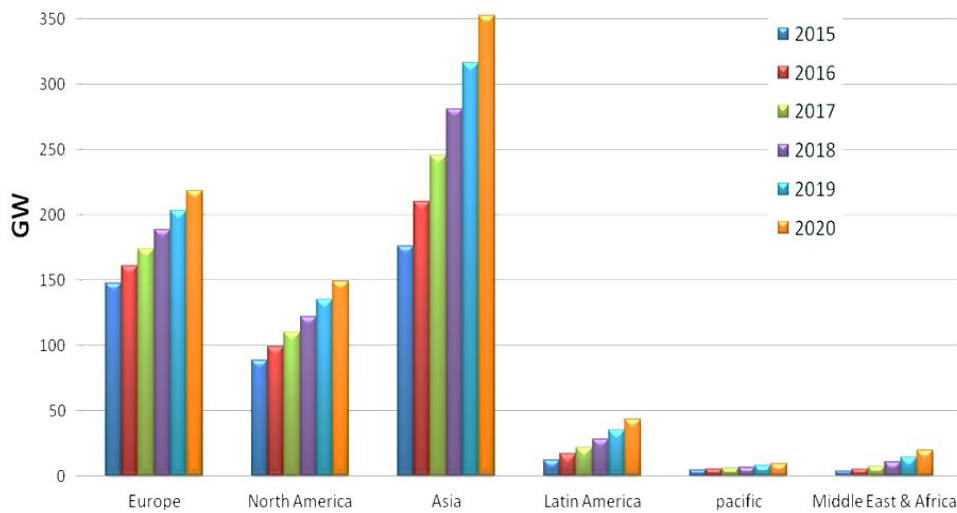


Figure 4: Cumulative market forecast by region 2016-2020 [6].

3. FUTURE RENEWABLE ENERGY PENETRATION FROM COUNTRIES

Recent predictions by the International Energy Agency (IEA) have shown that the demand for energy will triple by 2050 [17]. Presently, renewable energy sources contribute to less than 20% of the world’s energy [18]. Future predictions in Figure 5 have shown that the percentage of the installed capacity of non-fossil energy systems will increase to 45% by 2035. Also, the World Bank and the IEA have indicated the need to double the global installed energy capacity. This will help to meet the demand from the developing countries in the next 40 years. Many countries are aiming for a higher penetration of renewable energy by 2050, as a result of this; the global share would be between 15 and 82% as shown in figure 5. Denmark generates 39.1% of its overall electricity from cleaner sources and has a target of 50% and 100% by 2020 and 2050 respectively. The United Kingdom aim to meet 15% of the demand by 2020, when the Scottish and Northern Ireland intend to achieve 100% and 40% by 2020 respectively. The Welsh government indicates the

potential of generating twice the amount of electricity it currently uses from renewable energy sources by 2025. Spain has set a target of 40% penetration of renewable energy by 2020 while Ireland, which has one of the best wind resources has set a target of a 40% penetration of renewable energy resources by 2020. China being the global leader in renewable energy is envisaging that 15% of its energy needs will be from renewable energy sources by 2050. More renewable energy development in Asian countries can be found in [19] and in Africa in [20].

4. MICROGRIDS

A microgrid can be defined as a small electrical distribution system that could connects multiple customers to multiple distributed sources of generation and storage through power electronic devices that provide the necessary interface [22]- [23]. The concept of microgrids is not new as it is dated back to 1882 by Thomas Edison whose company built the first 50 DC power plant. Recently, realities have shown that rising cost of installation, aging infrastructure, natural disaster and lack

of accessibility to rural areas could hinder continuous power supply. Besides, the global concern on economy, reliability, complexity, demand and control of power system call for a shift from conventional mode of power supply which relies on common/single/national grid. Thus, there is need for smart microgrid system which depends on advance technology that are available in today's world. The development of microgrids is one of the drivers towards a more reliable and quality power to consumers. Depending on the application, a microgrid can be DC, AC or a combination of both (hybrid mode). It can be in single or three phases and sometimes can be connected to a low voltage or medium voltage distribution network [24]. In some cases, it can be operated as a standalone mode. In any of the cases, the system requirements differ in control, stability and reliability, etc. Microgrids systems are usually designed on a small scale with either solar or wind or a combination of the two or more energy sources.

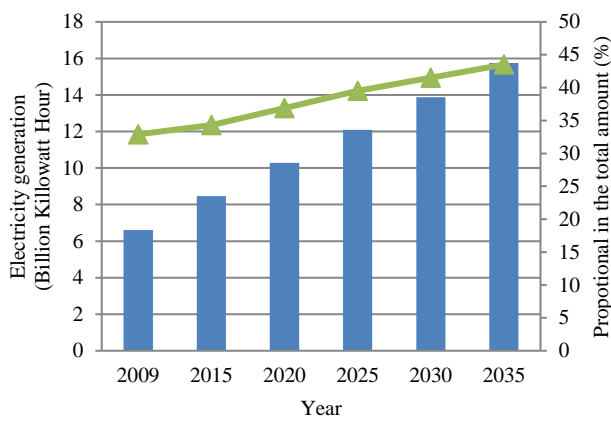


Figure 5. Electricity generation and future development of non-fossil system [21]

The characteristics of a microgrids is the ability of the system to be operated as a small scale power system with ability to generate, distribute and regulate the flow of electrical energy to local customer. Although, it has similar characteristic with backup power system which could temporarily provide power to local customers/loads when there is power outage from the national grid. However, microgrids have benefits and more flexibilities than backup power systems. Some of the benefits include making grid more resilient, counter climate change, adding economic growth, generating making more revenue, saving money, increasing reliability and improving local energy delivery.

Proper sizing of the renewable energy microgrid system depends on many factors. Some of the factors include the amount of renewable energy generation, the weather data, the price of diesel, the load demand and other components [25]. In addition, other issues with the renewable microgrid include economy, control and the reliability of the power supply [26].

4.1 Research efforts in optimum design of microgrids

This section reviews some of the recent researches in the area of optimum design of solar, wind and hybrid microgrids across the globe. In [27] the characteristics of lead acid battery as a storage system in the hybrid microgrid were considered, the system is installed for the

supply of electricity in the Dongfushan Island in China. An optimization model developed considered only the cost, fuel, environmental and operations costs of the systems. Non dominated sorting genetic algorithm (NSGA II) was used in minimizing cost of generation and minimized the battery life loss. Zhang [28] proposed Dividing the Rectangle (DIRECT) algorithm in the design of PV/Wind/diesel with battery storage system.

Wang [29] design a hybrid PV-wind generating system by modifying the particle swarm optimization; the algorithm developed simultaneously optimized cost and the reliability of the system. The system designed considered uncertainty in load, wind and solar radiation at different times. Standalone system consisting of solar, wind and battery storage system has been designed using particle swarm optimization in [30]. The system design was for the Northern Iran with a life span of 20-year. However, the system may not be optimum when considering a diesel generator and power from the renewable energy sources.

Another algorithm capable of design hybrid energy system includes simulated annealing in [23]. Simulated annealing is of the algorithm that has been used to design hybrid energy system. The algorithm optimized both system operation and unit cost of the system. Other factor that could factors such as uncertainty in the load and load which affect optimum operation were not given due attention. This may make the developed system not be optimum for isolated microgrid especially when uncertainties are incorporated.

Algorithm for the determination of unit sizing and cost analysis for wind, photovoltaic and their hybrid has been proposed in [31]. The algorithm demonstrated the possibility of meeting systems demand and the objective function with the minimum total annual cost of the system. However, the algorithm focused on the economic evaluation of the system without giving attention to the system technical parameters such as battery state of charge, energy balance and component rating etc. Besides, the reliability analysis of the microgrid was not considered; therefore, the developed model may not be the optimum for isolated load.

Procedure capable of maximizing system reliability and minimizing system cost of pv-wind hybrid system using constrained mixed-integer multi objective particle swarm optimization (CMIMOPSO) algorithm was developed in [32]. The inclusion of diesel generator in the design could makes the algorithm not to be optimum for isolated loads. This is because diesel generator may not ensure continuity of supply of electricity especially, when the renewable energy sources and the storage cannot supply the demand. Another algorithm capable of designing a microgrid system is time matching simulation algorithm [33]. However, it has been concluded that, the location of the microgrid may affects the optimum microgrid design [33]. Moreover, the system designed may not be optimum when the diesel generator is introduced in the design.

Recently in [34] model for the optimum design hybrid renewable energy microgrid is proposed, the model minimized system cost while the ratio of cost to reliability minimised. Other effort includes the optimal sizing of a pv/wind/diesel hybrid energy system that can supply a building in Malaysia. The optimal system developed has being confirmed with the result obtained from the HOMER software [35]. [36] Investigated the possibility of using

wind and solar in the northern part of Jordan. This has actually demonstrated the fact that, microgrid penetration is on the increase around the globe. Study in [37] has carried out an experimental investigation of using solar and wind for power generation in Algeria. The system designed was for freezing and cooling system in the area. The design considered gas emission and renewable energy as the environmental factors while Net Present cost (NPC) and Cost of Energy (COE) were the economic factors. In another development, [38] used multi objective optimization to minimize cost of production, customer outage and emission pollution of a microgrid. More details about the recent hybrid microgrid introduced in the last twelve years and their outcome can be found in [39], [40]. Recently authors in [41] have investigated the effects of battery storage and PV technologies on the optimum design of hybrid renewable energy microgrids; the findings have shown the sensitivity of optimum design to benefit-to-cost ration, payback periods of battery storage and rated powers of wind and solar energy conversion system.

4.2 Research efforts in reliability studies of microgrids

Reliability is defined as the probability that a system, product or service operates properly for a specific period of time under operating conditions without failures [34]. Irrespective of the system configuration, the reliability of the system is the most important factor for system planners. However, the success of any design could be attributed to the success of the system when it operates for a longer period.

The relationship between size, location and the reliability of wind turbine has been investigated in [42]. Similar study was carried out by adding storage in the model [43]. In [44]- [45], method of discrete wind speed frame analysis was proposed to analyse the reliability of microgrids. A more advance technique base on multi-state model was proposed in [46] to study the reliability of power system including wind generator. In addition, capacity limitations and transmission line forced outage rates were incorporated in the study [47]. In the same way, Reliability analysis of grid connected microgrids consisting of wind turbine were presented in [48]- [49]. Another investigation was reported on how the rated capacity, charging and discharging behaviour of storage system on the microgrid are related in [50].

Reliability analysis of solar energy microgrid systems in a standalone mode were considered in [51]- [52]. In [51] a multi stage model of a solar conversion model was developed while similar method for the reliability of solar energy microgrids system was proposed in [52]. Other studies carried out on microgrids reliable analysis development includes [53]- [54]. Hybrid renewable energy microgrids reliability analysis were carried out in [53]. A multi-state model for the reliability analysis of the WECS and SECS was proposed in [55], a multi-state technique at hierarchical level II was introduced in [54]. Revised capacity outage probability table was used in the reliability study of hybrid microgrid in [56].

Parallel operation of wind and solar energy sources improved the reliability of hybrid energy microgrids in [57]. Authors in [58] Considered the stochastic nature of

wind and solar energy using state-sampling taking priority loads into consideration; the results have shown that integration these energy sources increased the reliability of the system. A hybrid technique for the reliability evaluation hybrid renewable energy microgrid consisting wind, solar and battery storage system has been proposed in [57].

Furthermore, Monte Carlo simulation technique as well as effect of load and generation on the reliability of microgrid have been presented and analysed [59]- [60]. Loss of load expectation (LOLE) and loss of load factor (LOLF) are among the reliability indices in which their applications were demonstrated in [59]. A similar analysis was carried out in [61] in which solid oxide fuel cell (SOFC) was added to the microgrid. The relationship between cost and reliability analysis of hybrid PV and wind microgrid have been considered in [62]. A hybrid technique that combined deterministic and probabilistic technique to determine the reliability of hybrid microgrid is proposed and implemented in [63]. Detailed analysis on the effects of implementing PV, WT on the reliability of existing microgrid has been analysed [64]. The relationship between renewable sources of energy variability, periodicity, intermittency and typical distribution demand on the reliability of the microgrid was investigated in [65]. Complexity of storage and variability in the output power of renewable energy sources makes sequential Monte Carlo and minimal path as another viable method to obtain the reliability of grid connected microgrids [60]. A hybrid technique has been proposed to investigate the effects of weather and battery storage on the availability of hybrid renewable energy microgrid [66].

Additionally, minimum path method has been applied to investigate the effects of operation mode and load types on the reliability of renewable energy microgrids [67]. Also, it has been shown that the protection system and operating condition could affect the reliability of microgrid [68]. In [69] minimum path method has been applied to investigate the effects of operation mode and load types on the reliability of renewable energy microgrids. In the same way, the extent at which of the repair rate influenced the reliability of microgrid has been analysed [70]. Other efforts include the effects of the renewable energy resources on the reliability of microgrid [71]. Recently, in [72] the reliability of renewable energy microgrid considering the customers' interruptions cost was considered.

In the same vein, studies on microgrid reliability include the development of a load demand model which increased the degree to which microgrids satisfy load efficiently is carried out in [73]. Authors in [74] investigated the impacts of microgrids on distribution system using Failure Mode Effects Analysis (FMEA) technique which shows the ability of microgrid to reduce local load point interruptions and shorten the interruption duration. In addition, the concept of effective capacity is proposed in order to compare the reliability of conventional and renewable energy resources [75]. The analysis showed that either lower FOR or higher average power contributed to better generation reliability. In [76] capacity outage probability is used to calculate LOLE, EIR, REP and MCPP reliability indices for microgrid.

Most of the literatures on control of microgrid investigated either pv, wind on standalone or both with or without battery. Recent development in [77] proposed coordinated strategy for DC microgrid with variable generation and

4.3 Research efforts in control of microgrids

storage. The same authors [78] studies a comprehensive control strategy of a DC voltage control of a four terminal microgrid consisting of variable generation and multiple slack terminals. The system consists of wind, AC, grid, DC load and energy storage system. Investigation of DC voltage control strategy of a DC microgrid as function of different terminals was carried out [71]. Voltage droop power sharing is proposed among the slack terminals in order to achieved power smoothing during normal and grid operations of microgrids.

Some authors [79] have developed a control algorithm for both grids connected and standalone microgrid consisting PV and storage battery only. The algorithm demonstrated the capability of DC power flow between input and output terminal of the microgrid. Multi-loop algorithm capable of inverter control considering battery charge limit and state of charge for PV-storage microgrid has been devised [80]. The choice of control parameters for stability of pv-storage microgrid has been investigated by [81]. [82] Used advanced power control techniques to satisfy the load demand, state of battery, prevent blackout and extend the life of battery of a pv/wind microgrid. This was achieved by the development of active-reactive power control of the microgrid. Similarly another paper [83] considered the use of inverter for the control of standalone microgrid; the developed control strategy was able to cope with variations and disturbance happening in microgrid.

Possibility of splitting the control of a microgrid into top and local level controls has been introduced in [84]. Recently, the control PV/wind/diesel/diesel generator [85] active-reactive power and damp controls have been investigated. It can be seen that the control of microgrid could be either central or autonomous [86].

5 EXISTING MICROGRIDS AROUND THE GLOBE

This section reviews some of the existing microgrids in the literatures across the world.

Mesa del Sol mixed commercial-residential development in Albuquerque, New Mexico microgrid. The system comprised of 80 kW fuel cell, a 240 kW natural gas-powered generator, a lead-acid battery bank, hot and cold thermal storage, and an adsorption chiller.

Fort Carson microgrid in Colorado Springs USA consists of a 1 MW PV array and three diesel generators with a total power of 3 MW, and 5 electric vehicles (EVs) with V2G capability. Some of the problems faced during the implementation of the microgrid project and the demonstration were system ownership and communication related issues.

Santa Rita Jail is the site of one of the best existing microgrid demonstrations in the world today. The system has approximately 1.5 MW of PV, a 1.0 MW molten carbonate fuel cell, back-up diesel generators and 2 MW-4 MWh Lithium Iron battery. The system can function on grid connected or islanded.

The Sendai Microgrid Project, Japan contains two 350 kW natural gas fired generators, 50 kW of PV, and battery storage. The developed microgrid network is capable of supplying six varying levels of power quality supplied in different circuits.

Chile's first microgrid project was developed in the University of Chile in a remote Andes Mountains community of 150 residents. The proposed system consists of a 150 kW diesel generator, 22 kW tracking solar PV, a 3 kW wind turbine, a 170 kWh battery, and an energy

management system. The system is capable of online set points for generation while minimising operating cost taking renewable energy resources forecast, load, solar tracking and water consumption into consideration. These were achieved with help of energy management system.

Hartley Bay in British Columbia, Canada is a remote coastal village only accessible by air or water. The Gitga'at native community of 170 members operates a remote microgrid there, providing power. Hartley Bay relies on three diesel generators, two of 420 kW and one of 210 kW to provide electricity to the 62 residential and 20 commercial buildings.

In the same way the University of New York developed a microgrid that supplies electricity to 22 buildings and heat to 37 buildings across campus. The microgrid network consists of two 5.5 MW gas turbines and a 2.4 MW steam turbine. This has been a great step towards the commitment that the university made to the City of New York to decrease its greenhouse gas emissions by 30%.

Borrego Springs microgrid system has installed capacity 4 MW, with the main technologies consisting of two 1.8 MW diesel generators, a large 500 kW/1500 kWh battery at the substation, three 50 kWh batteries, six 4 kW/8 kWh home energy storage units, about 700 kW of rooftop solar PV, and 125 residential home area network systems.

The Fort Collins Microgrid in Colorado consists of solar PV, CHP, micro turbines, fuel cells, plug-in hybrid electric vehicles, thermal storage, load shedding, and demand side management. The microgrid has a total of 345 kW of solar PV, 700 kW of combined heat and power, 60 kW of micro turbines, and 5 kW of fuel cells. The system has additional diesel-based backup generators totalling 2,720 kW in capacity, which are mostly used on emergency situation.

Isle of Eigg microgrid project is termed as one of the most successful microgrids project globally. The system is highly successful in integrating multiple renewable of sources into an island-wide community. The system consists of 110 kW of hydro power generator, two small generators, 24 kW from four wind turbines and 32 kW of PV.

Illinois Institute of Technology, USA microgrid project is considered as another breakthrough in implementation of microgrid. The peak load of IIT's campus is around 10 MW. The on campus microgrid consists of two 4 MW combined cycle gas units and a small wind turbine. The University plans to add rooftop PV as well as a 500 kWh battery. Total renewable energy capacity will be about 9 MW. Once this is achieved, the campus will be able to operate as an island most of the time, without importing any power from the grid. The developed microgrid is able to eliminate least three power outages per year resulted in a series of teaching and research disruptions with an estimated cost of \$500,000 annually and a growing demand for energy.

The UCSD microgrid project supplies electricity, heating, and cooling for 450 hectare campus with a daily population of 45,000. It consists of two 13.5 MW gas turbines, one 3 MW steam turbine, and a 1.2 MW solar-cell installation that together supply 85% of campus electricity needs, 95% of its heating, and 95% of its cooling.

The island of Bornholm is a Danish island situated just south of Sweden that represents roughly 1% of Denmark's population and electricity load. The supply technologies in the Bornholm Island microgrid consists of 14 diesel generators (34 MW), 1 oil-fired steam turbine (25 MW), 1

steam turbine running off a mixture of oil, coal, wood chips (37 MW), 35 wind turbines (29 MW), and 2 biogas turbines (2 MW). The site is considered as a field test for European commission to commission and test different microgrid technologies.

Microgrid set up with objective to test centralized and decentralized control strategies for islanding is Kythnos Island. The Island is located in the Aegean Sea and the project was financed fully by the European FP 5 Microgrids program. The system comprised of 10 kW of PV at two locations, 53 kWh battery bank, and a 5 kW diesel generator.

The microgrid project in Mannheim-Wallstadt, Germany, was set up for further microgrid operations and innovations to be tested and operated in city. The system has 4.7 kW fuel cell, A 3.8 kW solar PV system, A 1.2 kW flywheel storage unit and Two CHP units rated at 9 kW and 5.5 kW (electrical).

Hangzhou Dianzi University microgrid is Located on the University campus. The microgrid system comprised of PV (120kW), a small diesel generator (120kW) and fuel cells. The PV system consists of 728 solar panels, occupying an area of 946m². Thus, the microgrid is regarded as the first microgrid to achieved 50% PV system penetration globally. More details on the existing microgrids can be found in Table 2.

Critical look at the preceding section shows that regional difference exists in terms of state of art in microgrid. North American countries focused mostly on the reliability of power supply with help of microgrid. On the other hand, European and Asian microgrids are mostly on the utilisation of renewable energy resources. In addition, Asian microgrids are mostly centrally controlled microgrids except China that uses agent based control. However, European microgrids are either centrally controlled or agent based.

6. FUTURE WORKS AND RESEARCH AREAS

Microgrid is still one of the futures of power industry; therefore, there are many aspects which are considered as research areas independently. Many areas constituted are hybridized in order to achieve the concept in reality. Some of these concepts include network operation and control, system protection, power electronics, renewable energy, distributed generation, economics issues and communication issues. This is a clear indication that the microgrid will continue to grow in the future. The forgoing review has indicated that while considerable attention has been given in some areas; others are left behind the scheme of things. Table 3 shows some of the future research areas that must be dealt with in order to achieve a realistic penetration and implementation of microgrid.

2	Protection of microgrids against fault current and design of new protection scheme	Design of new protection scheme that will respond to the needs of microgrid operation mode and components.
3	Incorporation of high speed communication between components, operators, equipment etc	ICT is needed for smart-metering, and network controls applied to microgrids. Example wireless communication, power line communications, bus signaling etc. There is still difficulty on how to implements some of the proposed models.
4	Policy and Standards	Standard procedure and policies are needed in order to achieve higher penetration of microgrid across the globe.
5	Optimization	Online and offline optimization systems are required to enhance energy price, power losses and economics
6	AC Microgrids	Conventional island systems to support AC loads are needed in areas such as rural, remote and islands.
7	DC Microgrids	Future microgrids and low voltage distributions are expected to be DC due to the new generators storage photovoltaic, superconductors, LEDs electronic equipment and laptops to mention just a few.
8	Modeling	There is need for new modeling techniques due to complexity of the future microgrids. This is as a result of emergence of new generators, energy storage systems, loads, power electronic interfaces, distribution network's needs, frequency ranges and time.
9	Energy storage	New designs of storage are expected with high energy and power densities in order to coordinate inertia less microgrids.

Table 3: Future research areas for microgrids

S/ No	Concept	Remark
1	Microgrids energy management	Implementations or simulations on some of the proposed models should be carried out

6. CONCLUSION

Renewable energy microgrid penetration is on the increase due to environmental concern. Unfortunately, the development introduces various opportunity and challenges. This paper has presented a comprehensive review of renewable energy microgrids across the globe. The future energy demands and the renewable energy potential of some selected countries across the globe were presented. Three areas of interest to researchers, educators

and developers of microgrid are considered. The review comprised of present and future penetrations and market potentials of wind and solar energy resources across the globe, optimum design, reliability, and control studies of wind and solar energy microgrids. Regional and global status of microgrid has been investigated; also existing microgrid across the globe are critically reviewed. The paper has concluded that the utilisation of microgrids depends on the reason of application. Similarly, variations are observed in many areas such as method of control, application, reliability and utilisation of renewable energy power.

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