Wind-hybrid Power Generation Systems Using Renewable Energy Sources-A Review

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Abstract- The depleting conventional energy sources and world population growth at a rapid rate predict the severe global energy crisis in near future. As an alternative, the world has started considering renewable energy sources as they are ubiquitous, environmentally affable and freely available. One of the fastest expanding renewable energy sources is wind energy. The stand-alone wind energy systems may not be practical for fulfilling the electric load demands at the places having unsteady wind speeds with high unpredictability. At those places wind-hybrid energy systems, comprising of the wind energy system combined with one or more other renewable energy systems, can be of great significance in overcoming the weaknesses of stand-alone wind energy systems. This paper mainly focuses on wind energy and wind-hybrid power generation systems used to electrify various locations. This paper also describes the details of renewable energy sources and wind energy softwares, worldwide wind energy potential and use, demonstrations of wind-hybrid power generation systems and some examples of their feasibility studies and implementations at different sites all over the world.

Keywords: RE sources; Wind Energy; Hybrid systems; Wind-hybrid systems; Energy Storage.

1. Introduction

Electrical Power supply has become one of the most vibrant requirements of the current time. As per estimation of International Energy Agency (IEA) and The World Bank, the installed capacity of the energy sources would have to be doubled over the coming 40 years in order to fulfil the predicted energy demands of the developing world. [1] For meeting the electricity demand, conventional power generation systems have been deployed for a long time which include thermal power generation, hydroelectric power generation and some distributed utilities (i.e. combustion and micro turbines etc.).[2-3] The constraints like fast depleting trend of conventional fuels reserves, inadequate water reserves, unpredictable prices of the conventional fuels, large capital and maintenance costs of diesel generators and the escalated threat of global warming resulting from the usage of fossil fuels have brought the enhanced concern about the option of conventional energy sources. [4-5] In the developing countries, 1.3 billion of the people living in remote areas have been deprived of utilizing electricity from the grid and 80 % of them are conventionally using wood to accomplish their energy requirements which has resulted in increased deforestation around the world. [6-7] One solution to these potential concerns is to utilize the sustainable energy sources as alternative energy (AE) sources that comprise of the natural renewable sources (i.e. wind, PV, microhydro, biomass, FC, Tidal etc.). Alternative energy (AE) sources are immense, non-depletable, non-polluting and available in free. The core AE and conventional energy sources and their features have been listed in "Table 1". The deployment of the energy systems mentioned in Table 1 is valued by their dignified benefits, which include: lessened emissions of carbon, better reliability of power and less operational and maintenance costs. During the past fifty years, much of the research work has been accomplished in the area of AE sources concerning their control, efficiency, modeling and simulation techniques, feasibility and experimental work. [8-10] Electrification of the electricity deprived remote and isolated areas, with no grid supply, has attained a great degree of importance for the development of their living standards. To realize this purpose, a number of off-grid power generation systems based on the AE sources have been proposed and designed. [20]

The most common downside of AE sources is their intermittent nature which accounts for their inability to harness the power for substantial duration of time over the year. This is because the AE sources are governed by the natural phenomenons which are inevitably influenced by a number of mutable factors. [5, 11-12]

The hybridization process minimizes the energy storage needs and makes the power generation operation reliable and cost effective. This also diminishes the deficiency of harnessed power when one source doesn't work due to absence of natural phenomenon driving that source (i.e. during the night time, wind will work to produce electricity when PV doesn't work.). [16] In order to utilizing the hybrid systems more efficiently, the constituent systems which formulate the hybrid system require to be sized and combined properly which will lead to the system with improved control and dispatch and enhanced performance. [17-19]

Rest of the paper has been arranged as follows: Section 2 discusses the importance, worldwide potential and the use of wind energy. Section 3 discusses the hybrid power generation systems that are based on the wind energy source.

Table 1. Core AE and conventional energy sources and their features. [13]

	Main Energy Sources	Capacity Factor (%)	Efficiency (%)	Cost ($/kWh)	Intermittency
Alternative Sources	Solar/Photovoltaic (PV)	20-25	12-22	$0.18-0.27	High
	Biomass	80-85	35-40	$0.10-0.15	Very Low
	Wind	25-35	40-50	$0.08-0.20	Very High
	MicroHydro	51-55	85-90	$0.09-0.14	Very Low
	Fuel Cells	90-95	40-60	$0.16-0.24	Low
	Ocean(tides and waves)	30-50	85-90	$0.10-0.30	Low
	Geothermal	85-95	15-20	$0.09-0.21	Very Low
Convention Sources	Oil	07-10	32-42	$0.23-0.41	N/A
	Gas	45-55	30-40	$0.17-0.24	N/A
	Coal	50-65	35-45	$0.08-0.15	N/A
	IGCC	55-65	30-45	$0.12-0.19	N/A
	Gas Combined Cycle	55-65	35-50	$0.08-0.12	N/A

The power generation systems based on AE sources turn out to be expensive and oversized when used independently for meeting a load demand. [14] Considering the valuable benefits of these systems, system designers have started considering their integrated operation. This operation comprises of two or more than two of these AE sources complemented with storage requirements to make different hybrid systems for the constant power generation. [1, 15] "Table 2" gives different energy storing methods.

Working and construction of these hybrid systems, softwares dealing with their analysis and some examples of each of the hybrid systems, referenced from the literature have been presented in this section. Worldwide potential and implementation of each renewable energy source (including solar, microhydro, fuel cells and biomass) has also been discussed in this section. Special focus has been paid to describe the renewable sources based energy situation in Pakistan. Section 4, at the end, concludes this study.

Table 2. Methods for Energy storage.

Batteries: Energy is stored in rechargeable, secondary batteries.	**Super capacitors:** Energy is stored electrostatically by charging.
Fly wheels: Energy is stored as rotational energy by rotating a flywheel.	**Compressed air:** Energy is stored in an underground reservoir by compressing the air.
Pumped hydro: Energy is stored as potential energy by pumping water from lower source to a higher reservoir.	**Hydrogen Storage:** Storing energy in the form of hydrogen gas which is produced by electrolysis of water.
Molten Salts: Energy is stored by melting solid salt through heat.	**Thermal means:** Energy is stored in the form of heat.
Magnetic Storage: Energy is stored in magnetic field of superconducting magnetic materials.	**Chemical fuels:** Energy is stored in form of chemical energy as fuels like diesel, petrol, gas, biodiesel etc.

2. Wind Energy

Wind mills or wind turbines extract wind energy from air flows to generate electricity. Wind energy represents an alternative energy source to conventional fuels. Wind is abundant, broadly distributed, renewable, clean, emission less source of energy and requires less land. [20] Capacity factor of the wind is estimated to be in the range of 35-44 percent. [21] One of the fastest expanding sources of alternative energy is the wind energy. Global Wind Energy Council (GWEC) has reported 44% growth in the annual market of wind power generation, mounting to 50GW for the first time in the year 2014. [22] Fig. 1 shows the share of different countries in global wind power production.

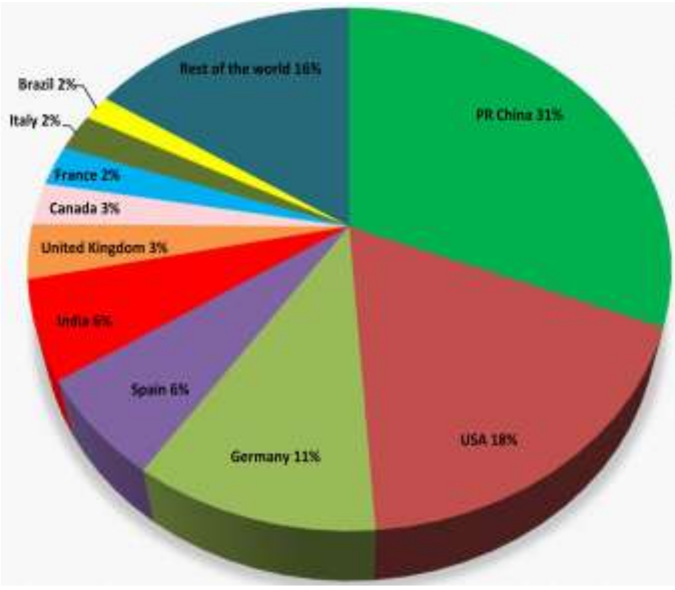

Fig. 1. Share of Countries in Wind Power Production.

Until 1990, U.S led the world in installed capacity of the wind. In 1997, Germany surpassed the U.S. in installed capacity. Between the years 2000 and 2006, wind power generation capacity of the world rapidly increased, doubling about every three years, and became more than quadrupled. Global Wind Energy Council (GWEC) statistics depict that the total installed wind capacity was 74 GW and 94 GW in 2006 and 2007 respectively. The annual wind market sustained to rise at predicted rate of 37% in 2007, following 32% growth in 2006. China has been swiftly growing its wind installations and became the world leader thereby crossing the U.S. in 2010. Around the world, more than eighty three countries were utilizing wind power on commercial scale until the end of 2011. [23-24]. As of 2012, there were more than two hundred thousand wind turbines working worldwide, with a total nameplate capacity of 283GW. [25]

"Fig. 2" shows the statics of global cumulative installed wind capacity. Wind power capacity has been expanding rapidly and reached to 369.553 GW to fulfill 4% of the world electricity demand till the end of 2014. [26-27] Cumulative wind capacity growth rate was 12.3% and 14.9% in the years 2013 and 2014, respectively. The forecasted wind capacities for the years 2015 and 2016 are 416.4 GW and 472.1 GW, respectively. It is estimated that the wind power penetration in the market will reach 8% by the year 2018. [28-29]

Pakistan is facing the worst energy crises and it has become necessary to incorporate the renewable energy sources in the existing energy structure. This needs to exploit the cheap renewable energy sources, like wind, through the development of essential knowledge about these sources. Pakistan is blessed with high wind speeds near the main hubs. Wind speed in the Capital city, Islamabad varies from 6.2 ms-1 to 7.5 ms-1. Wind speed in Karachi city, which is the economic hub of Pakistan, varies from 6.2 ms-1 and 6.9 ms-1. Other than Karachi and Islamabad, there are other wind energy-rich zones in Pakistan. The Jhimpir Wind Power Plant is the first ever wind power plant in Pakistan. It was completed in 2012 and it has generation capacity of 50 MW.

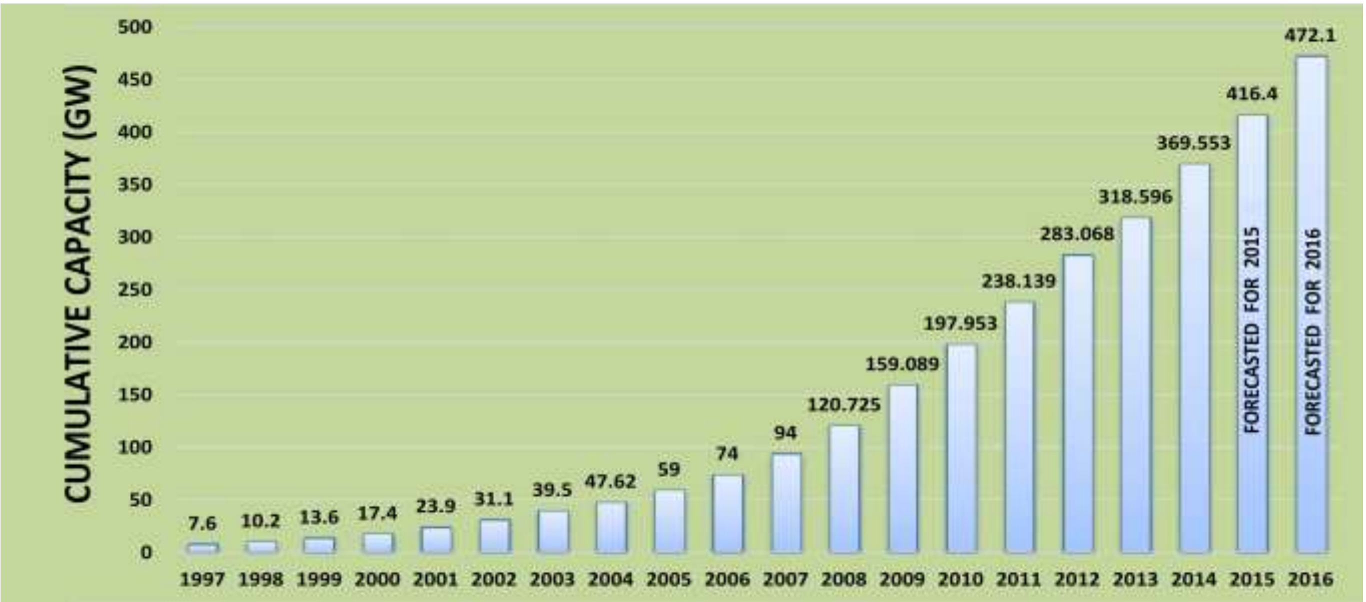

Fig. 2. Improvement in Global cumulative installed wind capacity. [26].

Eighty five micro wind turbines have been installed in Mirpur Sakro to power 356 homes. Forty wind turbines have been installed in Kund Malir to power 111 homes. More wind turbines still have to be installed by the Alternative Energy Development Board (AEDB) of Pakistan and 18,000 acres of land has been acquired for this purpose. [30] "Fig. 3" shows the statics of cumulative installed wind capacity in Pakistan.

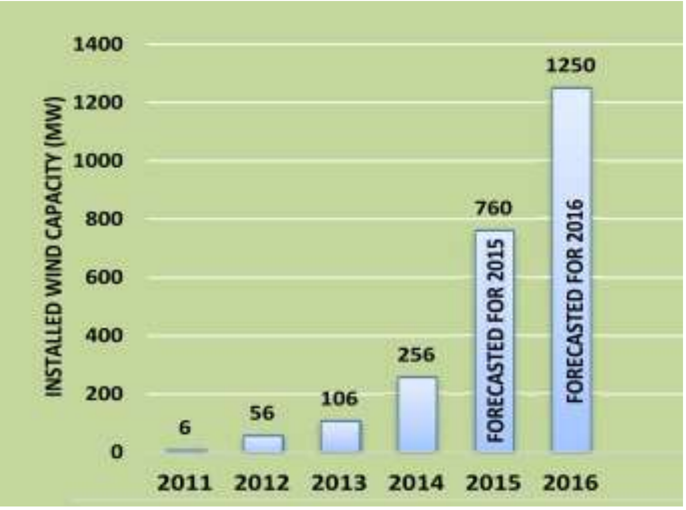

Fig. 3. Improvement in Pakistan's installed wind capacity. [31]

In 2011, installed wind capacity in Pakistan was only 6 MW and it raised to 56 MW in 2012. The next year, 2013, was good for wind power and its installed capacity reached to 106 MW. 2014 was even good year in this regard and installed wind capacity reached to 256 MW at the end of the year. Pakistan intends to add 0.5 GW of wind power capacity by the year 2015 and 1-1.5 GW by the end of 2017.

3. Wind-Hybrid Power Generation Systems

Power availability on continuous basis is restricted because of the intermittent nature of the alternative energy sources as they depend on the natural phenomenons like wind, sun etc. To make sure the power availability on continuous basis, hybridization/integrated-operation of these sources is considered. This hybridization, equipped with some storage means, achieves the load demand reliably and compensates for the discontinuity which is faced in stand-alone operation. [32] These systems are commonly considered for rural electrification, where the grid supply is absent. [33] Three types of Buses can be used to hybridize the power generation systems which include AC buses, DC Buses and Hybrid (or AC-DC) Buses. [34] PG sources which furnish DC output are hybridized using DC buses. [35] PG sources furnishing AC outputs are hybridized using AC buses. [36] Hybrid (AC-DC) bus comprises of a DC-bus and an AC-bus and infers a master inverter in-between. PG sources furnishing AC and DC outputs are hybridized using hybrid buses. [37]

Power generated from the wind generator is uncertain and variable on account of the intermittency of the wind. To make the power generation process reliable, wind generation is combined with some other renewable energy source to make a wind-hybrid power generation system. Thus, combined operation of the two sources, equipped with some suitable backup storage system, makes the power generation process efficient, robust and reliable. The backup storage system makes up for the fluctuations arising from the uncertainty associated with the hybrid system operation. [38]

"Fig. 4" shows the general construction scheme of a wind-hybrid power generation system.

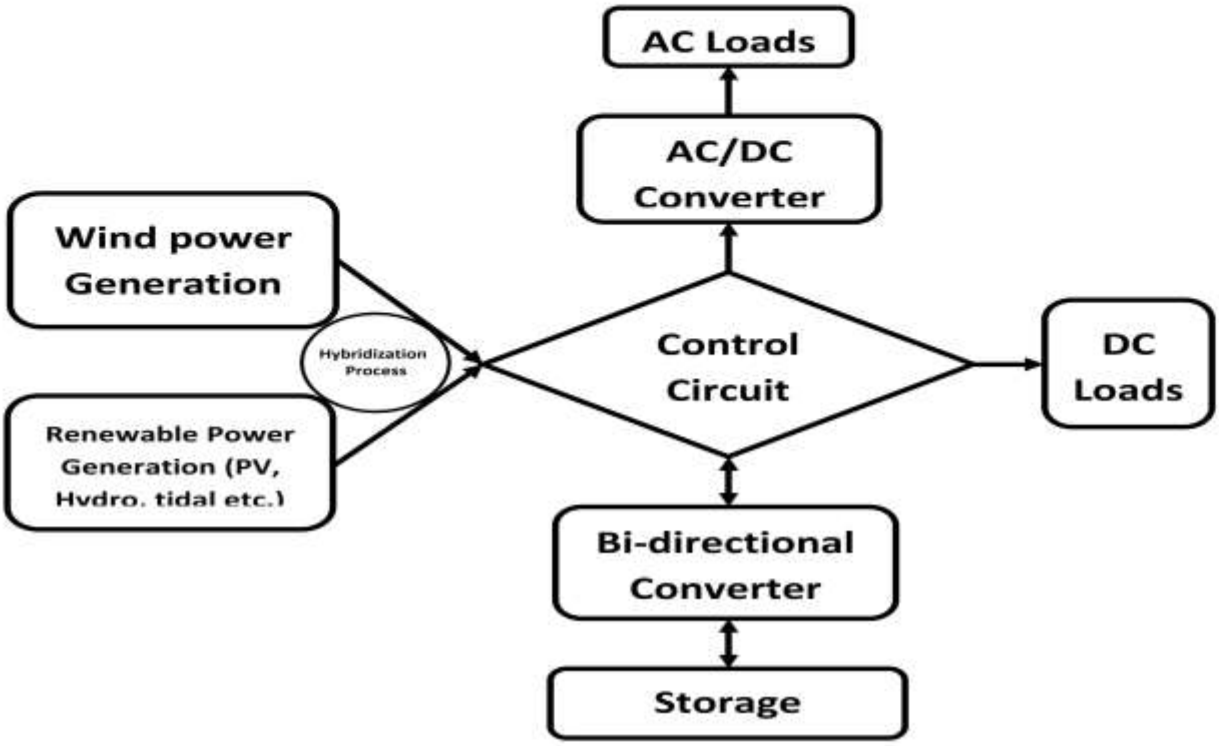

Fig. 2. General construction of Wind-Hybrid Power systems

Table 3. Main off grid Wind-hybrid PG systems and their pros & cons.

Hybrid System	Pros	Cons
Wind-MicroHydro	i. Enhanced reliability as compared with microhydro-only or wind-only operation. ii. Free of cost fuel. iii. O & M cots are low. iv. Pollution free operation. v. Low energy cost.	i. Backup storage needs due to the high uncertainty in wind availability. ii. High intermittency of the system. iii. Noisy operation due to wind turbine presence. iv. Affects the visual grace of the site. v. Suitable only for windy areas.
Wind-PV	i. Immense fuel without cost. ii. Environment friendly sources. iii. Low cost of energy. iv. Low O&M costs. v. Enhanced reliability as compared with PV-only or Wind-only.	i. Very high intermittency. ii. Large backup needs. iii. High initial capital investments. iv. Suitable only for windy and sunny areas. v. Noisy operation of wind turbines. vi. Reduced visual grace of the site.
Wind-Tidal	i. Fuel is freely available. ii. Low cost of energy. iii. Reduced storage needs. iv. No danger of pollution. v. Improved output and robust operation.	i. High intermittency. ii. High transmission costs as the sites are available far from the population. iii. High capital and maintenance costs. iv. Tidal generation is immature technology.
Wind-Fuel cells	i. Wind is free available source. ii. Emissions free and environment friendly operation. iii. Improved output- fuel cells have high capacity factor. iv. Low O&M costs.	i. Huge safety concerns because of the Hydrogen storage for fuel cells. ii. Wind has high intermittency. iii. Slightly high cost of energy. iv. Requires high initial capital investment. v. Suitable only for windy areas.
Wind-Biomass	i. Biomass is of no use and has negative cost. Also, wind is freely available source. ii. Low cost of energy. iii. Enhanced reliability in meeting the load.	i. Burning of biomass causes pollution. ii. High intermittency of the sources. iii. Large backup needs. iv. Large space requirements.

Table 3. Details of Simulation Softwares for Wind based PG systems.

Simulation Software	Developer	Description	Reference
HOMER	NREL	HOMER is the most renowned simulation software which simulates and sizes the hybrid power generation systems comprising of AE sources on the basis of their Net Present Costs (NPCs).	[42]
WindSim	Vector AS	WindSim uses CFD analysis for the optimization of wind turbine employment in offshore and onshore wind farms.	[43]
HYBRID2	NREL	HYBRID2 is an efficient simulation software which assesses the long performance of hybrid AE systems by performing the economic analysis.	[44]
WindPRO	EMD International	WindPRO is used worldwide for the designing and planning of wind farm projects.	[45]
WindFarmer	DNV GL	WindFarmer is an advanced software tool for optimization, designing, and analyzing a wind farm. It helps to rapidly make a complete layout of wind farm and the optimized model for the details of the considered site.	[46]
RAPSim	Alpen-Adria-Universität Klagenfurt	RAPSim simulates the hybrid systems which may consist of PV, wind and diesel generators (DGs).	[47]
Windographer	AWS Truepower	Windographer is the leading software in industry for analyzing wind resource data measured by SODAR, met tower or LIDAR. It automatically determines the wind data structure by quickly importing the data from almost any format.	[48]
TRANSYS	University of Wisconsin	TRANSYS simulates the renewable energy systems including wind, solar thermal, PV and fuel cells. It does not optimize the simulated systems.	[49]

Main off-grid Wind-hybrid PG systems using alternative energy sources and their pros & cons have been listed in "Table 3."

The optimized design and operation of the hybrid power generation systems has appeared as a hot subject. The optimized design and operation involves optimal sizing, optimal location and optimal configuration of the hybrid systems to meet the specific area load demand at the lowest expenditures. [39] Cost analysis of the power generation systems consists of various criteria which may include: Cost of energy (COE), Net present Cost (NPC), Life cycle cost (LCC), initial capital cost (ICC) etc. [40-41] Softwares developed for the analysis of wind based power generation systems have been described in "Table 4."

The following section deals with the concise study of main wind-hybrid power generation systems which have been listed in Table 3. The section has been designed to debate, particularly, on the importance and global generation potential of renewable energy sources as well as wind-hybrid systems based on these renewable energy sources. Each type of the wind-hybrid system has been discussed with some examples from the literature.

3.1. Wind-Microhydro Hybrid System

Since ancient times, hydroelectric power has been an important component of energy producing sector around the world. At present, the hydroelectric power fulfils 19% power needs of the world. [50] Hydroelectric power utilizes water resources which are superior to other energy resources, such as thermal and nuclear energy resources, in terms of cost and sustainability. Moreover, these water resources along with power generation can be used for irrigation purposes. [51] Generally, the small hydro-power system generating 5 to 100 KW is categorized as microhydro (MH) power system. [52] Through hybridization, microhydro power plants with small storage can be useful to diminish the variations occurring in the stand alone operation of small wind power systems. [53] As of 2008, 28% growth of small hydro deployments were witnessed as compared with the year 2005. China leaded the world in microhydro installations with 70% contribution (65 GW). [54] As of 2013, installed microhydro power around the globe was projected to 75 GW whereas the total world potential of microhydro power was estimated to be approximately 173 GW and China was producing 160 TWh per annum from small hydro power installations. Above 50% of the world's microhydro potential was reported in Asia. [55-58] Combined operation of microhydro generator and wind generator makes the microhydro-wind hybrid system. In order to fulfil the load requirements on continuous basis, and because of the intermittent nature of stand-alone wind system, it is hybridized with the suitable microhydro generation system assisted with the storage system. [59-60]

Around the globe, microhydro-wind hybrid systems have been designed and deployed for the accomplishment of different purposes. Haque et al. [61] reported HOMER based sizing, design and analysis of MH/wind hybrid system that optimally fulfilled the typical domestic type load requirements in St. John's, USA. Sen et al. [62] reported the optimized electrification of remotely located area in India through a well sized MH/wind hybrid system. Ashok et al. [63] presented a well sized MH/wind hybrid power generation system as the optimal solution for the electrification of a remotely located village area in India. Sadiqi et al. [64] proposed a MH/wind hybrid system for the optimal electrification of a typical domestic load in Bamiyan Province, Afghanistan. Atiqur Rahman et al. [65] reported a well-designed MH/wind hybrid system as an optimal solution for fulfilling the load demand of a remote area in Bangladesh. "Table 5" illustrates the reported examples of MH/wind hybrid systems in detail.

3.2. Wind-PV Hybrid System

Sun is an immense source of free energy that can be harnessed directly or indirectly by some means and commonly known as solar energy. Direct utilization techniques are known as passive energy techniques and they include no conversion of sun radiations to other forms of energy while the indirect utilization techniques are referred to as active energy techniques and they include the conversion of solar radiations into other forms. PV installation and solar-thermal systems are the most popular active energy techniques used for solar energy utilization. [66-67] Most people around the world live in the regions with the daily solar radiations levels of 3.5 to 7.0 kWh/m2. World Energy Council has estimated the annual global potential of solar energy to be minimum 1,575 EJ and maximum 49,837 EJ. [68] US spaceships utilized solar energy in 1950s. This was the first use of solar radiations for power production. [69] Solar energy gained worldwide popularity in 2000s and last decade has been tremendous for its increased implementation. In 2010, solar production contributed 40 GW to the world energy supply. [70] IEA predicts that the solar energy contribution would mount to 11% of the world energy demand by 2050. [71-72]

Combined operation of wind generator and PV system makes a PV-wind hybrid system. [73] When working alone, either of the source may fail to meet the load demand because of the variations in solar radiation and fluctuations in the wind flows. [74] Hybridization makes these sources reliable in meeting the load demand and diminishes the possibility of power shortage thereby eliminating the load dependency on either of the single intermittent source. [75] Power Shortage from one source is compensated by the other and the system is made more reliable by aiding with some backup system like battery bank and diesel generator. For instance: Power deficiency from PV system at night might be fulfilled by wind generator and battery backup system. [76]

According to NASA, Pakistan lies in the second highest solar radiations region where the annual solar radiations fall is almost 1800-2200 KWh/m2. [77] At present, more than 800 companies are working in Pakistan concerning the solar installations. First solar power grid of 365 KW was installed in capital city Islamabad in 2012. [78] Government of Pakistan aims to invest for the growth of solar power generation and solar power project of 1000 MW has been started in Bahawalpur City.

Around the globe, wind/PV hybrid systems have been designed and deployed for the accomplishment of different purposes. Nurunnabi et al. [79] reported a well sized PV/wind hybrid power generation system for the purpose of optimally meeting the load demand of a rural area in Bangladesh. Niazi et al. [80] presented a well sized PV/wind hybrid power generation system for meeting the load demand of a typical house located in Balochistan, Pakistan. Guo et al. [81] designed and recommended a PV/wind hybrid system for Electrical Load of Hangzhou Dianzi University Qing Shan Hu Campus, China. Maatallah et al. [82] suggested a PV/wind hybrid system for fulfilling household and water pumping load of a rural area located in Bizerte, Tunisia. Baek et al. [83] presented a well sized PV/wind hybrid system and analyzed it for optimal electrification of a remote area load in Yeongjong Island, South Korea. "Table" 6 illustrates the reported examples of wind/PV hybrid systems in detail.

Table 5. Details of some Wind/MH hybrid systems reported in literature.

Specifications	Location	Load Type & Main Outcomes		Source
Wind Turbine = 30kW MH-generator = 30kW Backup system: Battery bank, 40 pieces (Model: 6CS25P)	Remote rural village, Indian.	Load Type	Rural community primary electric load-1 with average of 222 kWh/day and 51.2 kW peak. Primary electric load-2 with average of 212 kWh/day and 39.4 kW peak. Deferred load with average of 58.6 kWh/day and 68.6 kW peak.	[62]
		Outcomes	i- Wind/MH hybrid system was designed and analyzed for the remote rural area. ii- For optimized operation, PV of 30 kW was incorporated with the hybrid system. iii- COE and NPC of the system were $0.420/kWh and $673,147 respectively.	
Wind turbine = 2 kW MH- generator = 1 MW No backup system was specified.	St. John's, USA.	Load Type	Household load with average demand of 50 KWh/day and 11 kW peak.	[61]
		Outcomes	i- Wind/MH hybrid system was optimized for the household load. ii- Microhydro and wind contributions were 43% and 30% respectively. iii- For optimized operation, 7% PV penetration was incorporated with hybrid system. iv- COE and NPC of the system were 0.162 $/kWh and $34314, respectively.	
Wind turbine = 15 kW MH-generator = 5 kW Backup system= Bank of 32 batteries (each of 6V, 360 Ah)	Remote village area, India.	Load Type	Domestic load of the remote village with 120 families.	[63]
		Outcomes	i- Wind/MH hybrid system was sized, designed and analyzed to optimally meet the village area load. ii- Microhydro and wind contributions were 78% and 22% respectively. iii- COE of hybrid system was 7.09 INR/kWh.	
Wind turbine = 5 kW MH-generator = 5.15 kW Backup system = Bank of 10 batteries (Model: H800)	Remote area, Bangladesh.	Load Type	Household load with 21 kW peak.	[65]
		Outcomes	i- Wind/MH hybrid system was sized for a remote area in Bangladesh and analyzed for optimum operation conditions. ii- COE of hybrid system was 0.188 $/kWh. iii- NPC and initial capital costs of the system were $145917 & $46702 respectively.	
Wind turbine = 50 kW MH-generator = 10 kW Backup system= Bank of 180 batteries (Model: L16P)	Bamiyan Province, Afghanistan.	Load Type	Domestic load of the village, 430 houses with load of 670 kWh/day and 60 kW peak.	[64]
		Outcomes	i- Wind/MH hybrid system was sized, designed and analyzed to optimally meet the village area load. ii- COE of hybrid system was 0.176 $/kWh. iii- NPC and initial capital costs of system were 553787$ and 388147$, respectively.	

Table 6. Details of some Wind/PV hybrid systems reported in literature.

Specifications	Location		Load Type & Main Outcomes	Source
1000 KW PV system, 300 KW wind turbine Typical VBR backup (6v, 144000Ah),	Hangzhou Dianzi University, China.	Load Type	Electrical Load of Hangzhou Dianzi University Qing Shan Hu Campus with daily load demand of 32877KWh.	[81]
		Outcomes	i- Wind/PV hybrid system was designed and analyzed to optimally fulfil the specified load demand of the university. ii- COE of hybrid system was 0.89 ¥/KWh. iii- NPC and initial capital cost of the hybrid system were found to be 34,138,636¥ and 9,880,000 ¥ respectively.	
300 KW PV system, 100 KW wind turbine (3 units) Bank of 40 batteries (each of 40KWh)	A rural area, Bangladesh.	Load Type	Rural area with daily average load demand of 654.73 KWh and daily peak load of 101.32 KW.	[79]
		Outcomes	i- PV/wind hybrid system was feasible option for meeting the demand of remote load. ii- COE of the hybrid system was 0.391 $/kWh. iii- NPC and initial capital cost for system were $1210000 and $11700000, respectively.	
1 kW PV modules, 1 kW wind turbine, No backup system was specified.	Balochistan, Pakistan.	Load Type	Typical house with daily average electrical load of 13 KWh and peak load of 2.9 KW.	[80]
		Outcomes	i- Hybrid system comprised of 16% and 52% contribution from PV and wind respectively. ii- 32% of the demand was purchased from grid. iii- COE and NPC of the hybrid system were 0.087 $/kWh and $15872, respectively.	
0.1 kW PV modules, 3.2 kW wind turbine, Bank of 24 batteries, (each of 2V, 265Ah).	Bizerte, Tunisia.	Load Type	A typical household daily average load demand of 13 KWh and peak load demand of 3 KW. A typical water pumping load for irrigation with daily average load demand of 21 KWh and peak load demand of 3 KW.	[82]
		Outcomes	i- Hybrid system was designed and analyzed for meeting the specified load demands. ii- Diesel generator of appropriate capacity was incorporated in hybrid system. iii- COE and NPC of the hybrid system were 0.383 $/kWh and $5784, respectively.	
357 kW PV system, 10 kW wind turbine (11 units), Battery bank of 825 batteries (each of 6 V, 1.15 Ah).	Yeongjong Island, South Korea.	Load Type	Remote area load: average load of 297597 KWh/year.	[83]
		Outcomes	i- Hybrid system comprised of 88% and 12% contribution from PV and wind respectively. ii- COE of the hybrid system was 0.545 $/kWh. iii- NPC and initial capital cost of the system were $3506509 and $1861625 respectively.	

3.3 Wind-Biomass Hybrid System

Biomass is composed of the organic matter resulting from living organisms and commonly refers to the plant based sources. Wood is considered the most prime constituent among the biomass energy sources. Other constituents may include tree stumps, dead tree branches, wood chips, crops residue, rice husk, wheat straws, bamboo, sugarcane and even municipal solid waste. [84] Biomass can be utilized as a potential energy source either directly by combustion to generate heat or indirectly by conversion into different biofuels. Most common methods for achieving the biomass conversion into biofuels are roughly categorized into chemical, thermal and biochemical methods. [85-86] Energy generation from biomass has been categorized as the promising source in the near future. The estimated world biomass production potential is 146 billion tons per annum. [87] To exalt the importance of biomass use, researchers have estimated that the world wide biomass potential could provide 1.4 times the estimated annual 150000 Terawatt hours needed to meet the present world energy consumption. Globally, about 1x10^11 tons of biomass annually generate roughly 25 Terawatts. [88] The implementation of biomass energy generation projects has been a sluggish but stable course. In the last decade, between the years 2002 and 2012, the generation of these projects has increased by 14%. [89] In industrialized countries, biomass contributes merely 3% of the primary energy consumption. In the developing countries, biomass generation accounts for 35% of the primary energy consumption and is responsible for the 14% of the world total primary energy consumption. [87] The biomass energy generation potential in future will greatly rely on the availability of land devoted to the biomass energy generation projects. Presently, only 0.19% (25 million hectares) of the entire world's land is devoted to the biomass energy generation projects. [90]

Pakistan has huge potential for power generation from biomass. Every year, thousands of tons of biomass available in the form of sugar cane trash, cotton sticks, dairy waste and municipal waste can be utilized for power generation. Pakistan could produce 48781 Gigawatt hours and 50993 Gigawatt hours from the available biomass potential in the years 2010 and 2011 respectively that could contribute 65% to the total power consumption in the country. [91]

Combined operation of the biomass generation and wind generation makes wind-biomass hybrid system. Wind generator is driven by the wind to directly produce electricity. The gasification of biomass gives biogas which is then utilized to run a turbine in power conversion unit (PCU) for electricity production. [92] Wind production directly depends on availability of wind flows and this makes it less reliable in meeting the load demand as the wind flows keep changing with massive amount of fluctuations. [93] To enhance the reliability, biomass generation is incorporated with the wind power generation. For the compensation of the mismatch between the predicted wind generation and the real output, battery banks and diesel generators are included for backup supply. [92, 94]

Table 7. Details of some Wind/Biomass hybrid systems reported in literature.

Specifications	Location	Load Type & Main Outcomes		Source
10 kW wind turbine (10 units), 500 kW Biogas generator, Bank of 600 batteries (each of 6 V,1156 Ah)	Distant village in Kwazulu Natal, South Africa.	Load Type	Distant village with total load demand of 353.49 KWh/month.	[97]
		Outcomes	i- Wind/biomass hybrid system was designed and analyzed to meet load demand of the distant village. ii- NPC of the wind/biomass hybrid system was $2912532 while COE of the system was 0.521$/KWh. iii- System comprised of 11% and 89% contribution from wind and biomass units respectively.	
30 kW wind turbine, 60 kW biomass-plant. Bank of 48 batteries (each of 6V, 1156 Ah)	Seven different regions, Australia.	Load Type	The proposed daily average load of 200 KWh with daily peak of 27 kWh.	[95]
		Outcomes	i- Wind/Biomass hybrid system was designed for seven different regions by considering the same proposed load demand. ii- The designed system was found most optimum for the Queensland region. iii- NPC and COE of the system were $336405 and 0.393$/KWh	
0.5 kW wind turbine, 350 kW Biomass-power plant, Suitable battery bank for storage needs.	Kallar Kahar, Pakistan.	Load Type	Small community in rural area with 5-10 households and total peak load of 375kW.	[98]
		Outcomes	i- Wind/biomass hybrid system was feasible for electrification of the rural area. ii- COE and NPC of wind/biomass hybrid system were 0.268 $/kWh and 6687$, respectively. iv- System comprised of 35% and 65% contribution from wind and biomass respectively.	
25kW wind turbine (4 units), 150 kW Biomass-gasifier, Bank of 200 batteries (each of 12 V, 200 Ah).	Remotely located village in Chennai, India.	Load Type	Remotely located village with monthly average load demand of 148 KW and peak demand of 290 Kw.	[96]
		Outcomes	i- Wind/biomass hybrid system was designed to meet the load demand of distant village. ii- System comprised of 47% and 53% contribution from the wind and biomass units respectively. iii- COE and NPC of the hybrid system were 3.49 INR/kWh and 107,791,952 INR respectively.	

Around the globe, Wind-Biomass hybrid systems have been designed and deployed for the accomplishment of different purposes. Liu et al. [95] presented the size, design and analysis of a wind-biomass hybrid system for seven different regions in Australia and reported that the system was most optimum for Queensland region. Balamurugan et al. [96] designed and analyzed wind-biomass hybrid system as a feasible solution for meeting the load demand of a remotely located village in chennai, India. Raheem et al. [97] sized and analyzed a wind/biomass hybrid system and reported it to be the feasible option for electrification of small community in a rural area of Kallar Kahar, Punjab, Pakistan. Baloyi et al. [98] worked on the design and analysis of a wind/biomass hybrid system and reported that the designed system was suitable for electrifying the distant village in Kwazulu Natal, South Africa.

"Table 7" readily illustrates the reported examples of Wind/Biomass hybrid systems in detail.

3.4 Wind-Fuel cells Hybrid System

A fuel cell harnesses electrical power through the conversion of chemical energy of a fuel into electrical energy by establishing chemical reaction of positively charged hydrogen ions with the oxidizing agents like oxygen. [99] There are different types of fuel cells but they all possess the same basic components i.e. anode, cathode and the electrolyte. The catalysts on cathode and anode causes the fuel to go through oxidation reactions to breed hydrogen ions and electrons. The presence of electrolyte makes the electricity production possible by allowing the flow of hydrogen ions and electrons between the two borders of the cell. [100] Numerous techniques are used for the production of hydrogen including production through electrolysis of water or through the reformation of natural gas and stored in a storage tank. [101] This stored hydrogen is utilized by the fuel cells to generate electricity. [102] Fuel cells are used to generate electricity for residential, industrial and commercial applications. They find their special applications as a power source in remote sites such as communications centers, remote weather stations, space-crafts and rural areas electrification. [103]

World has great potential for power production through the deployment of fuel cell power generation systems. Around the globe, several large scale fuel cell power generation systems have been installed till the time. The largest deployment in this regard is a 59 WM fuel cell power generation system located in South Korea. This system feeds the base load electricity to the grid on continuous basis and provides high quality heat for district heating system. Delmarva Power (Delaware) is operating 30 MW fuel cell power system in USA. This power system provides the reliable grid power on continuous basis, enough for entertaining the load of 22,000 homes in the area. Dominion Energy Company is running a 14.9 MW fuel cell power system in Virginia. This system feeds the Connecticut Light & Power grid. [104] A 2.8 MW fuel cell power generation plant in California is running to provide 24 hours backup to the small off-grid residential area. [105] In addition to the large scale fuel cell power generation systems, small scale systems (≤1 kilowatt) are commercially existing in Japan. More than 100,000 small scale residential fuel cell systems have been deployed to power homes and apartment buildings. Also, in Europe, 1,000 small scale residential fuel cell systems have been deployed to power homes. [104] In 2007, about 11, 000 fuel cell stacks were shipped worldwide while in 2010, these shipments increased to about 140,000. From 2011 to 2012, an annual growth of 85% was observed in the fuel cell stacks shipments. [106] In 2012, Asian pacific countries shipped more than 3/4 of the total fuel cell systems worldwide and the revenues of fuel cells industry exceeded $1 billion market value worldwide. [107]

Combined operation of a wind generator and a fuel cells (FCs) generation system makes a Wind-Fuel cells hybrid system. [108] Wind generator produces electric power by utilizing the wind flow while fuel cells system generates electric power by utilizing the stored hydrogen. [109] As the wind generation is dependent on the wind flow availability and wind flow is intermittent, generation from the wind is variable which may drive the generation system into a situation of observing a mismatch between the generation and the load demand. Therefore, fuel cells generation system is combined with the wind generation system as a compensation for this mismatch. In order to enhance the reliability of the wind/FCs generation system, the system is equipped with the additional batteries and diesel generator back up. [109-110]

Around the globe, Wind/FCs hybrid systems have been designed and deployed for the accomplishment of different purposes. Leva et al. [111] reported a well-designed wind/Fcs hybrid power system for the production, distribution and consumption of energy in a distant house situated in Milano, Italy. Nelson et al. [112] designed, analyzed and suggested a wind/fuel cell hybrid system for power generation to meet the demand of a remote load in Montana. Cetin et al. [113] designed a wind/Fuel cell hybrid system and reported that it was feasible for meeting the load requirements of a green energy house located in Turkey. Mills et al. [114] presented the size and design of a typical wind/fuel cell hybrid system for meeting the load demand of a residence in Chicago, USA. Eroglu et al. [115] reported a wind/fuel cell hybrid system to meet the electric load requirements of a typical mobile house in Turkey.

"Table 8" illustrates the reported examples of Wind/FCs hybrid systems in detail.

3.5 Wind-Tidal Hybrid System

Tidal power or tidal energy is a form of hydropower that is obtained from the conversion of oceanic tides energy into electricity. [116] Tides in the oceans are created by the gravitational attraction put forth by moon and the sun. As the moon and the sun have consistent orbital pattern around the earth, the occurrence of these tides in the oceans is persistent. [117] Over the years, different methods have been introduced to utilize tides to generate electricity. Some common methods of production from tides include: Tidal stream generator method, tidal barrage method, dynamic tidal power technology and tidal lagoon method. [118]

Table 8. Details of some Wind/FC hybrid systems reported in literature.

Specifications	Location	Load Type & Main Outcomes		Source
400 W wind turbine, 2.4 kW Fuel cell, Bank of 16 batteries (each of 12V, 150Ah)	Denizli, Turkey.	Load Type	Typical green energy house with daily average load of 6.1 kWh.	[113]
		Outcomes	i- System was designed to meet the load requirements of a green house in Turkey. ii- Suitable PV system was incorporated in the wind/fuel cell system. iii- The life cycle cost (LCC) of the system with specified load equipment was €35,525.75.	
12 KW wind turbine, 1 kW Fuel cell, Bank of 2 batteries (each of 6V, 360Ah)	Chicago, USA.	Load Type	Typical residential load with 1 kW mean over 24 hours.	[114]
		Outcomes	i- System was sized and designed to meet the typical variable load demand of a residence. ii- Hybrid system met an average load of 1 kW for 1 year utilizing the renewable resource. iii- No cost analysis was presented.	
1 kW wind turbine, 2 kW Fuel cell, Bank of 8 batteries (each of 12V, 220Ah)	Istanbul, Turkey.	Load Type	Typical mobile house with average daily load of 4220 Wh/day.	[115]
		Outcomes	i- Wind/fuel cell hybrid system was successfully sized, designed and analyzed to meet the typical mobile house electric load requirements. ii- PV system of 800W was also incorporated in the wind/fuel cell system. iii- No cost analysis was presented.	
0.5 kW wind turbine. 1 kW Fuel cell. Battery bank of 20.16 kWh.	Milano, Italy.	Load Type	Remote power load, average load of 4.5kWh/month.	[111]
		Outcomes	i- System was designed to produce, distribute and consume the energy in a remote house with load of 4.5 kWh/month. ii- Wind turbine contributed 90 % while fuel cell contributed 10% in meeting the load demand. iii- NPC and COE of the hybrid system were 58060 EUR (64752$) and 0.849 EUR/kWh (0.950 $//kWh), respectively.	
1 kW Wind turbine, 3 kW Fuel cell, Typical battery bank for storage.	Remote location, Montana.	Load Type	Typical electric load with the annual energy demand of 17045.5 kWh/year.	[112]
		Outcomes	i- Wind/Fuel cell hybrid system was designed to produce power to meet the typical load. ii- Suitable PV system was included in the wind/fuel cell hybrid system. iii- NPC and COE of the system were $6304.15 and 0.699 $/kWh, respectively.	

The world has immense potential for power generation from ocean energy sources. It has been estimated that the world can generate over 32,000GW from the favorable sites of ocean energy sources. [119] Till the time, a number of tidal power generation projects have been deployed around the globe. Rance tidal power plant with 240 MW installed capacity, completed in 1966 at La Rance, France, was the first ever project in this regard. It was the largest project until the installation of Sihwa Lake Tidal Power Plant with installed capacity of 254 MW, completed in 2011 at Sihwa Lake, South Korea. [120-121] North America started generation from ocean energy sources by installing Annapolis Royal Generating Station on an inlet of the Bay of Fundy. With 20 MW installed capacity, this station was made operational in 1984. [122] In china, Jiangxia Tidal Power Station was made operational in 1985. It was built in the south of Hangzhou city with current installed capacity of 3.2 MW. [123] In South Korea, Jindo Uldolmok Tidal Power Plant, with 1 MW installed capacity, was made operational in 2009. Later on, its installed capacity was expanded to 90 MW in 2013. [124] In New York City, 1.05 MW was generated in 2015 by installing 30 tidal turbines on the East River. [125] In UK, construction of 320 MW tidal power plant has been planned to take place outside the city of Swansea in 2016. This project, once completed, will supply 155000 homes. [126] India has started construction of Asia's first commercial tidal power plant in the state of Gujrat while a project of 50 MW has already been undertaken in the Gulf of Kutch. [127] According to International Energy Agency (IEA), total installed capacity of tidal power generation was 530 MW in 2012. Ocean Energy Systems (OES) predicts that the total installed capacity of tidal power generation will reach 337 GW by the year 2050. [128]

Pakistan, despite of having potential sites for tidal generation along its 990km coastline, has not yet made mentionable progress in this arena. National Institute of Oceanography has revealed that only the Creek Network in the Indus Deltaic Region, spreading over 70km along the Arabian Sea, has potential of generating 900MW tidal power. [129] Located on the sea, near Karachi city, Chan Waddo, Phitti and Korangi creeks have been identified as the potential sites for tidal generation with estimated generation capacities of 280MW, 78MW and 174MW respectively. In Sindh province, two potential tidal generation sites are available at Indus delta creek and Korangi Creek. Government of Pakistan issued license to private companies in 2013 for the construction of tidal power stations and the engineering work was started for the only proposed 10MW station at Sonmiani Bay. [130] Combined operation of a wind generator and a tidal generator system makes a wind-tidal hybrid system. Wind generator produces electricity through the utilization of wind flow and the tidal generator produces electricity through the utilization of water from tides. As the wind generation is dependent on the wind flow availability and wind flow is not constant, generation from the wind is variable which may result in a mismatch between the generation and the load demand. Therefore, wind generation is assisted with the tidal generation in meeting the load requirements. In order to enhance the reliability, hybrid system is equipped with the batteries and DGs backup system. [131-132]

Around the globe, Wind/Tidal hybrid systems have been sized, designed and analyzed for the accomplishment of different purposes. Mohammed et al. [136] sized, designed and analyzed a wind/tidal hybrid system to produce electricity for the off-grid site of the Ouessant French Island located in Bretagne, France. Park et al. [133] presented a well sized wind/tidal hybrid system for meeting the demand of a typical load located in Jeju Island, South Korea. Da et al. [134] reported the size, design and analysis of a wind/tidal hybrid system for fulfilling the load requirements of the proposed 1000-2000 households in Chicago, USA. Mousavi et al. [135] presented the size, design and analysis of different hybrid systems and suggested that the wind/tidal hybrid system was most suitable for optimally meeting the requirements of typical AC load in Tehran, Iran.

Table 9 illustrates the reported examples of Wind/Tidal hybrid systems in detail.

Table 9. Details of some Wind/Tidal hybrid systems reported in literature.

Specifications	Location	Load Type & Main Outcomes		Source
1.5 MW wind turbine, 1.0 MW tidal turbine, No backup system was specified.	Chicago, U.S.	Load Type	The proposed 1000-2000 households with a typical load demand of 2.3 MW.	[134]
		Outcomes	i- Wind/tidal hybrid system was sized, designed and analyzed to fulfil the proposed load requirements. ii- On average, wind generator contributed 0.7MW to 1.4 MW and the tidal generator contributed 0.5 MW to 0.8 MW. iii- No cost analysis was presented for the proposed hybrid system.	
3 W wind turbine, 180 W tidal turbine, Typical battery bank of 80 Wh. (each battery of 12V, 6.7Ah)	Jeju island, South Korea.	Load Type	Typical load of 20 W operating for 24 hours a day.	[133]
		Outcomes	i- Wind/tidal hybrid system was sized, designed and analyzed to meet the typical load proposed to be operating all the time. ii- Appropriate PV system of 30W was incorporated to optimize the system. iii- COE incurred by the wind and tidal generators were 0.09 US$/Wh and 0.19 US$/Wh respectively.	
2.3 MW Wind turbine (3 units). 500 KW Tidal turbine. (4 units). Typical battery bank of 46.5 MWh.	Ouessant French Island, Bretagne, France.	Load Type	Typical Island load demand of 16GWh/year with 2MW peak load.	[136]
		Outcomes	i- Wind/tidal hybrid system was sized to produce energy for typical island load of 16GWh/year with 2MW peak load. ii- The load demand was tested for the three scenarios and it was found that the scenario considering wind/tidal combination was the most optimum option. iii- Penetration of appropriate PV system was also made to optimize the hybrid system.	

4. Conclusion

Owing to the threat that the conventional energy reserves will end in coming years and on account of the great environmental concerns associated with their usage, the consideration of renewable energy sources as alternative sources of energy has gained firm significance in order to accomplish the mounting energy needs and preserve the environment. These renewable energy sources include wind, solar, microhydro, FCs, biomass, tidal etc. One of the fastest expanding sources of renewable energy is the wind energy. The stand-alone wind energy systems may not be able to cater the demands of specific loads owing to the low wind speeds and high unpredictability concerns. A wind-hybrid energy system comprises of the wind energy system combined with one or more other renewable energy systems and a suitable backup system in the form of batteries bank or diesel generator. Combined operation in the form of hybrid system enhances the reliability and compensates for the drawbacks perceived in stand-alone systems.

In this study, renewable energy sources (wind, solar, microhydro, biomass, FC and tidal) were discussed in detail and 5 main off-grid wind-hybrid power generation systems using these renewable energy sources were predominantly focused. Wind energy has an immense potential to cater for the energy needs throughout the world. As reported by Global Wind Energy Council (GWEC), wind energy market is expected to grow at a rapid rate because of its low prices and zero harmful emissions. Although, the surveys and feasibility reports have shown that the availability of wind energy and other renewable sources is highly scattered, unpredictable and limited to specific locations around the globe. However, the compensation for such downsides of the wind energy can be made by optimized hybridization with other energy sources. Remote locations and rural areas, where the literacy rates are poor and the grid supply is not available, are the main stakeholders for the utilization of wind energy and its implementation in these areas can help to improve the living and educational standards of the communities existing in these areas. Hence, from this study, it is recommended that the wind-hybrid energy systems are one of the best feasible options for the electrification of remotely located, electricity deprived areas because of the cheap and readily available resource.

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