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Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review

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ABSTRACT

Global environmental concerns, increasing energy demands and developments in renewable energy technologies present a new possibility to implement renewable energy sources. Solar energy is the most prominent among renewable sources, as it is an inexhaustible resource and its exploitation has thus far been ecologically friendly. The potential amount of solar energy is considerably greater than current worldwide energy demands. Solar energy has been developing more rapidly than the other renewable energy sources for the last few decades. The best way to harvest the sun's power is photovoltaic (PV) technology. This paper presents a study on solar energy in the form of a stand-alone and hybrid power generation system used to electrify off-grid locations. The stand-alone solar-PV system developed here is intended to be used to power a single house or a small community and it also functions as a mini-grid, generating power in places where adequate solar radiation is available throughout the year. However, many places throughout the world experience unsteady amounts of solar radiation and in those places, a hybrid solar-PV system is the most efficient solution for electrification. The main benefit of the hybrid system is that the weakness of one source is covered by the other source. This paper also presents some comparative case studies, project examples and demonstrations of stand-alone solar and hybrid solar systems implemented at various locations throughout the world over the last twelve years.

Contents

1. Introduction

The World Bank and International Energy Agency (IEA) estimated that the world will require a doubling in installed energy capacity over the next 40 years to meet the anticipated demands of developing countries [1]. In another estimate, the IEA reported that the 1.3 billion people in developing countries who live very far from cities have been prevented from utilizing grid electricity [2]. Although grid propagation or installation are the first options for electrification, this approach becomes uneconomical for areas with lower energy requirements due to the large investment required [3]. The 80% of people in developing countries who live in remote areas have traditionally used wood to meet their energy needs. As a consequence, deforestation has also become one of the most important environmental issues around the world [4]. Finite energy sources, such as natural gas, coal and unprocessed oil, are currently the major sources of energy worldwide.

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Because population and energy demand are both growing exponentially, the world cannot depend only on limited conventional sources to meet that demand [5].

Inexhaustible sources of energy, alternatively known as renewable energy sources, are present in copious amounts and can be obtained free of cost [6]. During the last few decades, renewable energy has received a considerable amount of attention as a source for the production of electricity due to the dwindling supplies of fossil fuels and natural gas, the unpredictable price of oil, the growing demand for power and the increasing awareness of the dangers of global warming. Although renewable energy seems to be a promising path forward, it still suffers from some serious disadvantages, including sources that are available in unpredictable amounts over time, that are not strong enough in all locations and that require high capital costs. The initial cost of renewable energy systems is much higher than that of fossil-fuel systems. For this reason, 80% of the global energy demand is currently fulfilled by fossil fuels, resulting in significant environmental impact. To maintain the Earth as a hospitable home for mankind and other living things, government research centers, institutes, universities, laboratories and private sector institutions across the world have conducted many studies, demonstrations and implementations of renewable energy over the last 42 years [7].

The progress of solar energy towards practical applicability since the oil crises of the 1970s has been noteworthy compared with other forms of renewable energy. Those crises began the worldwide effort to reduce dependence on non-renewable energy sources and focus on the development of renewable energy. Worldwide, many solar energy sources have been implemented to electrify distant areas, as stand-alone systems or as hybrid systems where the monthly average solar irradiation range is 3 ± 6 kWh/m^2 [8,9]. PV solar energy technology has received a great deal of attention for efforts to electrify off-grid rural areas because of its well-proven ability to produce electricity and because many implementations have been successful throughout the world. Solar-PV technology is also the most environmentally friendly technology because it produces no GHG emissions, no sound pollution during operation, its capacity can be easily expanded as required and little maintenance is needed [10]. Stand-alone solar-PV systems have played critical roles in electrification efforts. The design of off-grid stand-alone solar-PV systems depends on the load required for the intended use. PV technology is a far more economical way of meeting a single house's energy demand than commonly used rural sources such as diesel generators. That type of system is called a solar home system (SHS), consisting of a PV array, a charge controller, the loads and a battery [11].

However, in contrast with conventional energy sources, renewable energy sources are unable to supply constant power to meet energy demand because some sources vary in abundance with season (e.g., solar, wind) or depend on the location (e.g., hydroelectric). However, the disadvantages of renewable energy sources can be eliminated by using solar energy in a hybrid system [4]. To reduce increasing fuel costs and the cost of grid propagation, hybrid energy is best solution for electricity generation in rural areas. It is also the best generator substitute [12]. Hybrid energy systems combining renewable energy sources such as solar, wind, small/mini/micro/pico-hydroelectric, or geothermal with conventional sources such as diesel/petrol generators and a battery or fuel cell energy storage device, have performed well as power supplies in distant areas. Most sites with hybrid systems have prioritized solar energy because of its worldwide availability. Where solar radiation is inadequate, the potential problem of the reliability of the solar-PV technology is solved by the hybridization. The design of hybrid solar energy systems depends on the weather conditions and the availability of various energy sources at the site and should consider which source combination would be the most cost-effective and reliable to avoid excessive investment and meet demand [3].

The power generation sector of Malaysia has rapidly grown alongside other sectors, including the industrial and manufacturing sectors [13]. Electricity generation in Malaysia has mainly depended on fossil fuels and nuclear power. Estimates indicate that oil and gas usage is increasing such that the reserves of those sources will last for around another 33 years and 19 years from 2011, respectively [14]. Consequently, the government has devoted a great deal of attention to renewable energy as an alternative power source. Due to its geography, hydroelectric energy and solar energy have very high potential in Malaysia. Because of the average daily solar irradiation of 5.5 kW/m^2, solar energy has been used as a standalone system or in hybrid systems to electrify remote areas while reducing the use of fossil fuels [14–16].

This research highlights the use of solar energy as a power source for people living in rural areas where grid transmission and other power sources become uneconomical, undependable and ecologically hazardous.

2. Solar energy

The sun is a source of infinite energy that can be used directly or indirectly and the energy harnessed from the sun is known as solar energy [17]. In response to concerns of environmental pollution, solar energy is playing a leading role in reducing environmentally hazardous gasses produced in electricity generation. The IEA has reported that solar-PV technology could prevent 100 Gt (Gigatons) of CO_2 emissions during the period from 2008–2050 [18]. Solar energy production has no effects on cultivated land, reduces the cost of the propagation of grid transmission lines and improves the quality of life for people in distant areas who adopt this technology [19].

Fig. 1 depicts the array of available solar energy technologies and reports their market availability. Technologies in which the light and heat from the sun are used directly without changing form are referred to as passive solar energy technologies and those in which the energy is converted are called active solar energy technologies [20]. An example of the latter is PV technology, which converts the sun's radiation into electrical energy. Solar-PV systems can be conceptually divided between grid-connected systems and stand-alone systems. Grid-connected solar-PV systems are used as a power supply with grid connections, most often to a city or urban area. In contrast, stand-alone solar-PV systems are generally used to supply power to distant areas. These systems can supply electricity to a single house in combination with a battery, solar panel, or charge controller inverter, or can supply an entire village [21].

Although the first use of solar cells occurred in the 1950s to power US spaceships, the most noteworthy application of a solar-PV cell was in 1958 as a power supply for the satellite Vanguard-1 [22]. In the early 2000s, solar energy became increasingly popular worldwide and its implementation has increased tremendously over the last decade. Before 2011, the global contribution of solar-PV systems to the energy supply amount to 40 GW, with 1095 MW coming from concentrated solar power [17]. According to IEA estimates, solar energy could supply approximately 11% of the global energy demand in 2050 [18,23].

Although solar energy systems remain more expensive than other systems of energy production, continuing improvements to modern PV technology have gradually reduced the cost of solar energy systems [24]. The cost of solar energy has decreased over the last few decades, with the cost of solar modules decreasing from around US$27,000/kW in 1982 to US$4000/kW in 2006 and

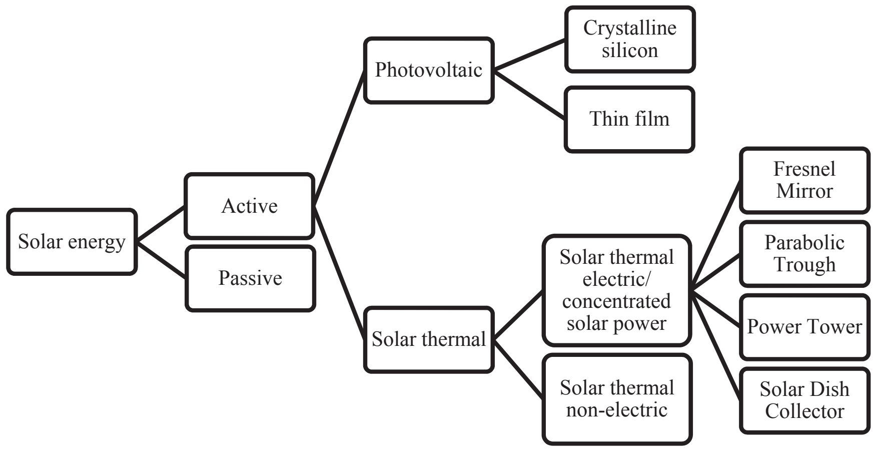

Fig. 1. Assorted types of solar energy based on global market availability [17].

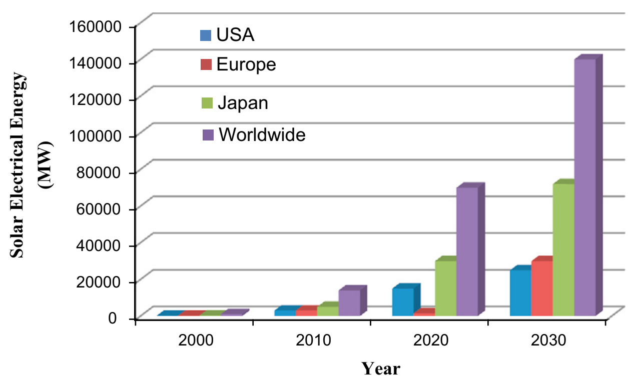

Fig. 2. Improvement and implementation of solar-PV in leading countries [15].

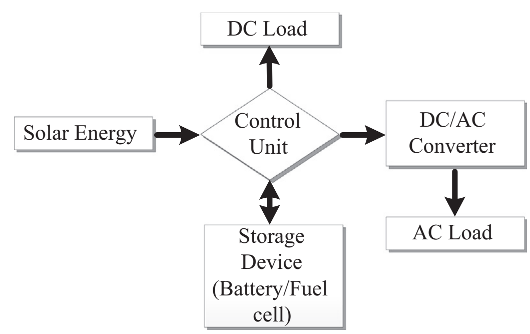

Fig. 3. General architecture of solar energy systems [25].

the cost of solar-PV installation decreasing from around US $16,000/kW in 1992 to US$6000/kW in 2008. Regardless of the cost, R&D in this area has achieved tremendous progress because of worldwide movements in support of renewable energy and because of governmental policies. Although solar energy contributes a negligible amount to the global energy supply, solar energy has the potential to meet the world's energy requirements [17]. For this reason, many countries with solar energy technology have implemented policies to increase solar energy utilization. Fig. 2 presents the implementation and future expected improvements in solar-PV systems in some leading countries [15].

2.1. Stand-alone solar energy

A stand-alone solar energy system can be designed as shown in Fig. 3. A stand-alone solar energy system consists of a PV module as an energy harvesting technology, a battery as a storage device, a charge controller as a control unit and a DC/AC converter for AC loads. Stand-alone solar-PV systems have become widespread in both developed and developing countries [25].

The most important requirements for a storage system for stand-alone solar-PV applications are low cost, high energy efficiency, longer lifetime, low maintenance, self-discharging and simple operation. Although battery storage systems are the best known storage elements of stand-alone PV systems, they require high initial investments. Consequently, it is important to manage battery usage because operating conditions and charge-discharge protection have strong influences on battery lifetime and cost [26–28]. Stand-alone PV systems have also used lead-acid batteries because of their cost-effectiveness and longer lifetimes [27]. The required battery size usually depends on the load capacity and required backup period. Some researchers have also concentrated on the development of low power consumption appliances to minimize battery size and panel size to enable the development of a cost effective system [29,30]. Fuel cell technology is also a major focus for the storage and production of electric power and thermal energy. However, fuel cells are still not applicable for small scale applications, especially in stand-alone PV systems because of their component costs and operational complexity. To make this stand-alone solar-PV system feasible, cost-effective and low maintenance for rural settings, researchers have developed many theories and mathematical methods. Some of those methods are reviewed here.

Li et al. [31] evaluated the quantity of solar irradiance transmitted to the PV module using the luminous efficacy approach and based on their data, they investigated the efficiency and functional performance characteristics of a small solar-PV system. Yu et al. [32], with the aim of improving the efficiency of a 3 kW solar-PV system under dissimilar isolation conditions, proposed a novel two mode maximum-power-point-tracking (MPPT) control algorithm including modified constant voltage control and incremental conductance. Hung et al. [33] designed a solar-PV system that reduces the hardware needed for a MPPT solar-PV system but operates very near to this point, named near-maximum-power-point-operation (nMPPO). After long-term operation at different temperatures, the overall efficiency of nMPPO was found to be greater than 93%. Keogh et al. [34] introduced a design for solar cells and a module measurement tester by adopting a constant-voltage design approach that is easier, cheaper, reduces transient errors and extracts a family of *I*–*V* curves over a decade range of light intensity, providing comprehensive information on cell performance. Stember [35] introduced a system-level approach that is a useful way to analyze the reliability of the system and illustrated the usefulness of this approach to designing a solar-PV

Table 1
Some stand-alone solar-PV systems introduced over the last twelve years and their outcomes.

Study/Project location	Load type	Design capacity	Outcome	Source
Kerman, Iran	50 typical rural households with an annual load of 24.4 MWh	19 kW solar-PV, 12 components (2 V, 3000 AH) battery	i. The solar-PV/battery system was selected for this site because of its low maintenance and low cost and the good availability of solar radiation ii. Without a power supply shortage, the COE of the solar-PV/bat system = $0.247/kWh, the wind/bat system = $0.379/kWh and the hybrid solar-PV/wind/bat system = $0.243/kWh iii. Over its 20 year projected life, the total net present cost (NPC) of the solar-PV/bat system = $120,738, the wind/bat system = $185,375 and the hybrid solar-PV/wind/bat = $118,965	[41]
Rural area, India[a]	219 kWh/yr load consisting of 3 lamps, 1 TV, 1 Radio	150 W solar-PV, 60 Ah battery	i. The solar-PV system was found to be more economical than a diesel generator system or grid propagation ii. At distances greater than 6.08 km, the cost of the grid system become uneconomical when the solar-PV system was subsidized by 50% iii. Without any subsidy, the solar-PV system became economically viable after 8.64 km iv. The COE of solar-PV system = $0.145/kWh, without subsidy $0.258/kWh and the COE of the grid system = $0.12/kWh	[42]
Rural areas, southern Iraq	A health clinic load of 11,534 kWh/yr	6 kW solar-PV, 80 pieces (6 V, 225 Ah) with a battery	i. The designed solar-PV system was found to be more cost-effective than the DG-alone system ii. The solar-PV system reduces the emissions of CO_2 and other harmful gases by 14,927 kg/yr iii. The COE and NPC of the solar-PV system = $0.238/kWh and $60,375 and of the diesel-alone system = $1.332/kWh and $352,303	[43]
Rural area, Bangladesh	A load of operating 2 fluorescent and 2 WLED lamps for 3 h in the night time	25 W solar-PV, 12 V, 30 Ah battery	i. The SHS is more cost-effective and eco-friendly than the oil lamp system ii. The SHS system would reduce CO_2 emissions by 4.82 tons over 20 years iii. At an oil price of $0.64/l, the total energy cost per year for the SHS = $37.825 and for the oil lamp system = $64.1	[44]
Tunisia, located in North Africa	Small remote communities, 24 h load approximately 83,161.6 kWh/yr	41.6 kW (260 pieces at 160 W) solar-PV, 228 kWh battery bank	i. The solar-PV system is cheaper than the site's available DG system ii. The solar-PV system could save 207174 gallons of fuel over 30 years iii. The COE and total cost over the 30 year period for the stand-alone solar-PV system = $0.240/kWh and $542,618, for the DG-alone system = $0.289/kWh and $651,822	[45]
Village in the northeast of Thailand[b]	The load of a rural house including 3 lights, 1 fan, 1 radio, 1 TV, for a total of 197.83 kWh/yr	220 W solar-PV, 250 Ah BD125 battery	i. The solar-PV system was found to be more economical than grid propagation for this low load application at a distant location ii. The COE of the stand-alone solar-PV system = $1.234/kWh and of a 5 km grid connection = $26.80/kWh iii. The total life cycle cost over the 20 year projected life for the stand-alone solar-PV system = $4886.26 and of a 5 km grid connection = $106,070.5	[46]
Tripios Kythnos[c]	The load of a farm house, approximately 4.2 kW	2160 W solar-PV, 30 pieces with a lead-acid battery (50 kWh nominal capacity)	i. The solar-PV system is more cost-effective than grid propagation to this project location, which is 1000 meters away from the grid generation station ii. The total investment cost with 18% vat for the solar-PV system = $31,837.86 and for grid extension = $54,465.01	[47]
Tocantins, Brazil	The load of a rural household approximately 8.7 MWh/yr	6.28 kW solar-PV, 16 pieces (12 V 220 Ah lead acid) with a battery	i. The solar-PV system with battery storage was more cost effective than the solar-PV/fuel cell system ii. The COE and NPC of the solar-PV system = $0.657/kWh and $49,711 and of the solar-PV/fuel cell = $1.351/kWh and $102,323	[48]

The currency was converted according to exchange rates in December 2012.

[a] US$1 = 54.62 Indian Rupee.
[b] US$1 = 30.64 Thai Baht.
[c] 1 Euro = US$1.3102.

system. Oko et al. [25] developed an automated Microsoft Excel spreadsheet that can be used to design a solar-PV system and analyze its economic efficiency. The approach presented in that study can be used for any geographic location once the input data have been sorted. Khatib et al. [36] introduced a simple, broadly valid approach for the optimization of stand-alone solar-PV systems by optimizing the size of the PV array and of the battery storage. After analyzing the energy flow of this system, a MATLAB fitting tool was used to fit the resulting sizing curves to derive general formulas for the optimal sizing of PV arrays and batteries. Vázquez et al. [37] developed a methodology using parallel connected DC/DC converters to optimize stand-alone solar-PV systems for any location and used several algorithms to determine the annual energy savings by connecting a DC/DC converter in parallel. Rahman and Khan [38] presented a mirror reflection method to enhance the performance of a solar-PV system. In this method, the average short-circuit current of the solar panel increased by approximately 20–25%. Shen [39] introduced a method to optimize the PV array and battery size for an economical stand-alone solar-PV system. This study showed that the cost of energy (COE) or per unit cost of energy of the system depends on the PV tilt angle and the battery depth of discharge (DOD). As an example, a case study was presented for a load of 3.51 kWh/day, determining that the lowest COE ($0.788/kWh) of the system was achieved at a 10 degree tilt angle and a battery DOD of 20%. For the same system, the COE was $1.138/kWh for 80% DOD.

Masakazu et al. [40] presented a 100 MW solar-PV system designed for the Gobi desert. Based on a project life of the system of 30 years, the energy-payback-time (EPT), the rate of CO_2 emissions and the cost of power generation were estimated using the life-cycle analysis method. Consequently, the rate of CO_2 emissions was found to be 12 g C/kWh and the EPT was 1.7 years. This estimation shows that despite the higher cost of generation ($0.086/kWh) compared to the national energy tariff of China ($0.039/kWh), the solar energy system would be the best power solution from the ecological and economical points of view [40]. Similarly, many authors around the world have published many case studies of projects following these methods of optimization. Some of those studies are presented in Table 1.

3. Hybrid solar energy

Electrical power generation systems consisting of two or more energy sources are known as hybrid systems. Hybrid systems can consist of two renewable sources or combinations of renewable and conventional sources. For example, solar and wind energy can be combined together or with other renewable sources (hydroelectric, geothermal, biomass, etc.), or with a diesel generator (DG) or electrical grid. Hybrid systems also contain storage devices, such as batteries or fuel cells. While hybrid energy systems are usually implemented to electrify remote areas, they can also operate in parallel with the grid power system [49,50].

However, the design, optimization and operation control of hybrid energy systems with two or more energy sources are complex and the risk of failure is increased. Researchers have studied a wide variety of methods to reduce the complexity of designing hybrid energy systems. Some useful methods include Probabilistic, Analytical, Iterative and Hybrid methods [49]. A number of studies have used these methods to design optimal hybrid systems combining two or more energy sources. For example, Yang et al. [51], Celik [52] and Tina and Gagliano [53] used probabilistic methodologies to present an optimal hybrid system, while Kamel and Dahl [54], Diaf et al. [55], Dufo-López et al. [56], Mondol et al. [57], Kaldellis et al. [58] and Khatod et al. [59] have used analytical methodologies. Hakimi and Moghaddas-Tafreshi [60], Ekren and Ekren [61], Yang et al. [62], Ashok [63], Yang et al. [64], Dufo-López and Bernal-Agustín [65] and Koutroulis et al. [66] have studied iterative methodologies. Katsigiannis et al. [67], Wang and Singh [68], Bernal-Agustín et al. [69], Shi et al. [70], Hontoria et al. [71], Mellit et al. [72] and Mellit et al. [73] have used hybrid methodologies.

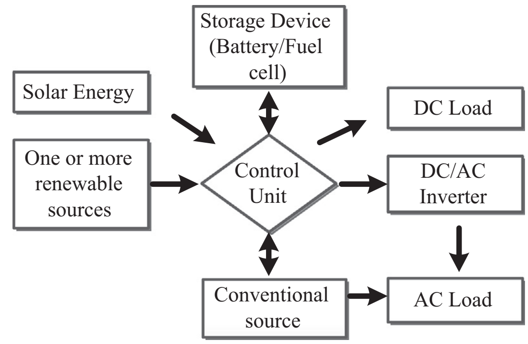

Fig. 4. General architecture of hybrid solar energy systems [75].

Additionally, some efficient software tools have also been employed to support the design of optimal, cost-effective, eco-friendly hybrid systems. The most used and best known of these software tools is the Hybrid Optimization Model for Electric Renewables (HOMER), developed by the US National Renewable Energy Laboratory. Another useful software tool has been developed by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts, named HYBRID2. Hybrid optimization using Genetic Algorithms (HOGA) is the easiest of these software programs to obtained and was developed by the Electrical Engineering Department of the University of Zaragoza, Spain [74].

The omnipresence and rapid development in solar energy technology have led to the more frequent inclusion of solar energy in hybrid systems compared with other renewable sources [24]. The acceptance of the hybrid solar energy system alongside the stand-alone solar system has increased because the solar energy is not strong enough to meet the electricity demand in many places. Thus, solar energy has been implemented in hybrid systems (shown in Fig. 4) with another source, a storage device and a control device and these systems have become more competitive and practical for the electrification of remote areas without access to the grid [75].

3.1. Varieties of hybrid solar energy

Worldwide, hybrid solar systems consisting of solar power and other sources are performing successfully. In some places, electrification is achieved by combining solar energy with a single or several renewable sources such as wind or small/mini/micro/pico hydroelectric energy sources. Hybrid solar energy systems consisting of 100% renewable energy reduce the dependence on the conventional fossil-fuel system. However, in some places conventional energy sources are cheaper and more reliable than renewable sources. In particular, diesel generators are one of the best known power solutions for remote areas and so solar energy is often combined with this conventional source in such places. This section presents a comparative review of different hybrid solar energy systems consisting of renewable or conventional sources for the electrification of rural areas.

3.1.1. Hybrid solar energy combined with renewable sources

Many locations feature plentiful renewable energy resources with an excellent potential to fulfill energy demand. Solar energy, hydroelectric energy and wind energy are attractive renewable sources for distant communities. Based on long term projections, the implementation of a hybrid system consisting solely of available renewable sources will become more feasible than investing in diesel generators from the environmental and cost-competitive points of view [76]. This section includes summaries of studies on hybrid solar-wind and solar-hydroelectric energy systems.

3.1.1.1. Hybrid solar-wind energy. Wind energy was harnessed beginning in ancient times and this form of energy became a priority just after the oil crisis as a source of electricity production. Approximately 28 thousand wind turbines are currently in operation worldwide to generate power [77]. The wind speed is the main factor influencing the power generation, but the wind is not sufficiently fast to be useful in all locations. In that sense, this source of energy is more unpredictable compared to solar energy [12,78]. Although, solar and wind energy are the most ubiquitous and environmentally friendly renewable energy sources worldwide, both become unpredictable and are sometimes unable to meet peak demand as changes in the weather and climate occur. For this reason, solar or wind energy systems alone cannot always provide sufficient power to meet the demand [62,79]. As an example, Fig. 5 shows average power for a specific site over time. Fortuitously, the intensity of energy provided by one source is often adequate to compensate for the other, enabling the energy demand to be met. For this reason, hybrid systems are becoming more suitable [62].

To avoid the loss of investment and capital costs, it is critical to choose a suitable system that provides dependable system power [80]. To obtain a reliable power system at a low cost, it is absolutely necessary to optimize the system components. In the literature, this exercise is referred to as “sizing” [81]. Since the popularity of solar and wind energy systems and their usage began to increase in 1980, researchers have been trying to determine the best solutions and they have presented a wide variety of ways to optimize system costs and reliability [64]. Died et al. [55] used analytical methods to design five hybrid systems for five locations with different weather with zero loss of power supply probability (LPSP) without UPS. These hybrid systems have also been compared with solar only and wind only power systems for individual locations and the LCE of the hybrid system was found to be more cost-effective than the solar and wind only systems [55]. Some similar studies and the outcomes of hybrid solar-wind energy systems are listed in Table 2.

3.1.1.2. Hybrid solar-hydroelectric energy. Hydroelectric energy has played an important role in producing energy throughout the world since ancient times. Hydroelectric power currently provides 19% of the world’s power supply [93]. Hydroelectric energy projects have many benefits compared with other energy sources such as nuclear or thermal energy. Hydroelectric power systems exploit water resources, which are inexhaustible and cost free and the water can be used for other purposes such as irrigation and home supply after passing over the turbine [94]. Although hydroelectric power systems are more cost-effective

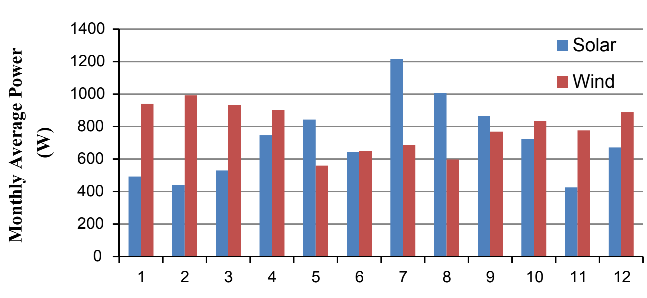

Fig. 5. The average monthly power contribution of solar-PV and wind-turbines on an island [62].

than other renewable sources, the expense depends on the head height, with higher head systems requiring less water flow to generate electricity, thus avoiding the requirement of large and costly machinery [93]. Hydroelectric energy systems can be classified into categories such as large hydroelectric, small hydroelectric, mini hydroelectric, micro hydroelectric and pico hydroelectric, but these terms have no specific definitions. Many countries consider above 25 MW as large hydroelectric systems, 2.5–25 MW as small hydroelectric, less than 2 MW as mini hydroelectric, less than 500 kW as micro hydroelectric and less than 10 kW as pico hydroelectric power systems [93,94].

The world has a great deal of negative experience with large hydroelectric power plants since 1970. Large scale hydroelectric power plants have required large reservoirs and dams to hold considerable amounts of water to produce electricity, subsequently destroying generative lowlands and river and grassland ecosystems. These negative effects of large hydroelectric power generation systems are not limited to environmental debasement but also contribute to global warming due to the emission of methane and nitrous oxide. Due to these effects, hydroelectric power seems to be not much better than fossil fuel-based electricity generation systems according to environmental impact. Many people often have to relocate to enable the construction of a dam for a large hydroelectric system. Large dams also have a risk of failure because of poor construction, natural disaster, or other factors. Lastly, dam construction requires significant investment, which is sometimes not possible for poor or developing countries to take on [94].

To avoid these disadvantages of large hydroelectric systems, most countries currently prefer small scale hydroelectric systems. Small scale hydroelectric power is one of the most promising and lucrative solutions for electrification, especially for rural electrification in developing countries, because of its cost-effectiveness and robustness and it is also an environmentally friendly technology for electrification. Systems on this scale do not require vast amounts of water to be held, eliminating the need for dams. In many cases, these systems are used to produce electricity based on the “run of the river.” At the end of 2010, small hydroelectric power has provided 47,000 MW of electricity worldwide [94].

However, variations in the hydraulic head, water discharge rate and device efficiency have changed the power output of hydroelectric systems. A head of at least 3 m is required to enable the development of a site [4,95]. Although a small scale hydroelectric system can generate power throughout the year, the amount is not consistent because the water flow varies from month to month. Because of this inconsistency in the power supply, another source is required to obtain a reliable power supply throughout the year. When considering hybrid systems, solar energy is an ideal energy input because of its regularity and natural availability in a variety of locations. Without solar and water energy, no other renewable energy is available to naturally produce sustainable energy [96]. Some comparative studies are discussed below.

Kusakana et al. [97] presented a hybrid solar-PV hydroelectric system, using Kwa-Zunu Natal, a rural site in South Africa, to show the differences between conventional and hybrid solar-PV hydroelectric power systems. In this case the electricity was used to power household appliances and a sawmill. The average solar radiation was between 4.5 and 6.5 kWh/m^2 and the head height of the hydroelectric system was 5 m and the water flow rate was 187 1/s. The optimal design combination was 12 kW solar-PV with 7.44 kW micro hydroelectric for a 53290 kW/yr load with a 15 kW peak load. For the same load, 15 kW diesel generators were used for comparison with the hybrid power system. While the initial capital cost ($87,720) of the hybrid system was much higher than that of a diesel generator system ($9225), the COE was significantly lower ($0.197/kWh for the hybrid system compared with $7.391/kWh for the DG system) because the diesel generator consumed 23,833 l/year of fuel, costing

Table 2
Hybrid solar-PV/wind systems that have been introduced throughout the world over the last twelve years and their outcomes.

Study/Project location	Load type	Design capacity	Outcome	Source
Vadodara, India	AC home appliances, 1825 kWh/yr	2 kW solar-PV, 1 kW wind turbine, Vision 6FM 200D (12 V, 200 AH) battery	i. The COE of the hybrid solar-wind system was noticeably lower than those of the solar and wind alone systems ii. The hybrid system reduced GHG emissions by 80 to 90% compared with a DG system iii. The COE and NPC of the hybrid system= $1.232/kWh and $28,975, of the solar-alone system=$1.572/kWh and $36,964, of the wind-alone system=$2.923/kWh and $68,783	[82]
Juara village, Tioman island, Malaysia	The chalet loads are a refrigerator, air conditioner, TV and multimedia set, lighting and electrical oven, with a total load of approximately 181.04 MWh/yr	200 kW solar-PV, 40 kW wind turbine, 540 pieces, Surrette 6CS25P battery	i. This hybrid system emitted zero harmful gases, while the diesel only system emitted 213,938 kg/yr ii. The hybrid system would be more economical than the diesel-alone system at a diesel price of $2.10/l iii. The COE and NPC of the hybrid system= $1.104/kWh and $2,554,228 and of the diesel-alone system=$1.127/kWh and $2,608,481	[83]
Two different sites: 1. Nice, France, 2. Nicosia, Cyprus[a]	Both locations consider 500 houses with an average daily load of approximately 24 kWh or 8760 kWh/yr	10.98 kW solar-PV, 1.5 kW wind turbine, 108 kWh battery for Nicosia, Cyprus, 9.9 kW solar-PV, 4.8 kW wind turbine, 108 kWh battery for Nice, France	i. The NPC and COE of the hybrid systems were cheaper than the PV-alone system ii. For Nice, the NPC of the hybrid system= $137,535.62 and for the PV-alone system= $160,511.3; for Nicosia, the hybrid system=$135,867.74, the PV-alone system=$136,615.9	[84]
Dalajia Island in Guangdong Province, China	A telecommunications station including a 1300 W GSM base station and 200 W for microwave communication, for a total load of 1500 W	7.8 kW solar-PV, 12 kW wind turbine, 5000 Ah, 24 V GFM-1000 (2 V) battery	i. The hybrid system was found to be the most economical solution compared to the stand-alone solar or wind system. ii. At LPSP=2%, the COE and the total cost of the hybrid system=$0.753/kWh and $9708, for the PV-alone system=$0.865/kWh and $11,145, for the wind-alone system=$1.311/kWh and $16,889	[62]
Sitakunda, Bangladesh	DC loads such as DC lights, fans and TVs, for a total load of 61,685 kWh/yr	27 kW solar-PV, 39 kW wind turbine, 370 pieces, (6 V 225 AH) battery	i. The COE of the hybrid solar-PV/wind system were 78% and 48% less than those of the solar/battery and wind/battery systems, respectively ii. This system reduced the CO_2 emissions iii. The COE and NPC of the hybrid system= $0.363/kWh and $319,132, of the solar only system=$0.525/kWh and $461,600, of the wind only system=$0.646/kWh and $569,659	[85]
Nabouwalu Vanua Levu Island, Fiji	The government hospital, institutions, school, shops, staff quarters and the village with 180 residents. The primary load is 360.985 MWh/yr	200 kW solar-PV, 64.8 kW wind turbine, 500 Hoppecke 12 OpzS 1500 battery	i. The hybrid system emitted no CO_2, while the diesel-alone system emitted 250 tons/yr ii. The fully renewable based system was more feasible than the other, which had a 10% annual capacity shortage iii. The COE and NPC of the hybrid system= $0.780/kWh and $3,312,476, for the diesel-alone system=$0.979/kWh and $4,518,316	[86]
Sukhalai, Hoshangabad, Madhya Pradesh, India	Typical village load 15,768 kWh/yr	8 kW solar-PV, 7 kW wind turbine, 44.29 kWh battery	i. The optimized hybrid system was the most reliable power solution for this location compared to the wind-alone or PV-alone systems considering the cost of energy ii. The COE of the hybrid system=$0.47/kWh, solar alone system=$0.38/kWh, of the wind alone system=$0.24/kWh	[87]

Table 2 (*continued*)

Study/Project location	Load type	Design capacity	Outcome	Source
Three different sites in Corsica Island, France: 1. Cape Corse 2. Ajaccio and 3. Calvi	Typical residential home loads in the range of 1095 kWh/yr	800 W solar-PV, 800 W wind generator for Cape Corse, 1200 W solar-PV, 400 W wind generator for Ajaccio, 850 W solar-PV, 1000 W wind generator for Calvi.	i. According to the load, the lowest LCE was found at zero LPSP for the 3 sites ii. For three sites with different weather patterns, feasible and reliable optimal hybrid systems were found iii. The COE of the hybrid system for Cape Corse=$0.882/kWh, Ajaccio=$1.383/kWh, Calvi=$1.373/kWh	[88]
Turkey	Lighting load of the Solar Energy Institute Building, 1142 kWh/yr	500 W solar-PV, 400 W wind turbine, 2.64 kWh battery	i. The optimized hybrid system was the most reliable and eco-friendly power solution for this location, although the unit cost was higher than the cost of grid supply ii. The COE of the hybrid solar/wind system=$0.89/kWh, Turkey grid=$0.23/kWh	[89]
Patenga, Chittagong, Bangladesh	Typical rural load approximately 58.4 MWh/yr	25 kW solar-PV, 42 kW wind turbine, 384.75 kWh battery	i. The hybrid solar-wind system was more economical than the solar or wind only systems and even than grid extensions longer than 8 km or 12.4 km ii. The COE and NPC of the hybrid system=$0.47/kWh and $391,492, of the wind only system=$0.63/kWh and $532,343, of the solar only system=$0.666/kWh and $552,824	[90]
Samothrace, a Greek Island	Typical household load in Samothrace	3 kW solar-PV, 2.5 kW wind turbines, 41.85 kWh battery	i. The hybrid solar/wind system with 35% solar energy penetration was found to be more economical than the wind/diesel system, although the NPC of the wind/diesel system was lower ii. The COE and NPC of the hybrid solar/wind system=$0.408/kWh and $37291, of the wind/diesel system=$0.647/kWh and $24498.11	[91]
Urumqi, China	Household load approximately 4.015 MWh/yr	5 kW solar-PV, 2.5 kW wind turbines, 8 pieces (6 V 1156 Ah) battery	i. The hybrid solar/wind system with 72% solar energy penetration was found to be more economical than the solar or wind only systems ii. The COE & NPC of the hybrid system=$1.045/kWh and $53,296, of the wind only system=$1.173/kWh and $59, 779, of the solar only system=$1.150/kWh and $ 58,659	[92]

The currency was converted according to the rate at the time of the case study.

[a] 1 Euro=US$1.3102 (December 2012).

US$31,777 [97]. The cost of grid extension has also been calculated for comparison with the hybrid system, as the grid was 18 km away from the load center. Although the local COE of the grid supply was $0.144/kWh, the COE of the grid system exceeded the COE of the hybrid system once the grid was extended more than 3.07 km (as shown in Fig. 6) [97].

Similarly, Kenfack et al. [98] presented a design of a hybrid Solar-PV micro-hydroelectric system for Batocha sites in the western province of Cameroon. The most cost-effective solution was found to be 3 kW solar-PV and 2.59 kW hydroelectric with battery storage ($54,636 NPC and $0.234/kWh COE) for a 16279 kWh/yr load with a 13% annual capacity shortage. However, if a 1 kW diesel generator was considered as a backup solution, then no capacity shortage would be found, although this system would have a higher NPC ($70,042) and COE ($0.278/kWh). The hybrid system is also more feasible than propagation of the grid.

In an another study, Sadiqi et al. [76] presented a hybrid solar-PV micro-hydroelectric system (19 kW solar-PV, 27.5 kW micro-hydroelectric) capable of supplying a 244.55 MWh/yr load for four villages' houses, stores and schools. The optimal hybrid system had an NPC of $331,928 and a COE of $0.105/kWh and this represented the most cost-effective solution for the location under study.

Thus, it is clear that hybrid solar and small scale hydroelectric energy can supply not only cost-effective but also environmentally friendly electricity for rural electrification, surpassing the conventional or grid system where solar and hydroelectric resources can be exploited.

3.1.2. Hybrid solar energy systems with conventional sources

In many locations far from the electricity grid, diesel fuel remains a cost-effective and well proven energy generation

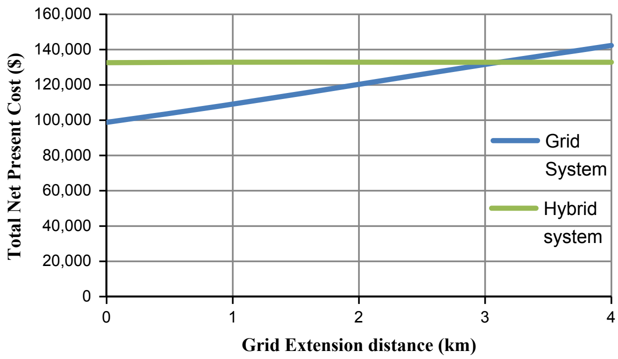

Fig. 6. Electrification cost [97].

technology. Although a diesel generator is the most commonly used technology for electricity generation in rural sites, over the long term the use of diesel power alone becomes uneconomical due to the fluctuations in diesel prices. For this reason, the diesel generator is used with a renewable source like solar energy and while the diesel part of the system emits harmful gases, these emissions are significantly below those of diesel systems alone [99,100]. This section discusses some hybrid solar-diesel energy systems that have been implemented over the last twelve years.

3.1.2.1. Hybrid solar-diesel energy. To achieve rural electrification in developing countries, renewable energy is playing a critical role, especially solar energy [101]. The hybrid solar photovoltaic system is a better energy source than fossil fuels and its acceptance is increasing around the world, not only to shield consumers from increases in oil costs but also to reduce the emissions of harmful greenhouse gases. To enable a 24 h power supply, the hybrid solar-PV diesel energy system is one of the most cost-effective, simple and environmentally friendly solutions for remote areas, where the diesel generator acts as a backup solution in the absence of solar radiation or in the night time [101,102].

In Malaysia, 200 km away from Miri, the Ulu Baram district of Sarawak is situated. This site is used as an example to understand the benefits of a hybrid solar-diesel system compared with a standalone diesel generator (DG) system. A software program was used to determine where the hybrid solar-PV diesel system was the optimal and most cost-effective solution. Long run projections (25 years) predicted a significantly lower COE and NPC of the hybrid system at a diesel price of $2.03/l. Another substantial contribution of the hybrid system is that it helps to reduce the environmental impact. The simulation found that the annual emissions would amount to 432,259 kg for the diesel generator system and 342,246 kg for the hybrid solar-PV diesel system [100].

In most cases, the diesel price has increased in remote areas due to the costs of long distance transportation and issues with fuel availability. In many areas, the difference in cost between diesel-only systems and hybrid solar-PV diesel systems has decreased. However, the hybrid solar-PV diesel energy system is preferable in terms of environmental pollution and its ability to reduce dependence on fossil fuels [50]. Due to those concerns, many studies have been conducted included analyses and case studies and their findings are described in Table 3.

3.1.3. Hybrid solar energy systems with two or more sources

The rate of population growth is higher than the rate of grid propagation in poor and developing countries and hybrid energy systems are playing a vital role in increasing the availability of electricity. The availability of energy resources varies across the world for both conventional and renewable sources [111,112]. The most commonly available inexhaustible sources are solar and wind energy. At many distant locations far from the grid, solar or wind energy alone would not be able to supply the required demand [79]. Therefore, another source is required to meet the demand. While the reliability of the system will increases as sources are added, it becomes more complex to design an optimal, reliable and cost-effective system with two or more sources, storage devices and control devices. To overcome this complexity, researchers have developed many cost-effective hybrid power solutions using different sources by applying optimization methods and software programs [49,74]. Hybrid solar energy systems with two or more sources are discussed and compared below.

3.1.3.1. Hybrid solar-wind-diesel energy. Diesel prices in most remote areas are higher than the usual prices in cities or urban areas, making the energy cost of the hybrid solar-wind-diesel energy system competitive with the energy cost of the diesel generator system. In the hybrid system, the diesel generator is used to minimize the size of the solar-wind system as well as the cost [113]. While a hybrid solar-wind system can supply enough power in places where the solar radiation and wind speed are high enough, many remote areas do not have enough solar radiation and wind speed throughout the year, making it difficult for these systems to meet the peak demand. This problem could be solved by over designing the system, but that would not be cost-effective; instead a diesel generator can be used as a backup solution. Hybrid solar-wind-diesel systems have lower maintenance requirements than the diesel power generation system [114,115]. The combination of the hybrid solar-wind-diesel system is selected based on the site's power demand, weather data and the prices of diesel and the other components [116]. In many distant locations, the costs of electricity generation systems, such as solar, wind or hybrid solar-PV-wind-diesel systems, are similar, making the main goal to develop an environmentally friendly system that can meet the required demand without a capacity shortage [115].

Setiawan and Nayar [117] presented a study of a hybrid solar-PV-wind-diesel system to electrify a distant island in the Maldives after a tsunami disaster, where two diesel generators had previously been used to supply power. The designed hybrid system was found to be more economical, eco-friendly and reliable than a diesel-only system. The COE and NPC for the hybrid solar-PV-wind-diesel system were $0.438/kWh and $634,064, respectively, compared with $0.510/kWh and $709,055 for the diesel-only system. The hybrid system also reduces fuel consumption by 20,381 l/yr. In an another study, Chen et al. [118] presented a solar-PV-wind-diesel hybrid system based on an island's weather conditions. The hybrid system designed with 77% renewable sources was the most cost-effective solution for the island and other locations with similar weather conditions [118]. Some more case studies of hybrid solar-PV-wind-diesel energy systems under different weather conditions are described in Table 4.

3.1.3.2. Hybrid solar-wind-diesel systems with hydroelectric/biomass energy. Technically viable renewable energy sources are available at different levels in different locations and the optimization of a hybrid system depends on those renewable sources as well as the load demand. The cost of the hybrid system also depends on the source's quantity, quality and component prices. Sometimes, involving more sources in the hybrid system makes it more cost-effective and reliable [112]. Some studies with several components are presented here.

Deepak Kumar Lal et al. [112] designed an optimal hybrid solar-wind-hydroelectric-diesel (HSWHD) system meeting a 1085.9 MWh/yr load for the location of the Sundargarh district of Orissa State, India and compared the designed system with another hybrid system without hydroelectric power. This study determined that the HSWHD system is more cost-effective and

Table 3
Hybrid solar-PV/diesel systems introduced over the last twelve years and their outcomes.

Study/Project location	Load type	Design capacity	Outcome	Source
SMK Balleh, Sarawak, East Malaysia[a]	Boarding schools with 600 people	35 kW solar-PV, 150 kW DG	i. The hybrid system is more cost-effective than the DG-only system without battery storage at a PV module price of $2.90/Wp ii. The COE and life cycle costs of the hybrid system = $0.1027/kWh and $1,017,394.73, of the DG-alone system = $0.1029/kWh and $1,020,184.21	[103]
200 km away from Miri, Sarawak, the Ulu Baram district in Malaysia	40 houses with a load of 421.94 MWh/yr	60 kW solar-PV, two 50 kW DG, Surrette 6CS25P (6 V, 1156 Ah) battery	i. The hybrid system with battery storage was the cheapest solution when the diesel price was $1.6/l or more ii. The hybrid system reduced the emissions of harmful gases compared to the standalone DG system. The emissions amounted to 432,259 kg/year by the stand-alone diesel system and 342,246 kg/year by the hybrid system iii. At a diesel price of $2.03/l, the COE and NPC of the hybrid system = $0.796/kWh and $4,292,632, of the DG-alone system = $0.875/kWh and $4,722,083	[100]
Kolkata, India[b]	Technical college with a load of 338.355 MWh/yr	400 kW solar-PV, 200 kW DG, 120 Surrette 6CS25P (6 V, 1156 Ah) battery	i. The hybrid system reduced the fuel costs by 70%-80% compared to the DG-alone system and reduces the emissions of CO_2 and other harmful gases by 90% ii. The hybrid system was also the most cost-effective solution for the location with 95% renewable friction iii. At a diesel price of $0.878/l, the COE of the hybrid system = $0.216/kWh, of the DG-alone system = $0.717/kWh	[104]
Remote settlements, Jordan	Houses in off-grid distant areas where the load is 48 kW/day or 17.52 MWh/yr	2 kW solar-PV, 4 kW DG, 2 Surrette 6CS25P (6 V, 1156 Ah) batteries	i. When the fuel price was higher than $0.15/l, the hybrid system became more economical than the DG alone for this site or another site with similar weather. ii. The hybrid system reduced annual fuel consumption by 18.53% as well as the GHG emissions by 18% compared to the DG system alone iii. At a diesel price of $0.238/l, the COE and NPC of the hybrid system = $0.297/kWh and $66,227, of the DG-alone system = $0.324/kWh and $72,068	[105]
Kavala Institute of Technology (Electrical Engineering Department), Kavala, Greece.	Several types of machines, some regular auxiliary loads such as lights, a refrigerator, coffee maker, control system, miscellaneous devices, air conditioning, PCs	6 kW solar-PV, two 8 kW DG, six Surrette 6CS25P (6 V, 1156 Ah) batteries	i. The solar-diesel hybrid system reduces the diesel consumption by 33.8% compared to the standalone DG system and is more cost effective than the PV-hydrogen system ii. At a diesel price of $1.36/l, the COE of the hybrid system = $0.929/kWh, of the PV-hydrogen system = $0.274/kWh	[106]
Dhahran, Saudi Arabia	Residential buildings in a remote location with a load of 35.405 MWh/yr load	4 kW solar-PV, 10 kW DG, Surrette 6CS25P battery (nominally 6 V, 1156 Ah)	i. The hybrid system yielded a fuel savings of 19% compared with the diesel-only system ii. The hybrid system reduced carbon emissions by 19%, representing 2 tons/year. iii. At a diesel price of $0.1/l, the COE and NPC of the hybrid system = $0.178/kWh and $98,911, of the DG-alone system = $0.129/kWh and $71,397	[107]
Rawdat Ben Habbas Village near Rafha, Saudi Arabia	Village houses, with a primary load of 17,155 MWh/yr	2000 kW solar-PV, 1250 kW, 750 kW, 2250 kW and 250 kW DG, 300 pieces battery (4 V 19,00 AH)	i. The hybrid system with 21% solar-PV could reduce GHG emissions by 66,422 tons throughout the plant's lifetime ii. The hybrid system would be the most economical solution for the site at a fuel price of $0.60/l or above compared to the diesel generator system	[108]

Table 3 (*continued*)

Study/Project location	Load type	Design capacity	Outcome	Source
			iii. At a diesel price of $0.2/l, the COE of the hybrid system = $0.219/kWh, of the DG-alone system = $0.190/kWh	
Three sites in Bangladesh: Cox's Bazar, Sylhet and Dinajpur[c]	50 rural households with 18.25 MWh/yr primary loads for each site	6 kW solar-PV, 10 kW DG, 10 piece battery (2 V, 800 Ah)	i. The solar-PV diesel hybrid system was more economical and eco-friendly than the commonly used DG system ii. The hybrid system designed here reduces CO_2 emissions by 15,421 kg or 38% annually iii. The COE and NPC of the hybrid system = $0.371/kWh and $95,814.423	[109]
Brac Island, South Croatia	Mobile phone base station with a load approximately 3.504 MWh/yr	2.5 kW solar-PV, 0.6 kW DG, 8 piece battery (12 V, 300 Ah)	i. The hybrid solar-PV/diesel system was the economical solution for this location ii. At a diesel price of $1.8/l, the COE of the hybrid solar-PV/diesel system = $0.534/kWh, of the hybrid solar-PV/fuel cell system = $0.662/kWh, of the solar-PV alone system = $0.722/kWh	[110]

Currencies were converted according to the months specified below.

[a] US$ 1 = 3.80 Ringgit (March 2002).

[b] US$ 1 = 54.62 Indian Rupee (December 2012).

[c] US$ 1 = 68.5 Taka (June 2009).

less dependent on diesel fuel, with a COE and NPC of the HSWHD system of $0.194/kWh and $2,687,272, respectively, compared with $0.239/kWh and $3,320,838 for the HSWD system.

Bekele and Tadesse [127] studied a site in Taba in the Dejen district of Ethiopia. The hydroelectric power potential is much higher than those of other sources, but to avoid capacity shortages, they included solar, wind and diesel energy sources in the system. Despite the slight increase in the COE ($0.16/kWh) of the hybrid system compared to the national COE ($0.101–$0.115/kWh), the hybrid solar-wind-hydroelectric-diesel system was preferred for the location in Taba at a diesel price $1.05/l. This study showed that to produce a cost-effective and reliable system, it is important to utilize the sources available at the site.

Gupta et al. [128] introduced an economical hybrid system consisting of solar-PV, wind, micro-hydroelectric, biomass and diesel energy sources. This project was located at Jaunpur block of the Tehri Garhwal district of Uttaranchal State, India and had an annual energy requirement of 810 MWh. The micro-hydroelectric and biomass received more focus at this site than solar or wind due to the energy potential at this site. However, including more sources increased the stability of the power supply and made the energy cost economically feasible ($0.062/kWh) for this site.

In another study, Kumaravel and Ashok [129] also designed a hybrid system with solar, hydroelectric and biomass energy sources and compared that system with another system. The hybrid system was designed for a 20.44 MWh/year load for a remote area in Kakkavayal, a forest region in Kerala, India. The hybrid system was more cost-effective and preferable for the location under study. The cost of energy (COE) was found to be $0.164/kWh for the 2 kW solar-PV, 15 kW pico-hydroelectric, 5 kW biomass generator hybrid system. For the same load and location, solar-PV/biomass, solar-PV/hydroelectric/diesel and solar-PV/hydroelectric systems were also designed for comparison with the proposed hybrid system. The cost of energy (COE) of those systems was found to be $0.253/kWh (for the solar-PV/biomass system), $0.273/kWh (for the solar-PV/hydroelectric/diesel system) and $0.323/kWh(for the solar-PV/hydroelectric system).

4. Conclusion

The World Bank and the IEA have reported that the worldwide demand for electrical power is increasing so rapidly that a doubling in installed capacity will be required in the next few decades. To meet the anticipated demand, solar energy is one of the best solutions. This study confirms the utility and cost-effectiveness of solar energy, particularly solar-PV technology and highlights its performance in stand-alone and hybrid energy systems for off-grid rural electrification over the last few decades. A great deal of research has been conducted to make this form of energy a feasible source of power generation. This review of the last twelve years of research, demonstrations and case studies revealed that solar energy can be a viable solution for the provision of power throughout the world, especially to electrify rural off-grid locations as an eco-friendly and cost-effective solution.

Due to the variations in climate among different locations, the usage of solar energy varies geographically. This study showed that some places experience sufficiently strong solar radiation that a stand-alone solar-PV system is able to reliably meet the energy demand for small loads such as household, agricultural or small office loads in distant locations. However, in some places where the solar radiation is not consistent enough and a high load must be met to power a large community or industry located far from the grid, another source needs to be added to obtain a reliable, cost-effective power supply. Other sources, including wind, hydroelectric and diesel generators, have been successfully combined with solar power in hybrid systems. Despite its harmful gas emissions, the diesel generator provides a trustworthy energy source for coupling with solar energy due to its well proven technology. However, the maintenance of this system is a major concern for rural people, who are often poor, with low levels of education and a lack of familiarity with modern technology. For those individuals, both the stand alone solar-PV system and the hybrid solar-PV system will provide excellent electrification performance without high maintenance demands. Thus, this study

Table 4
Hybrid solar-PV/wind/diesel systems introduced over the last twelve years and their outcomes.

Study/Project location	Load type	Design capacity	Outcome	Source
Al-Mazra'a Al-sharqiyah, Ramallah, Palestinian	Lighting fixtures, radio/TV, domestic appliances (washing machines, fans, refrigerators and others), street light, for a total load of 18,250 kWh/yr	7.3 kW solar-PV, 5 kW wind turbine, 4 kW DG, 40 kWh battery	i. With a 60% contribution from solar-PV, the COE of the designed system has become cheaper than the other solutions ii. The hybrid system also significantly reduces the CO_2 production compared to the diesel-only system iii. The COE of the PV/wind/diesel system=$0.281/kWh, of the PV-diesel system=$0.332/kWh, of the wind-diesel system=$0.433/kWh, of the wind-only system=$0.534/kWh, of the PV-only system=$0.743/kWh, of the diesel-only system=$0.743/kWh	[119]
Johor Bahru, Malaysia[a]	A four story Electrical Engineering Faculty building at the University of Technology Malaysia (UTM), with a load of 278.495 MWh/year.	80 kW solar-PV, 80 kW BWC Excel-S wind turbine, 80 kW DG, 50 units Surrette 6CS25P battery	i. The hybrid system significantly reduces the fuel consumption and CO_2 emissions by approximately 30 and 34.5%, respectively ii. While the COE of the hybrid system was higher than that of the diesel-only system, the system would be more cost-effective at a diesel price of $2.26/l iii. At a diesel price of $0.565/l, the COE and NPC of the hybrid system=$0.510/kWh and $3,201,243.86, of the DG-alone system=$0.437/kWh and $2,740,458.01	[120]
Kuakata, Bangladesh	Typical load for distant areas	20 kW solar-PV, 20 kW wind turbine, 10 kW DG, 6 V 225 Ah Trozan T-105 battery	i. Although the energy cost of the wind/diesel system was low, this system was not reliable due to the variable nature of wind energy ii. The hybrid solar-PV/wind/diesel system was selected for this site due to the variable nature of solar and wind in winter and the rainy season iii. The COE and NPC of the hybrid solar-PV/wind/diesel system=$0.071/kWh and $474,139, of the hybrid solar-PV/diesel system=$0.145/kWh and $973359, of the hybrid wind/diesel system=$0.029/kWh and $192975, of the diesel only system=$0.216/kWh and $1,447,352	[121]
Rawdat Ben Habbas Village, Saudi Arabia	Village load approximately 17,043.4 MWh/yr	1 MW solar-PV, 1.8 MW wind turbine, 4.48 MW DG	i. The hybrid system reduced annual CO_2 emissions by 4976.8 tons, consequently saving 10,824 barrels of fuel per year ii. The COE of hybrid system=$0.212/kWh, of the DG-alone system=$0.232/kWh	[116]
Remote location in Ethiopia	200 families with a total load of approximately 52.049 MWh/yr	5 kW solar-PV, 20 kW wind turbine, 44 kW DG, 40 pieces Surrette 6CS25P battery	i. The hybrid system with 51% renewable energy yielded a slightly higher COE than the diesel-alone system, but the GHG emissions were decreased ii. The COE and NPC of the hybrid system=$0.383/kWh and $239,756, of the DG-alone system=$0.322/kWh and $201,609	[122]
Dakar, Senegal[b]	Varying load	470 W solar-PV, 10 kW wind turbines, 5 kW DG, 860 Ah battery	i. The hybrid solar-PV/wind/diesel system was more cost-effective than the other tested systems ii. The total cost of the hybrid solar-PV/wind/diesel system=$92,298.35, of the hybrid wind/diesel system=$244,077.16 and of the hybrid solar-PV/diesel system=$108,788.53	[123]
Three sites in Oman: 1. Saiq 2. Khalouf 3. Al Zahiya	Different loads for the different areas	1 kW solar-PV, 6 kW wind turbine, 6 kW DG, 5 pieces Surrette 6CS25P battery for Saiq;5 kW solar-PV, 180 kW wind turbine, 450 kW DG, 60 pieces Surrette 4KS25P battery for Khalouf; 5 kW solar-PV, 180 kW wind turbine,	i. The load characteristics and RE sources are not similar among these three areas, although wind is the priority in all three locations because of its availability. However, for all sites, the hybrid solar/	[124]

Table 4 (*continued*)

Study/Project location	Load type	Design capacity	Outcome	Source
		300 kW DG, 50 pieces Surrette 4KS25P battery for Al Zahiya	wind/diesel system was preferred because of the variable nature of wind energy. ii. The hybrid system significantly reduces the emissions of polluting gases. iii. The COE and NPC of the hybrid system are \$0.233/kWh and \$93,000 for Saiq, \$0.162/kWh and \$3,154,000 for Khalouf and \$0.194/kWh and \$2,344,000 for Al Zahiya	
The rural villages of Ethiopia	The total energy demand was 28.47 MWh/yr	5 W solar-PV, 3 kW wind turbines, 15 kW DG, 16 kWh battery	i. This study showed that the COE of the hybrid solar-wind-diesel system increased as the renewable fraction (RF) increased ii. The COE at 0.84% RF was \$0.302/kWh, while the COE at 100% RF was \$0.376/kWh	[125]
Ain-Guezzam/ Tammanrasset, situated on the border between Algeria and Niger	16.425 MWh/yr with a peak demand of nearly 3.7 KW.	1 W solar-PV, 2.48 kW wind turbines, 2.6 kW DG, 13 (12 V 125 Ah) batteries	i. The hybrid PV-wind-diesel system with a 47% renewable fraction was the most economical system ii. The COE and NPC of the hybrid PV/wind/diesel system=\$0.533/kWh and \$79,627, of the hybrid solar/diesel system=\$0.584/kWh and \$87,239	[126]

Currencies were converted according to the rates in the months specified below.

[a] US\$ 1=3.096 Ringgit (February 2011).

[b] 1 Euro=US\$ 1.3102 (December 2012).

suggests that solar energy is a cost-competitive, eco-friendly, low maintenance, alternative power solution for any load in rural locations far from the grid.

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