Off-Grid PV-Based Hybrid Renewable Energy Systems for Electricity Generation in Remote Areas

H. El-houari, A. Allouhi, M. S. Buker, T. Kousksou, A. Jamil, and B. El Amrani

Abstract Wind, solar, biomass, and geothermal energy are renewable energy sources known as promising alternatives for electricity generation, especially with the depletion of fossil fuels. Renewable energy sources are present, with huge quantities, free access, and without a negative impact on the environment. The electricity produced by renewable energies is gradually becoming economically and technically advantageous. In most cases, integrating a single source of renewable energy can lead to over-sizing and therefore a very expensive implementation. To remedy this, systems consisting of one or numerous renewable energy sources are adopted in order to guarantee maximum electricity production as well as practical reliability at encouraging costs. In addition, the electricity generated by renewable energy sources such as wind turbines, solar, biomass, geothermal energy … has a particular interest in isolated spaces. This chapter provides an updated literature review about Off-grid PV-Based Hybrid Renewable Energy System for electricity generation in remote areas. First, after the introduction, a presentation of the world energy situation was discussed in order to see the progress of the implementation of renewable energies on a global scale. Secondly, a section was reserved for renewable energy alternatives in order to discuss each source separately, before starting the part devoted to off-grid hybrid renewable energy structures. These structures have been examined in a large number of researches works with the aim of electrifying remote areas in several countries of the world. Finally, a detailed presentation of the main reliability, economic, and environmental performance indices is given for the evaluation of these systems.

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1 Introduction

A growing number of the world population, development of civilization, progress in the technological fields, and other factors contribute to growing energy needs in order to increase welfare on all scales. Electricity is a fundamental factor for economic development, urbanization, and industry in countries [1–3]. Production of electricity originates mostly from burning large quantities of fossil fuels. This excessive use of fossil fuels causes its exhaustion and consequently destroy the environment through greenhouse gas emissions, which has led to negative climate change experienced today [4, 5].

Under the current status of high energy demand, it is very necessary to seek other types of energy sources to be able to meet the energy demand in big cities also in isolated and remote regions. These sources should be environmentally friendly, with good performances at competitive costs [6]. The worldwide population without access to electricity is around 1.2 billion and 48% of them are located in the developing countries of Sub-Saharan Africa [7]. The adoption of multiple renewable energy is a good way to produce clean electricity and can be tailored for each geographic zone with respect to its renewable energy potential [8–11]. Furthermore, the overall efficiency and economic performance presented by these off-grid Hybrid Renewable Energy Systems (HRESs) were proven to be encouraging as highlighted by several studies [12–14]. Solar power generations including photovoltaics (PV) and Concentrating Solar Power (CSP), hydroelectric (small and large), wind turbines (onshore and offshore), biogas, and biomass have experienced a particular interest in recent years [15–17].

The main shortcoming of standalone renewable energy sources is that such systems produce electricity intermittently. Hybridization solves this problem since two or more technologies complement each other to avoid intermittency of energy supply [18, 19]. In this context, the HRESs can be exploited in two different ways either grid-connected; or operating autonomously with the storage systems. The latter option is more suitable for villages, regions, areas, and isolated islands. In the case of energy surplus, the excess energy can be stored for later use when the hybrid system cannot satisfy the energy demand.

In the case of HRES connected to the network in cities, towns, universities, factories, etc., the excess energy can be directly injected into the electrical network. In this method, the cost of electricity produced by the HRES is lower than the autonomous system [20].

Therefore, several studies suggested that HRES with storage implement in isolated zones requires a specific regulation as well as an adequate policy to accompany such standalone systems [21, 22]. These regulations must be diverged from already-adopted ones for HRES connected to the network and must support standalone HRES to face technical, regulatory, and financial challenges and constraints [23, 24]. These regulations and policies should in addition, respect and agree with the local and national conditions of each country [25, 26]. Having acknowledged these challenges and ensuring that standalone Hybrid Renewable Energy Systems can offer significant advantages socially (sustainable development and reduction of poverty), environmentally (reduction of greenhouse gases), and economically (predictable energy price). All these can satisfy the energy demand without a network with easy integration and simple installation of the system [20, 27].

Since the optimal design of HRES is a primary factor with likely combinations, therefore, several studies have already been carried out by using various software. The evaluation of HRESs is performed based on numerous criteria for looking into the sizing problem comprehensively [13, 28, 29].

This chapter focuses on standalone PV-based HRES for power generation in rural areas, villages, and remote islands by reviewing various HRESs architectures, formulating basic mathematical background for modeling multiple energy source systems, and proposing key performance indicators for the techno-economic assessment of such systems. Although there are numerous studies about the hybrid renewable technologies in the existing literature, the sizing procedures regarding various renewable systems with energy storage are not investigated extensively. Therefore, the novelty of this article is to present a comprehensive discussion about various HRES configurations with energy storage and demonstrate detailed reliability, economic, and environmental performance indices of the evaluated systems. In line with the objectives, this manuscript is structured as follows: Sect. 2 provides an overview of the global renewable energy sector; Sect. 3 presents the modeling of the subsystems. Section 4 details various combinations of the standalone hybrid renewable energy systems, as well as multi-criteria performance indexes, are discussed in Sect. 5.

2 Overview of the Worldwide Renewable Energy Sector

The sector of renewable energy (RE) as well as their widespread use is at the top of the worldwide energy policy, especially for the many environmental and energy outcomes they are providing [30–32]. The whole world needs to increase the share of renewable energies for electricity production, especially with the increase in population and industrialization, the exhaustion of fossil fuels, and the environmental damage they have caused.

Keeping in mind these considerations, several countries adopted national energy strategies in order to accompany the world energy transition. In recent years, renewable energies have experienced rapid development and growth, taking profit from reduced production costs of technologies (especially wind turbines and photovoltaic panels) as well as the adopted policies and strategies.

Table 1 Production growth achieved by each technology in 2018 and average annual growth 2018–2030

Renewable technologies	Production growth achieved in 2018 (%)	Average annual growth 2018–2030 (%)
Solar PV	31	16
Onshore Wind	12	7
Offshore Wind	20	–
Hydropower	3	2.5
Bioenergy	5	6
Concentrating solar power (CSP)	17	26
Geothermal	5	10
Ocean power	16	24

According to the **International Energy Agency**, electricity which comes from renewable energies represents 1/5 of the world's energy needs.

Moreover, on a global scale, 2018 saw 26% of global electricity production via renewable energies, which indicates an increment of 7% compared to the year 2017 [33]. It is interesting to highlight that the production of WT, solar, and hydroelectric represents 90% of the electricity originating from the total renewable energy in 2018 [34].

To reach the objective for the Sustainable Development Scenario 2000–2030, it is necessary to ensure that there is a global growth of 7% of production via renewable energies. The following Table 1 shows the production growth achieved by each technology in 2018 [34], as well as the average annual growth that each of these technologies will reach between 2018 and 2030 so that at the end, the annual growth of 7% can be achieved.

However, this growth in renewable energies is not uniform across the world. Today, it is in Europe that renewable energies represent the most important part of energy consumption, with 17% on average according to the International Energy Agency. South America is also doing well with its large hydroelectric infrastructures: in Brazil, for example, 42% of energy consumption is from renewable sources. But this is not the case in all the countries of the region, some of which still have an energy mix with a very poor share of renewable energy.

For the United States, only 10% of the energy consumption is obtained from renewable energies. China and India are capped at 10 and 11%, respectively.

Morocco is one of the countries that have acceded to international conventions to fight global climate change. It was the organizer of the Conference Of the Parties (COP22) in 2016 in Marrakech. Since 2009, Morocco has adopted an energy strategy to improve the effectiveness of its power sector. The ambitious strategy adopted had a challenge of increasing the production of electricity by exploiting renewable energies to reach 42% at the end of 2020 and 52% by 2030 as shown in Fig. 1 [35].

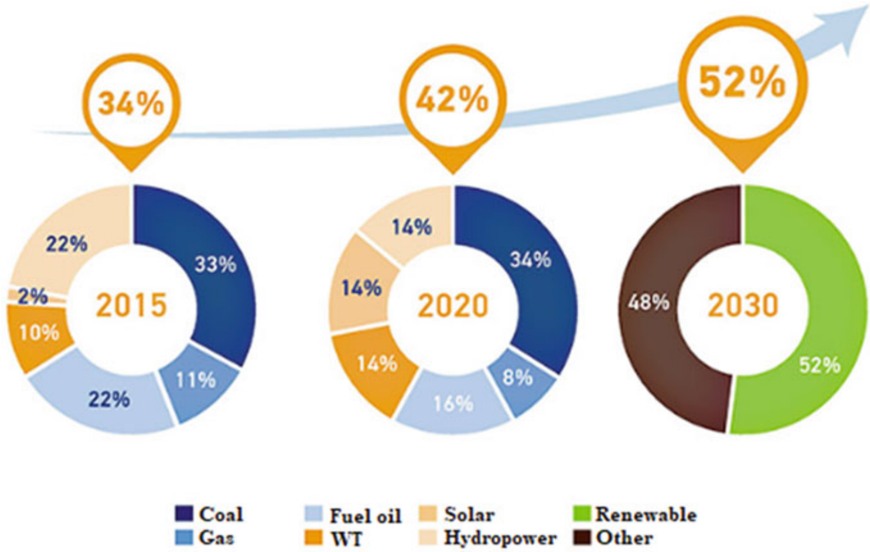

Fig. 1 Increase in the Moroccan energy mix between 2009 and 2030

According to the Ministry of Energy of Morocco, in 2018 the country has already installed power of 3700 MW of renewable energy which represents a rate of 34% of the national need for electricity.

3 Renewable Energy Alternatives

For modeling the various subsystems of an HRESs, there are several methods used by researchers. The most widely and simple modeling approaches are treated in the next section.

3.1 *Photovoltaic*

The power generated P_{PV} (kW) by a PV panel is illustrated in the **equation** [36–39]. The PV panel contains cells placed in parallel and in series with each other to produce the required power. The energy produced is dependent on solar radiation and the cell temperature:

$$P_{PV}(t) = P_{rated} \times Y_{PV} \times \left(\frac{G}{G_{ref}}\right) \times \left[1 + K_T\left(T_c - T_{ref}\right)\right] \quad (1)$$

P_{rated} is the estimated power that the PV panel can generate under standard conditions, Y_{PV}(-) means the derating factor of the Photovoltaic panels, $G\left(\frac{w}{m^2}\right)$ and $G_{ref}\left(\frac{1000}{m^2}\right)$ means the incident solar radiations and the conditions of the test standards respectively, K_T is taken around 0.4 and 0.6% according to [40] is the Photovoltaic temperature factor; $T_c(C)$ is the temperature of the cells that make up the PV panel and T_{ref} (25 °C) means their temperature under the conditions of the test.

3.2 Wind Turbine

Multiple mathematical models of the wind energy production process have been employed by the research community. The power produced by a WT is influenced by three parameters which are the wind speed, the hub height, and the power curve of the wind turbine. The estimate of the power generated by the wind turbine $P_{WT}(kW)$ is explained as follows [41]:

$$P_{WT} = \begin{cases} 0 & V < V_{cut-in}\, and\, V \geq V_{cut-out} \\ \frac{P_r(V - V_{cut-in})}{(V - V_{cut-in})} & V_{cut-in} \leq V < V_r \\ P_r & V \leq V < V_{cut-out} \end{cases} . \tag{2}$$

Or

$$P_{WT} = \left(\frac{\varphi}{\varphi_0}\right) \times P_{WT,STP} \tag{3}$$

where V_r and P_r represent the nominal wind speed and the nominal power, respectively. V_{Cut-in} and $V_{Cut-out}$ means the speed in and out, respectively. $P_{WT,STP}$ means the estimated power of the wind turbine under standard conditions (kW), φ and φ_0 represents the real density of the air and the density of the air in the test conditions (1.225 kg/m^3).

3.3 CSP

CSP referring to concentrated solar power, is a power plant that concentrates the rays of the incident sun using mirrors in order to heat a heat transfer fluid which generally makes it possible to produce electricity via a thermodynamic cycle. This type of power plant allows, by storing this fluid in a tank, to prolong the operation of the power plant for several hours beyond sunset.

3.4 Hydropower

Hydroelectricity is the conversion of hydraulic energy into electricity. The kinetic energy of the water current, natural or generated by the level difference, is transformed into mechanical energy by a hydraulic turbine, then into electrical energy by a synchronous electric generator. The hydroelectricity power $P_{hydro}(kW)$ can be calculated by the following equation.

$$P_{hydro} = \frac{\eta_{hydro} \times \varphi_{water} \times Q_{turbine} \times g \times H_{net}}{1000W/kW} \tag{4}$$

where $\eta_{hydro}(\%)$ is the turbine efficiency, $Q_{turbine}$ represents the nominal water flow of the turbine (l/s), φ_{water} means the water density (1000 kg/m^3), g means the acceleration due to universal gravitation (9.81 m/s^2), and $H_{net}(m)$ represents the net height.

3.5 Biomass

The generation of electrical energy from biomass can be carried out according to two mechanisms either by the thermochemical process (pyrolysis or direct combustion, gasification) or using the biochemical mechanism (anaerobic digestion or gasification). At the end of the two mechanisms, there is a recovery of a fuel which can be either in the gaseous state or in the liquid state [42]. The gasifier transforms biomass (solid) into fuel (gas), the output power of the biomass generator $P_{ge,bio}$ is illustrated in the following equation [43–46].

$$P_{ge,bio} = \eta_{ge,bio} \times Q_{ge,bio}(t) \times LHV_{bio} \tag{5}$$

where $\eta_{ge,bio}$ (%) is the electrical conversion efficiency, $Q_{ge,bio}$ (m^3/h) represents the flow rate of the fuel consumed LHV_{bio} (kWh/m^3) means the low calorific value of the biogas.

4 Off-Grid Hybrid Renewable Energy Structures

HRESs are generally divided into two broad categories: on-grid and standalone. The second category is the main focus of this study in order to design an optimal system for the electrical needs of remote areas. As hybrid renewable energy systems are the combination of two or more energy sources, at least two essential elements must be taken into account to structure a hybrid renewable energy system. The first criterion is the existence or absence of a storage system. Storage systems will store energy

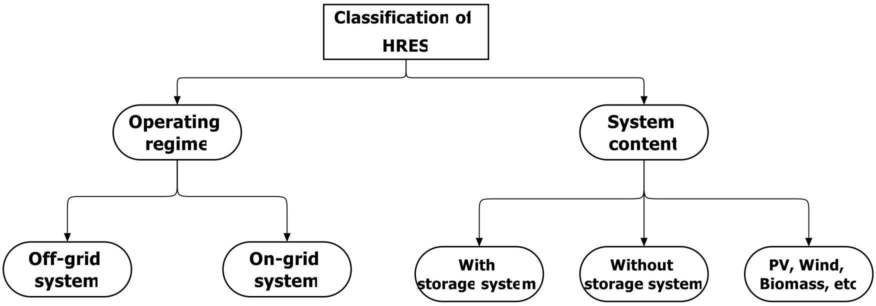

Fig. 2 General classification of hybrid renewable energy systems

during excess production and reuse when needed. The second criterion is the structure of the HRES, comprising various renewable technologies (PV, Wind, Hydro, etc.). Figure 2 shows the general classification of HRESs.

To successfully satisfy the energy demand, the configuration of the proposed system is key. It should be carefully tailored considering available energy sources and the capacity of the system as well as the specifications of the storage system. Thus, the cost of energy will be reduced, CO_2 emissions will be minimized and energy requirements will be met. Given the number of configurations for HRESs (see Fig. 3) and their complexity, the palpable approach is the optimization of these systems [28]. Favorably, several algorithms and software have been developed [47] to help to optimize the energy systems.

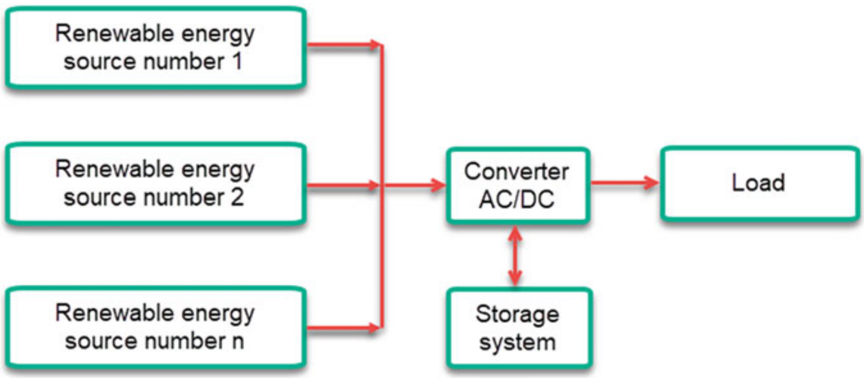

Fig. 3 Renewable hybrid energy system with n sources

4.1 Hybrid System with Two Renewable Energy Source and Storage System

4.1.1 Off-Grid PV/Wind

The PV–Wind off-grid system is a mixture of a wind turbine, solar panels, converter, and storage system, as shown in Fig. 4. Photovoltaic solar is considered to be a random and variable power [48], the solar radiation is variable during the day and all seasons. On the other hand, the wind turbine is considered a reliable source of energy taking into account the presence of constant wind blows during day and night despite the variation in wind speed [49]. In detail, electricity production is obtained mainly from PV panels during the day and from windmills during the night [50]. Hence, this PV–WT combination is massively adopted given the complementary energy production through this configuration, its reliability, and adaptability in any weather condition [51–53]. Moreover, the energy storage system will store excess energy production from hybrid PV–WT combination and meet the energy demand when electricity supply through the system is insufficient.

A significant number of studies have been carried out in the literature concerning these configurations including PV–Wind, PV, and Wind with a storage system. In [54, 55], the system that combines the two technologies (PV–Wind with a storage system) is the most profitable for isolated areas. Another study is conducted aiming to optimize the number of wind power units, PV panels, and batteries in order to reduce the capital cost of the system while securing the reliability of the hybrid renewable system [56]. Ghorbani et al. [57] presented a specific optimization and analysis process for a wind–solar system in isolated areas in the south of Brazil, with the aim of reducing the initial costs of the system. Store et al. [58] studied two energy management methods for a standalone Wind–PV system for a residential site in Denmark. Custom models have been set up as well as the actual renewable sources have been used. Papadopoulos et al. [59] have shown that the use factor of the electrolyzer is influenced by the configuration containing renewable energy sources,

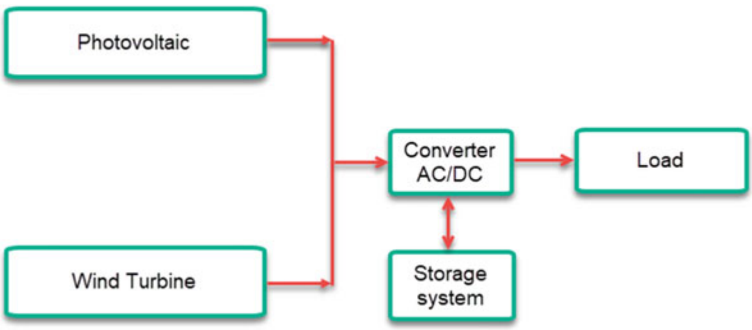

Fig. 4 Standalone PV–WT hybrid system

for this purpose several combinations of PV–Wind and storage technologies have been developed. Belouda et al. [60] presented a study focused on optimal design of the PV–Wind–Battery multi-objective system to satisfy the electrical load of a remote area. The two optimization points discussed are the loss of power supply probability (LPSP) and the general cost of the system using a multi-objective NSGA-II algorithm. Zhang et al. [61] have carried out a study on a PV–Wind–Battery system by adopting NSGA-II genetic algorithm which has as the objective of determining the number of PV, wind, and battery as well as the LPSP and general cost of the system for an isolated island. The system was tested under four scenarios of weather conditions. A study on a system composed of PV, wind turbines, and batteries for an island of Jeju was carried out by [62]. The study showed that LCC and LCOE equal to 84.3 BUSD and 0.42 $/kWh, respectively. Samy et al. [63] have set out a study of three combinations of a PV–FC, PV–Wind–FC, and Wind–FC hybrid system in Remote district, Beni-Suef, Egypt. The study showed the PV–Wind–FC system is the best combination with an energy cost worth 0.47 $/kWh. Another study which was carried out by [64] to satisfy the energy demand of Makadi Bay, Red Sea, Hurgada, Egypt in the presence of PV, Wind, and battery as well as a comparison was performed between PV–Wind–Battery and PV only and Wind only scenarios. The results showed that the PV–Wind–Battery system is the best configuration in terms of installation cost of the three systems. Benavente et al. [65] presented a modeling and simulation of a PV–Battery system for a rural area containing a school, household, and a health center in the highlands of the Bolivian Altiplano. The simulation was carried out on the basis of real consumption data as well as meteorological data, the results found that to avoid the SD effect and ensure that system is profitable, it is necessary to have a greater power of the PV field rather than increasing the battery capacity.

4.1.2 Off-Grid PV/Biomass

The second off-grid HRESs configuration is the PV, Biomass, converter, and a storage system as shown in Fig. 5. The proposed configuration is a promising alternative for

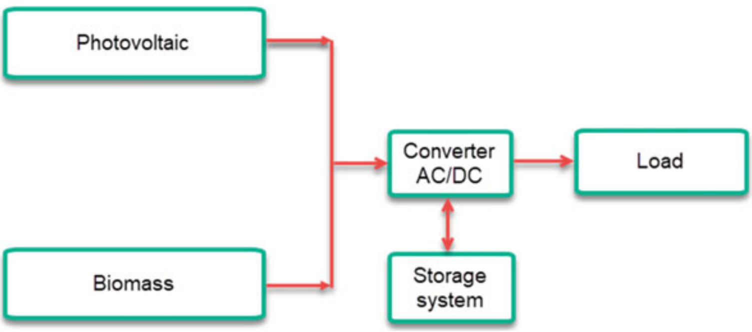

Fig. 5 Standalone PV–Biomass hybrid system

electricity generation, especially in remote areas. In most rural areas there is the abundant presence of an animal, agricultural, municipal waste, etc. [66] can be well utilized as a fuel for biomass generator. The advantage is that biomass is controllable (present when needed) which is considered to be the 4th biggest source of energy total in 8.5% of global energy consumption. The drawback of biomass is that when the fuel is not available, it must be somewhat purchased [67]. In operation, anaerobic digestion is considered to be one of the best-known techniques of energy extraction. Moreover, biogas is considered to be one of the end products that is used to generate electricity [68–70] using a biogas generator [43, 71].

To name a few recent studies about PV, Biomass, converter, and a storage system configurations, Shahzad et al. [72] represented a technical-economic study of a sytem composed of PV–Biomass–Battery for a small village (farm and residential) in Pakistan. The optimal configuration obtained in the results is 10 kW of PV, 8 kW of biogas generator, 12 kW for the converter, and 32 unit of batteries the recovery period was estimated to be 9.5 years and the cost of electricity was found to be equal to 5.51 PKR/kWh. Ganthia et al. [73] carried out a study on energy demand of the Khalardda village located in Odisha and the system chosen for this objective is PV–Biomass. Kohsri et al. [74] analyzed a PV–Biomass–Battery system in a rural area of an educational institute in Thailand. The results showed that optimal configuration comprises three converters each with a capacity of 12 kW, a biomass generator with a capacity of 33.7 kW, battery with a capacity of 60.9 kWh, 12,285 kW of PV, and 13.8 kW of three BDIs. Heydari and Askarzadeh [45] have designed an off-grid PV–Biomass system to meet the electrical needs of agricultural wells located in Bardsir, Iran. As several scenarios were analyzed, the PV–Biomass system was found to be better in comparison to PV alone or biomass alone system. The cost of electricity was estimated at 0.1855 $/kWh and the capacity of the Biomass and PV system was found to be 180 kW and 75.2 kW respectively. Singh and Baredar [75] presented an off-grid system composing Biomass–PV–FC–Battery at Maulana Azad National Institute of Technology, Bhopal in India. The simulations were carried out via Homer, the cost of electricity and the NPC were found equal to 15.064 Rs/kWh and 51,89003 Rs, respectively. Eteiba et al. [76] used three algorithms to find an optimal solution for the standalone biomass, PV, and battery system for a Monshaet Taher village in Egypt. The results pointed out that the system must include 200 kW of biomass, 131.04 kW of PV, and 298 batteries. Ghenai and Janajreh [77] presented a system composed of Biomass–PV to satisfy the need for electricity in the city of Sharjah in the United Emirates. The COE found equal to 0.328 $/kWh. Pradhan et al. [78] analyzed the performance of a standalone Biomass–PV–Battery system to satisfy the electrical charge of around 20 kWh/day for a house located in a remote area. Chowdhury et al. [79] developed an autonomous mini-network made of Biomass–PV for a remote area of Ashuganj, in Bangladesh to be able to meet the annual energy demand of 14,161 MWh. Analysis showed that the return on investment period was found to be 6.9 years as well as the amount of CO_2 avoided is approximately 3.81 tons/year.

4.1.3 PV/Hydro

In this section off-grid, PV–Hydro hybrid renewable system will be analyzed to meet the energy needs for isolated areas. The combination comprises photovoltaic solar and hydropower (see Fig. 6). Since PV panels are highly affected by ambient conditions, hydroelectricity is, on the other hand, a more flexible, stable, and adjustable sort of energy source [80, 81]. This is another complementary system as there is less solar irradiation but a high level of water during the winter and there is a risk of dry dams but abundant solar irradiation during the summer. Recently, the price of the PV system has dropped drastically, therefore the PV–hydro system seems economically feasible [82].

Yibo and Honghua [82] fitted out a study on a standalone PV–hydro system in Yushu in China, the structure of the PV panels belongs to the MW class as well as the battery of the DC bus. Das and Akella [83] presented a PV–hydro–battery hybrid system with a management control strategy and simulated using MATLAB/Simulink. The results found show that the battery life will be extended once the SOC is born between its limits. Singh [84] developed an autonomous PV–Hydro system to meet the energy needs of remote areas. In this study, a VSC control model was proposed. Kougias et al. [85] presented an optimization algorithm to ensure complementarity between the two renewable technologies of PV–Hydro. Also, the proposed strategy was tested in a case study. Shan et al. [86] performed a study regarding the complementary between PV and hydroelectric in California Independent System Operator (CAISO). The results showed that when the share of electricity production of PV increases by 1%, on the other side hydroelectricity increases between 0.01% and 0.06% this correlation is important to meet peak energy needs. Silvério et al. [87] studied a technical-economic design approach for PV–Hydro hybrid systems, as well as a case study of the São Francisco hydroelectric station in Brazil which suffers from intense drought. The results showed that PV panels should have been tilted at 3° and the proposed system can be generated from electricity at low cost.

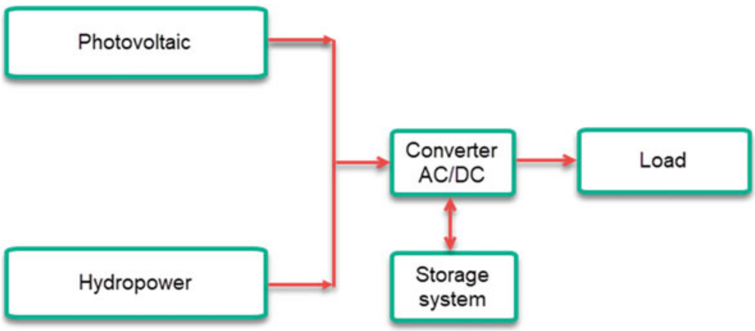

Fig. 6 Off-grid PV–Hydropower hybrid system

4.1.4 CSP/PV

The fourth combination to study is the CSP/PV hybrid standalone renewable energy system. This is the combination of two different technologies fed by the same energy source as shown in Fig. 7. The CSP technology is still immature compared to PV technologies, worldwide the capacity of the installed CSP does not exceed 5.5 GW until the end of 2018 [88]. The common preference of the two technologies is the abundance of solar radiation. The electrical conversion efficiency by these two technologies is greatly influenced by dirt, clogging, and the deposit of dust [89, 90].

CSP is suggested as a continuous and stable power generation technology in parallel with a thermal storage system [88]. But so far CSP was among the least deployed technologies compared to other solar technologies as the installed capacity of CSP by the world in 2018 was around 5.5 GW [91]. The cost of electricity generated via CSP is higher than that of conventional sources, on the other hand, PV is in the same range [92]. The PV–CSP combination has several advantages as a whole, especially in terms of the cost of electricity [93] and also the large capacities provided through these two technologies. This combination has been tested in the Atacama desert in Chile, the results showed that the capacity generated by this system can exceed 85% and have a reduced LCOE compared to CSP-only power plant [94–96].

In another study about off-grid PV–CSP–battery system [97] an optimal configuration was proposed for two sites in Italy and Morocco based on the analysis of several strategies. Also, a parametric study has been done in [98] on a large scale of a hybrid CSP–PV system with two types of BESS storage implemented in working operation. Also, Zhai et al. [99] optimized a PV–CSP system in order to achieve the lowest possible cost of electricity by integrating a small capacity battery and improving its use. Zurita et al. [88] conducted a study to assess the effect of time resolution on the modeling of the PV–CSP system with thermal storage and batteries for two sites in Carrera Pinto and Santiago in Chile. Hernández-Moro and Martinez-Duart [100] developed a mathematical method for estimating the cost of energy produced by the PV–CSP system on the basis of other inputs. Aguilar-Jiménez et al. [101] presented a technical-economic study of a PV–CSP system for a remote area of

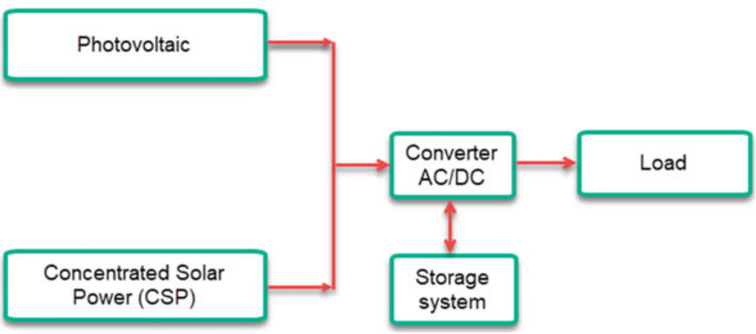

Fig. 7 Off-grid PV–CSP hybrid system

Puertecitos in Mexico. The cost of electricity generated by this system is estimated as 0.524 USD/kWh. Technical and economic analysis of a PV–CSP system by [102] was carried out in three different sites Tabuk, Majmaah, and Najran in Saudi Arabia. The system was designed at the same power output of 100 MW. The results showed that the cost of electricity by the hybrid system is estimated to be 0.105 $/kWh, 0.110 $/kWh, and 0.1 $/kWh for Najran, Majmaah, and Tabuk, respectively. Table 2 summarizes some of the recent research works.

4.2 Hybrid System with Three and More Renewable Energy Sources and a Storage System

4.2.1 PV/WT/Hydro

Another scenario is an off-grid system, constituted of PV–Wind–Hydro energy with a storage system. Solar technology and wind power are naturally intermittent due to depending on the weather conditions. However, as hydroelectricity is controllable, this increases the level of reliability and stability of this configuration. This type of HRESs has been a special focus in the existing research literature as it offers certain advantages including higher electric power supply, high profitability, and efficiency comparing the mono source systems [106].

Bekele and Tadesse [107] treated a feasibility study of a system composed of PV–Wind–Hydro in the district of Dejen, Ethiopia as the study concerned 23 different villages. In the Taba region the price of electricity was found equal to 0.16 $/kWh. Zhang et al. [108] proposed an estimation-simulation approach in order to mark the uncertainties of the systems tester on three optimal short-term operating model as well as the estimation of the probability density function of the operating mechanism. Wei et al. [109] presented a study of a PV–Wind–Hydro system in southwest China with the integration of deep neural networks, the findings showed that the performance of the hybrid plant must be improved. Ye et al. [110] proposed a feasibility study and a simulation of the PV–Hydro–Wind system in the EMTP/ATP platform.

4.2.2 PV/WT/Biomass

This section presents an off-grid system composed of Biomass–Wind–PV sources. Biomass is an energy source that has become very popular especially in remote areas [111]. The combination of these three technologies with storage system is robust in terms of high power output.

In literature, Balamurugan et al. [112] presented a hybrid system composed of Biomass–PV–Wind for remote areas in India, a feasibility and economy analysis was provided by the authors. Dhass and Santhanam [113] quantified a Biomass–Wind–PV system for electrified remote areas on the basis of the life cycle price. Rahman

Table 2 Summary of research work

PV	WT	Bio	Hyd	CSP	Place/Contry	Outcome	References
✓		✓			Bardsir, Iran	The minimum Total Net Present Cost obtained is $ 1672296.6881 with a PV and Biomass portion of 15 and 85% respectively. The COE and perste of electrical supply are 0.1885 $/kWh and 1.9997%, respectively	[45]
✓	✓				House, Tehran, Iran	In this study, a comparison was made between the results found by Homer and hybrid genetic algorithm with particle swarm optimization (GA-PSO) with the aim of minimizing the current total cost. The results found of 0.502 of the discounted cost of energy for the system being studied is considered to be the best result of the two methods	[57]
✓	✓				Zelzate, East Flanders, Belgium	Studied the effect on the employment factor of the electrolyzer when using a renewable energy source instead of the electric grid. Four scenarios were studied with an unchangeable 1 MW electrolyzer: (A) 15 MW PV, (B) 15 MW PV, 2 MW Wind, (C) 15 MW PV, 2 MW Wind, Battery, (D) 15 MW PV, Wind of 15 MW plus the factor is found equal to (A) 41.5%, (B) 65.5%, (C) 66.0e86.0%, (D) 82.0% respectively	[59]
✓	✓				Remote area Borj Cedria, Tunisia	The primary question in this research is the optimal dimensioning of the components taking into account the irradiations, charge cycles, and wind speed based on NSGA-II multi-objective algorithm, the cost of the system, and the LPSP to be optimized	[60]

(continued)

Table 2 (continued)

PV	WT	Bio	Hyd	CSP	Place/Contry	Outcome	References
✓	✓				Island, southeast coast of China	Analysis of the variability of the components of the hybrid system in this study is done via the genetic algorithm (NSGA-II) with two objective functions the loss of electrical power and the total cost of the hybrid system. The results revealed in the case of power demand of 24 V DC, 3500 W, 220 V AC, 2200 W, 2 sets of 6000 W wind turbines, five banks of 24 V 1000 Ah batteries, and 78 PV modules with a peak power of 100 W have been selected	[61]
✓	✓				Jeju Island, South Korea	The COE and life cycle costs were found at 0.42 $/kWh 84.3 BUSD for the optimal capacities of onshore and offshore wind turbines, photovoltaic solar panels, and Li-ion batteries are rated at 16 MW, 1,532 MW, 6,076 MW, and 14,651 MWh, respectively	[62]
✓	✓				Remote district, Beni-Suef, Egypt	The optimization of the total cost of the three combinations of HRESs and the performances were optimized via the Firefly algorithm, the results obtained were compared to those found from the Shuffled Flog Leaping algorithm and the optimization of the particle swarms (PSO). The PV/WT/fuel cell combination incorporated into an electrolyzer. The COE found is 0.47 $/kWh for this hybrid system	[63]

(continued)

Table 2 (continued)

PV	WT	Bio	Hyd	CSP	Place/Contry	Outcome	References
✓	✓				Makadi Bay, Egypte	The optimal dimensioning of the HRESs in this study is made by the TORCHE technique. The results of the analysis showed that the PV/WT/Battery system is economically cheaper than installing each technology individually	[64]
✓		✓			Agricultural farm and the small community, Pakistan	A technical-economic study is carried out by Homer of the PV–Biomass–Battery system. The results found of the optimal solution composed of 10 kW of PV, 8 kW of the bioagas generator and 32 batteries are the initial capital investment cost of 2.64 million PKR, NPC of 4.48 million PKR, the COE 5.51 PKR/kWh the investment return time is estimated at 9.5 years	[72]
✓		✓			Bhopal, Indian state of Madhya Pradesh	The Net Present Cost (NPC) found to be Rs.51, 89003 and the COE raised equal to 15.064 Rs/kWh. The loss of power found is 0%	[75]
✓		✓			Monshaet Taher, Egypt	The optimal configuration is that which contains the Nickel Iron (Ni-Fe) battery with PV-Biomass, with 298 Ni-Fe batteries, 24 PV Panels, and four biomass power systems. The COE and the NPC are 0.084 $/kWh and 2.408.895 $ respectively	[76]
✓		✓			Sharjah, United Arab Emirates	The portion of renewable energy in the HRESs is 74% and 26 of PV and biogas generator, respectively. The COE of the optimal system is estimated at 0.328 $/kWh	[77]

(continued)

Table 2 (continued)

PV	WT	Bio	Hyd	CSP	Place/Contry	Outcome	References
✓		✓			Remote area	In this article the simulation of the HRESs PV-Biomass is carried out by Homer. The portion of electrical production is 62% and 38% of PV and Biomass, respectively, the cost of HRESs is 900,000 Rs /—and the period of return on investment is found equal to six years	[78]
✓			✓		California Independent System Operator (CAISO)	If the production that comes from PV increases by 1% the small hydraulic power plant increases production from 0.01–0.06%	[86]
✓				⊖	Puertecitos Baja California, Mexico	The leveled COE is 0.524 $/kWh for the CSP-PV hybrid system	[101]
✓				⊖	Tabuk, Majmaah and Najran in Saudi Arabia	The LCOE of the three Majmaah photovoltaic power plants, Tabuk, and Najran are 0.038 $/kWh, 0.036 $/kWh, and 0.037 $/kWh, respectively. Conversely, the LCOE of the three CSP factories is 0.110 $/kWh, 0.100 $/kWh, and 0.105 $/kWh in Majmaah, Tabuk, and Najran, respectively	[102]
✓	✓				Remote island, Jiuduansha, Shanghai	In this study a mathematical model is proposed to study the effect of the saturation of a resource by decreasing the other resources, on the scale of the battery park, state of charge, excess energy, NPC, COE, and loss of electrical power. The results showed that a 2 kW wind turbine was chosen with 90% wind saturation penetration on the island studied. The result also reveals that wind power, charge, and battery cost can impact the COE compared to other factors	[103]

(continued)

Table 2 (continued)

PV	WT	Bio	Hyd	CSP	Place/Contry	Outcome	References
✓	✓				Çeşme, Izmir province, Turkey	In this study 24 simulations were made via Homer in order to find the lowest COE. In the results found, the COE of the hybrid system outside the networks and above the electric grid, also battery storage and economically places than hydrogen storage	[104]
✓	✓				Lafarge factory, Al-Tafilah, Jordan	The results found are an optimal system of 26 MW wind power, 20.75 MW PV, and 16.8 MWH Lithium-Ion batteries. The COE is 0.203 $/kWh, the return on investment is estimated at 3.44 years and the net present value is 206.63 M $. The proposed system is capable of reducing the energy bill by 21.58 M $ as well as 71,373 tons of CO_2 emissions avoided	[105]

et al. [114] proposed a design using Homer software of a Biomass–Wind–PV system for a site in Bangladesh. Singh et al. [111] proposed a hybrid Biomass–Wind–PV sizing system with a system to satisfy the electrical charge of a narrow area. The authors used an artificial bee colony (ABC) algorithm to size the components of the central hybrid. The results obtained were compared with those found by Homer and with the particle swarm optimization algorithm.

5 Performance Indexes

Intensive capacity can increase the initial cost of an HRESs. Nevertheless, it is very complex to supply reliability. Therefore, it is very essential to optimize and adjust the capacity of the system to ensure the load [30, 115].

First is to have the design of the HRESs, choosing the right type of renewable energy sources to integrate, is crucial. The second step is to model the subsystem taking into account all the subsystems. Objective functions must be traced. Then, a design of dimensioning is chosen correlating the constraints and specificity of the problems. Finally, the right capacity scheme taking into account the objectives is set. The objective functions are managed by multiple indicators, which have a very great impact on the system. In general, the reliability of the system, the economic and environmental indices are considered. These indicators will be dealt with in the subsections.

5.1 Reliability Index

The electricity production of HRESs systems is very much influenced by weather conditions and the climate, which does not leave the electrical supply considered to be reliable and safe. Reliability indices were taken into account in order to examine the capacity of the integrated system to meet the desired electrical charge.

The reliability indices essentially include the Possibility of Failling Power Supply (PFSP), Possibility of Failing Load (PFL), Hoped Energy not Provided (HEP), Possibility Lack of Power Supply (PLPS), Loss of Load Desired (LLD).

5.1.1 Possibility of Falling Power Supply (PFSP)

PFSP is determined to be an electricity supply margin which is not taken into account to meet the electrical demand [116]. This indicator is considered one of the most important factors for measuring the reliability of the HRESs. There are two ways to calculate this index either based on the chronological simulation, which is difficult on the computer scale because it requires temporary data or by a commitment to apply technical probabilities based on the instability of the energy and charge [117, 118]. The following equation [118, 119] has been used to optimize the capacity of a system not connected to the network in Iran [120].

$$PFSP = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)\Delta t} \tag{6}$$

$$PFSP = \frac{\sum_{t}^{T} Power\ Failure\ Time(P_{supplied}(t) < P_{load}(t))}{T} \tag{7}$$

where $DE(t)$ means the energy-efficient at date t (kWh), $P_{supplied}(t)$ is the energy produced by the hybrid power plant at date t (kW), $P_{load}(t)$ is the load requested at date t (kW), Δt is the time margin (h), T is the total number of periods in specific calculation time.

5.1.2 Possibility of Falling Load (PFL)

PFL is the division of global energy insufficiency and the need for global electrical charge during a well-defined period [116], it can be measured by the following equation [117, 121]:

$$PFL = \frac{\sum_{t=1}^{8760} ES(t)}{\sum_{t=1}^{8760} LD(t)} \tag{8}$$

where $ES(t)$ means the electricity failure at time t (kWh), $LD(t)$ represents the electrical requirement at t hour (kWh).

5.1.3 Hoped Energy not Provided (HEP)

HEP is the desired energy which is not delivered to the electrical demand under state when demand exceeds available power generation capacity [55, 122, 123], as mentioned in [117, 122]:

$$HEP = \sum_{t=1}^{8760} E_{not-delivered}(t) \tag{9}$$

$$EIR = 1 - \frac{HEP}{E_0} \tag{10}$$

where $E_{not-delivered}(t)$ is the energy that will not be used at t hour over the full year (kWh); E_0 means the overall energy load of the system (kWh); EIR represents the energy index agreement.

5.1.4 Possibility Lack of Power Supply (PLPS)

The PLPS is determined as the division between the totalities of values LPS (lack of power supply) on the summation of load requirements for a specific period, and this describes the contingency of a missing power supply situation when the HRESs cannot satisfy the electrical demand [122] as mentioned in [117, 121].

$$PLPS = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} LD(t)} \tag{11}$$

$$LPS = \sum_{t=1}^{T} LD(t) - E_{sist}(t) \tag{12}$$

with *LPS* (lack of electrical supply) represents a frequent element when the central hybrid cannot satisfy the electrical load, $E_{sist}(t)$ means supplied with energy by the central hybrid at t hour (kWh/year).

5.1.5 Loss of Load Desired (LLD)

LLD indicates the sum of hours in a full year where the load exceeds the electricity production available in the year (h/year) [117, 121]:

$$LLD = \sum_{h=1}^{H} \sum_{i \varepsilon S} T_i \times P_i \tag{13}$$

where S means the total loss of the states of charge of the system, H is the number of hours in the year 8760 h, T_i represents the time of a charge exceeds the production (hour), P_i means the probability of the system meeting state i.

5.2 Economic Indexes

The economic order is embodied in the concept of HRESs, taking into account the installation of the system, its maintenance, and operating phases of the HRESs.

The improvement of the HRESs requires finding the relationship between the cost and the optimal yield of the system. Therefore, economic indices considering the initial cost, maintenance costs, operating cost, and other system costs have become paramount indicators to study the feasibility of HRESs. The most widely used economic indices are the annual global cost (AGC), the annualized cost of the HRESs (ACHRES), (COE), life cycle cost (LCC), LCOE, NPV, etc., are discussed below.

5.2.1 Annual Global Cost (AGC)

AGC is the addition of capital cost, maintenance, and annual cost of the HRESs [124, 125] reported in [124] as below:

$$TGC = C_{acap} + C_{amain} \tag{14}$$

with C_{acap} means the annual fundamental cost of HRESs; C_{amain} is the annual HRESs maintenance cost.

5.2.2 Annualized Cost of the HRESs

Annualized cost of the HRESs (ACHRESs) is the summation of the annual replacement cost, the annual capital cost, and the annual maintenance cost of the HRESs.

$$ACHRES = C_{acap} + C_{amain} + C_{arep} \tag{15}$$

with C_{arep} means the annual replacement cost of the HRESs.

5.2.3 Cost of Energy

The cost of energy (COE) is the division of the annualized cost of the hybrid renewable energy system (ACHRESs) on the annual overall energy production (AOEP). It sets out the cost per unit of energy produced by HRESs [121]:

$$COE = \frac{\sum_{i=1}^{n} ACHRES}{\sum_{i=1}^{n} AOEP_i} \tag{16}$$

5.2.4 Net Present Value (NPV)

The net present value can be estimated by adding the values of all the costs of the discounted revenues including capital cost, maintenance, and operating expenses by subtracting the current revenues during the lifetime of the HRESs that it can earn [116, 126, 127].

$$NPV = \sum NPV_{end} - C_{investment} - \sum NPV_{OM} - \sum NPV_r \tag{17}$$

with NPV_{end} is the currently discounted reward of income from the residual value of the subsystems at the end of the life of the HRESs; $C_{investment}$ is the initial investment cost; NPV_{OM} is the present value of future exploitation and maintenance costs during the life of the HRESs; NPV_r represents the present value of future replacement costs to replace components during the lifetime of the system.

5.2.5 Levelized Cost of Energy (LCOE)

LCOE corresponds, for a given HRESs installation, to the sum of the updated costs of energy production divided by the amount of energy produced by this system, which is also updated. It is typically expressed in $/kWh (or other currency).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{18}$$

where n is the life of the HRESs, C_t represents all the costs, E_t is the annual clean energy production by the HRESs and r the annual discount rate.

5.2.6 Life Cycle Cost (LCC)

The LCC is determined as the addition of the NPVs for the total cost of the HRESs expenses such as investment expenses, operating and maintenance expenses, replacement expenses, etc., minus the net present value of the revenue value S_{NPV} [116, 117].

$$LCC = C + OM_{NPV} + R_{NPV} - S_{NPV} \tag{20}$$

where C is the total cost of HRESs; OM_{NPV} represents the net present value of maintenance and operation; R_{NPV} means the replacement net present value.

5.3 *Environmental Index*

The environmental index is an indicator for assessing the state of the environment. However, conventional energies generate pollution through the rejection of greenhouse gas emissions, mainly CO_2. As a result, the development of Renewable Energies appease the global energy disturbance, reduce environmental pollution, and enhance sustainable development. Therefore, environmental indices should occupy a significant place in the concept of optimization of HRESs [30].

In this context, the approach to assess the mitigation of the amount of CO_2 avoided admits that each kWh of electricity generated by HRESs replaces each kWh of electricity generated by conventional systems. Thus, the CO_2 emission rates deviated by the capacity of the installed system can be estimated.

6 Conclusion

This chapter aims to shed light on standalone PV-based hybrid renewable energy systems for power generation in rural areas, villages, and remote islands by reviewing various HRESs architectures, formulating basic mathematical background for modeling multiple energy source systems and proposing key performance indicators for the techno-economic assessment of such systems. The use of renewable resources to supply electricity where the grid connection is not technically or economically viable remains a challenge, especially for remote areas. Various configurations of PV hybridization with other renewable resources such as wind, biomass, hydroelectricity, and CSP in off-grid areas have been discussed and the physical modeling of each system is presented. Finally, the indexed performances were expressed including the reliability indexes, the economic indexes, and the environmental indexes. Based on the analysis of various HRES configurations, the main concluding remarks can be outlined as follows;

To successfully satisfy the energy demand, the system configuration is key. It should be carefully tailored by considering available energy sources, the capacity of the system as well as the specifications of the storage. In this way, the cost of energy will be reduced, CO_2 emissions will be minimized and energy requirements will be met.

In PV/Wind configuration, electricity production is obtained mainly from PV panels during the day and from windmill during the night. Hence, this combination is massively adopted given the complementary energy production, its reliability, and adaptability in any weather condition. Moreover, the energy storage system will store excess energy production from hybrid PV–WT combination and meet the energy demand when electricity supply through the system is insufficient.

PV/Biomass configuration is a promising alternative for electricity generation, especially in remote areas where there is an abundant presence of an animal, agricultural, municipal waste, etc. The advantage is that biomass is controllable (present when needed). On the other hand, when the fuel is not available, it must be somewhat purchased which is a standing drawback.

In PV/Hydro configuration, as PV panels are highly affected by ambient conditions, hydroelectricity is, on the other hand, a more flexible, stable, and adjustable sort of energy source. This is another complementary system as there is less solar irradiation but a high level of water during the winter and there is a risk of dry dams but abundant solar irradiation during the summer.

In PV/CSP configuration, there are two different technologies fed by the same energy source. This combination has several advantages as a whole, especially in terms of the cost of electricity and also the large capacities can be provided through these two technologies.

In HRES with three renewable energy sources, and a storage system, PV–Wind–Hydro stands out as a reliable configuration. Although solar and wind power are naturally intermittent due to dependence on the weather condition, hydroelectric, however, is a controllable and stable source. Therefore, this configuration offers certain advantages including higher electric power supply, high profitability, and efficiency comparing the mono source systems.

PV–Wind–Biomass is also popular in remote areas. Even for large capacities, biomass is known for its profitability. The combination of these three technologies with storage system is robust in terms of high power output.

In order to increase the reliability of these systems and create a better balance between supply and demand, such systems require controlling approaches, and storage systems should be adapted to geographical requirements for a continuous supply. Therefore, the integration of storage systems may be of great interest in the design of hybrid renewable energy systems.

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