Off-Grid Hybrid Electrical Generation Systems in Remote Communities: Trends and Characteristics in Sustainability Solutions

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Abstract: The objective of this review is to present the characteristics and trends of hybrid renewable energy systems for remote off-grid communities. Traditionally, remote off-grid communities have used diesel oil-based systems to generate electricity. Increased technological options and lower costs have resulted in the adoption of hybrid renewable energy-based systems. The evaluated 168 studies from the period 2002–2019 considered energy developments in Asia, northern Europe, Africa and South America, with the great majority in the northern hemisphere (n = 152, 90.5%). Many of the studied systems were located in tropical (44.1%) and subtropical areas (31.0%). Our review shows that most of the studied approaches combined photovoltaic (PV) and wind energy and that diesel generators are the preferred backup system (61.3%), while batteries are the preferred method of energy storage (80.4%). Communities far from coasts have more options for renewable energy sources, such as biogas. Although half the studies were related to communities with access to marine-based renewable energy resources, their use was only referred to in fifteen studies. In terms of trends, the studies show a mature development of PV and wind-power technology for off-grid hybrid systems independent of the latitude, which is preferred as they are proven and accessible methods. The preferred storage method is batteries, and diesel is the preferred backup system given the low efficiency of PV and the intermittent character of wind power.

Keywords: hybrid power system; renewable energy; remote communities; HRES

1. Introduction

The development of communities is closely related to uninterrupted access to electrical energy. The isolation of communities in remote rural areas hinders the provision of electrical energy by traditional electrical power generation and transmission methods. The World Bank reported in 2018 that around 724 million people did not have a regular and reliable supply of electrical energy, with 84.2% of these people living in rural areas isolated from power grids, and the remaining 15.8% living in urban areas [1]. Electrical energy is a fundamental pillar of economic and social development, because of which it is common that the highest indices of poverty and the lowest levels of technological development are found in rural communities [2]. The problem is more acute with remote communities and communities on islands. One of the characteristics of rural communities is low population density. The families that make up these populations are widely scattered, making it difficult to meet energy demands and making electrical transmission networks expensive. Complex geographic conditions and low energy demand make providing electrical energy by conventional methods impractical (that is, extension of electrical transmission networks and substations), especially in developing countries, where electricity is vital for economic participation and the social welfare of rural communities. Areas that do not have electricity generally also lack essential infrastructure like schools, medical centers,
means of communication, access to potable water and others, which is reflects the fact that the human development indices of electrified communities are higher than those of communities without electricity [3].

A widely used method for generating electricity for remote communities is distributed generation systems, characterized by the use of electric generators that produce electricity by burning fossil fuels, in particular diesel [4–8]. Diesel generators are relatively inexpensive, the technology is wide-spread, and the construction time for an electrical station is comparatively short. Remote communities are often not easily accessible, so that system maintenance can be deficient. Because fuel and replacement parts must be obtained from urban centers, together with continuous fluctuations in fuel prices, this approach is not advisable for poor rural communities [9]. The use of diesel plants in remote areas depends on the presence of roadways to deliver the fuel, with high transport costs for remote communities. The remoteness of communities also negatively affects the required and frequent maintenance. Despite all the disadvantages, diesel is still the main resource for generating energy for isolated communities [10]. Diesel is associated with other negative effects like: (i) contributing to concentrations of greenhouse gases [11], (ii) reducing air quality [12], (iii) deteriorating human health [13], (iv) high transport [14] and storage costs, (v) volatility in international prices [15], (vi) the need for periodic maintenance [10] by qualified staff, (vii) fire hazard during transportation and storage [16], and (viii) it is a limited primary resource [17] that is not renewable on a human time scale.

Off-grid hybrid renewable energy systems (HRES-OFF) have been proposed to mitigate the negative aspects of using diesel to generate electricity ([18–20]). These systems involve different renewable resources to generate electricity, like solar, wind, hydro, geothermal, biomass, biofuel, wave, tidal, and fuel cell energy, among others, as well as energy storage systems like batteries, pumped hydro storage (PHS), hydrogen, flywheel and others. They can also involve small electrical generators. Solar and wind power are the most often used renewable energy sources worldwide in HRES-OFF. The main studied and implemented HRES-OFF configurations are photovoltaic (PV)–wind–diesel–battery, PV–wind–battery and PV–diesel–battery.

Batteries are the main storage method used in HRES-OFF systems, followed by hydrogen and pumped hydro storage systems, which have limited application owing to the topography in many isolated areas. However, the level of solar radiation decreases at latitudes nearer to the poles, while offshore wind power is greater in middle and high latitudes [21]. Related to stronger and more consistent winds is the generation of waves along coasts, which can be used as an energy source by remote coastal communities. Likewise, tidal changes are a common phenomenon to all the marine coasts of the world and reach extraordinary levels in certain places in the middle and high latitudes [22], making the tides an alternative source of renewable energy.

Investing in a single technology generally results in oversizing systems, which increases initial costs. A hybrid system can overcome the intermittent nature of renewable energy sources and the problem of oversizing and improve the reliability of energy supply. However, hybrid systems have received limited attention because of their greater complexity and the scarcity of works that have considered the question of reliable supply of electricity to rural areas [23]. We expect this study will contribute to decision-making regarding the use and configuration of HRES-OFF systems in remote communities as the use of renewable energy becomes more economically viable due to the increased cost of fossil fuels and lower costs of equipment to make use of renewable energy [24].

This article is structured as follows: Section 2 presents the criteria used in this review of the state-of-the-art in implementing or simulating off-grid hybrid systems in remote communities. Section 3 summarizes the results found in the reviewed studies in terms of the methodologies used (Section 3.1), geographic location (Section 3.2), the latitudes of the studied areas (Section 3.3), the population where HRES-OFF are established (Section 3.4), the type of energy used (Section 3.5), and trends in these factors (Section 3.6). Section 4 discusses the main findings, and finally, the conclusions are presented in Section 5.
2. Methods

We reviewed around 250 articles that had a combination of keywords “remote areas”, “hybrid-power systems”, “hybrid renewable energy systems”, and “off-grid power systems”. We excluded articles that described on-grid systems and off-grid systems in urban areas, given that our interest is off-grid power systems in remote communities. We also excluded studies that only quantified the availability or variability of renewable energy [25–28]. This selection led us to study in detail a total of 168 articles investigating HRES-OFF in remote communities isolated from electricity grids. The articles were classified according to the variables: geographic location, HRES-OFF configuration, electricity demand, number of inhabitants, and main economic activity. The geographic location includes several components, namely: i) hemisphere, ii) latitude according to the classification of three main climatic zones: tropical (latitudes between $+23^\circ$ and $-23^\circ$), subtropical ($+23^\circ < \text{latitude} \leq +36^\circ$ and $-23^\circ > \text{latitude} \geq -36^\circ$) and temperate ($+36^\circ < \text{latitude} \leq +63^\circ$ and $-36^\circ > \text{latitude} \geq -63^\circ$), iii) continent and country. Categorizing the geographic locations of target communities establishes an evaluation criteria in terms of the potential of local energy resources, that is to say, coastal communities (which can be island communities and communities near coasts) have greater access to marine-based solar and offshore wind resources, while communities in continental interiors have more access to biomass, small-scale hydro, geothermal and other energy resources.

The renewable energy sources, storage strategy and combination with backup electric generating systems of all the HRES-OFF were identified, as well as the number of inhabitants and economic activities, these being variables that indicate the behavior and energy profile of isolated communities. Therefore, daily energy requirements vary according to economic characteristics and the potential of the surrounding territory.

3. Results

HRES-OFF have been implemented and evaluated around the world to meet the need to generate electricity in areas isolated from conventional electrical networks (Figure 1). The evaluated HRES-OFF studies were concentrated in the northern hemisphere (90%), with only 10% of the studies dealing with HRES-OFF applications in the southern hemisphere.

![Figure 1. Geographic locations of the investigations that evaluated HRES-OFF in remote communities.](image)
3.1. Methodologies Used

The investigations into HRES-OFF did not have a common systematic methodology to characterize the power generation system and the relevant communities. Consequently, it was not possible in all cases to determine the technical and socioeconomic variables established for this review.

Regardless of the state of development of a renewable energy project, off-grid or on-grid, it is essential that researchers employ software tools or analytical methodologies to determine the technical and economic feasibility of the proposed system. According to the classification in [29], RETScreen and HOMER are widely used tools in renewable energy systems, including hybrid systems. RETScreen includes all aspects related to heating and electricity. The tool H$_2$RES models all aspects of the heating sector, as well as transport technology related to the use of biofuels as vehicle fuel. Consequently, each tool responds to a particular objective. In HRES-OFF studies, a different frequency of use was observed.

Table 1 presents the main computer programs used in the HRES-OFF studies or in the absence of computer programs, the methodologies used. A marked preference can be noted for the HOMER program [30], which was developed by the National Renewable Energy Laboratory in the USA. HOMER includes wind turbines, PV arrays, biomass, microturbines, run-of-river hydropower, fuel cells, and internal combustion engine generators as energy sources, and batteries, flywheels and hydrogen as storage strategies. It does not include wave, tidal, OTEC, salinity gradient and geothermal as primary sources of energy. Twelve studies did not indicate the software/methodology used to analyze the hybrid system. In some investigations, the authors used two analytical methods. For example, in [31], the authors investigated an optimal HRES-OFF system based on PV arrays and wind turbines, which precisely and adequately resolved the technical and economic feasibility of employing a hybrid distributed power generation system in a community in northeastern Nigeria. To do that, the researchers used RETScreen to analyze the feasibility and HOMER to optimize the HRES-OFF system. Finally, 35 studies used algorithms and mathematical models designed by the authors, using different informatic tools like C++, THESIS, Excel Spreadsheet, and Engineering Equation Solver (EES), among others.

Table 1. Methodology or software used in HRES-OFF analyses.

| Software/Methodology                               | # Articles |
|----------------------------------------------------|------------|
| HOMER                                              | 90         |
| Not indicated                                      | 12         |
| MatLab                                             | 6          |
| GSA/NGSA                                           | 5          |
| Genetic Algorithm                                  | 4          |
| HOMER and Matlab                                   | 3          |
| TRNSYS                                             | 3          |
| HOMER and RETScreen                                | 2          |
| HOMER and HYBRIDS                                  | 1          |
| HOMER and Digsilent                                | 1          |
| HOMER and Grasshoppper-Cuckoo-TLBO                 | 1          |
| HOMER and PSO-CPSO                                 | 1          |
| H$_2$RES                                            | 1          |
| HOGA                                               | 1          |
| RETScreen                                          | 1          |
| WindPro                                            | 1          |
| Others                                             | 35         |
|                                                     | 168        |

3.2. Results by Geographic Location

A total of 152 studies focused on communities in the northern hemisphere. Table 2 shows the main variables of the representative investigations. There were only 16 studies for the southern hemisphere, the details of which are shown in Table 3. The highest number
of HRES-OFF studies were in Asia, followed by Europe in second place, Africa close behind, the Americas in fourth place with nine studies, and finally Oceania (Figure 2). The Asian country with the largest number of HRES-OFF-related studies was India, with 21 studies, which may reflect the introduction of an electrification policy in 2003, as well as the need to reduce the use of fossil fuels. India intends to increase the share of non-fossil fuels in generating electricity from 15% (2016) to 57% (2027) [32]. Bangladesh, Greece, Malaysia, Iran and China, with 13, 12, 12, 10 and 9 studies, respectively, complete the list of countries with the highest number of HRES-OFF-related studies. Of these, the only developed country is Greece, according to the classification of the United Nations [33]. The others are in transition toward development, that is, they have made a transition from an agricultural to a more industrial economy. Oceania had the lowest number of publications on HRES-OFF, with four for Australia and one each for Fiji and Tonga.

Given their geographic situation, island countries, islands, and coastal areas (communities located less than a kilometer from a coast) have more access to marine-based energy resources (wave, tidal, OTEC, salinity gradient), offshore wind energy (with more plant factors than with onshore/inland wind power systems), which can be used as a renewable resource in the definition of HRES-OFF. Communities located in continental interiors have a wider range of available renewable energy sources, such as biomass (associated with residues from forests, harvests, wastewater and solid waste), biogas, small-scale hydro generators, solar, wind and others. Figure 3 shows that 54% of the studies, excluding marine-related studies that compared the performance of PV–diesel–battery systems in ports or on ships [13], deal with communities surrounded by or near the sea, that is, more than half deal with communities that have access to marine-based energy resources.
| Item | Country/Site | Position | Population | Economical Sector | Energy Demand | Software | Application | Ref. |
|------|--------------|----------|------------|-------------------|---------------|----------|-------------|------|
| 1    | Greece/Agathonisi | Island   | 105        | Livestock, fishing farming and tourism | 450 MWh/a    | Homer    | Simulation  | [6]  |
| 2    | China/Remote Island in Hong Kong | Island   | 100        | N/A | 250 kWh/d | Customized ¹ | EO | [34] |
| 3    | India/Bastar district | Continental | 1624 | Agriculture | 434 kWh/d | Homer | EO | [23] |
| 4    | Greece/Ikaria | Island   | 9000       | Fishing and Tourism | 4020 kWp | Customized ² | Installed | [35] |
| 5    | Ethiopia/Dejen District | Continental | 63,000 | N/A | 563 kWh/d | Homer | EO | [36] |
| 6    | Nepal/Remote villages | Continental | 1700 | Agriculture | 4.67 kWh/d | N/A | Installed | [37] |
| 7    | Cape Verde/Sao Vicente | Island   | 74,301     | N/A | 57 GWh/a | H₂RES | EO | [38] |
| 8    | Algeria/Remote village | Continental | 425 | N/A | 4.6 MWh/d | Homer | EO | [39] |
| 9    | Canada/Brochet | Continental | 537 | N/A | 8 MWh/d | Homer | EO | [40] |
| 10   | Bangladesh/Dhankhali village | Continental | 884 | Agriculture and Fishing | 255 kWh/d | Homero | EO | [41] |
| 11   | Saudi Arabia/Rafha | Continental | 10,000 | N/A | 44 MWh/d | Homoer | EO | [42] |
| 12   | Oman/Masirah | Island   | 12,825     | N/A | 171.5 MWh/d | Homoer and Digsilent | EO | [43] |
| 13   | Mexico/Cozumel island | Island   | 79,535     | Tourism | 312 up to 1305 GWh/a | Homer and RETScreens Software Red Eléctrica | Installed | [44] |
| 14   | Spain/El Hierro island | Island   | 10,995     | N/A | 44.6 GWh/a | Homer | EO | [45] |
| 15   | Turkey/Bozcaada island | Island   | 375        | N/A | 1875 kWh/d | Homer | EO | [46] |
| 16   | India/Madhya Pradesh | Continental | 120 | Agriculture | 70 kWh/d | Homer | EO | [47] |
| 17   | Malaysia/Kapit | Island Country | 350 | N/A | 140 kWh/d | Homer | EO | [48] |
| 18   | Italy/Island of Salina | Island   | 44,362 ³ | Tourism | 11.36 kWh/d/pers | TRNSYS | EO | [49] |

EO = Evaluation only; ¹ mathematical models designed by the author; ² a Monte Carlo simulation; ³ 2504 residents and 41,858 tourists in 2009.
Table 3. Characteristics of the evaluated off-grid hybrid systems in the southern hemisphere.

| Item | Country/Site | Position | Population | Economical Sector | Energy Demand | Software | Application | Ref. |
|------|--------------|----------|------------|-------------------|---------------|----------|-------------|------|
| 1    | Indonesia/Island Country | 1475     | Agriculture | Two cases: 162.5 and 558.5 kWh/d | N/A | EO | [7] |
| 2    | South Africa/Continental and Coastal | N/A     | N/A | 5.6 kW_p | Homer | EO | [50] |
| 3    | Kenya/Continental | 500       | N/A | 190–200 kWh/d | Homer | EO | [51] |
| 4    | Australia/Continental | 1000     | Tourism | 15,000 kWh/d | Homer and Hybrids | EO | [52] |
| 5    | Brazil/Continental | 50        | Research | 23.8 kWh/d | Homer | Installed | [53] |
| 6    | Republic of Fiji/Island | 200      | N/A | 222 kWh/d | Homer | EO | [54] |
| 7    | Kingdom of Tonga/Island | N/A      | N/A | 4.2 MWh/d | Homer | EO | [55] |
| 8    | Brazil/Island | 393       | N/A | 4134 kWh/m | Scada | Installed | [56] |
| 9    | Australia/Island | 2072 and 4417 | N/A | 4.8 and 15 kWh/d | Homer | EO | [57] |
| 10   | Australia/Island | 180^1     | Sheep and cattle farming | 2777 kWh/d | Spreadsheet and Homer | EO | [58] |
| 11   | Republic of Maldives/Island | N/A | N/A | 26,442, 3202, 1051, 373 and 483 MWh | Homer | EO | [59] |
| 12   | South Africa/Kwazulu Natal/Continental | One Household and BTS | N/A | 35 and 59 kWh/d | Homer | EO | [60] |
| 13   | Zimbabwe/Rural community clinics | N/A | Health | N/A | Matlab | EO | [61] |
| 14   | Australia/Frenchs Island | Island and Continental | 30, 50 and 180 | Tourism | 20.2, 409 and 2600 kWh/d | Homer | Installed | [62] |
| 15   | South Africa/Kwazulu-Natal and Cape Columbine | Continental and Coastal | N/A | N/A | 9.5 and 58.8 kWh/d | Homer | EO | [63] |
| 16   | Indonesia/Minggir subdistrict | Island Country | Fish pond | Aquaculture | 2 kWh/d | Homer | EO | [64] |

E0 = Evaluation only; ^1 90 full-time residents and 90 part-time; ^2 BTS = base transceiver station.
3.3. Results by Latitude

One of the advantages of renewable or unconventional energy resources over fossil fuels (coal, petroleum, gas) is their availability and wide distribution globally. However, the energy potential of a renewable resource varies according to atmospheric and geographic conditions, the time of day, and even astronomical forces, such as the tide. There is less solar radiation closer to the poles, and offshore wind power increases in middle and high latitudes. Wave generation all along the coast is associated with stronger and more consistent winds. Likewise, the tides are a physical phenomenon common to all the coasts of the world and reach extraordinary levels in certain places in the middle and high latitudes.

Some 44.1% of the studies were focused on tropical areas, where solar rays are almost perpendicular. The second highest number of HRES-OFF studies by latitude, with 30.95% of the studies, was the subtropics. There were fewer studies that dealt with HRES-OFF in the middle and high latitudes (Figure 4). Therefore, a staggered evaluation was made in each of the climatic zones defined above, making a brief description of some of the studies carried out and a classification of the types of specific configurations (relative to HRES-OFF), type of primary energy source, and storage strategy.

3.3.1. Tropical Areas

Ranaboldo et al. (2015) [65] proposed an off-grid electrification project in Nicaragua that would combine solar and wind energy in two power generation strategies, small microgrids that use the two renewable energy resources, and independent power generation points according to the analysis of demand and the energy potential of the resources at the micro-scale. Ismail et al. (2013a) [66] conducted a technical-economic analysis of an optimal
PV–diesel–battery system on a Malaysian island. The main objective of this study was to select the components that make up the hybrid system to minimize the total cost of the system, ensuring the power supply at the required load. To do this, the authors made an energy balance in an 8750-hour time series, and with the application of a genetic algorithm, they established an adequate fit between the energy generated and the load profile at the site of interest. Blum et al. (2013) [7] analyzed a conventional autonomous system (diesel-based electrical generation), and renewable energy options, PV-battery, micro-hydro and hybrid PV–diesel–battery systems to meet the energy demand of an Indonesian community. The parameters for evaluation defined by the authors were the levelized cost of energy generation (LCOE) and the costs and potentials of CO$_2$ emission abatement. The results showed that micro-hydro electrical generation has the lowest cost of any of the energy technologies, reaching values between 0.14 and 0.16 €/kWh. Hybrid systems that combine diesel and PV are more economical than PV–battery system if diesel price subsidies are integrated into the analysis and/or the community’s location is not remote.

A study of a system for a remote island in Hong Kong examined the economic performance of two possible energy storage systems, batteries and pumped hydro storage in a reservoir, using two renewable energy sources, solar and wind (Ma et al. 2014) [34]. The results indicate that the life cycle cost is higher with conventional batteries in an off-grid PV–battery system than with advanced deep cycle batteries, noting that the latter system is more appropriate for renewable resource-based power generation systems. In addition, a PV-pumped hydro storage system combined with a bank of batteries would be only 55% of the cost of the PV–battery system (deep cycle), making the combination PV-pumped hydro storage-battery much more competitive than the option that only considers batteries. Ani (2016) [8] described a PV–battery system to meet the energy demand of a residential area in Nigeria. The author simulated the system to determine the loss in power generation and compared this to a diesel–battery system in economic and environmental terms.

Kumar et al. (2014) [67] studied the technical and economic feasibility of establishing hybrid PV–diesel–battery systems in different climatic zones of Tamil Nadu State in India. They found that the arid zone in Kanyakumari was the optimal climatic zone to establish hybrid PV–diesel–battery systems, taking into consideration factors like the renewable energy fraction (RF), contaminating gas emissions (tons/year), diesel consumption (liters/year) and net present cost (NPC). Adaramola et al. (2014) [18] conducted an economic analysis of an off-grid hybrid PV–wind–diesel–battery system in rural areas of southern Ghana. Using the software Hybrid Optimization of Multiple Energy Resources (HOMER), the authors determined that the hybrid PV–wind–diesel system (with or without batteries) is the best option economically. The contribution of RF ranged from 47% (PV–wind–diesel system, the most viable) to 17% (PV–diesel system, the least viable). The COE of the PV–wind–diesel system was $0.276/kWh, and of PV–wind–diesel–battery system, it was $0.281/kWh.

Table 4 shows the different HRES-OFF configurations according to latitudes between the Tropics of Cancer and Capricorn (that is, $-23^\circ \leq \text{latitude} \leq +23^\circ$). There is a marked tendency to use solar energy (alone or with wind energy) as the main form of renewable energy in simulated or implemented HRES-OFF. The battery is the main energy storage strategy to meet energy demands at times when the supply of energy from renewable sources is insufficient. Likewise, there is a preference for PV–wind–diesel–battery systems (16 investigations), followed by PV–diesel–battery (9 investigations) and PV–wind–battery systems (7 investigations), as the main power generation strategies for remote areas. Finally, few studies considered marine-based energy sources as renewable HRES-OFF sources. Two studies evaluated wave energy [15,68] and three considered tidal energy [41,69,70]. One study analyzed the flywheel as an energy storage system in combination with batteries, taking advantage of the high energy density that this system provides and the high depth of discharge, which are favorable characteristics in the transition between renewable energy sources and the storage system.
Table 4. Configurations used in off-grid hybrid systems in tropical areas.

| PV | Wind | Biomass | Biogas | Small Hydro | Wave | Tidal | Fuel Cell | Micro-Turbine | Diesel | Battery | Pumped Hydro Storage | H₂ | Flywheel | Refs. |
|----|------|---------|--------|------------|------|-------|-----------|---------------|--------|---------|----------------------|----|----------|-------|
| ✓  | ✓    |         |        |            |      |       |           |               |        |         |                      |    |          | [65,71–74] |
| ✓  |      | ✓       | ✓      |            | ✓    |       |           |               |        |         |                      |    |          | [53,76] |
| ✓  |      |         |        |            | ✓    | ✓     |           |               |        | ✓       |                      |    |          | [8,66,67,77,78] |
| ✓  |      |         |        |            | ✓    | ✓     |           |               |        | ✓       |                      |    |          | [19,59,61,79] |
| ✓  |      | ✓       |        |            | ✓    |       |           |               |        |         |                      |    |          | [7]^{1}, [9,80] |
| ✓  |      |         |        |            | ✓    |        |           |               |        |         |                      |    |          | [34] |
| ✓  |      |         |        |            | ✓    | ✓     |           |               |        |         |                      |    |          | [11,18,81–83] |
| ✓  |      |         |        |            | ✓    | ✓     |           |               |        |         |                      |    |          | [3,25,56,64,85] |
| ✓  |      |         |        |            | ✓    | ✓     |           |               |        |         |                      |    |          | [31,47,86–88] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [89] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [23]^{2}, [36,90,91] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [92] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [93,94] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [95,96] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [30] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [97]^{3} |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [51,88] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [99] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [12] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [53] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [100] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [41,69] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [101] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [43,44] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [64,102,103] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [54,104,105] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [70] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [106] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [107] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [108] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [68] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [109] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [48] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [110] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [113] |
| ✓  |      |         |        |            | ✓    |       |           |               |        |         |                      |    |          | [115] |

* Includes Mini- and Micro-Hydro systems; ^1 Micro-Hydro was evaluated independently of the hybrid PV-Diesel-Battery system; ^2 The author installed a bio-diesel generator; ^3 A co-generation biomass plant a stirling solar dish were included in this system.
3.3.2. Subtropical Zone

Table 5 shows the HRES-OFF configurations of the 52 studies we found that evaluated different hybrid systems in tropical zones, that is, between the latitudes $+23^\circ$ and $-23^\circ$: $+23^\circ < \text{latitude} \leq +36^\circ$ and $-23^\circ > \text{latitude} \geq -36^\circ$. As in the tropical zone, PV and wind systems are the main renewable resource in HRES-OFF, accounting for 88.5% and 67.3%, respectively. Biomass energy appears to be more important in this zone, with six studies, which is twice the number for the tropical zone. There were no studies that considered tidal energy as a renewable HRES-OFF resource. Three studies considered waves as a potential energy source [112–114]. A study in the subtropical zone applied exergy analysis to an ocean thermal energy conversion system (OTEC) to determine the optimal evaporation and condensation temperatures of different working fluids [115]. Three Japanese islands isolated from the electrical grid were considered in an investigation to define the optimal configuration of a HRES-OFF PV–wind–diesel–battery system, using hourly data on solar radiation and wind speed over a year (Senjyu et al. 2007) [5]. A genetic algorithm was used in this study to determine the cost of the hybrid system.

Rehman et al. (2012) [116] optimized a hybrid PV–wind–diesel system, thus reducing fuel consumption by a conventional autonomous system, without affecting the energy required in a remote community in Saudi Arabia. HOMER obtained an optimal configuration to produce electrical energy, with 26% from wind, 9% from solar and the remainder from five diesel generators. Offshore wave and wind resources on the Canary Island of Fuerteventura were evaluated using eleven measurement sites, as well as the optimal areas for installing wave/wind farms, taking into account wave height, energy period and predominant wave direction around the island, bathymetry, environmental areas and the distance to ports (Veigas et al. 2014) [112].

Dekker et al. (2012) [50] determined the most technically and economically feasible approach to providing electricity to an off-grid system in six distinct climatic areas in South Africa. The authors determined that the optimal area in South Africa for a hybrid PV–diesel–battery system is the subtropical coastal region. The results indicate that the proposed system not only functions better than conventional autonomous systems in terms of costs based on six simulations but also had better results in categories of electricity, fuel consumption and emissions released to the atmosphere. A study that evaluated the feasibility of installing a hybrid PV–diesel–battery system in southern Algeria found that transforming the current autonomous conventional system to a hybrid system would represent a savings of 54,100 liters of fuel per year, which would represent a 90.4% reduction in fuel consumption (Khelif et al. 2012) [117]. Ismail et al. (2013b) [118] investigated the feasibility of using microturbines as a backup to a PV–battery system. The optimal size of the hybrid system was determined with the aid of an algorithm (mathematical model of the HRES-OFF components), with a minimum energy cost based on the optimal angle of inclination and azimuth angle for the solar panels. A comparison of microturbines and conventional diesel-based generators as backup systems showed that microturbines have a lower energy cost. A study in Iran determined the feasibility of a hybrid PV–wind–diesel–battery system for an area with a significant energy demand in Shiraz (9.9 MWh/d) (Baneshti et al. 2016) [119]. With the aid of HOMER software, the optimal system was configured and analyzed for two scenarios, one off-grid and the other on-grid.

Table 5 shows that batteries are the main storage strategy, appearing in 80.77% of the studies overall, and 86.49% of studies dealing with tropical areas. Pumped hydro storage and hydrogen systems are less common in subtropical areas. The authors of [120] proposed ocean renewable energy storage (ORES) for offshore and onshore wind systems, having the advantage that such systems can be installed at great depths (up to 800m) and serve as anchors for offshore wind generators.
Table 5. Evaluated off-grid hydro systems in subtropical areas ($+23^\circ$ latitude $\leq +36^\circ$ and $-23^\circ$ latitude $\geq -36^\circ$).

| PV | Wind | Biomass | Biogas | Small Hydro $^a$ | Wave | OTEC $^b$ | Fuel Cell | Micro-Turbine | Diesel | Battery | Pumped Hydro Storage | H$_2$ | ORES $^c$ | Refs. |
|----|------|---------|--------|------------------|------|-----------|-----------|--------------|--------|---------|----------------------|------|---------|-------|
| ✓  | ✓    |         |        |                  |      |           |           |              |        |         |                      |      |         | [5, 52, 119, 121, 122] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        |         |                      |      |         | [123–127] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        |         |                      |      |         | [57, 128] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        |         |                      |      |         | [14, 116] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        |         |                      |      |         | [112, 113] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [20, 50, 117, 129, 130] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [42, 131, 132] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [118] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [45, 133] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [37] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [134–138] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [139], [140] $^1$ |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [141] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [142] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [143] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [144] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [145, 146] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [147] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [148] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [114] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [120] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [149] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [60], [63] $^2$ |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [115] |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [150] $^3$ |
| ✓  | ✓    |         |        |                  |      |           |           |              |        | ✓       |                      |      |         | [151] |

$^a$ Includes mini- and micro-hydro systems; $^b$ ocean thermal energy conversion (OTEC); $^c$ ocean renewable energy storage (ORES); $^1$ this study was carried out in an educational facility with access to an electricity grid; $^2$ the author evaluated four independent configurations: hydro–battery, PV–battery, wind–battery and diesel; $^3$ hydrogen is employed by the diesel generator.
3.3.3. Temperate Areas

Table 6 shows the configurations used for HRES-OFF in middle and high latitudes between $+36^\circ < \text{latitude} \leq +63^\circ$ and $-36^\circ > \text{latitude} \geq -63^\circ$. Solar and wind energy are the most widely used renewable resources. Wind energy was assessed in 80.9% of 42 studies and solar energy was assessed in 76.2%. Biomass, biogas and small hydro were each assessed in a single study. Marine-based energy sources received more attention in temperate zones than in the other climatic zones, accounting for 16.7% of studies. Tidal energy was assessed in two studies [152,153] and wave energy in five [154–158]. Batteries continue to be the most widely used technique for energy storage in HRES-OFF, representing 69.1% of studied systems. Hydrogen and pumped hydro storage are more common at middle and higher latitudes, representing, respectively, 16.7% and 14.3% of the studied systems.

A study on Lesbos Island in Greece used HOMER software to optimize an off-grid hybrid wind–diesel system without the integration of a storage system, resulting in a high COE associated with an operating reserve of 50% of wind power generation (Giannoulis et al. 2011) [4]. The technical feasibility of wave-based electrical generation on St. George Island on the Bering Sea coast of Alaska was evaluated. The island was obtaining electrical energy from a generator, and the authors sought to lay the foundation for specific design and control elements essential in wave–diesel hybridization of small remote power grids. The assessment of the island’s wave potential yielded an average of 28 kW/m, which could meet 9% of the island’s energy demand (Beatty et al. 2010) [154].

An assessment was made of an initiative for an isolated community on the small Greek island of Agathonisi to have autonomous electrical energy and potable water based on local nonconventional renewable resources. The proposed hybrid PV–wind–biogas–battery system, optimized by HOMER, could meet electrical, heating and potable water demands through a reverse osmosis desalination plant, with a five-day autonomous period. Wind energy provided the major contribution at 50%, followed by solar and biogas energy at 30% and 20%, respectively (Kaldellis et al. 2012) [6]. Yilmaz et al. (2017) [17] made a technical and economic analysis of a hybrid PV–diesel–battery system to identify the system’s optimal size. Using HOMER, the authors determined that 84.6% of total energy could be generated by solar panels and that the hybrid system could reduce carbon emissions by 44 tons per year.

A study in Russia that proposed the design of a multi-purpose hybrid PV–diesel–battery system (Bortolini et al. 2015) [159] identified the average power output of a PV plant, the capacity of the storage system (battery) and the optimal technical configuration to reduce the levelized cost of electricity (LCOE) and the carbon footprint of energy (CFOE). The results showed that the best environmental scenario is a PV plant with an average power output of 95 kW_p and a storage capacity of 200 kWh (8 Ah), resulting in a CFOE of 0.374 kg CO_2eq/kWh (50% savings). A study by Gan et al. (2015) [160] developed a tool to optimize a hybrid PV–wind–diesel–battery system, with the objective of helping investors to decide between batteries and diesel generators given the availability of local renewable resources and the demand for energy. The results show that a PV–wind–diesel system has a lower COE (0.677 £/kWh). In contrast, the PV–diesel system has a COE of 1.55 £/kWh, more than double that of the wind–diesel (COE = 0.724 £/kWh) and PV–wind–diesel systems for total autonomy. The comparison of a wind–diesel and PV–wind–diesel system shows that twenty additional solar panels would result in a 33% reduction in storage capacity.
Table 6. Evaluated off-grid hybrid systems in temperate areas (+36° < latitude ≤ +63° y −36° > latitude ≥ −63°).

| PV | Wind | Biomass | Biogas | Small Hydro a | Wave | Tidal | Fuel Cell | Flywheel | Diesel | Battery | Pumped Hydro Storage | H₂ | CAES b | Refs. |
|----|------|---------|--------|-------------|------|-------|-----------|----------|--------|---------|----------------------|----|--------|-------|
| ✓  | ✓    |         |        | ✓           | ✓    |       | ✓         |          | ✓      | ✓       | ✓                    |    |         | [4]   |
| ✓  | ✓    | ✓       |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [154] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [6]   |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [10,13,17,159] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [160–164] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [62]  |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [165–169] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [24,170,171] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [35,172] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [173] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [155] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [154] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [174] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [175] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [166] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [40]  |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [152] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [156] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [157] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [58]  |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [49]  |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [177] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [178,179] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [180] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [158] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [46]  |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [153] |
| ✓  | ✓    |         |        |             | ✓    | ✓     |           |          |         | ✓       | ✓                    |    |         | [181] |

a Includes mini- and micro-hydro systems; b compressed air energy storage (CAES); 1 the author considered an ideal battery (without loss); 2 the author studied a small dairy cattle farm with grid connection; 3 the author studied different storage devices such as: lead-acid battery, Na-S battery, flow battery, flywheel, pumped hydro and fuel cells; 4 a heat storage tank was installed in the power system. It was not used to store electricity.
3.4. Results by Population

Some 15.5% of the evaluated studies indicate that the main economic activity of the community is primary: farming, fishing, mining, and logging, etc. Tourism is the main activity of 11.3% of communities, while 64.3% of the studies did not indicate the predominant economic activity of the relevant communities. The remaining percentages are specific cases that include research centers, a base transceiver station (BTS), and small scale industries, among others.

Some 76 of the evaluated investigations provided complete population and daily energy use data (Figure 5). Seven investigations analyzed HRES-OFF in communities with more than 20,000 inhabitants, six of these on islands and one continental. The study with the largest number of inhabitants was on the island of Sandwip in Bangladesh (Figure 5), although this study did not represent the highest daily demand for electrical energy with 93,000 kWh/d [70]. The study that represented the highest level of energy consumption was that of [44], in which the authors considered five energy demand scenarios for Cozumel Island, Mexico, in 2018, 2020, 2024, 2035 and 2050. Cozumel Island is the target for developing sustainable tourism to improve the quality of life of the island’s inhabitants. One of the strategies in this process is developing a PV–wind–diesel system.

![Figure 5. Daily energy use versus the number of inhabitants. The result of 76 studies with information available.](image)

Of the 76 investigations, 46.1% involved providing electricity to isolated communities with no more than 200 inhabitants (Figure 5), while 7.9% involved communities with 200 to 500 inhabitants, 11.84% dealt with communities with populations between 500 and 1000 inhabitants. The percentages were 18.4%, 2.6%, 5.3% and 7.9%, respectively, for communities with populations of 1000–5000, 5000–10,000, 10,000–50,000 and over 50,000.

3.5. Results by Type of Energy Storage

HRES-OFF energy storage strategies ensure an ongoing supply of electrical energy at times when energy production by renewable sources is low or highly intermittent. Diesel generators remain the preferred HRES-OFF backup strategy and were employed in 103 of the 168 studied cases. The principle of a battery-based backup system is simple, the excess energy generated by renewable energy sources is stored in the battery, using load regulators to appropriate charge and discharge levels. The strategy was different in some investigations [3,23,147], with a backup system (diesel generator) to supply the required
level of energy and, in turn, charge the batteries of the hybrid system. In the latter case, the renewable energy source does not supply power to the batteries.

The most widely used type of battery in the evaluated HRES-OFF is lead-acid owing to its technological maturity, easy acquisition, low cost and wide use in different applications worldwide. Some 80.4% of the publications analyzed in this paper involved the use of batteries, either alone or in combination with another energy storage method (Figure 6). In second place were HRES-OFF without any type of energy storage, that is, in these cases, renewable energy sources are the only means used to meet electric power demands. The lack of a storage system can result in oversizing the electrical generating system or more use of diesel generators to meet energy demands in the context of limited availability of appropriate renewable resources. Thirdly is hydrogen fuel cells using an electrolyzer, followed by solid oxide fuel cells (SOFC), which provide electrical energy from stored hydrogen when the energy demand is greater than the supply from renewable sources. Some 7.7% of the studies considered pumped hydro storage, which takes advantage of favorable topography. Only a few investigations, around 2%, dealt with HRES-OFF that used flywheels [109,180], ORES [120] or CAES [58] as the main energy storage methods.

![Figure 6. Main energy storage technologies used in HRES-OFF worldwide.](image)

### 3.6. Trends

Based on the 168 selected articles from among a total of approximately 250 articles for the period 2002–2019, the trend worldwide in HRES-OFF for remote communities is toward using solar and wind energy (Figure 7). Although one of the objectives of establishing local energy generation systems is to reduce dependence on fossil fuels, thermal units are still used as backup systems owing to the recognized intermittent character of renewable resources and the low plant factors associated with renewable energy conversion technologies. As noted above, the technological maturity, broad commercialization and availability of the resource are the main advantages of the sun and wind over other renewable resources. Although hydroelectricity is widely known and used, its use is problematic in island and coastal areas because of the low availability of water, which in some places is even inadequate to meet requirements for human consumption. The use of marine energy sources in HRES-OFF is weak owing to economic, technological and developmental aspects noted above. There is little use of marine-based energy sources due to economic, technological and developmental factors already mentioned. However, since 2013, there has been more interest in marine-based energy resources for communities with low energy demand.
The battery is categorically the most widely used storage system used in HRES-OFF (Figure 8). The number of studies in which batteries formed part of hybrid systems began to decrease in 2016. There is growing interest in using hydrogen as a more dynamic option HRES-OFF. Since 2010, at least one study has presented water pumping storage systems (PHS) as an alternative in areas with topography conducive to storing water at high altitudes. There is more interest among coastal and island communities in pumped hydro energy storage using seawater, the lower reservoir is the sea and only favorable topography is needed for storage at high altitudes. It is evident that storage systems in marine environments require more research and are in a very early stage of development.

The trend in recent years (2017–2019) is also in the number of the articles found suitable for review (Figure 9). The change in the number of articles published in recent years could reflect a change in interest in off-grid systems rather than in renewable energy sources.
4. Discussion

Unlike fossil fuels, most renewable resources are more equitably distributed and used widely in different latitudes. Energy production by renewable resources (hydro, solar, wind, geothermal, biomass and marine energy) increased globally from 93,776 TWh in 1965 to 667,349 Twh in 2018, which represents an increase of 712% [182]. The International Energy Agency (IEA) stated that renewable resources, including hydroelectricity, accounted for 25.3% of the global electrical generation matrix in 2017 [183].

Correctly defining an HRES-OFF requires a precise evaluation of local renewable resources and characterization of the energy demand profile. Given this, appreciating the geographic location of subject communities of HRES-OFF studies is an important step in understanding the potential of renewable resources. Communities located on an island or within a kilometer of a coast have access to marine energy resources like wave, tidal, salinity gradient and OTEC. These communities lack year-round access to water hydro energy resources and have limited access to biomass and geothermal energy, but do have access to strong offshore winds and ever-present sunlight. In contrast, isolated inland communities have more access to biomass and water resources appropriate for small-scale hydro power, high and low enthalpy geothermal energy source, and certainly, ample and widespread use of solar radiation and wind.

Differences in latitude are associated with greater or lesser potential of renewable resources. Solar rays are almost perpendicular in the tropical zone, which allows a greater availability of direct and diffuse radiation on the earth’s surface. At higher latitudes, solar radiation passes through more air mass (AM), which decreases the amount of useful solar radiation. Wind energy is employed almost everywhere in the world on both land and on the high seas. However, the use of this resource is not distributed uniformly. Its use is erratic and not very predictable, and the best wind regimes are not always located close to energy consuming centers [184]. The potential of wave energy is greater at middle and high latitudes, that is, in subtropical and temperate zones. According to [185], densities of annual potential greater than 50 kW/m are found in coastal areas or inner seas in Australia, the United States, Chile, New Zealand, Canada, and South Africa, which is 44% of the available theoretical potential, as estimated in the same study. However, the 2.1 TW of theoretical potential in waves is far from being drawn upon because of: (i) the lack of technological convergence in the design of wave energy converters (WEC), (ii) gaps in environmental legislation, (iii) limited private investment, and (iv) the lack of coastal infrastructure with connections to submarine cables [186]. Likewise, tidal and offshore wind energy face barriers similar to those faced by wave energy, with the difference that the
technology of energy extraction is a stage of mature development and has been sufficiently tested. According to [187], tidal energy is used around the world, while the energy potential of OTEC is largely exploited in tropical areas where the temperature difference the ocean surface and depths of more than 1000 m are in the order of 20 degrees. Extraordinary levels of difference between low and high tide are found in middle and high latitudes, with differences of 7.5 to 13 m in Canada, Russia, Australia and the United States, and of 6 to 7 m in Argentina, Great Britain, Mexico and India, the latter two located in tropical areas [188].

Geothermal energy has an uneven distribution globally, and its presence is often at depths too great for practical use [189]. Exploratory drilling and test wells are too expensive to allow for identifying geothermal potential in a given area [190]. In addition, the high costs and highly qualified staff required in the operation of geothermal plants make this option unfeasible for remote communities that have low energy demands and low population density. These difficulties in implementing and operating HRES-OFF are clearly related to the lack of studies that consider geothermal energy as a viable renewable resource in off-grid energy systems. Biomass is represented by a wide range of fuels. The concept of biomass includes solids, liquid fuels, and several gases. There are drawbacks to biomass energy in terms of availability and sustainable renewal of the resource for island and coastal communities, as well as concern about the use of potential food crops as sources of biomass energy and resulting air pollution, depending on the technology used in energy conversion [191]. Consequently, there has been limited integration of biomass into HRES-OFF, and it has been represented mainly by the use of livestock manure, which through an anaerobic conversion technique provides methane for use in electric generators or food preparation (Figure 10).

Figure 10. Evaluated sources of primary HRES-OFF energy worldwide.

4.1. Technical and Economic Aspects of Conversion Technology

According to [192], the main factors that have helped lower solar panel costs and increase their commercial use are lower primary material costs, a substantial increase in the production of solar panels in China, technological innovations and increased investment at
the industrial level. Similarly, wind turbines are occupying an increasing role in the energy matrices of several countries, encouraged mainly by economies of scale, learning curves, higher plant factors that reduce the levelized cost of energy (LCOE) and an increase in supply with the emergence of wind turbine factories in China [184].

Run-of-the-river systems with a capacity of 10 MW are considered small-scale hydro power (SHP). According to [193], the main benefits of SHP are high efficiency, proven and reliable technology, long-term usefulness and appropriateness to the electrification needs of rural areas. Certain political, economic and social conditions are required to establish SHP, such as financing loans to developers and landowners, training of local personnel in the different stages of operation and maintenance and transfer of technologies to local developers [194]. Likewise, this same study concluded that the economic success of SHP systems depends on the load factor and the associated load, that is, the demand for electrical energy must be associated with commercial and industrial activities, not just domestic demand. In this sense, and highlighting that the economic activities of the studies referenced in this review are associated with agriculture, fishing, farming and tourism (where there is no special electrical energy requirement), SHP solutions are not an economically viable option, since they would be working with load factors of around 10%, which would extend the period of return on investment.

Generating electrical energy from marine sources is in the early stages of development, with the exception of tidal barrage. Wave energy presents several difficulties in its use and integration in energy matrices. Some of these difficulties are: (i) a wide range of designs and prototypes that have not lead to technological convergence, (ii) the evaluation of coastal systems based on the establishment of wind farms [195], (iii) anchoring systems for offshore installations, (iv) extreme climatic events that threaten the integrity of WEC, and (v) the need for more research into environmental impacts and biofouling. Tidal energy has a promising future reflected in electrical generation systems established in countries like France, Canada, the United States, South Korea, China, and Russia. These systems employ tidal barrage technology, which has been used for several years to deliver electrical energy to national transmission networks. Turbines for tidal currents and waves are still in their infancy [196]. Among the main limitations of this technology is difficulties in installing systems and transmitting the electricity that is generated, environmental impacts, biofouling and maintenance requirements [197]. Microturbines best fit the distribution power generation approach. According to [198], microturbines offer several advantages, including lower initial investment (CAPEX), lower operating costs (OPEX) and less impact on the environment. In contrast, generating electrical energy by OTEC technologies and salinity requires more investigation and prototype tests [199] to ensure participation in future power generation systems. Government policies to increase the use of renewable energy source in energy matrices should promote the development of marine energy, which has a significantly higher energy potential than current world energy demand.

4.2. Population and Economic Activities

Most of the reviewed studies did not make reference to the main economic activity of the relevant community. An analysis by country identified that 24.4% of the studies deal with developed countries as represented by member countries of the European Community (including Great Britain), Japan, the United States, Canada, Australia, Russia and South Korea (Figure 3). In contrast to developed countries, where the basic energy needs of the population tend to have been met, there are still gaps in access to energy among the poorest and most isolated groups in developing countries. According to [200], access to energy has positive effects on health care, education, incomes, and development. Nevertheless, the low demand for energy in remote communities implies a high cost to electricity, making access to energy for the poorest families more difficult [201]. In this regard, the poorest families commonly use biomass and kerosene for cooking and lighting. The use of kerosene and paraffin involves the emission of contaminating gases that are dangerous to human health. According to [143], the gases emitted by kerosene can cause cancer and tuberculosis in
women and children. Thus, alternatives to biomass (when it is not sustainable), liquid and solid fuels like paraffin and kerosene, can improve the quality of life of families.

4.3. Key Findings

There is a lack of research on the integration of marine energies as active resources of HRES-OFF in insular/coastal communities. The OTEC theory was conceptualized in the 19th century; however, its implementation in HRES-OFF is evidenced in only one article ([115]). Focusing research efforts on better working fluids and heat exchangers can increase the overall efficiency of the OTEC process. On the other hand, there is much to explore and investigate in the simulation of WEC, tidal turbines and salinity gradient as active renewable resources of HRES-OFF. Only 15 articles studied wave and tidal energy in HRES-OFF (Figure 10), a very low integration index considering that almost half of the 168 articles focus on island communities, which can take advantage of this type of energy.

A total of 61% of HRES-OFF investigations still propose genset as backup systems. The use of fossil fuels has adverse effects on human health and the environment, in addition to maximizing the energy dependence of isolated and island communities. Therefore, research efforts in sustainable energy solutions, based on local renewable resources, should be increased. The investigations [73,93,95,113,174] deepen the diversification of the energy mix towards 100% energy autonomy communities. However, the use of fossil fuels is exacerbated if only HRES-OFF research from the Southern Hemisphere is analyzed (Table 3). In this hemisphere, 81% include genset in their case studies. Added to this is that remote and island communities in the Southern Hemisphere are poorly studied (Figure 1).

5. Conclusions

The development of communities is closely related to ongoing access to electrical energy. Electrical energy is a fundamental pillar of the economic and social development of communities, because of which it is common to find the highest indices of poverty and the low levels of technological development in rural communities. The geographic dispersion of communities in remote and rural areas hinders the provision of electrical energy through conventional electrical generation and transmission techniques owing to the high cost of extending electric transmission grids. Electricity is a vital tool for the economic participation and social wellbeing of rural communities. Areas without electricity have limitations in essential infrastructure, like schools, medical centers, communication and access to potable water. Fossil fuel-based electrical generation is commonly used in these cases, particularly diesel-based systems, given that this is relatively inexpensive, the technology is widespread and the time required to construct an electrical central is relatively short. However, remote communities often do not have easy access to fossil fuels, and owing to their isolation, the system may lack maintenance, which can result in harmful effects for human health and the environment.

Our review was focused on 168 articles published between 2002 and 2019 on the use of off-grid hybrid electrical generation systems as a response to the need to decrease consumption of and dependence on fossil fuels through the integration of different nonconventional renewable resources. HOMER was used in the majority of studies as a methodological tool to analyze cases. The subjects of the analyzed studies were concentrated geographically in the northern hemisphere, mainly in Asia. The majority of the studies dealt with HRES-OFF in tropical or subtropical zones. Photovoltaic arrays and wind turbines, alone or together, were the main renewable resources used in HRES-OFF (Tables 4–6), associated fundamentally with their technical, operational and economic advantages. These systems use batteries as the main method to store energy, while diesel systems are the preferred option as the preferred backup system in the context of intermittent supply of renewable energy. At higher latitudes, HRES-OFF can make better use of other sources of renewable energy like wind energy for non-coastal areas and wave and tidal energy in coastal areas. However, our review found a small number of studies that included marine-based renewable resources as an energy source for coastal communities.
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