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Review

A Hybrid Renewable Energy (Solar/Wind/Biomass) and Multi-Use System Principles, Types, and Applications: A Review

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Abstract: Benefiting from renewable energy (RE) sources is an economic and environmental necessity, given that the use of traditional energy sources is one of the most important factors affecting the economy and the environment. This paper aims to provide a review of hybrid renewable energy systems (HRESs) in terms of principles, types, sources, hybridization methods, cost of unit energy produced, and applications. The works were reviewed for HRESs with and without energy storage. The results can be summarized as follows: It is noted from the studies that Greenius, SAM, HOMER, and TRNSYS were often used in simulating, designing, evaluating, and optimizing these systems. There is often a difference in the economic and environmental indicators between different projects due to the type, fraction, price of energy and components, and efficiency of RE sources. All the studies showed that there are environmental benefits from hybrid systems, not only compared with conventional energy systems but also with RE systems with a single source. All of the related studies showed that hybridization between biomass and concentrated solar energy (biomass-CSP) presents a promising option for producing thermal energy and electricity, and this option also provides a solution for environmental problems related to waste biomass, such as municipal solid waste and wastewater and many industrial wastes, and provides high-quality fertilizers for agriculture. In addition, the multi-use of HRESs increases the economic and environmental benefits, which makes these systems more sustainable. There are various options available for hybridizing RE sources, particularly in the context of energy source integration. The selection of the appropriate options depends on several factors: system type, size of the system, type of energy needed, availability and prices of RE sources, technical knowledge, and experience in operation and maintenance. Several parameters play a crucial role in evaluating HRESs: system makeup and capacity, the fractions of RE in the overall energy produced, efficiency, investment, and energy costs, technical knowledge requirements, and environmental effects.

Keywords: electrical energy; energy storage; hybrid renewable energy system; renewable energy resources; solar power generation; thermal energy

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1. Introduction

In recent times, the world has recognized the necessity of transitioning to renewable energy (RE) in various sectors, including domestic, industrial, and commercial. This shift is motivated by several reasons, such as the extensive consumption of fossil fuels and the impending risk of depletion, the challenges posed by greenhouse gas emissions and global warming, and the volatile political conditions and conflicts that affect energy supply and prices. The attribution of RE is up to 29% of the world's total electricity demand [1]. Energy efficiency and utilizing all energy sources are necessary to meet the world's increasing energy demand. Renewable energy sources are limitless and clean, but the sporadic nature of most types is their biggest drawback. To solve this issue, a hybrid renewable energy system (HRES)—a combination of multiple energy sources—is created.

Power plants play a crucial role in producing the electricity needed for a grid and saving thermal energy for comfort requirements in several approaches. As to the comparatively high cost of electricity produced from RE, the construction of power plants that rely on RE sources requires government decisions and substantial investments. Consequently, researchers rely on software for modeling and simulating possible projects. Considering the intermittent nature of solar power generation, which ceases completely at sunset and fluctuates throughout the day due to weather conditions, it becomes feasible to combine two energy sources. For instance, biogas can be used as an alternative source, stored, and used conveniently in case of need. Thermal input is typically converted into electricity, or it may be used in heating and cooling systems for industrial or domestic services. In power plants, heat is the only thing added to the thermodynamic cycle if the energy source is a fossil fuel, nuclear fuel, or RE source. In general, RE systems can include both conventional and renewable sources, as opposed to conventional energy systems, which rely exclusively on conventional sources. Energy systems are classified as follows:

- Number of RE energy sources: single or hybrid;
- Energy sources: RE only or with conventional fuel;
- Use of energy: single-use (electricity, heat only, or cooling effect only), dual-use, or trigeneration use (electricity, heat, and cooling effect); sometimes the heat used for desalination or any application needs thermal energy;
- Energy storage: with/without energy storage, type (thermal or chemical in batteries);
- Goal of the plant: on-grid or off-grid.

This paper aims to provide a literature review in the field of hybrid RE in terms of principles, types, and applications. The study focuses on hybrid systems that depend on solar energy, wind energy, and biomass energy, which are the most widespread with or without energy storage. This paper could provide the searchers with the current projects and search indicators, so the searcher can select the sides that can be studied or developed according to the project design conditions and help to add new improvements and enhance the performance of the real/planned systems.

The work was divided into six sections. After an introduction that includes the principle, types of HRESs, and the modulation and simulation of these systems, all configurations of hybrid energy systems (HESs) are explained in the second section. In the third section, the multi-uses of HESs are explained; in the fourth section, the environmental benefits are addressed; in the fifth section, there is an economic analysis regarding the simple payback (SPB) period; and finally, in the sixth section, the conclusions and recommendations are presented.

Due to the erratic nature of the RE resources, the most important goal of the RE power plant is to produce stable electricity. In generating electricity systems, RE sources like solar, wind, biomass, geothermal energy, etc., are used. Different hybrid configurations that may be used in this context cause varying energy and financial performance for these systems. Compared to other combinations, such as wind, biomass, and photovoltaic (PV) energy sources, they are more commonly studied in the literature for micro-scale applications. A viable method of addressing intermittent concerns is the hybridization of several RE sources. Another possibility is to provide the system with a conventional source, energy storage, and management to secure demand at all times. Figure 1 shows the available ways to hybridize systems based on solar energy and biomass energy. Gasification is suitable for lignocellulosic biomass, as reported by Verma [2]. It involves the use of heat and chemical processes to convert biomass into energy. In addition, some studies have demonstrated that gasification gives superior efficiency for hybridization, as reported by Hurtado et al. [3]. Rizwana et al. [4] have shown that gasification provides hybridization possibilities with higher efficiency.

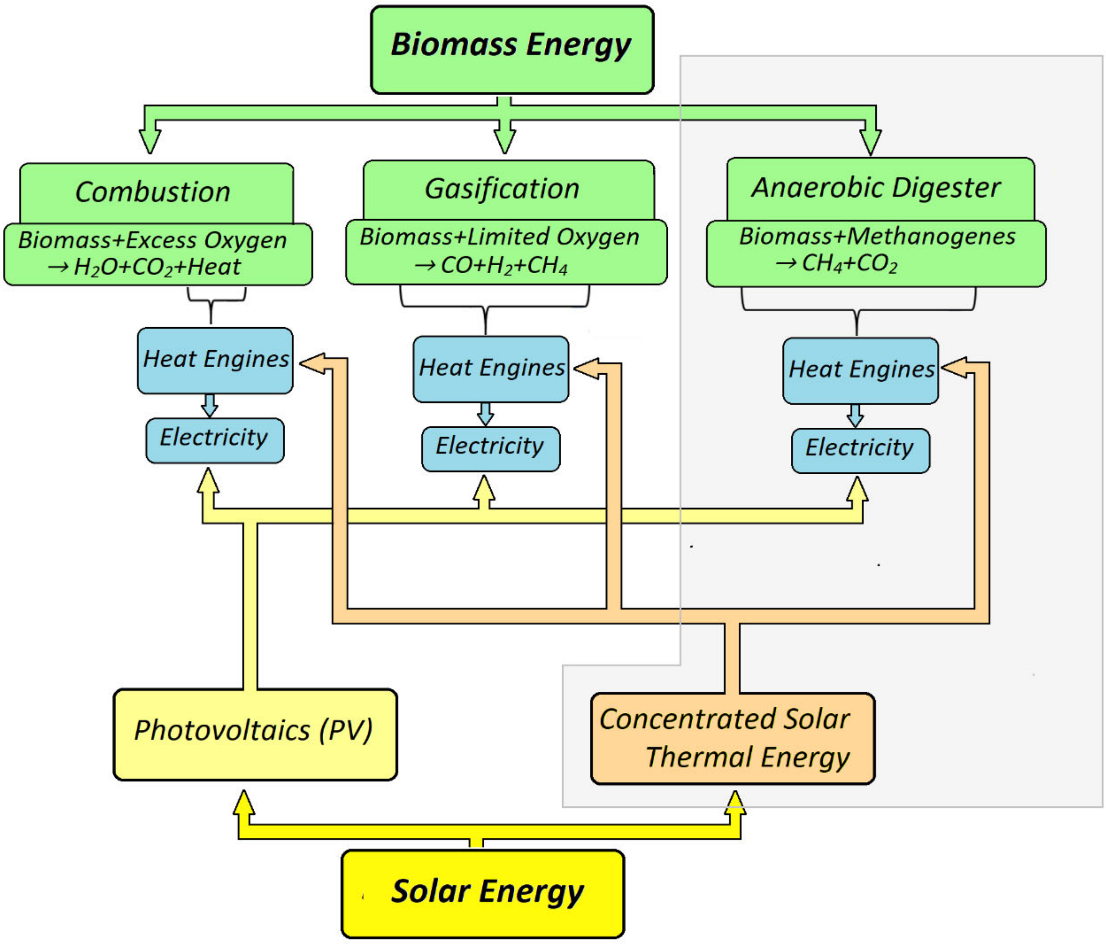

Figure 1. Hybridization option: solar–biomass energy systems.

To achieve a shared energy end-use, an HES combines two or more energy conversion units. When grid extension becomes impractical owing to technological or financial limitations, isolated hybrid systems can be used to provide electricity, such as in rural areas. Due to the possibility of combining renewable and conventional resources, there are many choices for energy integration in hybrid systems. Environmental pollution can be decreased and energy efficiency increased with hybrid power generation due to the natural strengths of various energy forms concerning time and location. Cogeneration technologies have become a necessary trend in development as a result of the global energy crisis. Ammari et al. [5] examined several approaches used to address each of the four primary concerns of an HRES: sizing, optimization, control, and energy management. The authors concluded that HRESs are necessary for levelized cost of energy (LCOE) reduction, the electrification of an isolated location, feeding the main grid, and providing steady electricity generation and energy conservation.

The authors noted that there are two configurations for hybridization hybrid power plants based on the method of combination: electrical conjunction and energy sources conjunction, as illustrated in Figure 2, and Table 1 provides an overview of the advantages and disadvantages of each type. In electrical conjunction, there is no connection between the energy sources before the power block; each source has its own generating unit (G1, G2, and G3), and in some cases, a synchronization system may be necessary. The most common cause of this type of hybridization is the combination of wind and PV. Figure 3 demonstrates the typical on-grid PV-WT system without storage; the system meets the load and can export/import electricity from/to the grid according to the load requirements. Conversely, in energy source conjunction, only one generating unit is required, and there is a relationship between the energy sources before reaching the generating unit. One common example is the combination of solar energy and a biogas power plant. In this case, solar thermal energy can be used to generate steam, and then biogas is used to superheat the steam and secure the temperature required to operate the turbine, or solar thermal energy could be used for heating the anaerobic digester. In the Mildura region of Australia, Peterseim et al. [6] investigated the external superheating of the live steam from a parabolic trough collector (PTC) plant using biomass. Potentially, the peak solar-to-electricity efficiency might exceed 30%. Although other fuels can also be utilized for superheating, the authors claim that biomass offers a good choice for producing electricity. Because of the smaller solar field and the greater efficiency, concentrated solar power (CSP) costs can be immediately reduced by up to 23.5%. In the fiercely competitive electricity market, this is crucial and could bolster CSP.

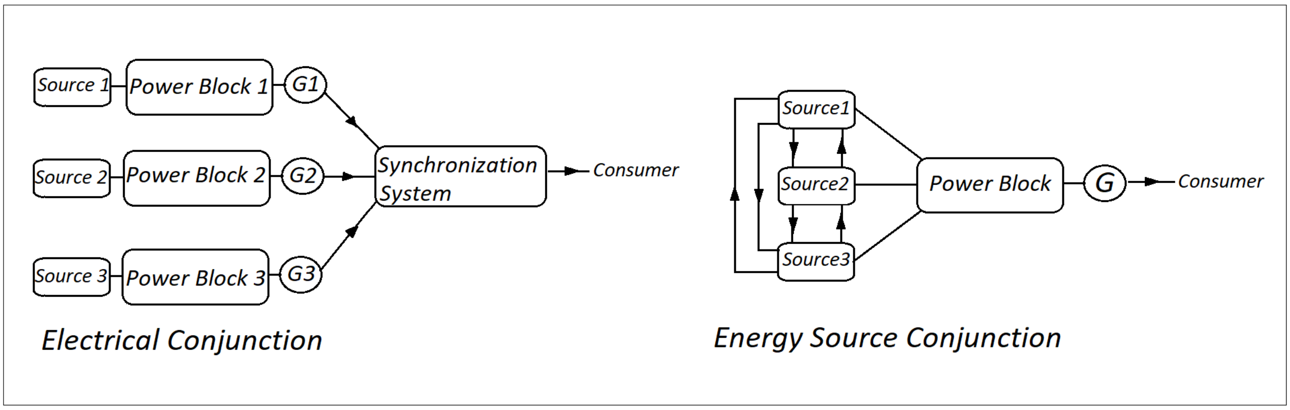

Figure 2. Two configurations of hybridization of energy sources in power plants.

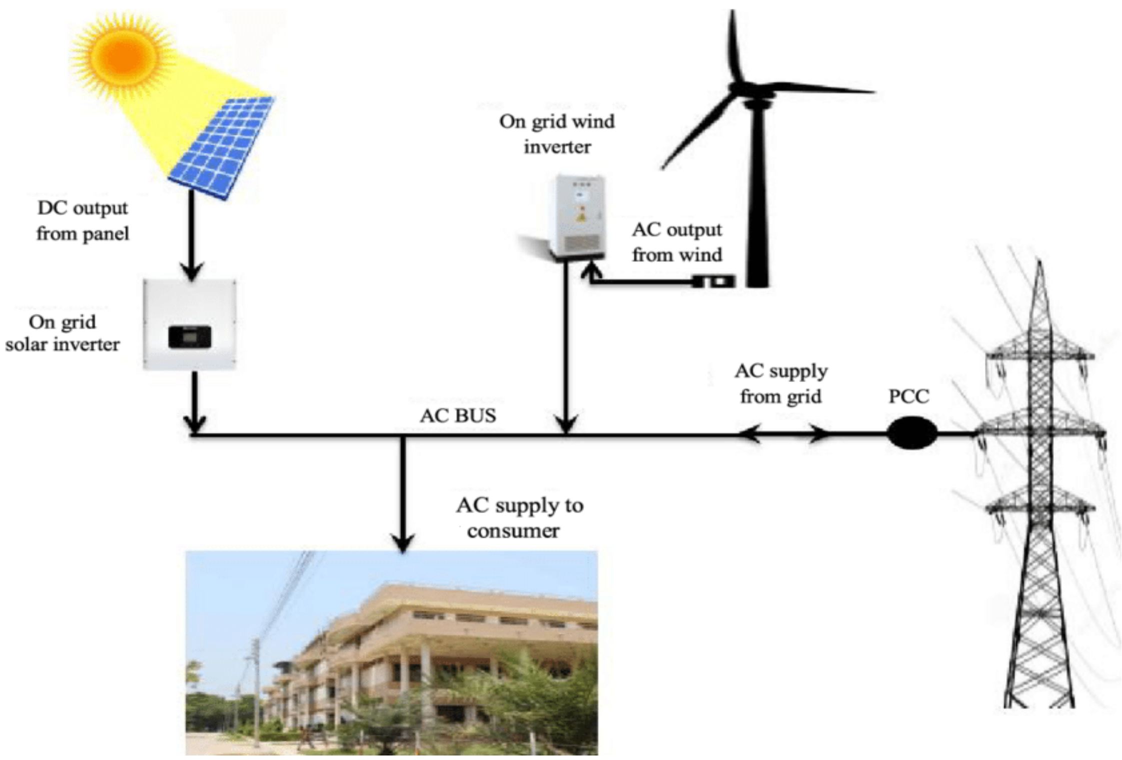

Figure 3. PV-WT hybrid system (electrical conjunction) [7].

Table 1. Benefits and drawbacks of hybrid power plant conjunction methods.

	Electrical Conjunction	**Energy Source Conjunction**
Generation unit	One for every energy source	One for all energy sources
Synchronization system	Need	No need
Relation between sources	No	Yes
Suitable for	Wind turbines (WTs), PV systems, nuclear energy fuel cells, hydraulics...	Biomass, biogas, solar thermal, geothermal, fossil fuel...
Efficiency	The efficiency of each unit is separated from the other	It depends on the relations between the energy sources

Modeling and simulation software provide help for many goals:

- Estimating the technical potential of technology in a specific region;
- Studying the impact of a policy on the economic aspects of a typical system;
- Analyzing various utility rate structures for RE;
- Comparing different technologies, sites, or configurations;
- Estimating the environmental impacts of a system under different conditions;
- Estimating the LCOE and financial aspects of the suggested project.

For modeling and evaluating hybrid power plants with electrical conjunction, the Hybrid Optimization Model for Multiple Energy Resources (HOMER) can be used. This software provides three tools: HOMER Pro, HOMER Grid, and HOMER Front [8]. The two most popular pieces of commercial optimization software are HOMER PRO and RETScreen. This section highlights some commonly used modeling software that can be beneficial for modeling hybrid power plants with multiple energy sources: System Adviser Model (SAM), Transient System Simulation Tool (TRANSYS), and Greenius. These and other programs are used for general thermal and electrical systems such as PV systems, energy storage, thermal solar systems, marine energy (wave and tidal), wind energy, fuel cells, geothermal, solar water heating, biomass combustion, and generic systems. The SAM software was developed at the National Renewable Energy Laboratory (NREL); it is free software that enables detailed technical and financial performance [9]. The highly customizable visual-based software environment TRNSYS is used to model the behavior of transient systems. Although the vast majority of simulations are focused on analyzing the performance of thermal and electrical energy systems, TRNSYS can be used to represent other dynamic systems [10]. Powerful simulation software called Greenius is used to calculate and analyze RE projects from the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center, Cologne, Germany) [11,12].

2. Hybrid Energy Systems Analysis

2.1. Hybrid Energy Systems without Electrical Energy Storage

Studies on the utilization of hybrid systems to produce electricity and thermal energy are widely available. According to Jahangiri et al. [13], hybrid PV-WT systems can meet Middle Eastern grid standards. The authors discovered that several locations are particularly well suited for the construction of solar–wind power plants, including parts of Iran's eastern, central, and southwestern regions; Oman's southern region; nearly all of Iraq; Yemen; some of Egypt's northern and eastern regions; Jordan's southern region; and some places in Syria and Turkey. Ashok and Balamurugan [14] studied a biomass gasifier-based hybrid system consisting of a 20 kW PV, an 83 kW WT, and a 200 kW gas generator to supply power to three villages in India using the software HOMER. The authors reported that the energy demand was 3.5 MWh. On Pantelleria Island in Italy, Figaj et al. [15] used TRNSYS software to quantitatively examine a hybrid system powered via biomass, solar, wind, and a liquified petroleum gas (LPG) generator for multi-use for 10 families. The findings demonstrate that the suggested system provides excellent primary energy-saving performance in each of the examined situations, with an average saving of more than 94 percent. With the same program, Figaj et al. [16] demonstrated a technical-economic analysis of a hybrid ground–solar–wind system for a single-family household in Gdansk, Poland. The production of electrical energy meets 68.6 percent of user demand, and the consumption of primary energy is reduced by 66.6 percent when compared to a traditional system with a natural gas boiler and electrical chiller, according to the authors. Figaj and Żołądek [17] provided an energy-economic study of a solar heating and cooling system with a heat pump and a sorption chiller for a single-family home. A small-scale trigeneration on-grid system for northern Poland that utilizes a biomass boiler, a steam turbine, a sorption chiller, and a WT was the subject of an energy and financial analysis by Figaj et al. [18]. Figaj [19] additionally modeled these combinations for Gdansk, Poland. In comparison to a reference system that employs natural gas, an electric chiller, and a grid, his research found that the system's primary energy savings were above 70%. The above-mentioned studies demonstrated the valuable benefits of hybridization systems for households, including meeting demand and increasing efficiency.

After such a concept was first introduced in the 1990s, Behar et al. [20] evaluated the R&D activities and published research since that time. The authors presented several configurations of the hybridization of solar energy with coal, natural gas, and other RE sources. Also, a commercial 22.5 MW_{el} hybrid power plant that has been in service in Spain since 2012 was presented. For modeling exercises, the majority of the aforementioned articles employed programs like TRNSYS, Thermoflex, EBSILON, Aspen Plus, and EES. Rehman [21] made a review to offer recommendations for choosing suitable hybrid power systems for various applications. The cost, control modes, efficiency, and technology of hybrid power systems were all investigated by the researcher. The study considered systems using batteries, pico hydro, and other technologies, both with and without energy storage. The researcher reported that PV/wind systems (28%) were the most studied and used, followed by PV/wind/diesel (22%), and PV/diesel (21%). The study's findings showed that the average LCOE for PV/wind, PV/diesel, and PV/wind/diesel were, respectively, USD 0.458, USD 0.349, and USD 0.355 per kWh, and the LCOE for wind–diesel systems ranged from USD 0.05 to USD 0.72 per kWh. In addition to outlining the primary types and applications of the combined power generation system, Qing [22] introduced research and the development of the hybrid power system. The author described the main types and uses of the HES in addition to outlining its development and research. The author presented the following types: wind-PV, solar–geothermal, solar–biogas, offshore WTs, tidal, and other types of hybrid systems.

Alzaid et al. [23] presented a hybrid wind/PV system with a capacity of 5 kW in Hafar Al-Batin (north-east) and Sharourah (south) in the Kingdom of Saudi Arabia (KSA). The authors reported that Sharourah is a preferable location for the deployment of the hybrid system over Hafar Al-Batin, with a lower LCOE and less energy excess due to the difference in DNI (Sharouah is more) and climate conditions. Dieckmann and Dersch [24] conducted a simulation to evaluate different scenarios of hybridization: CSP with a solar tower and a PV system using Greenius software. The goal was to assess the impact of hybridization on efficiency and the LCOE produced using the system. They also compared parabolic troughs with different capacities. They found that the PV system has a lower LCOE, and the increase in the capacity of the system leads to a decrease in the LCOE. According to Spelling et al. [25], compared to PTC power plants, advanced solar power generation hybrid combined-cycle power plants offer a 60% reduction in electricity prices. Furthermore, compared to a combination of PTCs and combined-cycle power plants, a 22 percent cost reduction and a 32 percent decrease in CO_2 emissions were achieved.

An economic feasibility assessment and design for a PV/wind hybrid power generating system for Geraldton, Australia, were offered by Loganathan et al. [26]. According to the authors, a combined 2800 W of solar energy and a single 1 kW WT are enough to meet 110 percent of summer demand and 85 percent of winter needs. The electricity generated is USD 0.623 per kWh, which is still much more expensive than grid-connected power sources. Alternative energy sources are becoming more appealing due to their advantages, including lower greenhouse gas emissions, lower operational costs, and a steady power supply. Malik et al. [27] researched a biomass-based HES that was grid-connected and designed to test its viability in the western Himalayan region. Three different hybrid system configurations were modeled using HOMER software: (Case I) PV/biomass gasifier/grid, (Case II) PV/biomass gasifier/wind/grid, and (Case III) solely grid. It was determined that (Case I) the lowest cost of energy (USD 0.102/kWh). In the ideal configuration of this system, the biomass gasifier contributes the majority (61 percent) of the total power output, followed by PV (22 percent) and the grid (17 percent). The proposed method will save emissions of 27.8 Mt CO_2 per year. Kaur et al. [28] concluded that using biomass to generate power using a PV/biomass-based microgrid system is a reliable solution to electrify Punjab's rural areas. By sustainably utilizing biomass through anaerobic digestion, the electricity can be delivered to the village at 0.0735 cents per kWh. Rajbongshi et al. [29] used the HOMER modeling program for the Indian town of Jhawani to develop a hybrid system based on PV/biomass gasification/diesel/grid for various load profiles. According to the authors, the cost of energy for an off-grid hybrid system with a 19 kW peak load (178 kWh/day energy demand) was USD 0.145/kWh. However, it drops to USD 0.091/kWh for the identical scenario when a hybrid system is connected to a grid. Bhattacharjee and Dey [30] investigated if a hybrid PV/biomass system was feasible in the Indian state of Tripura. According to the study, a hybrid system that is connected to the grid is a workable alternative. While the renewable fraction (RF) is found to be 0.91, the cost of producing energy from the hybrid system is USD 0.143/kWh. Table 2 shows the installation location, capacity, and LCOE for various hybrid systems without storage systems. It is noted from the table that PV/wind and PV/biomass systems are the most studied and used. The presence of a conventional generator or batteries often means that the system is off-grid. As it is noted from the table, a large difference in the LCOE may be due to several factors, including DNI, climate, system configurations, source fractions, capacities, economic factors, etc.

Table 2. LCOE of different hybrid energy systems without storage systems.

Location	References and Publication Date	Peak Load (kW)	Hybrid Proposal	LCOE (USD/kWh)
KSA, Hafar Al-Batin and Sharourah	Alzaid et al. [23], 2022	5	PV-wind	0.330–0.414
Spain, de Almeria	Dieckmann and Dersch [24], 2017	≈65 MW	PTC	0.104
		≈65 MW	PTC with solar tower	0.143
		44–50 MW	PV	0.086
			PTC	0.186
			CSP-PV	0.174
Australia, Geraldton	Loganathan et al. [26], 2019	3.8	PV-wind	0.623
Western Himalayan Region	Malik et al. [27], 2020	29.2	PV/biomass gasifier/grid	0.102
India, Punjab	Kaur et al. [28], 2020	50	PV/biomass	0.076
India, Jhawani	Rajbongshi et al. [29], 2017	19, 25, 41	PV/biomass gasification/diesel/grid	0.1–0.145
India, Tripura	Bhattacharjee and Dey [30], 2014	14	PV/biomass	0.143
KSA, Madinah	AlKassem et al. [31], 2022	1.37 MW	PV-wind	0.061
Eco-village in Malaysia	Hashim et al. [32], 2014	*	PV-biomass	0.280–1.360
KSA (Hafr AlBatin, Riyad, Sharurah, and Yanbu)	Alharthi et al. [33], 2018	2395	PV-wind	0.036–0.054
KSA, Arar	Rehman and El-Amin [34], 2015	4340	PV-diesel generator	0.038

* See text.

2.2. Hybrid PV-Wind-Battery Systems

In this section, the applications of hybrid PV-wind-battery systems will be explained. A hybrid PV-wind-powered reverse osmosis desalination system has been built and modeled by Mokheimer et al. [35] to be optimized for the lowest cost of desalinated water in the conditions of Dhahran, KSA. According to the authors, the price of the desalinated water produced ranges from USD 3.693/m^3 to USD 3.812/m^3. Krishan and Suhag [36] made a grid-independent wind-PV-battery-based proposal in response to a techno-economic analysis carried out in the Yamunanagar district of Haryana state, India, utilizing two separate platforms, HOMER and MATLAB. The optimal and most economical architecture that has been suggested consists of a 26.2 kW converter, 122 units of 260 kWh lead–acid batteries, a 10 kW WT, and a 121 kW PV system. Muleta and Badar [37,38] look into the isolated Ethiopian community of Jarre, which utilizes hybrid PV-wind and battery packs to provide electricity. Reliability of the power system, financial costs, and the consequences of greenhouse gas emissions are taken into account while evaluating the system's performance. Different optimization methods are used and contrasted to acquire the best design parameters. The authors reported that the best configuration was found with an LCOE of USD 0.1159/kWh. Table 3 shows the installation location, peak load, and LCOE for various hybrid PV-wind-battery systems. As it is noted from the table, a difference in the LCOE may be due to several factors, including DNI, climate, system configurations, source fractions, capacities, economic factors, etc.

Table 3. LCOE of hybrid PV-wind-battery systems.

Location	References and Publication Date	Peak Load (kW)	LCOE (USD/kWh)
KSA, Dhahran	Mokheimer et al. [35], 2013	1	0.624–0.672
India, Yamunanagar of Haryana state	Krishan and Suhag [36], 2019	*	0.288
Ethiopia, Jarre	Muleta and Badar [37], 2023	300	0.116–0.119
KSA, Alrais by Yanbu	Moria [39], 2019	6 + 5	0.226
KSA, different locations	Tazay [40], 2021	AC/DC 60/70	0.433–0.560
KSA, north-eastern sector	Alshammari and Fathy [41], 2022	500–1350 MW	0.03883

* See text.

2.3. Hybrid Systems with Various Storage Abilities

This paragraph discusses the HESs with the possibility of energy storage, which is often off-grid. Several hybrid configurations with solar, wind, biomass, geothermal, fuel cells, and diesel generators have been analyzed. Along with various designing criteria, challenges and gaps with future potential were thoroughly examined by Malik et al. [42]. The analysis showed that biomass-based HESs, especially for off-grid rural electrification, can provide a cost-effective and ecologically friendly option. The authors found that the hybrid PV/biomass energy systems in most research had an average LCOE of USD 0.300/kWh. Greenius software has been utilized to simulate two 50 MW power plants in Jordan by Dersch and Dieckmann [43]: the first one with a solar thermal power plant with PTC (with storage of 2 h) and the second one with a PV power plant. The simulation results are presented in Table 4. The results showed that LCOE for PTC is 1.56 times that of a PV system, and the investment cost is about 3.4 times that of a PV system, but the yearly net energy produced for PTC is about 2 times that of PV. Additionally, depending on the system type and environmental factors, solar PVs can only convert roughly 15–20% of the incoming radiation into power, as reported by Suresh et al. [44], while CSP with PTC technology can achieve efficiency of over 30%, as reported by Peterseim et al. [6].

Table 4. Results of the simulation of the two 50 MW parabolic tough collector and PV Plants in Jordan [43]. USD = EUR 0.91.

Parameter	PTC	PV	Ratio (PTC/PV)
Rated power (MW)	50	50	1
Total aperture area (m^2)	510,150	289,130	1.8
Total land area (m^2)	1,785,525	505,978	3.5
Net electric output (GWh/Year)	184.4	85.4	2.2
Total investment cost (M-EUR/kW)	288	85	3.4
Specific investment cost (EUR/kW)	5760	1700	3.4
LCOE (EUR/MWh)	156	100	1.6

At Oakland University, Alhawsawi et al. [45] and Alshakhs and Arefifar [46] presented studies of the ideal design of HRESs. By maximizing the incorporation of solar, wind, and energy storage technologies and utilizing CHP to meet energy needs, Chedid et al. [47] looked into the idea of gradually replacing diesel generators with a hybrid system made up of PV and batteries. The analysis demonstrated that the suggested system could secure electricity at a competitive price, while the diesel generators cost USD 0.210/kWh. An integrated biomass/PV system and solution for a load-shifted eco-village in Malaysia were discussed by Hashim et al. [32]. The capacity of solar PV is 386 kWp, biomass power is 170 kW, and energy storage is 258 kWh. When energy storage and load shifting are used together, the LCOE is reduced, basic case, from USD 1.36 to USD 0.28/kWh. According to Alturki and Awwad [48], a standalone hybrid WT/PV/biomass system was created and optimized utilizing various optimization techniques. The findings demonstrated that this hybrid system is both environmentally and financially feasible. It was discovered that the pumped-hydro storage hybrid system's LCOE was lower (USD 0.215/kWh) than the hybrid system for storing batteries (USD 0.254/kWh). According to the authors, the majority of the overall electricity need is satisfied by power produced by PV and WT (85%), with the biomass generator providing the remaining 15% of the total requirement.

To secure the electrical and heating requirements of Shiraz University's Eram Campus in Iran, a smart hybrid system was examined by Eisapour et al. [49]. The system consists of a gas turbine, boiler, PV system, and pumped hydro storage with capacities of 2650 kWh, 17 MWh, 13,754 kWh, and 70 units, respectively. Ghenai and Bettayeb [50] studied the effectiveness of a hybrid system of PV, fuel cells, and generators in Sharjah, United Arab Emirates. Solar PV, a solid oxide fuel cell, an electrolyzer for producing hydrogen, a tank for storing hydrogen, a backup generator, a battery bank, and a converter are the parts of the off-grid RE system. Backup generators, fuel cells, and solar PV systems all have capacities between 1025 and 1200 kW, 200 MW, and 100 kW, respectively. The findings showed that the anticipated solutions might deliver an RE fraction between 66.1% and 75.8%. To produce electricity for different uses and hydrogen for running an electric tram in Ouargla, Algeria. Mokhtara et al. [51] presented a design and analysis of a grid-connected PV/batteries/hydrogen HRES. The system's goal was to optimize self-sufficiency on a university campus using the HOMER program. The findings indicated that on-grid PV with a hydrogen system will be the best option going forward, while the best one without a hydrogen storage system is now the most cost-effective.

Using HOMER software, Miao et al. [52] investigated the possibility of an HES to provide heat and electricity for a family in the best possible arrangement in the United Kingdom (UK). The HES has a methane generator, PV, batteries, and a WT. It is determined that the HES system, which consists of a 1 kW WT, a 1 kW biogas generator, four battery units, and a 1 kW power converter, is the most practical option for producing enough heat and electricity. Additionally, the lowest net present cost (NPC) is USD 14,507. Using HOMER, Khosravani et al. [53] assessed the technological and economic viability of hybrid PV/wind/generator/batteries RE systems for four different climate zones across the United

States. The case studies' peak loads ranged between 1711.5 and 74,531.4 MW. According to the authors, high renewable fractions (RFs > 95%) are prohibitively expensive, but lower RFs offer more affordable possibilities, and HRESs can be created with LCOEs that are comparable to current averages and RFs ranging from 78 to 91 percent. Diesendorf and Elliston [54], on the other hand, concentrated on proving that these technological difficulties can be solved to achieve 100% RE systems, even when renewable sources are primarily variable, by using biomass alternatives.

India is characterized by the existence of multiple studies on HES using HOMER software, for example, the following: Rajbongshi et al. [55] presented HESs, including biomass gasification, PV, batteries, and diesel generators, as a backup for energy access for a small village in India. The system can provide a dependable energy supply to the village and has fewer emissions than a conventional system, according to the authors, who also noted that the cost of electricity has altered based on the demand profile and grid availability. HES, including WTs, a biomass gasifier, and batteries, was suggested by Balamurugan et al. [56] for Aachampati. The energy costs of the wind-biomass system and the wind-diesel system are also contrasted. According to the authors, India's rural areas would benefit the most from the recommended wind–biomass gasifier HES. Kobayakawa and Kandpal [57] assessed a multi-configuration hybrid off-grid 120 kWp PV system in Kaylapara, West Bengal. The authors reported that the economic indicators were significantly lower compared to the results with the actual system. Anand and Prashant [58] proposed an HRES that uses solar PV, a biomass gasifier, and a fuel cell-based generation system to meet India's electricity demand. The system was modeled for an energy demand of 4.4 kW at peak load and 56.52 kWh on average per day. This system generated more energy overall than was required. Wegener et al. [59] created four models of various hybrid biomass/PV systems for a hotel resort on Neil Island, which has an average daily power demand of 40.7 kW and an average daily electricity use of 977 kWh for the entire year. According to the findings, a biomass-based, PV-assisted combined cooling, heating, and power system has the potential to save more than USD 500,000 over 20 years and reduce CO_2 emissions by 365 t annually. According to Palatel [60], a standalone HES presents a viable choice for the electrification of outlying areas. In an existing residential complex in Gaul Pahari, India, a case study has been used to demonstrate a diesel generator-PV-battery bank system. The diesel generator is set to power 50 kW, while the PV array has a 15 kWp rating power. The battery bank has a 288 kWh overall energy capacity. León Gómez et al. [61] recently reviewed HRESs and stated that the majority of works concentrate on techno-economic goals. According to the authors, in residential areas, 68 percent of usage-isolated hybrid networks are the most popular design, and nearly a third of all related published papers worldwide come from India. The most popular combination of generation sources was the PV-wind-battery generator, and diesel generators were the most popular auxiliary generation source (used by 79 percent of users). The best studies were theoretical, using different algorithms and software, such as HOMER, and occasionally experimental research, such as that by Hurtado et al. [3]. Mishra et al. [62] simulated PV solar–biogas and wind–biogas hybrid systems for a daily average demand of 19.2 kWh. According to the authors, the PV-biogas system produced 18% of total electricity, compared to just 12% for the wind–biomass system.

According to Afrouzi et al. [63], MATLAB was used in Lundu, Sarawak, Malaysia, to determine the best possible combination of eleven solar panels, one WT, and nine batteries. It was determined that replacement costs made up the largest portion of the system cost, while WTs showed the highest operation costs. Eziyi and Krothapalli [64] evaluated a hybrid system for producing electricity and purified water that included PV/batteries/biomass generators with a gasifier in Nigeria. To ensure reliable electricity production, optimal system sizing, and an ideal LCOE, HOMER software was used to examine various system configurations. The study's conclusions point to co-generation using this technology as a feasible alternative for sustainable rural development. Mahmoud et al. [65] looked into the use of modern optimization techniques to determine the best arrangement of hybrid RE sources in Egypt's El-Baharyia Oasis. Solar panels, WTs, battery storage devices, and standby diesel engines are the components of these hybrid RE sources using MATLAB. El-Sattar et al. [66] and Diab et al. [67] created a modest standalone microgrid to supply electricity in Egypt. A generating system with different configurations showed how well the suggested approach worked to determine the generating and energy storage units' ideal capacity for the proposed grid-independent hybrid system. El-Sattar et al. [66] reported that a peak load of 420 kW can achieve a minimal LCOE of USD 0.211/kWh.

Aziz et al. [68] used HOMER Pro software to give a techno-economic and environmental feasibility analysis of a standalone HES for a rural Iraqi location. Based on combinations of PV, hydro, diesel generator, and battery energy storage, five design cases are suggested and evaluated. The simulation findings indicate that the hybrid system, which comprises a 5 kW diesel generator, a 9 kW converter, 14.7 kW of hydropower, 13 kW of PV modules, and 8 units of storage batteries, is the best option. The LCOE ranges from USD 0.0458 to USD 0.054 per kWh.

Ribó-Pérez et al. [69] used HOMER software to present technical and financial evaluations of islanded biomass-PV hybrid RE microgrids for two case studies of remote rural populations in Zambia and Honduras. This system achieved a competitive LCOE of electricity in the case studies of Mumbeji and El Santuario, with an LCOE of roughly USD 0.06/kWh in El Santuario. For Mumbeji, a higher value of USD 0.48/kWh was obtained.

Kozlov et al. [70] improved the performance of a conventional generator and a hybrid RE source (biomass gasification and PV). The generator was only taken into consideration in producer gas and dual-fuel mode (producer gas and diesel fuel) as a part of the authors' goal to establish an operation policy that minimizes costs. An off-grid system with a 30 kW load consisting of a 10 kW generator, 24 kWh of two batteries, and 10 kW of PV panels was used to evaluate the proposed control system. Table 5 shows the installation location, capacity, and LCOE for various hybrid systems with various storage abilities. It is noted from the table that all the presented studies used batteries, except for one that used pumped-hydro storage. Eisapour et al. [49] studied the state of energy storage in pumped-hydro storage, while Alturki and Awwad [48] included a comparison between the two technologies. Parihar et al. [71] considered the possibility of securing a maximum and minimum load for residential buildings of 19 and 2 kW in the Ballia district of Uttar Pradesh, India. The authors compared different stand-alone systems. A PV-hydro-biogas-batteries hybrid system was proposed by Kumaravel and Ashok [72] in their techno-economic feasibility assessment to provide the Forest Department in Kakkavayal, Kerala, India, with electricity. The authors suggested an ideal hybrid system that includes PV, hydro, biomass gasifier generators, and batteries with storage capacities of 2, 15, 5, and 120 kW, respectively. As noted in Table 5, a large difference in LCOE may be due to several factors, including geographical location, climate, system configurations, source fractions, capacities, economic factors, research period, etc.

2.4. Thermal Solar–Biomass Hybrid Energy Systems

These types of thermal HESs are considered highly effective. It utilizes solar energy, which is abundantly available in the daytime, and any excess heat energy generated can be stored for later use in the absence of sunlight or at night. Furthermore, the authors suggested that thermal energy can be employed to heat the biodigester, for increasing biogas production.

Table 5. LCOE of different configurations of hybrid systems with various storage abilities.

Location	References and Publication Date	Peak Load (kW)	Hybrid Proposal	LCOE (USD/kWh)
Congo, Kinshasa	Hurtado et al. [3], 2015	8	PV-biomass-batteries	0.777
Eco-village in Malaysia	Hashim et al. [32], 2014	*	WT-PV-biomass-batteries	0.254
USA, Oakland University	Alhawsawi et al. [45], 2023	9.958 MW	*	0.00274
Lebanon, Beirut	Chedid et al. [47], 2020	2.4 MW	PV- batteries	0.088–0.100
KSA, Dumat Al-Jandal	Alturki and Awwad [48], 2021	34	WT-PV-biomass-pumped-hydro storage	0.215
			WT-PV-biomass-batteries	0.254
Iran, Eram Campus, Shiraz University	Eisapour et al. [49], 2021	*	Gas turbine-boilers-PV-pumped hydro storage units	0.090
UAE, Sharjah	Ghenai and Bettayeb [50], 2019	*	PV-FC-diesel generator-hydrogen-batteries	0.092
Algeria, Ouargla	Mokhtara et al. [51], 2021	91–1916	PV-batteries-hydrogen	0.103
UK, Newcastle	Miao et al. [52], 2020	*	WT-PV-biomass-batteries	0.588
United States, New York; California; Milwaukee, WI; and Texas	Khosravani et al. [53], 2023	*	PV-WT-generator-batteries	0.077–0.208
India, Assam, Jhawani	Rajbongshi [55], 2016	19–41	PV-biomass-batteries-diesel generator	0.064–0.067
India, Aachampati, south of Chennai	Balamurugan et al. [56], 2011	290	WT-biomass-batteries	0.078
India, Kaylapara, West Bengal	Kobayakawa and Kandpal [57], 2016	120	PV-biomass-batteries	0.511–0.780
			PV-WT-biomass-batteries	0.596–0.890
India, Bhubaneswar	Mishra et al. [62], 2014	3.96	PV-biogas-batteries	0.174
			WT-biogas-batteries	0.358
Nigeria, Abia State, Umudike	Eziyi and Krothapalli [64], 2014	35	PV-biomass gasification-batteries	0.11
Egypt, El-Baharyia Oasis	Mahmoud et al. [65], 2022	340–375	PV-WT-generator-batteries	0.216
Egypt, Abu-Monqar	El-Sattar et al. [66], 2022	420	PV-biomass-FC	0.211–0.237
India, Ballia district of Uttar Pradesh	Parihar et al. [71], 2019	19	Biomass–batteries	0.250
			PV-biomass-batteries	0.300–0.370
India, Kerala	Kumaravel, and Ashok [72], 2012	*	PV-hydro-biomass- batteries	0.164
India, Chamarajanagar district, Karnataka state	Suresh et al. [73], 2020	49.21	Biogas-biomass-PV-WT-fuel cell-batteries	0.163–0.214
KSA, Makkah	Ramli et al. [74], 2014	1100–2200 MW	PV-batteries-diesel generator	0.119–0.141
KSA, Jubail	Baseer et al. [75], 2019	270–685	PV-WT-diesel generator-batteries	0.250
Egypt, New Borg El Arab City	Diab et al. [76], 2015	18.41	PV-WT-diesel batteries	0.190

* See text.

It is possible to connect the biomass and solar fields in two different ways: either by replacing the backup natural gas boiler with a biomass boiler or by connecting the solar field and biomass boiler in parallel. There are many simulation studies related to hybrid power plants that depend on solar/biogas as an energy source. However, the design and operational conditions for these plants are locally determined, aiming to address specific problems or make a significant local contribution to RE. This is primarily due to the nature of RE, which relies on the availability of local resources and addresses specific local challenges that can be solved through RE solutions. With the advancement of modeling and simulation software, it can now analyze and solve numerous similar systems. For example, the same energy sources can generate electricity with varying LCOE due to different weather and geographic conditions, annual direct normal irradiance (DNI), wind availability, biomass prices, and the construction of systems.

To be economically viable, these plants are typically built in areas within the subtropical latitudes of 15° to 40° both in the northern and southern hemispheres, such as the following regions: Middle East and North Africa, the Southwestern United States, Australia, Northern Mexico, and Western China [77]. In a case study of Senegal, Thiam et al. [78] reported the findings of the Sahel's selection of potential areas for hybrid CSP-biomass. The locations that were found have a DNI of more than 1600 kWh/m^2 per year. A standalone CSP plant normally requires DNI values of >2000 kWh/m^2 per year; however, the authors noted that the special reduction of CSP-biomass hybrid plants permits locations between 1400 kWh/m^2 per year and 2000 kWh/m^2 per year with large biomass potential. Locations with cheap solid fuels, such as waste products, are preferred to maximize economic feasibility. The following examples shed light on some of these studies/research around the world.

Research on a 10 MW hybrid power plant using biomass and PTC with a DNI of 2000 kWh/m^2 was introduced by Servert et al. in [79]. Three 10 MW power plant instances were analyzed in the study: a CSP power plant, a biomass power plant, and a hybrid CSP/biogas power plant. In Table 6, the findings of this comparison are presented. Compared to CSP or biomass power plants, the investment cost of the hybrid system is higher. It also shows that the hybrid system generates almost 2.7 times as much energy as the CSP plant, resulting in a lower LCOE for the hybrid power plant compared to CSP (64%).

Table 6. Comparative economic-energy assessment of 10 MW$_{el}$ Systems [79], USD = 0.91 EUR.

	CSP	Biomass	Hybrid CSP-Biomass
Investment Cost (M-EUR)	50	32	62
Operation Cost (K-EUR)	1102.400	5329.425	4641.310
Electricity Production (MWh)	26,000	75,000	71,934
LCOE (USD/MWh)	266	129	171

A commercial CSP/biomass power station called "Termosolar Borges" was described by Cot et al. [80] as enabling increased electricity production and improved system stability. It has been running since December 2012 and has a 22.5 MW$_{el}$ plant capacity. It is situated at Les Borges Blanques, Lleida, Spain, as reported by Peterseim et al. [81]. The authors studied 17 configurations for hybrid solar thermal/biomass plants using different source technologies (techno-economic and environmental). To compare the various configurations, a case study based on the yearly availability of 100,000 tons of wood biomass is used. The results demonstrate that while Fresnel–biomass hybrid systems had the lowest specific investment, solar tower–biomass hybrid systems achieved the best net peak efficiency of 32.9 percent.

A 100 MW$_{el}$ hybrid biomass/thermal solar system in Brazil is being used to generate power and desalinate water, according to a study by Khosravi et al. [82] utilizing TRNSYS. The proposed hybrid system, despite having somewhat higher capital investment costs, had the lowest LCOE when compared to the several power plant layouts, coming in at 7.865 cents per kWh. An overview of the energy and economic analyses is given in Table 7. The findings show that the hybrid system has the lowest LCOE but comes at a high cost. However, the investment costs for linear Fresnel systems, biomass power systems, and hybrid power plants are close in value. The power factor and annual energy output of the hybrid and biomass power plants are almost identical. This exemplifies the benefit of integrating a solar system with biomass.

Table 7. Technical-economic results of hybrid thermal solar/biomass systems [82].

	Annual Energy Production (GWh)	Net Capital Cost (M-USD)	Capacity Factor (%)
Linear Fresnel reflector system	201,215	352	24.4
Solar dish Stirling system	151,119	293	17.3
PV system	155,768	182	17.8
Biomass power system	834,925	376	95.3
Hybrid system	831,394	396	94.9

Liu et al. [83] designated and tested two hybrid thermal solar–biomass systems for combined power generation in western China. The first system uses a thermochemical process in which concentrated solar energy powers biomass gasification, which is used as a solar fuel. The compressed air in the second system's Brayton cycle is heated directly by solar energy thanks to the thermal integration idea. Under the particular gasification temperature of 1150 K, thermal solar–biomass gasification can convert and store solar energy into chemical energy with a net solar-to-fuel efficiency of 61.23% and a net solar fraction of 19.01%. The annual system overall energy efficiency and the solar-to-electric efficiency of the first system reached 29.36 percent and 18.49 percent, respectively, compared to 28.03 percent and 15.13 percent with the second one. Pedrazzi et al. [84] conducted a numerical simulation study of a PTC-biogas plant with a maximum power capacity of 5 MW in Messaad, Algeria. The feedstock for the digester in this hybrid power plant is sourced from the urban waste generated by approximately 120,000 inhabitants in the city. The digester produces a daily volume of 68,800 cubic meters of biogas. The power plant operates on a Rankine steam cycle. The generated biogas, along with methane, is utilized as a fuel in the boiler. A modest hybridization with methane was employed in the winter because RE sources were unable to meet the electricity demand. The power plant with the best compromise in terms of solar share of 20.73 percent, biogas share of 70.53 percent, and dumped solar heat fraction of 10.22 percent was that with a solar multiple (SM = 2.07) and full load hour (FLH = 9 h). Table 8 shows the annual summary results of the hybrid CSP-biogas power plant.

Table 8. Annual summary results of the hybrid CSP-biogas power plant [84].

Description of the Indicator	Indicator Value
Annual useful heat generation (MWh_{th})	130,999
Annual electricity generation (MWh_{el})	37,084
Solar share (%)	20.73
Biomass share (%)	70.53
Methane share (%)	8.73

As a backup energy source for Tunisian conditions, Soares and Oliveira [85] suggested a hybrid renewable power generation system that depends on thermal solar energy and biomass sources. A consistent operation close to the turbine design parameters led to an increase in SF efficiency of 3% and an increase in organic Rankine cycle (RC) efficiency of between 15% and 38%. On the other hand, hybridization encouraged energy surpluses mostly in the summer, showing that hybridization greatly reduces the requirement for storage, if not eliminates it.

Using the Greenius program in Tunisia, Soares et al. [86] investigated the performance of a 1 MW_{el} hybrid CSP/biomass power plant. In one system (Case 1), the emphasis was solely on producing electricity, whereas combined heat and power (CHP) was generated in the other model (Case 2). Table 9 shows the main results of two models of hybrid power plants. Herrera et al. [87] also thoroughly examined Case 1 to examine the socioeconomic and environmental viability of CSP and biomass in Tunisia. The authors reported a significant decrease in greenhouse gas emissions for the production of electricity, a decrease in plant sizes, and the creation of jobs. When comparing the two cases mentioned by Servert et al. [79] (10 MW) with Case 1 (1 MW) in Soares et al. [86], where electricity generation is the focus, there is a notable difference in the LCOE. This difference in LCOE can be attributed to several factors, including solar field, biomass fraction and type, power block expenditure, etc. Soares et al. [88] participated in two EU-funded projects that investigated the use of thermal solar energy and biomass for heating and cooling, as well as RE for electricity production. One of the prototypes is a demonstration of a small-scale centralized generating system (60 kW_{el}), built in Tunis, Tunisia, while the second prototype is a representation of micro-cogeneration systems (6 kW_{el}), put in Benguerir, Morocco.

Table 9. Main results for simulation of two models of hybrid power plant (CSP/biomass) [86]. USD = 0.91 EUR.

	Case 1 (Electricity Only)	Case 2 (CHP)
Capacity (MW_{el})	1	1
Electrical efficiency (%)	22.0	19.0
Heat output (kW_{th})	0	1960
Energy-to-heat ratio (%)	0	51.0
Mean annual efficiency (%)	13.7	33.8
Electricity production (MWh_e)	5840	5840
Heat production (MWh_{th})	-	11,600
Investment cost (EUR)	9,477,115	11,259,217
Operation cost (EUR)	283,339	283,339

Suresh et al. [89] went into great length about the many technologies that can be used in power generation systems to combine solar thermal energy with biomass energy. To meet demand after sundown, the biomass boiler can also generate power in stand-alone mode. Figure 4 shows a plant configuration of a proposed hybrid system by the authors, which consists of three main elements: a power block, a solar field, and a biogas boiler. The authors suggest that hybridization might be an effective, long-term solution. According to Suresh et al. [89], if the cost of biomass was USD 24/ton, the LCOE ranged between USD 0.041 and USD 0.114 per kWh for plants with a capacity between 1 and 20 MW. The plant's capacity utilization rises from 23% to 47% when operating in hybrid mode.

Sahoo et al. [90] conducted research on a 5 MW thermal solar–biomass hybrid power plant for the Gurugram region of Delhi, India. Intangible benefits, including the creation of jobs, environmental advantages, and dispersed power generation, will benefit society in addition to the financial gains for the projects' supporters, so the Indian government supports these projects. Sahoo and his team [91] examined a hybrid thermal solar–biomass system for the poly-generation process (power, cooling, and desalination). The full system satisfies the energy needs and increases the primary energy savings even as the output of electricity reduces. This system achieves a primary energy savings rate of 50.5 percent. Compared to a straightforward power plant, this technology increases energy output by 78.12%. Srinivas and Reddy [92] have set up thermal solar and biomass combustion in conjunction for electricity generation. According to the findings, when solar participation increases from 10% to 50%, the energy efficiency of plant fuel increases from 16% to 29%. Due to the low collector efficiency relative to combustion, the thermal efficiency of the hybrid plant during daytime operation decreases from 15% to 11% with the inclusion of solar collectors. Data on the different combinations of hybrid thermal solar/biomass energy systems in different nations are included in Table 10. Climate, geographical location, system makeup, source fractions, capacity, and economic factors can all be used to explain the variation in indices.

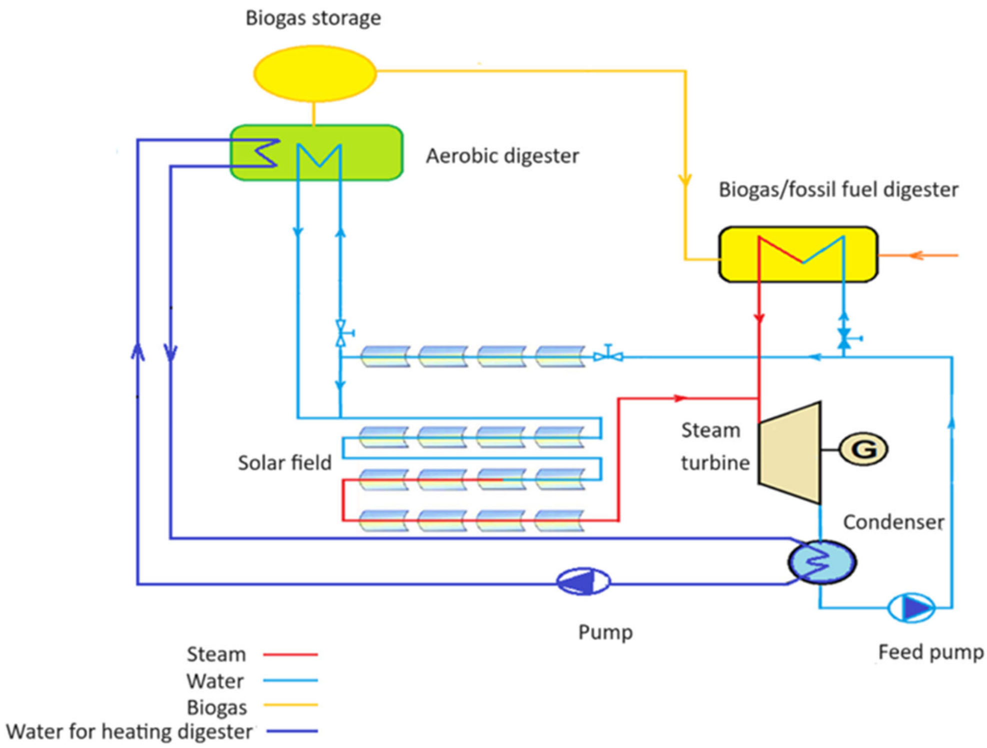

Figure 4. Thermal solar–biogas hybrid power plan.

Table 10. LCOE of hybrid solar–thermal energy and biomass to generate electricity.

Location	References and Publication Date	Peak Load (kW)	Hybrid Proposal	LCOE (USD/MWh)
Brazil, Natal-RN	Khosravi et al. [82], 2021	100 MW	Solar thermal	140
			PV	105
			Biomass	98
			Solar thermal–biomass	79
China, Yanqi, Xinjiang	Liu et al. [83], 2016	≈50 MW	Solar thermal–biomass	190–200
Algeria, Messaad	Pedrazzi et al. [84], 2019	5 MW	Solar thermal–biomass	108
Tunisia, Tunis	Soares et al. [86], 2018	1 MW	Solar thermal–biomass	140–194
India, Bengaluru	Suresh et al. [89], 2019	1–20 MW	Solar thermal–biomass	410–114

3. Multi-Use of Hybrid Energy Systems

In this section, some papers and points related to the multiple uses of energy hybrid systems will be discussed. Studies for the best HRES design to use CHP to meet energy needs were given by Figaj et al. [15,16,18], Figaj and Żołądek [17], and Figaj [19] for Poland. Figaj et al. [15] quantitatively examined a hybrid system powered by biomass/solar/wind/LPG generators for providing electricity, fresh water, heating, cooling, and domestic hot water for 10 families. Figaj et al. [16] also demonstrated a technical-economic analysis of a hybrid ground–solar–wind system for a single-family household in Gdansk, Poland. A small-scale trigeneration system for northern Poland that utilizes a biomass boiler, a steam turbine, a sorption chiller, and a WT was the subject of an energy and financial analysis by Figaj et al. [18]. Figaj and Żołądek [17] provided an energy-economic study of a solar heating and cooling system with a heat pump and a sorption chiller for a single-family home. Figaj [19] additionally modeled these combinations for Gdansk, Poland. In comparison to the reference system that employs natural gas, an electric chiller, and a grid, he reported that the system's primary energy savings were above 70%.

Alhawsawi et al. [45], Alshakhs and Arefifar [46], and Eziyi and Krothapalli [64] evaluated a hybrid system for producing electricity and water desalination that included a PV/batteries/biomass generator with a gasifier in Nigeria. The study's conclusions pointed to co-generation using this technology as a feasible alternative for sustainable rural development since it offers reasonably priced and dependable electricity and water services. Miao et al. [52] examined the possibility of an HES (methane generator, PV, batteries, and a WT) to provide heat and electricity for a family in the UK. Wegener et al. [59] created four models of various hybrid biomass/PV systems for a hotel resort on Neil Island, India. Nixon et al. [93] evaluated the viability and potential of hybrid solar–biomass power plants for a range of single and trigeneration applications in India. These plants are currently a viable choice for small-to-mid-size applications (2–10 MW_{th}), provided solar capital subsidies are maintained. While biomass-only systems are currently more profitable, hybrid systems have significant potential to help India's troubled biomass supply chain with just a minor LCOE increase. The authors concluded that subsidies for hybrid tri-generation systems should be given top priority by Indian energy regulators. In Austria, Faninger [94] conducted research on the advantages of using hybrid systems based on solar energy and biomass to secure heating and hot water in both stand-alone systems and in conjunction with district heating. According to the author, this system can completely meet the thermal energy load. An experimental study of a solar–biomass hybrid air cooling system was conducted by Prasartkaew and Kumar [95]. The findings showed that the system performs at roughly 75% of its nominal capacity and has an average overall coefficient of performance of 0.11. A comparison of the performance of solar cooling systems with various auxiliary heat sources reveals that the suggested system performs better than the others.

The thermodynamic and economic analysis of a micro-scale tri/co-generation system powered via biomass/solar energy for an apartment building on the Greek island of Milos was reported by Karellas and Braimakis [96]. According to the authors, reductions in fuel, oil, and electricity use have an internal rate of return of about 12 percent. According to Chasapis et al. [97], a hybrid solar thermal and biomass heating system for an office area was erected in Pikermi, Greece. A total of 52.9 percent of the entire heating demand was met using solar energy during the actual measurement period. According to the authors, achieving a 100 percent renewable home hot water and space heating system is a viable solution from an energy standpoint. Hussain et al. [98] reported that hybrid thermal solar energy and biomass power plants are technically sound alternatives to conventional fossil-fueled thermal energy and power production. Several critically important economic, technological, and regulatory concerns must be resolved to support the successful deployment of hybrid solar–biomass power plants across Europe. Sahoo et al. [99] presented a list of 14 thermal power stations to generate electricity, heat, cooling, and water desalination using hybrid solar thermal energy and the combustion of biomass in India. The capacity of the stations ranged between 2 and 23 MW. A CHP hybrid system powered by solar energy and biomass (gasification) was proposed and examined by Wang and Yang [100]. The generated product gas powers an internal combustion engine to provide electricity, while waste heat is used in conjunction with solar heat collectors to secure cooling and heating. According to the findings, the system's energy efficiency was 57.9 percent.

The CHP hybrid system is one of the types of energy systems that improve the efficiency of the system as a whole if it is used to generate electricity and utilize heat for various purposes such as cooling, heating, and water desalination, which means saving on energy consumption and thus improving economic and environmental conditions.

4. Environment Analysis of Hybrid Energy Systems

In this paragraph, the environmental benefits resulting from HESs are discussed. According to Loganathan et al. [26], a PV/wind hybrid power generating system for Geraldton, Australia, alternative energy sources are becoming more appealing due to their advantages, including having lower greenhouse gas emissions. Kaur et al. [28] concluded that a PV/biomass-based microgrid system reduced greenhouse gas emissions by more than 80%. Studies on the ideal design of HRESs dealing with environmental aspects were published by Alhawsawi et al. [45] and Alshakhs and Arefifar [46]. The findings demonstrated the viability of accessible and sustainable energy solutions, providing essential guidance on energy resilience and environmental monitoring. Wegener et al. [59] created four models of various hybrid biomass/PV systems for a hotel resort on Neil Island, India. According to the findings, a biomass-based, PV-assisted combined cooling, heating, and power system can reduce CO_2 emissions by 365 tons annually. El-Sattar et al. [66] reported that a peak load of 420 kW in a standalone microgrid to supply electricity in Egypt can achieve a greenhouse gas reduction of 792.534 tons per year with the algorithm of MOA.

Herrera et al. [87] examined the production of electricity using CSP and biomass in Tunisia. The authors reported a significant decrease in greenhouse gas emissions in this application. According to Wang and Yang [100], the hybrid CHP will reduce carbon emissions more effectively, and the solar subsystems play a significant role in it. An experimental investigation of a hybrid solar/biomass space heating system using solar collectors and a biomass boiler for a home in Lvliang City, China, was presented by Zhang et al. [101]. According to the authors, the system's total annual energy requirement is around 35.91 GJ, of which 63.31 percent comes from the solar system and 36.69 percent from biomass. The solar/biomass rural heating system has a primary energy efficiency of 67.66 percent. This system's energy conversion efficiency and degree of effective utilization are relatively higher than those of the conventional primary energy supply system, which can help reduce the consumption of fossil fuels and greenhouse gas emissions. Albar et al. [102] discussed the efficiency of solar energy and coal-fired hybrid power plants (PV 689 kWp and 615 MW coal-fired) using Helioscope software in Paiton, Indonesia. The examination of PV plant utilization revealed that in 2021, 1,096,105 kWh of electrical energy was produced. This result indicates a 0.4932 percent decrease in auxiliary power load. It is also estimated to be able to save up to 386.634 tons of coal per year. It is estimated to cut CO_2 emissions to 920.729 tons annually from an environmental standpoint.

It is noted from the results that the RE hybrid systems are more environmentally beneficial than the renewable systems with one source, and certainly more so than the traditional systems. The amount of savings in environmental pollution is determined based on the capacity of the system, the percentage of renewable sharing, and the type of source. The results indicate that it is necessary to study the environmental benefits of the systems in detail as well.

5. Economic Analysis—Payback

This paragraph describes the SPB period for RE hybrid systems. Alzaid et al. [23] reported the development of a hybrid wind/solar PV system with a capacity of 5 kWh in different locations in KSA. The SPB times for Sharourah and Hafar Al-Batin were 11 and 20 years, respectively. AlKassem et al. [31] investigated the design of a hybrid PV/wind microgrid system at the Islamic University of Madinah in the KSA. The results indicate that the SPB period for this system is 20.7 years. The notion of gradually replacing diesel generators with a hybrid system made up of PV and batteries was investigated by Chedid et al. [47]. The study also showed that the proposed technology has a 6-year SPB time.

Figaj et al. [15] examined a hybrid system powered via biomass/PV/wind/LPG generators for multi-use. Without any additional funding, the SPB for this system's investments varies between 5.67 and 12.20 years. Figaj et al. [16] also demonstrated a technical-economic analysis of a hybrid ground–solar–wind system for a single-family household in Gdansk, Poland. The authors reported that the SPB period is 21.6 years. Figaj and Żołądek [17] provided an energy-economic study of a solar heating and cooling system for a single-family home. The suggested system in Cracow (Poland) is not profitable because an SPB lasts about 20 years. Naples (Italy), however, sees the same index achieve a value between 8 and 12 years. A small-scale trigeneration on-grid system for northern Poland that utilizes biomass and WTs was the subject of an energy and financial analysis by Figaj et al. [18]. This study shows that the SPB of the proposed system is less than 6 years when free biomass, steam, and WT capacities under 4 kW are selected. Figaj [19] additionally modeled these combinations for Gdansk, Poland. An SPB of around 10 years is the consequence. Karellas and Braimakis [96] reported on the economic study of a tri/co-generation system powered via biomass/solar energy for a building on the Greek island of Milos. According to the authors, the SPB period is 7 years.

It is noted from the presented results that the SPB period varies even for the same system design and the same country, which means that other factors must be identified and studied in detail. Also, this shows the importance of using simulation software for RE systems in general and HESs in particular.

6. Conclusions and Recommendations

Energy efficiency and utilizing all energy sources are necessary to meet the world's increasing energy demand. Renewable energy sources are limitless and clean, but the sporadic nature of most types is their biggest drawback. To solve this issue, an HRES—a combination of multiple energy sources—is created. This paper aims to provide a literature review in the field of hybrid RE in terms of principles, types, and applications. The results can be summarized as follows:

- Simulation software provides valuable support in evaluating and designing hybrid power systems. It assists in assessing various design options and developing optimal operational plans tailored to specific project needs. It is noted from the studies that Greenius, SAM, HOMER, and TRNSYS were often used in designing and optimizing perfect;
- It was noted that the economic indicators are different, whether in terms of payback period or LCOE. The significant difference is because of several factors, including geographical location, climate, system configurations, resource fractions, capacity of systems, economic factors, research period, etc.;
- Concerning the environmental aspect, all the presented studies showed that there are good environmental benefits from hybrid systems, not only compared with conventional energy systems but also with RE systems with a single source, which makes these systems more sustainable;
- The multi-use of HRESs leads to improvements in efficiency and environmental benefits, making them more sustainable;
- Most studies in which electrical energy storage was available were usually off-grid;
- There are various options available for hybridizing RE sources, particularly in the context of energy source integration. The selection of the appropriate options depends on several factors: system type, size of the system, type of energy needed, availability and prices of RE sources, technical knowledge, and experience in operation and maintenance;
- Several parameters play a crucial role in evaluating a hybrid RE power plant: system makeup and capacity, the fractions of RE in the overall energy produced, efficiency, cost of energy and investment, technical knowledge requirements, and environmental effects;
- The importance of these factors varies depending on the specific case. For instance, the lower efficiency of a RE source might be justified by its availability;
- Due to the continual increase in fossil fuels and the risk of depletion, besides the greenhouse effect, the relatively high cost of energy produced via RE or HRESs compared to conventional sources should not affect more and more research, experimental models, and projects in various countries.

To find general conditions for the application of hybrid systems, future developments of this study will investigate the system's performance as a function of different users and locations, energy tariffs, and policies. They will also need to conduct a thorough, rigorous optimization to determine the impact of the design and economic parameters on performance. In particular, carrying out studies on hybrid systems of solar thermal energy and biomass energy can be suggested.

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Abbreviations

CHP	combined heat and power
CSP	concentrated solar power
DNI	direct normal irradiance
HES	hybrid energy system
HOMER	hybrid optimization model for multiple energy resources
HRES	hybrid renewable energy system
KSA	Kingdom of Saudi Arabia
LCOE	levelized cost of energy
LPG	liquified petroleum gas
MOA	mayfly optimization algorithm
NPC	net present cost
NREL	National Renewable Energy Laboratory
PCC	power control center
PTC	parabolic trough collector
PV	photovoltaics
RC	Rankine cycle
R&D	research and development
RE	renewable energy
RF	renewable fraction
SAM	system adviser model
SPB	simple payback
TRANSYS	transient system simulation tool
UK	United Kingdom
WT	wind turbine

References

1. UN.ESCAP; Asian Development Bank (ADB). *Asia and the Pacific Renewable Energy Status Report, 2019*; REN21 Secretariat; Asian Development Bank: Paris, France, 2019; p. 138. [CrossRef]
2. Verma, S.; Dregulo, A.M.; Kumar, V.; Bhargava, P.C.; Khan, N.; Singh, A.; Sun, X.; Sindhu, R.; Binod, P.; Zhang, Z.; et al. Reaction engineering during biomass gasification and conversion to energy. *Energy* **2023**, *266*, 126458. [CrossRef]
3. Hurtado, E.; Peñalvo-López, E.; Pérez-Navarro, Á.; Vargas, C.; Alfonso, D. Optimization of a hybrid renewable system for high feasibility application in non-connected zones. *Appl. Energy* **2015**, *155*, 308–314. [CrossRef]
4. Rizwana, R.; Firoz, A.K.; Mohammad, S.-A.-R. Solar-Biomass-CAES Hybrid System: Proposal for Rural Commercial Electrification in Bangladesh. *Int. J. Innov. Appl. Stud.* **2017**, *19*, 556–571.

5. Ammari, C.; Belatrache, D.; Touhami, B.; Makhloufi, S. Sizing, optimization, control and energy management of hybrid renewable energy system—A review. *Energy Built Environ.* **2022**, *3*, 399–411. [CrossRef]
6. Peterseim, J.H.; Tadros, A.; Hellwig, U.; White, S. Increasing the efficiency of parabolic trough plants using thermal oil through external superheating with biomass. *Energy Convers. Manag.* **2014**, *77*, 784–793. [CrossRef]
7. Nurunnabi, M.; Roy, N.K.; Pota, H.R. Optimal sizing of grid-tied hybrid renewable energy systems considering inverter to PV ratio—A case study. *J. Renew. Sustain. Energy* **2019**, *11*, 013505. [CrossRef]
8. Optimize the Value of Your Hybrid Power System—From Utility-Scale and Distributed Generation to Standalone Microgrids. 2018. Available online: http://www.homerenergy.com (accessed on 20 July 2023).
9. Blair, N.; Dobos, A.P.; Freeman, J.; Neises, T.; Wagner, M.; Ferguson, T.; Gilman, P.; Janzou, S. *System Advisor Model, Sam 2014.1. 14: General Description*; National Renewable Energy Lab (NREL): Golden, CO, USA, 2014.
10. TRNSYS, Transient System Simulation Tool. 2013. Available online: https://www.trnsys.com/index.html (accessed on 20 July 2023).
11. Greenius, 201-350 Oxford Street West, London, Ontario, UK. Available online: https://gogreenius.com/our-courses/ (accessed on 20 July 2023).
12. Quaschning, V.; Ortmanns, W.; Kistner, R.; Geyer, M. Greenius: A New Simulation Environment for Technical and Economical Analysis of Renewable Independent Power Projects. In Proceedings of the International Solar Energy Conference (FORUM 2001: Solar Energy—The Power to Choose), Washington, DC, USA, 21–25 April 2001; ASME: Washington, DC, USA, 2001; pp. 413–417.
13. Jahangiri, M.; Ghaderi, R.; Haghani, A.; Nematollahi, O. Finding the best locations for establishment of solar-wind power stations in Middle-East using GIS: A review. *Renew. Sustain. Energy Rev.* **2016**, *66*, 38–52. [CrossRef]
14. Ashok, S.; Balamurugan, P. Biomass Gasifier Based Hybrid Energy System for Rural Areas. In Proceedings of the IEEE Canada Electrical Power Conference, Montreal, QC, Canada, 25–26 October 2007.
15. Figaj, R.; Żołądek, M.; Homa, M.; Pałac, A. A Novel Hybrid Polygeneration System Based on Biomass, Wind and Solar Energy for Micro-Scale Isolated Communities. *Energies* **2022**, *15*, 6331. [CrossRef]
16. Figaj, R.; Żołądek, M.; Goryl, W. Dynamic Simulation and Energy Economic Analysis of a Household Hybrid Ground-Solar-Wind System Using TRNSYS Software. *Energies* **2020**, *13*, 3523. [CrossRef]
17. Figaj, R.; Żołądek, M. Operation and Performance Assessment of a Hybrid Solar Heating and Cooling System for Different Configurations and Climatic Conditions. *Energies* **2021**, *14*, 1142. [CrossRef]
18. Figaj, R.; Sornek, K.; Podlasek, S.; Żołądek, M. Operation and Sensitivity Analysis of a Micro-Scale Hybrid Trigeneration System Integrating a Water Steam Cycle and Wind Turbine under Different Reference Scenarios. *Energies* **2020**, *13*, 5697. [CrossRef]
19. Figaj, R. Performance assessment of a renewable micro-scale trigeneration system based on biomass steam cycle, wind turbine, photovoltaic field. *Renew. Energy* **2021**, *177*, 193–208. [CrossRef]
20. Behar, O.; Khellaf, A.; Mohammedi, K.; Ait-Kaci, S. A review of integrated solar combined cycle system (ISCCS) with a parabolic trough technology. *Renew. Sustain. Energy Rev.* **2014**, *39*, 223–250. [CrossRef]
21. Rehman, S. Hybrid power systems—Sizes, efficiencies, and economics. *Energy Explor. Exploit.* **2020**, *39*, 3–43. [CrossRef]
22. Qing, H. Main types and applications of hybrid power generation system. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *300*, 042054. [CrossRef]
23. Alzaid, O.S.; Salim, B.; Orfi, J.; Khan, S.; Alshehri, H. Hybrid Solar and Wind Power Generation in Saudi Arabia. *Energy Environ. Res.* **2022**, *10*, 25–38. [CrossRef]
24. Dieckmann, S.; Dersch, J. Simulation of hybrid solar power plants. *AIP Conf. Proc.* **2017**, *1850*, 160005.
25. Spelling, J.; Laumert, B.; Fransson, T. Advanced hybrid solar tower combined-cycle power plants. *Energy Procedia* **2014**, *49*, 1207–1217. [CrossRef]
26. Loganathan, B.; Chowdhury, H.; Allhibi, H.; Mustary, I.; Sony, S.M.; Alam, F. Design of a hybrid household power generation system for a coastal area: A case study for Geraldton, Australia. *Energy Procedia* **2019**, *160*, 820–826. [CrossRef]
27. Malik, P.; Awasthi, M.; Sinha, S. Study of grid integrated biomass-based hybrid renewable energy systems for Himalayan terrain. *Int. J. Sustain. Energy Plan. Manag.* **2020**, *28*, 71–88.
28. Kaur, M.; Dhundhara, S.; Verma, Y.P.; Chauhan, S. Techno-economic analysis of photovoltaic-biomass-based microgrid system for reliable rural electrification. *Int. Trans. Electr. Energy Syst.* **2020**, *30*, e12347. [CrossRef]
29. Rajbongshi, R.; Borgohain, D.; Mahapatra, S. Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using HOMER. *Energy* **2017**, *126*, 461–474. [CrossRef]
30. Bhattacharjee, S.; Dey, A. Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill. *Sustain. Energy Technol. Assess.* **2014**, *7*, 6–16. [CrossRef]
31. AlKassem, A.; Draou, A.; Alamri, A.; Alharbi, H. Design Analysis of an Optimal Microgrid System for the Integration of Renewable Energy Sources at a University Campus. *Sustainability* **2022**, *14*, 4175. [CrossRef]
32. Hashim, H.; Ho, W.S.; Lim, J.S.; Macchietto, S. Integrated biomass and solar town: Incorporation of load shifting and energy storage. *Energy* **2014**, *75*, 31–39. [CrossRef]
33. Alharthi, Y.Z.; Siddiki, M.K.; Chaudhry, G.M. Resource Assessment and Techno-Economic Analysis of a Grid-Connected Solar PV-Wind Hybrid System for Different Locations in Saudi Arabia. *Sustainability* **2018**, *10*, 3690. [CrossRef]
34. Rehman, S.; El-Amin, I. Study of a Solar Pv/Wind/Diesel Hybrid Power System for a Remotely Located Population near Arar, Saudi Arabia. *Energy Explor. Exploit.* **2015**, *33*, 591–620. [CrossRef]

35. Mokheimer, E.M.; Sahin, A.Z.; Al-Sharafi, A.; Ali, A.I. Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia. *Energy Convers. Manag.* **2013**, *75*, 86–97. [CrossRef]
36. Krishan, O.; Suhag, S. Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community. *J. Energy Storage* **2019**, *23*, 305–319. [CrossRef]
37. Muleta, N.; Badar, A.Q.H. Designing of an optimal standalone hybrid renewable energy micro-grid model through different algorithms. *J. Eng. Res.* **2023**, *11*, 100011. [CrossRef]
38. Muleta, N.; Badar, A.Q.H. Techno-economic analysis and design of hybrid renewable energy microgrid for rural electrification. *Energy Harvest. Syst.* **2022**, *9*, 39–51. [CrossRef]
39. Moria, H. Techno-Economic Optimization of Solar/Wind Turbine System for Remote Mosque in Saudi Arabia Highway: Case Study. *Int. J. Eng. Res. Technol.* **2019**, *8*, 78–84.
40. Tazay, A. Techno-Economic Feasibility Analysis of a Hybrid Renewable Energy Supply Options for University Buildings in Saudi Arabia. *Open Eng.* **2021**, *11*, 39–55. [CrossRef]
41. Alshammari, S.; Fathy, A. Optimum Size of Hybrid Renewable Energy System to Supply the Electrical Loads of the Northeastern Sector in the Kingdom of Saudi Arabia. *Sustainability* **2022**, *14*, 13274. [CrossRef]
42. Malik, P.; Awasthi, M.; Sinha, S. Biomass-based gaseous fuel for hybrid renewable energy systems: An overview and future research opportunities. *Int. J. Energy Res.* **2021**, *45*, 3464–3494. [CrossRef]
43. Dersch, J.; Dieckmann, S. Techno-economic evaluation of renewable energy projects using the software greenius. *Int. J. Therm. Environ. Eng.* **2015**, *10*, 17–24.
44. Suresh, A.K.; Khurana, S.; Nandan, G.; Dwivedi, G.; Kumar, S. Role on nanofluids in cooling solar photovoltaic cell to enhance overall efficiency. *Mater. Today Proc.* **2018**, *5*, 20614–20620. [CrossRef]
45. Alhawsawi, E.Y.; Habbi, H.M.D.; Hawsawi, M.; Zohdy, M.A. Optimal Design and Operation of Hybrid Renewable Energy Systems for Oakland University. *Energies* **2023**, *16*, 5830. [CrossRef]
46. Alshakhs, R.; Arefifar, S.A. Oakland University as A Microgrid—Feasibility Studies of Planning and Operation. In Proceedings of the 2020 IEEE International Conference on Electro Information Technology (EIT), Chicago, IL, USA, 31 July 2020–1 August 2020.
47. Chedid, R.; Sawwas, A.; Fares, D. Optimal design of a university campus micro-grid operating under unreliable grid considering PV and battery storage. *Energy* **2020**, *200*, 117510. [CrossRef]
48. Alturki, F.A.; Awwad, E.M. Sizing and Cost Minimization of Standalone Hybrid WT/PV/Biomass/Pump-Hydro Storage-Based Energy Systems. *Energies* **2021**, *14*, 489. [CrossRef]
49. Eisapour, A.H.; Jafarpur, K.; Farjah, E. Feasibility study of a smart hybrid renewable energy system to supply the electricity and heat demand of Eram Campus, Shiraz University; simulation, optimization, and sensitivity analysis. *Energy Convers. Manag.* **2021**, *248*, 114779. [CrossRef]
50. Ghenai, C.; Bettayeb, M. Modelling and performance analysis of a stand-alone hybrid solar PV/Fuel Cell/Diesel Generator power system for university building. *Energy* **2019**, *171*, 180–189. [CrossRef]
51. Mokhtara, C.; Negrou, B.; Settou, N.; Bouferrouk, A.; Yao, Y. Design optimization of grid-connected PV-Hydrogen for energy prosumers considering sector-coupling paradigm: Case study of a university building in Algeria. *Int. J. Hydrog. Energy* **2021**, *46*, 37564–37582. [CrossRef]
52. Miao, C.; Teng, K.; Wang, Y.; Jiang, L. Technoeconomic Analysis on a Hybrid Power System for the UK Household Using Renewable Energy: A Case Study. *Energies* **2020**, *13*, 3231. [CrossRef]
53. Khosravani, A.; Safaei, E.; Reynolds, M.; Kelly, K.E.; Powell, K.M. Challenges of reaching high renewable fractions in hybrid renewable energy systems. *Energy Rep.* **2023**, *9*, 1000–1017. [CrossRef]
54. Diesendorf, M.; Elliston, B. The feasibility of 100% renewable electricity systems: A response to critics. *Renew. Sustain. Energy Rev.* **2018**, *93*, 318–330. [CrossRef]
55. Rajbongshi, R.; Deb, P.; Mahapatra, S.; Dasappa, S. Biomass Gasifier Based Hybrid Energy System Optimization for Energy Access by Using Homer. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 1612–1618.
56. Balamurugan, P.; Ashok, S.; Jose, T.L. An Optimal Hybrid Wind-biomass Gasifier System for Rural Areas. *Energy Sources Part A Recovery Util. Environ. Eff.* **2011**, *33*, 823–832. [CrossRef]
57. Kobayakawa, T.; Kandpal, T.C. Optimal resource integration in a decentralized renewable energy system: Assessment of the existing system and simulation for its expansion. *Energy Sustain. Dev.* **2016**, *34*, 20–29. [CrossRef]
58. Anand, S.; Prashant, B. Power Sharing and Cost Optimization of Hybrid Renewable Energy System for Academic Research Building. *J. Electr. Eng. Technol.* **2017**, *12*, 1511–1518.
59. Wegener, M.; Isalgué, A.; Malmquist, A.; Martin, A. 3E-Analysis of a Bio-Solar CCHP System for the Andaman Islands, India—A Case Study. *Energies* **2019**, *12*, 1113. [CrossRef]
60. Palatel, A. Isolated Hybrid Energy Systems for Remote Locations. In *Encyclopedia of Sustainable Technologies*; Abraham, M.A., Ed.; Elsevier: Oxford, UK, 2017; pp. 205–216.
61. León Gómez, J.C.; De León Aldaco, S.E.; Alquicira, J.A. A Review of Hybrid Renewable Energy Systems: Architectures, Battery Systems, and Optimization Techniques. *Eng* **2023**, *4*, 1446–1467. [CrossRef]
62. Mishra, S.; Panigrahi, C.K.; Kothari, D.P. Design and simulation of a solar–wind–biogas hybrid system architecture using HOMER in India. *Int. J. Ambient. Energy* **2016**, *37*, 184–191. [CrossRef]

63. Afrouzi, H.N.; Hassan, A.; Wimalaratna, Y.P.; Ahmed, J.; Mehranzamir, K.; Liew, S.C.; Malek, Z.A. Sizing and economic analysis of stand-alone hybrid photovoltaic-wind system for rural electrification: A case study Lundu, Sarawak. *Clean. Eng. Technol.* **2021**, *4*, 100191. [CrossRef]
64. Eziyi, I.; Krothapalli, A. Sustainable Rural Development: Solar/Biomass Hybrid Renewable Energy System. *Energy Procedia* **2014**, *57*, 1492–1501. [CrossRef]
65. Mahmoud, F.S.; Diab, A.A.Z.; Ali, Z.M.; El-Sayed, A.-H.M.; Alquthami, T.; Ahmed, M.; Ramadan, H.A. Optimal sizing of smart hybrid renewable energy system using different optimization algorithms. *Energy Rep.* **2022**, *8*, 4935–4956. [CrossRef]
66. El-Sattar, H.A.; Kamel, S.; Sultan, H.M.; Zawbaa, H.M.; Jurado, F. Optimal design of Photovoltaic, Biomass, Fuel Cell, Hydrogen Tank units and Electrolyzer hybrid system for a remote area in Egypt. *Energy Rep.* **2022**, *8*, 9506–9527. [CrossRef]
67. Diab, A.A.Z.; Sultan, H.M.; Mohamed, I.S.; Kuznetsov, O.N.; Do, T.D. Application of Different Optimization Algorithms for Optimal Sizing of PV/Wind/Diesel/Battery Storage Stand-Alone Hybrid Microgrid. *IEEE Access* **2019**, *7*, 119223–119245. [CrossRef]
68. Aziz, A.S.; Tajuddin, M.F.N.; Adzman, M.R.; Azmi, A.; Ramli, M.A. Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq. *Renew. Energy* **2019**, *138*, 775–792. [CrossRef]
69. Ribó-Pérez, D.; Herraiz-Cañete, Á.; Alfonso-Solar, D.; Vargas-Salgado, C.; Gómez-Navarro, T. Modelling biomass gasifiers in hybrid renewable energy microgrids; a complete procedure for enabling gasifiers simulation in HOMER. *Renew. Energy* **2021**, *174*, 501–512. [CrossRef]
70. Kozlov, A.N.; Tomin, N.V.; Sidorov, D.N.; Lora, E.E.S.; Kurbatsky, V.G. Optimal Operation Control of PV-Biomass Gasifier-Diesel-Hybrid Systems Using Reinforcement Learning Techniques. *Energies* **2020**, *13*, 2632. [CrossRef]
71. Parihar, A.K.S.; Sethi, V.; Banerjee, R. Sizing of biomass based distributed hybrid power generation systems in India. *Renew. Energy* **2019**, *134*, 1400–1422. [CrossRef]
72. Kumaravel, S.; Ashok, S. An Optimal Stand-Alone Biomass/Solar-PV/Pico-Hydel Hybrid Energy System for Remote Rural Area Electrification of Isolated Village in Western-Ghats Region of India. *Int. J. Green Energy* **2012**, *9*, 398–408. [CrossRef]
73. Suresh, V.; Muralidhar, M.; Kiranmayi, R. Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas. *Energy Rep.* **2020**, *6*, 594–604. [CrossRef]
74. Ramli, M.A.M.; Hiendro, A.; Bouchekara, H.R.E.H. Performance Analysis of Hybrid PV/Diesel Energy System in Western Region of Saudi Arabia. *Int. J. Photoenergy* **2014**, *2014*, 626251. [CrossRef]
75. Baseer, M.A.; Alqahtani, A.; Rehman, S. Techno-economic design and evaluation of hybrid energy systems for residential communities: Case study of Jubail industrial city. *J. Clean. Prod.* **2019**, *237*, 117806. [CrossRef]
76. Diab, F.; Lan, H.; Zhang, L.; Ali, S. An environmentally friendly factory in Egypt based on hybrid photovoltaic/wind/diesel/battery system. *J. Clean. Prod.* **2016**, *112*, 3884–3894. [CrossRef]
77. The World Bank. *Concentrating Solar Power: Clean Power on Demand 24/7*; The World Bank: Washington, DC, USA, 2021; p. 65. Available online: https://pubdocs.worldbank.org/en/849341611761898393/WorldBank-CSP-Report-Concentrating-Solar-Power-Clean-Power-on-Demand-24-7-FINAL.pdf (accessed on 20 July 2023).
78. Thiam, A.; Mbow, C.; Faye, M.; Stouffs, P.; Azilinon, D. Solar parabolic trough—Biomass hybrid plants: A cost-efficient concept suitable for places in low irradiation conditions. *Nat. Resour.* **2017**, *8*, 531–547.
79. Servert, J.; Miguel, G.S.; Lopez, D. Hybrid solar-biomass plants for power generation; Technical and economic assessment. *Glob. NEST J.* **2011**, *13*, 266–276.
80. Cot, A.; Ametller, A.; Vall-Llovera, J.; Aguiló, J.; Arque, J.M. Termosolar Borges: A thermosolar hybrid plant with biomass. In Proceedings of the Third International Symposium on Energy from Biomass and Waste, Venice, Italy, 8–11 November 2010; Environmental Sanitary Engineering Centre: Venice, Italy, 2010.
81. Peterseim, J.H.; Hellwig, U.; Tadros, A.; White, S. Hybridisation optimization of concentrating solar thermal and biomass power generation facilities. *Sol. Energy* **2014**, *99*, 203–214. [CrossRef]
82. Khosravi, A.; Santasalo-Aarnio, A.; Syri, S. Optimal technology for a hybrid biomass/solar system for electricity generation and desalination in Brazil. *Energy* **2021**, *234*, 121309. [CrossRef]
83. Liu, Q.; Bai, Z.; Wang, X.; Lei, J.; Jin, H. Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems. *Energy Convers. Manag.* **2016**, *122*, 252–262. [CrossRef]
84. Pedrazzi, S.; Masetti, F.; Allesina, G.; Tartarini, P. Hybridization of solar power plants with biogas from anaerobic digestion: A modeled case study. *AIP Conf. Proc.* **2019**, *2191*, 020126.
85. Soares, J.; Oliveira, A.C. Numerical simulation of a hybrid concentrated solar power/biomass mini power plant. *Appl. Therm. Eng.* **2017**, *111*, 1378–1386. [CrossRef]
86. Soares, J.; Oliveira, A.C.; Dieckmann, S.; Krüger, D.; Orioli, F. Evaluation of the performance of hybrid CSP/biomass power plants. *Int. J. Low-Carbon Technol.* **2018**, *13*, 380–387. [CrossRef]
87. Herrera, I.; Rodríguez-Serrano, I.; Lechón, Y.; Oliveira, A.; Krüger, D.; Bouden, C. Sustainability assessment of a hybrid CSP/biomass. Results of a prototype plant in Tunisia. *Sustain. Energy Technol. Assess.* **2020**, *42*, 100862. [CrossRef]
88. Soares, J.; Varga, S.; Oliveira, A.C. Solar-Biomass Hybrid Systems. In *DCE21—Symposium on Mechanical Engineering: Book of Abstracts and Invited Lectures*; Departamento de Engenharia Mecânica, Faculdade de Engenharia, Universidade do Porto: Porto, Portugal, 2021.

89. Suresh, N.S.; Thirumalai, N.C.; Dasappa, S. Modeling and analysis of solar thermal and biomass hybrid power plants. *Appl. Therm. Eng.* **2019**, *160*, 114121. [CrossRef]
90. Sahoo, U.; Kumar, R.; Pant, P.; Chaudhary, R. Resource assessment for hybrid solar-biomass power plant and its thermodynamic evaluation in India. *Sol. Energy* **2016**, *139*, 47–57. [CrossRef]
91. Sahoo, U.; Kumar, R.; Pant, P.; Chaudhary, R. Development of an innovative polygeneration process in hybrid solar-biomass system for combined power, cooling and desalination. *Appl. Therm. Eng.* **2017**, *120*, 560–567. [CrossRef]
92. Srinivas, T.; Reddy, B.V. Hybrid solar–biomass power plant without energy storage. *Case Stud. Therm. Eng.* **2014**, *2*, 75–81. [CrossRef]
93. Nixon, J.D.; Dey, P.K.; Davies, P.A. The feasibility of hybrid solar-biomass power plants in India. *Energy* **2012**, *46*, 541–554. [CrossRef]
94. Faninger, G. Combined solar–biomass district heating in Austria. *Sol. Energy* **2000**, *69*, 425–435. [CrossRef]
95. Prasartkaew, B.; Kumar, S. Experimental study on the performance of a solar-biomass hybrid air-conditioning system. *Renew. Energy* **2013**, *57*, 86–93. [CrossRef]
96. Karellas, S.; Braimakis, K. Energy–exergy analysis and economic investigation of a cogeneration and trigeneration ORC–VCC hybrid system utilizing biomass fuel and solar power. *Energy Convers. Manag.* **2016**, *107*, 103–113. [CrossRef]
97. Chasapis, D.; Drosou, V.; Papamechael, I.; Aidonis, A.; Blanchard, R. Monitoring and operational results of a hybrid solar-biomass heating system. *Renew. Energy* **2008**, *33*, 1759–1767. [CrossRef]
98. Hussain, C.M.I.; Norton, B.; Duffy, A. Technological assessment of different solar-biomass systems for hybrid power generation in Europe. *Renew. Sustain. Energy Rev.* **2017**, *68*, 1115–1129. [CrossRef]
99. Sahoo, U.; Kumar, R.; Pant, P.C.; Chaudhury, R. Scope and sustainability of hybrid solar–biomass power plant with cooling, desalination in polygeneration process in India. *Renew. Sustain. Energy Rev.* **2015**, *51*, 304–316. [CrossRef]
100. Wang, J.; Yang, Y. Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system utilizing biomass and solar energy. *Energy Convers. Manag.* **2016**, *124*, 566–577. [CrossRef]
101. Zhang, X.; Yang, J.; Fan, Y.; Zhao, X.; Yan, R.; Zhao, J.; Myers, S. Experimental and analytic study of a hybrid solar/biomass rural heating system. *Energy* **2020**, *190*, 116392. [CrossRef]
102. Albar, S.; Windarta, J.; Wardaya, A.Y.; Elshaarani, T. Integrating PV plant 689 kWp into Coal-Fired Power Plant (CFPP) 615 MW at Paiton: To reduce auxiliary load and coal consumption. *Teknomekanik* **2022**, *5*, 103–111. [CrossRef]