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Review

Overview of Solar–Wind Hybrid Products: Prominent Challenges and Possible Solutions

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Abstract: Solar and wind power systems have been prime solutions to the challenges centered on reliable power supply, sustainability, and energy costs for several years. However, there are still various challenges in these renewable industries, especially regarding limited peak periods. Solar–wind hybrid technology introduced to mitigate these setbacks has significant drawbacks and suffers from low adoption rates in many geographies. Hence, it is essential to investigate the challenges faced with these technologies and analyze the viable solutions proposed. This work examined solar–wind hybrid plants' economic and technical opportunities and challenges. In the present work, the pressing challenges solar–wind hybrids face were detailed through extensive case studies, the case study of enabling policies in India, and overproduction in Germany. Presently, the principal challenges of solar–wind hybrids are overproduction, enabling policies, and electricity storage. This review highlights specific, viable, proposed solutions to these problems. As already recorded in the literature, it was discovered that academic research in this space focuses majorly on the techno-economic and seemingly theoretical aspects of these hybrid systems. In contrast, reports and publications from original equipment manufacturers (OEMs) and engineering, procurement, and construction engineers (EPCs) are more rounded, featuring real-life application and implementation.

Keywords: HPPs; solar–wind; PV–wind; energy policy; overproduction; electricity storage; enabling policy; case study

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1. Introduction

A hybrid power plant (HPP) refers to a power generator consisting of more than one power-generating module, a network, and connection points that convert primary renewable energy into electrical energy [1]. Solar–wind hybrids guarantee a more continuous power supply all year round as each technology makes up for the intermittency of the other. Months with longer days of sunlight are better suited for solar production [2]. In most locations, solar radiation is the lowest for 3 to 4 months annually. Additionally, optimal panel direction varies with seasons and months [3]. On the other hand, the efficiency of wind systems is more influenced by wind factors (such as density, speed, and turbulence) and turbine pitch than it is by sunlight [4–6]. Moreover, since nighttime is windier than daytime, wind energy generation is favored at night, whereas sunlight enables peak solar generation during the day [7]. Renewable energy intermittency mandates storing produced power to supply periods of low production. Large-scale electricity storage is significantly expensive [8,9]. Hence, solar and wind systems complement each other in hybrid setups [10]. Research shows that 2008 to 2016 witnessed a significant increase in people using renewable mini-grids. The increment was 0.2 million to 1.3 million end users across Africa and 3 million to 8.8 million consumers across Asia [11]. According to the datasets published by IRENA, these end users predominantly opted for mini-grids or small-scale hydro and solar photovoltaic (PV) solutions [11,12]. In 2019, the World Bank estimated at least 19,000 mini-grids (majorly diesel, hydropower, and PV mini-grids) installed in 134 countries [11].

Globally, the market size of hybrid solar–wind systems was valued at USD 925.2 million in 2019. It is predicted to grow at a 7.2% compound annual growth rate (CAGR) from 2020 to 2027; it will be approximately USD 1.61 billion by 2027. Market research shows that an ever-increasing demand drives this growth verdict for clean energy alternatives and favorable government initiatives are crucial in promoting the shift [10].

COVID-19 lockdown restrictions caused a 10–35% weekly reduction in the electricity demand in 2020. Prior to this, the capacity of renewable energy plants worldwide was predicted to be increased, as shown in Figure 1 [13].

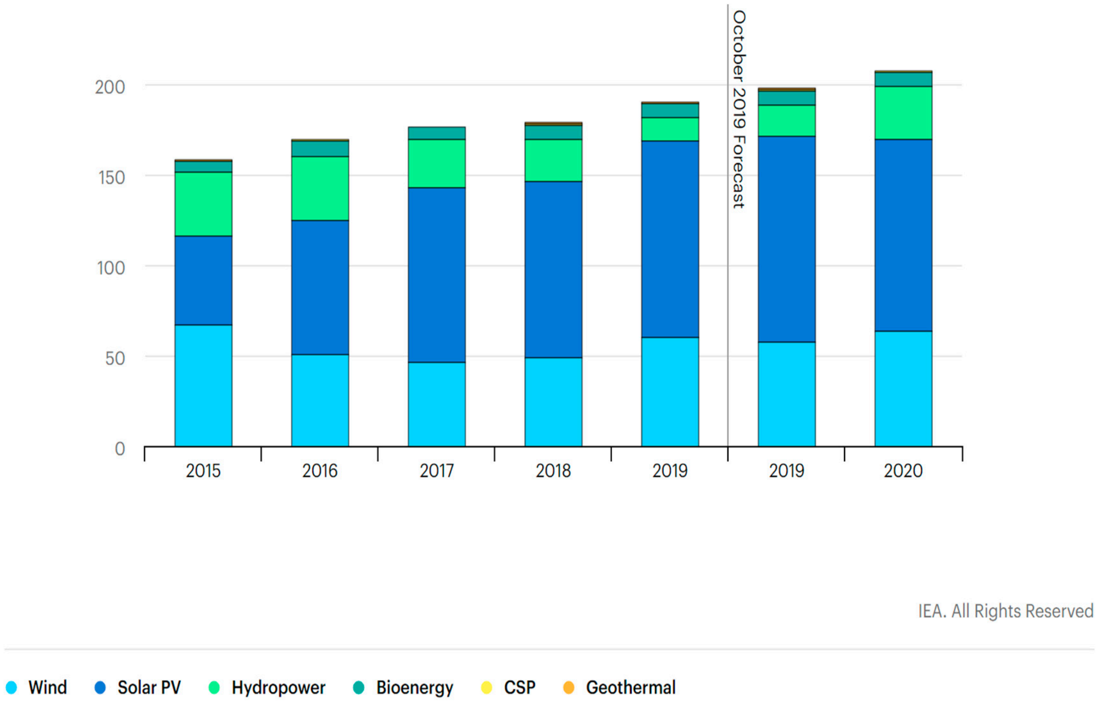

Figure 1. Predicted energy expansion by energy source [14].

During the pandemic scare, the renewable energy capacity additions were more than 11% less than the record of the first 6 months of 2019. The solar PV expansion was approximately 17% less than the record last year and the wind expansion 8% less [14]. Figure 2 below illustrates the expansion of renewables during the economic crunch during the COVID-19 lockdown period. Figure 2 also shows a breakdown of the renewable energy expansion by region, and the breakdown by energy source is illustrated in Figure 3.

1.1. Top Original Equipment Manufacturers and Developers

Publicly available market research further indicates that the solar–wind hybrid leaders are Asia Pacific (accounting for 37%) and North America (21.7%). Key vendors are OEMs (original equipment manufacturers) and EPCs (engineering, procurement, and construction) [10]. Comparing these market research insights with those from Google trends, we can further identify specific countries involved in the solar–wind hybrid market and research in this same industry [15]. Compared to solar energy (Figure 4) and wind energy (Figure 5), the interest in solar–wind hybrid energy (Figure 6) is minute.

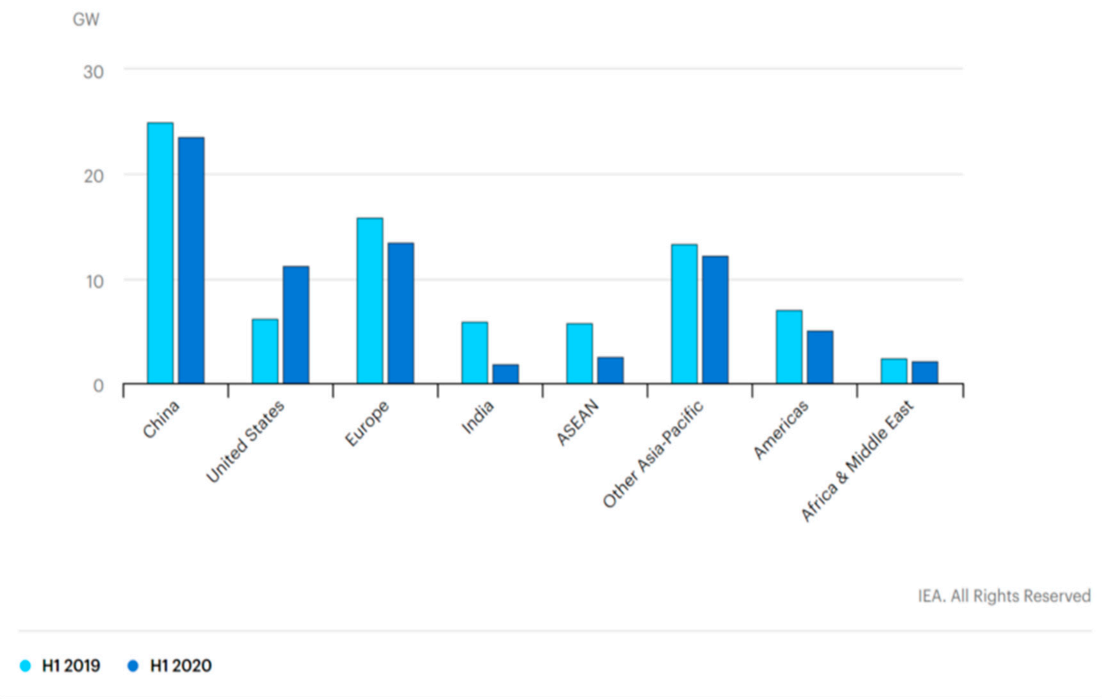

Figure 2. Energy capacity expansion by region during the lockdown of 2019–2020 [14].

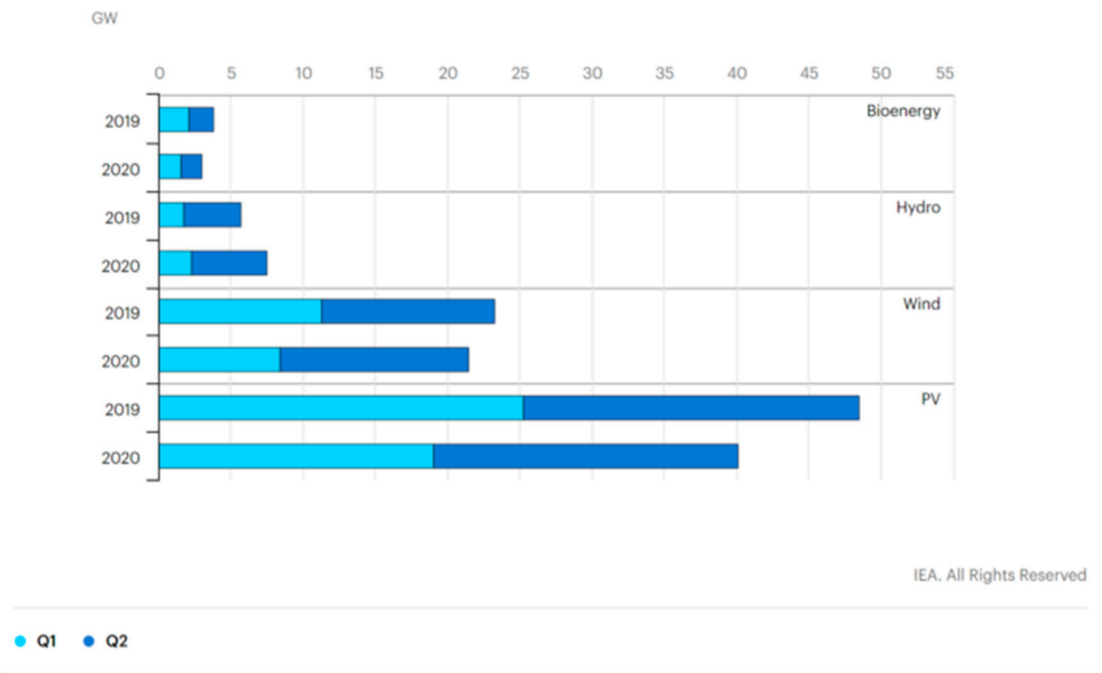

Figure 3. Energy expansion by energy source during the lockdown of 2019–2020 [13].

Solar–wind hybrids are yet to be significantly explored. Interest in such hybrids is still marginal. More people are majorly concerned with solar energy than they are with wind or solar–wind hybrids. This is probably because solar modules and system components pose lesser challenges as they are more resistant to adverse operating conditions [15]. The majority of attention in this space is from India. It should not be a surprise that only these countries have significantly invested in innovating the space, and others lag. In addition, some studies show that the long-term value of solar–wind hybrids might be limited [16]. These studies argue that PV electricity is cheaper than that produced by these hybrids. Market prices and inflation combined with currency fluctuations have fluctuated so much that it is challenging to identify reliable data on the current cost of commercial PV capital expenditures (CAPEX) and operational expenditures (OPEX) [16]. As of August 2022, the relationship between PV–wind systems and PV-based green hydrogen alternatives is shown in Table 1 below [17,18].

A case study of renewable energy costs in Zimbabwe illustrated this discrepancy showing that a higher wind capacity significantly increases the cost of the solar–wind hybrid system whereas a higher PV capacity increases it slightly. This is illustrated in Figure 7 below [19].

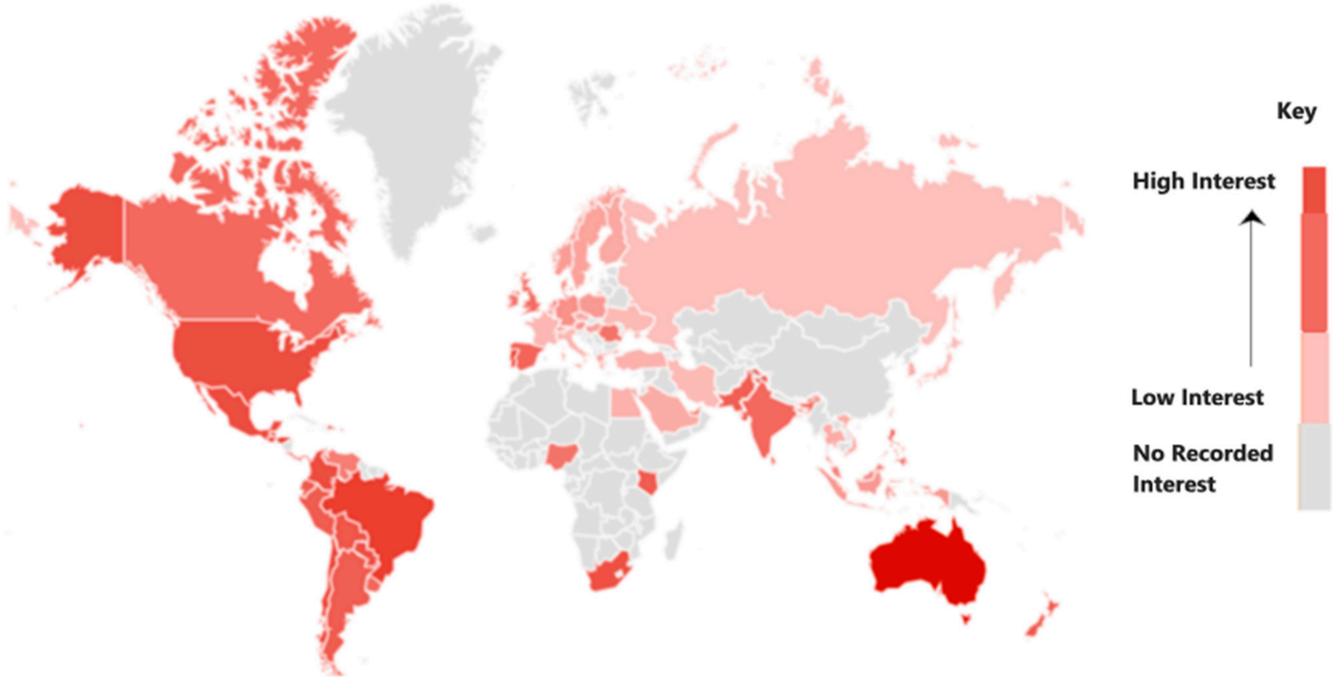

Figure 4. Map illustrating the interest in solar energy over the past 5 years [15].

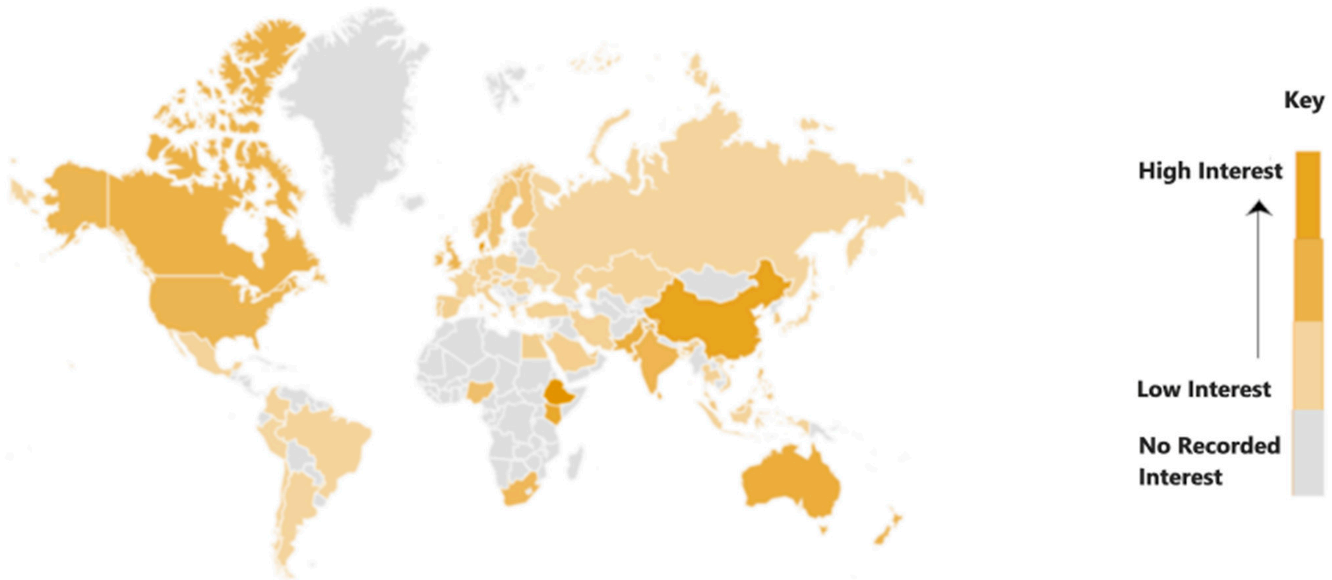

Figure 5. Map illustrating the interest in wind energy over the past 5 years [15].

Figure 6. Map illustrating the interest in solar–wind hybrid energy over the past 5 years [15].

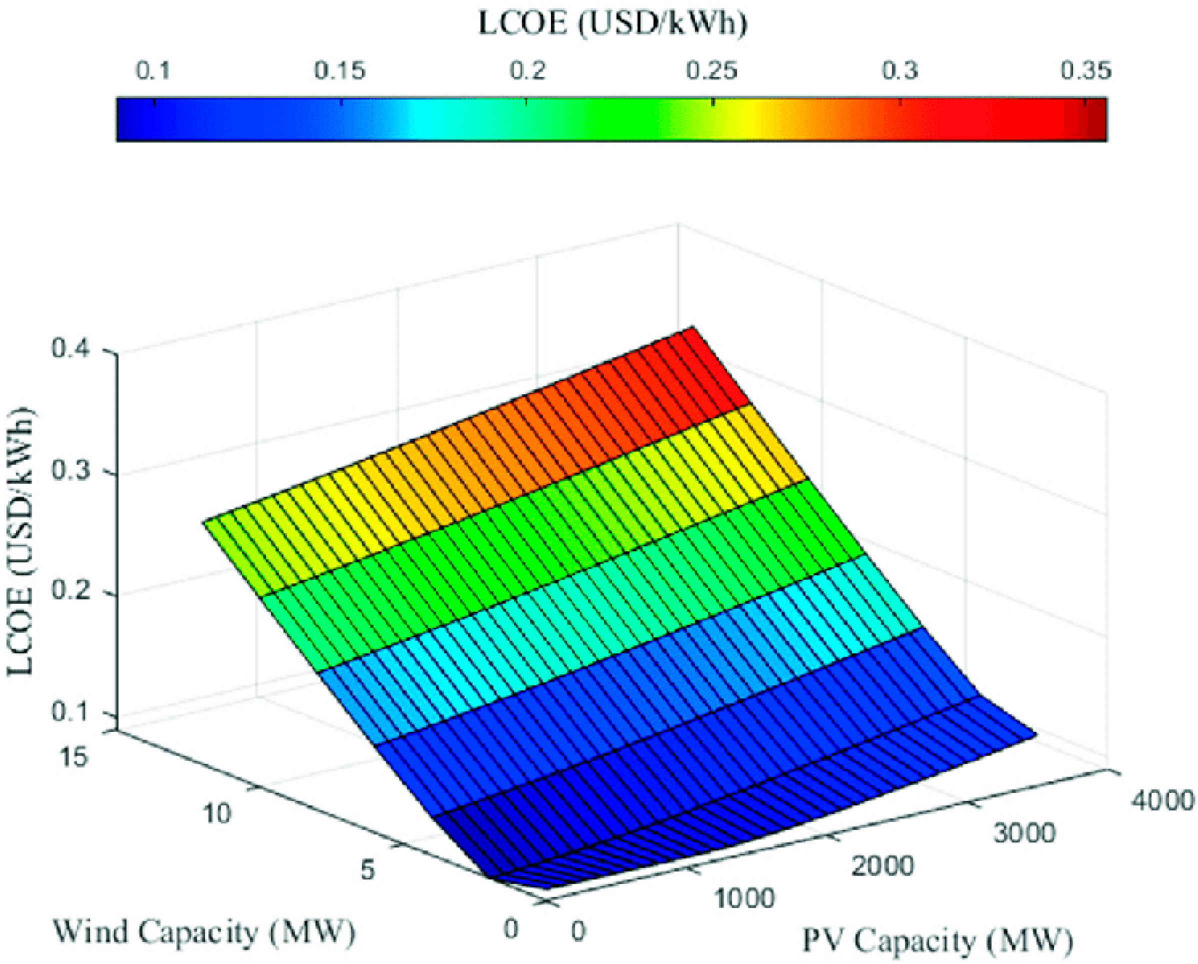

Figure 7. Levelized cost of PV–wind hybrids in Zimbabwe [19].

Table 1. Levelized cost of PV and wind systems compared [17,18].

Type	Levelized Cost of Electricity (LCOE)	Region	Year
Utility-Scale PV	EUR 24–57/MWh (USD 24.43–58.02/MWh)	Europe	2019
PV	USD 25–40/MWh	US	2022–2024 (Estimated in 2021)
Onshore Wind	USD 18–55/MWh	US	2022–2024 (Estimated in 2021)
PV	USD 45/MWh	US	2022
Onshore Wind	USD 46/MWh	US	2022
PV–Wind	USD 0.1/kWh	Zimbabwe	2020 (Hypothetical)

1.2. Structure and Approach

This study reviewed the literature on hybrid solar–wind systems, explicitly focusing on the products and recent data to highlight the importance of the field and foster its adoption. Firstly, this study aimed to build and increase the knowledge awareness regarding solar–wind HPPs and highlight the challenges faced by such devices. The study assessed whether viable solutions to the challenges faced by these plants are carefully considered in research. Finally, the study highlighted solutions to the identified challenges and proposed research lines to help further development, adoption, and innovation in this industry.

The scope of this paper was narrowed to photovoltaic (PV)–wind hybrid technology to assess the industry technically and economically. Regarding storage, the focus was on electrical energy storage (EES) (defined by the IEC 62933-1 standard as an installation able to absorb electrical energy, store it over a particular duration of time, and release the energy) [1]. Currently, there are few full HPPs (both in development and operation), limiting data availability as most developments are in their early phases and equipment manufacturers (OEMs) are reluctant to share possibly confidential information in order to secure competitive advantage [20].

In this review, the following questions were addressed:

Q1: What does the solar–wind hybrid product space look like? What are the top products, new products, and what limitations do they suffer?

Q2: Which product categories are technically and economically viable for more comprehensive applications to reach more end users?

Q3: What does academic research regarding solar–wind hybrid products look like, and what should be done?

Thorough research to furnish answers to these questions in this review is presented as follows. Section 2 presents the study's methodology and a brief overview of the solar–wind hybrid industry. Section 3 meticulously examines the major focus areas and research angles explored in several studies in this field. Finally, the final section presents the conclusions and recommendations drawn from these analyses.

The selected research articles and reviews were obtained from leading scientific journals, including (but not limited to) Energy Procedia, Solar Energy, Renewable Energy, and Applied Energy. The review also leveraged publications from relevant market research databases from reputable organizations in the industry. This review presents a partial SWOT analysis of the solar–wind hybrid product space as it is today [12].

2. Solar–Wind Hybrid Products

2.1. Pioneer Products

The concept of the solar–wind hybrid was initiated a long time ago. Different forms of electrical and technical alterations were made to solar and wind turbines to achieve hybrid configurations such as those available today. There has been relatively little innovation on the fundamentals of solar–wind hybridization to date. The concepts essentially remain the same: nothing has been radically changed. In this section, some pioneer commercial solar–wind hybrid systems are examined. This section also highlights the challenges these products face and the successful solutions employed by the developers (where available).

2.1.1. Europe's First PV–Wind HPP: Parc Cynog

Vattenfall made this commercial PV–wind hybrid. The project was developed to gain experience and explore the feasibility of solar–wind hybrids. In 2016, the project was upgraded to a 4.95 MWp solar PV farm and a 3.6 MVA onshore wind farm. One of the enabling factors for this project was the constant negative correlation between solar and wind irradiation in the area. Nonetheless, it was shown that adding a battery will smoothen the production profile of such plants. Additionally, initial farms such as those in Cynog Park suffered from massive curtailment. Manufacturers have mentioned the importance of performing curtailment simulations on a 10 min or 15 min basis [20].

2.1.2. The Villas Carousel

The Villas Carousel project in Southeast Mexico was one of the pioneer PV–wind hybrid projects developed and built by researchers from the Electrical Research Institute of Mexico. The project was aimed at assessing the feasibility of green energy supply to remote facilities. The authors built 15 mini PV–wind hybrid systems to power an eco-hotel in the region. Each hybrid included a 500 W wind generator, a single PV panel of 150–320 Wp (Watts peak), one 570 amp lead-acid battery, and one electronic charge controller. Data loggers were installed in 2 of the 15 systems to monitor performance.

There are some essential facts pointed out by the Villas Carousel project:

- The development of these PV–wind hybrids was completed within a year. Therefore, the development of these pioneer solar–wind hybrid microgenerators could be concluded to be significantly easy.
- Out of the 15, 11 of the wind generators were installed on the hotel's roof alongside the panels.
- The microgenerators were wired to power specific devices in the hotel while larger loads were connected to the grid to ensure smooth running, not the hotel. This highlights another problem of these pioneer systems: due to technological limitations, such devices could not produce sufficient power for large-scale commercialization.
- During its 12-month operation, the systems worked for 4439 h, generating a total of 448 kWh. Daily generation was recorded to be 2–5 times higher than daily consumption. This points out that the problem of excess generation was evident from pioneer projects and evaded solution since.
- The PV generation was always twice that of the wind generator, although the wind turbines installed had twice the generating capacity of the solar systems, and the wind profile of the region was favorable. Thus, the wind system was hindered by the operational conditions of the system as it could only produce for less than 200 h per month while the PV generated for over 350 h per month.
- The battery suffered overheating and outgassing caused by the unsuitability of the system control strategy in such generating conditions. This problem was solved.

2.1.3. Polanco's and Fraunhofer's Hybrid System

In 1995, a solar–wind hybrid was installed in Polanco, Uruguay. This hybrid system was put in place to provide energy for the then small village of Polanco. This system was designed to support 85% of the village's load. Each building required a supply of 5 A, 220 V, 50 Hz, and 300 W per house. Expenses were to be very minimal as the end users would cover them. The hybrid plant was comprised of three systems, each containing a 10 kW windmill, a 1.43 kWp PV array with 27 Isofoton cells, a stationary 48 V battery, 1416 Ah (10 h), and a 4 kVA converter. The system had several challenges in operation. The developers discovered that the ratio of windmills to solar cells was not optimal. Additionally, the systems were loaded with faulty gadgets that had excessive start current and high energy consumption.

The Fraunhofer Institute for Solar Energy Systems developed 30 remote solar–wind hybrid systems that supplied about 5 kW for about 20 kWh per day. Legacy models of these systems have been in operation since the late 1980s. These were early versions of a solar–wind hybrid. Table 2 below lists a few of the PV–wind systems realized by the Fraunhofer Institute [21].

Table 2. PV–wind systems by the Fraunhofer Institute [21].

Facility	Generators	Mean Daily Load [kWh]	Operating Since
Rappenecker Hof	PV–Diesel and Wind	9	1987
Meiler Htitte	PV–Diesel and Wind	2	1990
Rotwandhaus	PV–Diesel and Wind	30	1992

2.1.4. Some Important Facts from Pioneer Systems

- The photovoltaic components (especially the solar module) were (and still are) the most reliable and least troublesome components in these hybrids [21].
- One of the most popular options then, lead-acid batteries, had short 3–5 year life spans. These batteries were equally problematic and required various maneuvers to sustain the operation.
- Pioneer products suffered technological limitations; as a result, they were constructed such that they could not produce sufficient power for large-scale commercialization [21].
- Inverters were inefficient.
- The wind systems in such hybrids are more hindered by the operational conditions than the PV systems.
- According to calculations made for the pioneer solar–wind products of 1997, pure photovoltaic systems were cheaper than hybrid systems. PV systems were valued at USD 2.63/kWh, hybrid systems at USD 3.38/kWh, and conventional systems at USD 4.06/kWh.

Other examples of significant pioneer commercial solar–wind hybrid projects are:

- The Kavithal project (commissioned in 2018). This solar–wind hybrid was installed by Hero Future Energies and Siemens Gamesa in India. The plant's capacity was 50 MW wind, 28.8 MW PV, and 0 MW/MWh storage. In other words, its ratio was 63% wind and 37% PV powered [22].
- Kennedy Energy Park in Australia (2017) was installed by Window and Eurus Energy. The plant's capacity was 43 MW wind, 15 MW PV, and 2/4 MW/MWh storage. In other words, its capacity was 74% wind, 26% PV, and 3% storage. This project was the first solar PV–wind hybrid developed to understand the market [1,23].
- Minnesota's community solar-wind project (2018) was completed by Juhl Energy (GE partner). The plant's capacity was 5 MW wind, 0.5 MW PV, and 0 MW/MWh storage. In other words, its capacity was 90% wind 10% PV.
- Ollagüe, Chile, microgrid (2013), installed by Enel Green Power of the United States, was and still is used to supply a remote area not covered by the national grid. The plant's capacity was 0.3 MW wind, 0.205 MW PV, and 0.3/0.8 MW/MWh storage. In other words, its capacity was 59% wind, 41% PV, and 59% storage [24].
- The H2020 research consortium installed the Tilos hybrid plant (started in 2018) in Greece [25]. The plant's capacity was 0.8 MW wind, 0.16 MW PV, and 0.8/2.4 MW/MWh storage. In other words, its capacity was 83% wind, 17% PV, and 59% storage. This microgrid can supply 70% of the island's power demand. Nonetheless, it is highly vulnerable to maintenance issues due to the roughness of the sea [1].
- Younicos installed the Gracioso hybrid project in Portugal. This plant can also sustain 70% of the island's entire load. The plant's capacity was 4.5 MW wind, 1 MW PV, and 6/3.2 MW/MWh storage. In other words, its capacity was 81% wind, 19% PV, and 100% storage.
- The La Plana project (2017) in La Muela, Spain, was designed by Siemens Gamesa renewable energy [26]. The plant's capacity was 0.85 MW wind, 0.245 MW PV, and 0.4/0.5 MW/MWh storage. In other words, its capacity was 78% wind, 22% PV, and 37% storage [1].

2.2. Key Product Types

Solar–wind hybrids are broadly classified as standalone or grid systems [27]. In the enormous solar–wind hybrid market in 2019, standalone systems led the pack, accounting for 60% of the entire market value. Standalone systems are more suitable for energy supply because they can comfortably serve every member of society. On-grid systems are not ideal for off-grid industries such as manufacturing and healthcare, whose facilities are located in remote areas. The grid solution is not only inaccessible to some, but it is also noted as expensive [12]. With this in mind, it is essential to note that the primary consumers of solar–wind hybrids were members of the industrial end-user segment, accounting for 71% of the total market share. Summing these facts, the primary consumers are industrial end users who prefer standalone systems [12].

Categories of Solar–Wind HPPs

Experts suggest classification into two major types based on functional integration and independent operation of generating modules. These types are HPPs, in which wind and solar share a typical substation and grid coupling point, and HPPs, in which PV panels are integrated into the wind turbine plant [1]. Figure 8 illustrates the common types of HPPs. They include:

- Wind and solar plants sharing the same substation;
- Photovoltaic (PV) panels integrated into wind farms.

Wind and solar plants sharing the same substation is a configuration that is known for more energy savings in CAPEX when compared to setting up separate wind or solar plants. Additionally, the entire development procedures covering resource assessment, site conditioning, and operation and maintenance costs are less than those of separately located wind and solar. However, in cases where these kinds of hybrids are constructed so that additional photovoltaic capacity is located outside the confines of the wind farm to optimize the solar output, the energy saving mentioned earlier is not applicable. Nonetheless, since the wind and solar still share the same coupling to the grid, the HPP controller ensures network code compliance and simplifies operation and maintenance.

Photovoltaic (PV) panels integrated into wind farms. Onsite, integrated PV–wind hybrid plants combine PV and wind generators at a specific site before the electricity is fed to the grids [28]. The advantages of this category also cover those of the first category with a few specifics. In this configuration, the solar inverters can be excluded in cases of full-scale conversion within the wind turbines, ensuring a more efficient use of the converter. Converters are usually more efficient in "high full-load operation" and less efficient under partial load. Therefore, the PV generation will improve the converter's efficiency when there is partial wind generation. Nonetheless, the PV panels are shaded by the blades and the wind tower in certain angles, which is significantly disadvantageous. Fortunately, PV panels can be installed in areas with lesser shadows around the wind turbine, increasing cabling costs and creating line losses.

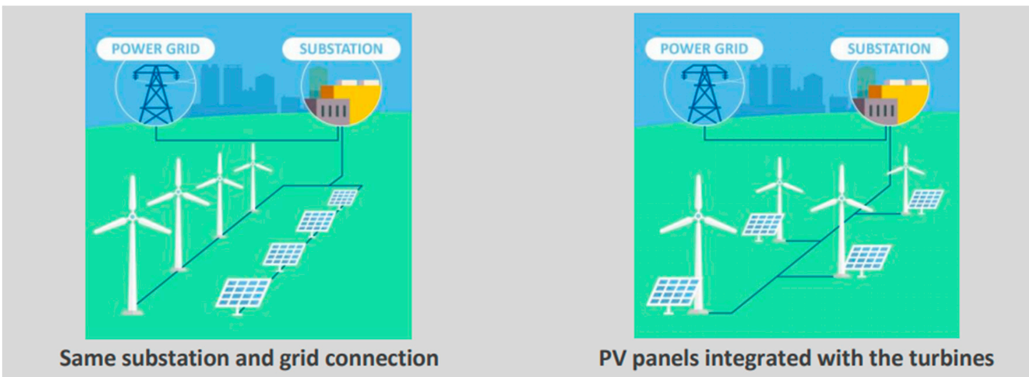

Figure 8. Common types of HPPs [1].

2.3. Current Top Products

Unfortunately, very few companies are providing these kinds of hybrids [10]. Companies that have been able to thrive in this space see the big picture and add long-term benefits to their motivation. Among their concerns are:

- Consolidating competitive profit margins;
- Government and industry regulations.

These top OEMs and trademarks include:

- Blue Pacific Solar;
- Windmills;
- ReGen Powertech;
- Siemens Gamesa;
- UNITRON Energy System Pvt. Ltd.;
- Supernova Technologies Pvt. Ltd.;
- Alternate Energy Company;
- Grupo Dragon;
- Polar Power, Inc.

2.4. Challenges Faced by the Top Products

Although solar–wind hybrids enable an uninterrupted power supply even at the wind and solar peak hours, several setbacks make developers and researchers question the feasibility of the market for specific large-scale applications [28]. Figure 9 shows a heatmap describing the world's PV–wind hybrid power plant on full load hours [29].

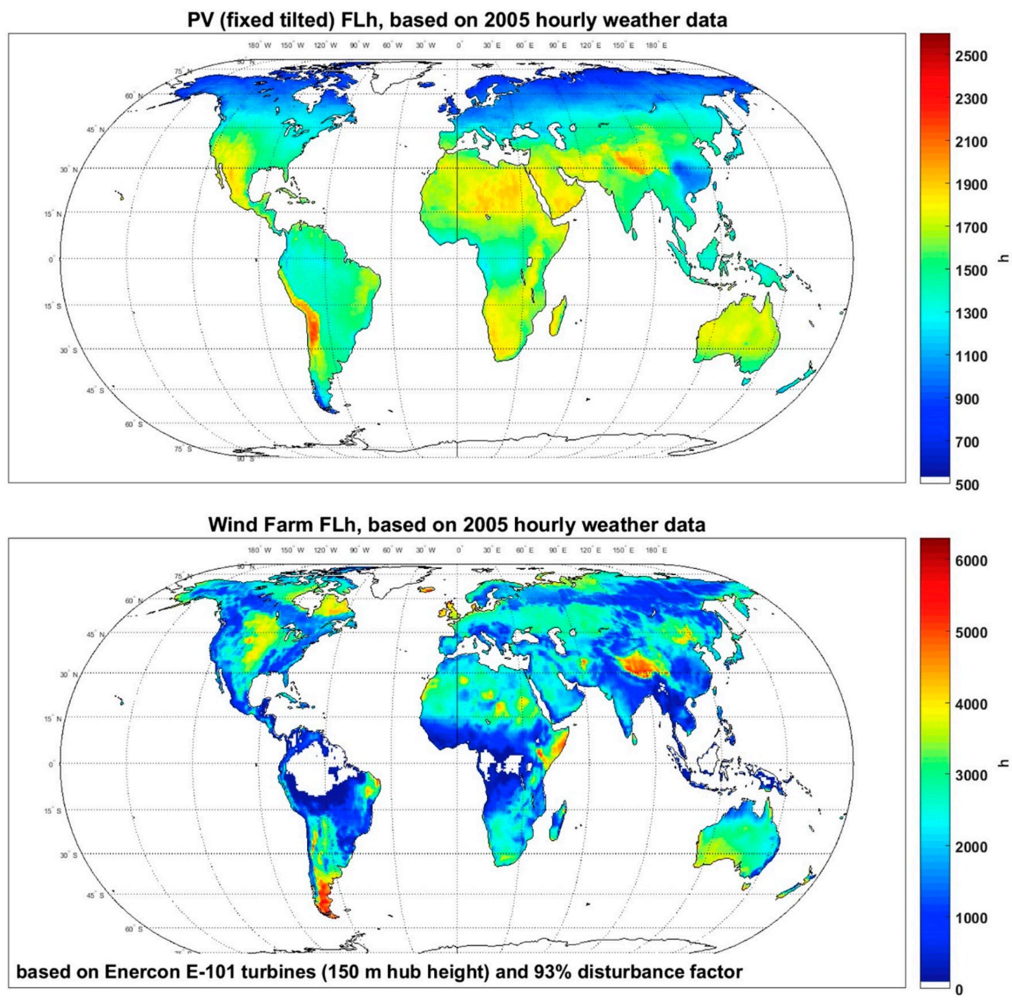

Figure 9. Heatmap describing the global PV and wind power full load hours [30].

Unfortunately, the grid capacity transmission investments to successfully integrate these plants are higher than those of simpler solar or wind alternatives and burdened by a lesser utilization over the years [12]. Unfortunately, HPPs face more problems than technical problems [1]. Some of the primary challenges faced by solar–wind hybrids are outlined below.

2.4.1. Policy Setbacks

In several countries, predominantly in Europe, policy challenges result in restrictions to applying solar–wind hybrids. Policy experts have highlighted the following as significant challenges [1].

- Many countries with operational policies for renewable energy treat solar–wind hybrids as either solar or wind plants. Thus, there is no distinct regulatory framework governing solar–wind hybrid systems in several regions. As many governments announce their sustainability goals, more developers and OEMs enter the market, increasing the need for regulatory standards. Some countries are already strategically updating policies to suit the market [31,32]. This framework must begin with a clear definition of the HPPs to streamline policy execution [1].
- Policies that standardize metering, grid supply requirements, and traceability procedures for renewable energy should be implemented [1]. These policies will make the hybrid plants easier to implement.
- As shown from the example on the German grid, most of these renewable energy plants produce more than required. Therefore, policies should be made to allow HPP developers to install whole plants with capacities beyond existing or standard grid connection capacities, even at the expense of curtailing some of the power generated (as in the German case study). Installing the total capacity of these plants will ensure an uninterrupted supply even during peak periods for solar or wind, thereby fully utilizing the potential of HPPs [1].
- HPPs that have integrated storage systems should be covered by a clear regulatory framework to guide monitoring procedures for energy flow between the storage device and the consumers. In a similar manner, additional taxes and charges must be expunged [1]. Storage device integration might require subsidies from government bodies [20].
- Governments should foster hybridization by extending grid connection standards to developers hybridizing already functional renewable energy plants. Such developers should not be made to re-apply for connection compliance so far as the plant's new capacity does not effectively go beyond the capacity approved in the previous connection compliance licenses [1].

There are already some HPP-specific policies enacted in certain countries. These policies have helped propel the adoption of HPPs and, in turn, improved the energy conditions in such nations (and, in specific cases, neighboring countries). Table 3 highlights some of the most prominent policies.

Table 3. Solar–wind hybrid policies in different countries.

Country	Selected Policies
Denmark	Old wind turbine solar plants are forbidden from being hybridized.
Germany	Electricity storage for 20 years is exempted from grid charges.
Greece	Regulatory framework exists to restrict minimum guaranteed power. For storage facilities, annual grid energy stored by the hybrid plant is forbidden to be more than 30% of that required to fully charge the storage device. The RES-to-storage capacity ratio must not be above 1.2.
Ireland	In 2020, Ireland's Department of the Environment, Climate and Communications (DECC) considered policy advice and economic suggestions to promote the development of new renewable energy facilities, particularly hybrid solar–wind and storage projects.
India	India formulated a national wind–solar HPP policy in 2017. The policy is continually being adjusted to cover various storage options. The policy also covers grid connection capacity substation utilization and storage minimums.

2.4.2. Case Study: India's Enabling Policies

Experts declare that the growth of renewables is heavily dependent on government policies. One primary reason for this is that enabling policy frameworks help secure renewable energy developers [7]. Studies show that high debt cost fueled by high interest rates is arguably RE financing's most prominent enemy [33].

In 2018, India's Ministry of New and Renewable Energy (MNRE) took the bull by the horns, introducing a wind–solar hybrid policy, one of the first of its kind [7]. The policy is reported to have changed the country's power deployment dynamics. The policy was defined to project a 180 GW national target to be attained through renewables by 2022. Out of this, 175 GW will cover a 100 GW solar installation and 60 GW of wind energy plants (onshore). For offshore wind power, the projected installation capacity was given as 5 GW and 30 GW by 2022 and 2030, respectively. Hence, the RE installation capacity targets are 57.14% and 34.29% for wind and solar plants, respectively. The beginning of 2020 saw the country achieving its renewable capacity goals as its renewable energy penetration was 23.41% of the national generation capacity. Under the policy, new and existing solar PV systems and wind generators are to be hybridized (designed with a single grid connection point).

Other provisions of the policy include [7]:

- The removal of additional connectivity and transmission charges for the hybridization of existing plants.
- When allowed, the additional transmission access to existing energy farms mandates the transmission augmentation for substation evacuation to be entirely on the developer.
- The government reserves the right to auction existing plants for hybridization and start new hybrid projects [7].
- The storage system (battery or otherwise) can generate power with a lower variability to ensure a higher productivity for the installed capacity [34].

Several crucial points of India's policy framework that foster these hybrids' increased penetration cover research grants, developer funds, competitive pricing, and other essential implementation drivers. These include [7]:

- The accelerated depreciation (AD) policy;
- The annual power purchase cost (APPC);
- The feed-in tariff (FIT);
- The power purchase agreement (PPA);
- The renewable purchase obligation (RPO);
- The viability gap funding (VGF).

In addition to the giant strides taken by India, other governments should consider policies that allow long-term debt for developers and investors to ensure energy is at a low cost [33]. It is also crucial to support private investors (also privatization) in the energy sector to boost the penetration of renewables for power generation [7].

2.4.3. Storing Electricity

Electricity cannot be effectively stored in substantial quantities. Therefore, conventional power plants are wont to generate electricity for immediate consumption. This mandates operators to continuously manage power plants to meet demand. Energy storage systems are generally classified as [35].

- Electrochemical (dry batteries): lithium-ion (LI), metal–air (MA), nickel-metal hydride (NMH), nickel-cadmium (NiCd), and polysulphide bromide (PSB).
- Electrochemical capacitor (EC) wet batteries: lead-acid (LA), sodium-sulfur (NaS), valve-regulated lead-acid (VRLA), and zero emission battery research activity (ZEBRA).
- Flow batteries (FB): vanadium redox (AVR), vanadium bromide redox (VBR), and zinc bromine (ZnBr).
- Chemical: fuel cell (FC), synthetic natural gas (SNG), and electrolyzer (EZ).

- Electromagnetic: capacitors, superconducting magnetic energy storage (SMES), supercapacitor (SC), and superconducting coil (SCC).
- Mechanical flywheel energy storage (FES), compressed air storage (CAS), and pumped storage arrangement (PSA).
- Thermal: cryogenic energy storage (CES), ice-based technology (IBT), electric thermal heaters (ETH), and pumped heat storage (PHS).

Some utility-scale storage solutions (operational in Europe) include:

- Pumped storage is utilized for hydropower and has a 70–80% efficiency and fast response rate. Pumped storage is used in a few plants in Germany [36].
- Underground pumped storage is used in derelict mines whose mineral content is converted to media that provide storage. It is used for hydroelectric power [37,38].
- Compressed air storage is conducted in sealed caverns. Excess power from the grid is used to drive a compressor via electric motors. This compressed air is then cooled and stored (60–70 bar). The compressed air is drawn back and heated to run a modified gas turbine. The United States and Germany have been operating such kinds of storage. Compressed air storage can also be used for renewable systems [39].
- Thermal storage involves storing energy in the form of heat energy [40]. This is achieved by heating insulated masses or performing a phase change of substantial materials. The first commercial solar thermal storage power plant is located in Spain.
- Flywheels store rotational energy. A torque generator is used to release the stored energy. Flywheel storage is used to regulate short-duration frequency. It can be used to store renewable energy [41].
- Electromagnetic energy storage stores power by moving electricity into electromagnetic fields. Two leading technologies used in this form of storage are supercapacitors and superconductor magnetic energy storage (SMES).
- Batteries are increasingly popular in electricity storage. Several dependent technologies, especially electric cars, are driving this trend. Additionally, battery technologies (especially lithium-ion batteries) are becoming more advanced, and demand is going up. There are three massive battery storage plants in the United States. Other popular battery technologies are lead-acid, sodium-sulphur, zinc, and flow batteries [42].

2.4.4. Overproduction (Waste)

The last and most interesting challenge to be examined is overproduction, which has been reported in almost all solar–wind hybrid setups. A case study of renewables in Germany is used to explain the gravity of this challenge.

2.4.5. Case Study: Germany PV–Wind Hybrids

Until today, countries benefiting from PV–wind hybrids such as Germany have been unable to consume all the power generated [36,43,44]. In Germany, the transmission grid is too weak to convey all the power generated in the north to the southern load centers, a longstanding challenge for the country that is only getting worse [45]. In 2020, the pandemic restrictions made Germany change from a net exporter of electricity to become a net importer. The share of renewable energy sources (RES) in its generation portfolio increased by 4.5% to 50.5% [36].

The country enjoys very favorable climatic conditions that help it generate up to 43% of its power supply from renewables (according to its 2019 records). In 2019, TenneT, a transmission system operator (that serves the Netherlands), brought a whopping 20.2 terawatt hours of onshore energy (enough power for more than 6 million average households). These transmission operators have to buy a lot of power that might end up wasted or sent to neighboring countries. This is not surprising as each German offshore grid connection carries more than 7 gigawatts of energy (exceeding the government's target of 6.5 gigawatts) [45].

Germany installed interconnecting phase-shifters to prevent overwhelming its neighbors [45]. This solution is far from desirable. Although it would be preferable to reduce power output simply, this would mean severe loss from disabling running power plants or completely pulling down some offshore plants [45]. Germany's high RES share in 2020 resulted in an urgent need to increase the intermittent energy production structure [36,46]. In other words, there is an urgent need for better systems to balance demand and supply. These methods include sector coupling, demand- or supply-side flexibility, and transmission flexibility. Another proposed solution is to equip these plants with suitable storage infrastructures such as ideal batteries or similar technologies [47]. Additionally, the onsite conversion of excess electricity to easily storable forms, such as methane or hydrogen, is viable though expensive [45].

Restricted mobility, suspended travel, and social distancing resulted in a reduction in transport activities. Steffen et al. [48] proposed principles for sustaining energy structure in times of crisis similar to the pandemic. These principles cover short-term decisions, taking advantage of energy transition opportunities, and sustainable policies to mitigate future shock. The harm of such times of crisis can be converted to promote long-term goals [49]. Studies have highlighted the importance of observing the lifestyle patterns exposed by the pandemic. Consumers used less energy [43,50]. The challenges caused by the pandemic led to German inter-regional electricity [36].

In 2020, Germany opted for increased international transmission [51,52]. The European Network of Transmission System Operators for Electricity (ENTSO-E) provides the framework for exchanging electricity via transmission lines. There are many similar interconnected power networks globally [46,52,53]. Tapping into such connections includes a more robust power generation scheme, increased competition, varying consumption structures, and supply security.

3. Excerpt from Product Reviews

Evidently, not everyone supports solar–wind hybrids (and renewables in general). Many studies have focused on emphasizing why renewables (and their hybrids) are not the way forward. Their principal complaint is the cost involved in the renewable shift. Pehlivanova and Atanasov [54] studied the viability of the autonomous hybrid solar–wind system for household usage. They compared the electricity (tariff) prices for small-scale and household usage in Okop, Yambol District, Bulgaria. Based on their results, regardless of the rising cost of electricity and fossil fuels and the zero-carbon goal, the price of electricity produced by the autonomous system was higher when compared with the price of electricity from the power grid [54]. They further concluded that using a hybrid solar–wind system will only be rationalized where there was no supply from the national grid as it is in isolated regions and islands. All the same, the merits outweigh the demerits. This section will examine previous studies focused on PV–wind hybrid products from different angles.

3.1. Popular Focus Areas

Several studies have been conducted to propose optimized PV–wind hybrid systems. Many of these studies focused on simulations [55]. Most of them had a similar significant achievement; they proved solar–wind hybrid implementation was possible in the specific region where they gathered data [56].

Harini et al. proposed a grid PV–wind system to be implemented in Iran. It was comprised of a generator, DC-DC, wind-side converters, and a grid inverter. The maximum power point tracking (MPPT) technique optimized the solar panels' DC voltage [56]. The system proposed was implemented in MATLAB Simulink. Input variables for the solver were derived from meteorological data based on the specifications of the PV and turbine components. The study showed that solar–wind power production is viable in Iran. Other grid hybrids or grid optimization studies analyzed power quality, the effect of wind and solar radiation fluctuations, and power losses [57]. Gorla and Salako [58] researched the feasibility of using PV–wind hybrid systems for space and service water heating to satisfy at least 50% of the energy demand for heating in Cleveland. Their results showed that it could provide only 28–36% of the energy required for the cold winter months, and an excess of 31–37% was generated during the summer months, which they recommended to be sold to the grid.

There are different approaches to determining the optimal combinatory specifications for solar–wind hybrids. These include [27]:

- An iterative approach that involves hill-climbing, linear, and dynamic programming.
- The application of artificial intelligence such as fuzzy logic, generic algorithms, or artificial neural networks (ANNs).
- Software solutions that have also been proffered, including HOMER and GUI software solutions.

Some designs have covered the control systems and strategies for PV–wind hybrids [59]. Studies have examined the economic aspects of residential solar–wind hybrids, such as minimizing cost and the number of components (PV modules and wind turbines) required [60]. Studies have also focused on the sizing optimization of PV–wind hybrids using a simulated annealing (SA) algorithm, iterative approach, and others; the techno-feasibility analysis of using simulation software (such as HOMER); design and simulation using MPPT, Simulink, and HOMER [27]. Other studies covered PV–wind hybrids for hydrogen production to power UV water purifiers [59,61].

However, most of these proposals have not seen practical commercial applications. The majority were computational analyses, simulations, and small-scale prototypes with results that were not exhaustively proven to be applicable in large-scale commercial farms (or single hybrid systems) [27]. Nonetheless, several readily actionable studies have also been conducted [61]. Authors have investigated systems that use PV–wind hybrids to produce hydrogen, which is a very commendable way of reducing the excess power generated by PV–wind hybrids. Such systems have generated up to 130–140 mL/min of hydrogen at solar radiation of 200–800 W/squared meter and wind speed of 2–5 m/s [61].

PV–wind microgeneration has not been given due attention in research [27]. Microgeneration is always an essential portion of power because it enables private individuals to support their energy consumption independently. A few authors have developed an optimized solar–wind hybrid for residential micro-power generation [62]. Additionally, a few studies have focused on actual power generation to support existing grids [27].

It is also important to mention that several studies have been conducted in Asia and Africa in this industry. Some selected works are highlighted below.

3.1.1. Africa

Wasonga et al. [63] analyzed the design of a PV–wind hybrid system for a new engineering complex the Technical University of Mombasa. The study determined the electrical load of the new complex and simulated possible scenarios. It showed that the building would produce excess electricity. Toual et al. [64] conducted research on a modified MPPT control strategy for a PV–wind hybrid power system. The aim was to create a balance of renewable energy with both quantity and quality relating to power fluctuation. The setup was comprised of a 1.5 MW wind energy conversion system (WECS) and a 400 kW photovoltaic system (PVS) that simulated using actual climatic data (wind speed, solar irradiance, and temperature) at an Adrar site that was believed to be the site with the most PV–wind potential in the south of Algeria. The study modified the MPPT and put forward a PVS control model that consisted of a fluctuating component to compensate for the fluctuations due to the intermittent nature of the power from the WECS and another component for power production. The result showed a satisfying balance between quantity and quality power production. Ahmed et al. [65] used fuzzy intelligent control (FIC)-based MPPT for a PV–wind system, which was found to be better in terms of performance than conventional perturb, observe, and hill climb search (HCS) algorithms by accurately tracking the reference signal. Muhammad et al. [66], in a feasibility analysis of the potential of PV–wind hybrid systems in Maiduguri town, concluded that hybrid systems could be a viable power generation means due to the annual energy output that was recorded, which was within the range of 2–5 MWh/m^2 every year. Maiduguri had an average wind speed of 6.72 m/s at a 30 m height and solar irradiance flux of 6.176 kW/m^2 from the site.

3.1.2. Asia

In the Uttarakhand State council, Johnson et al. [67] performed a feasibility study for a 200 kW PV–wind hybrid system for a newly constructed building. The study showed that, after simulation with HOMER software, the system produced excess electricity, about 87.3% of the electricity supplied by the system. Kumar and Kumar [68] examined anti-islanding protection for a 20 kW solar–wind hybrid inverter using real and reactive flow conditions. It was observed that the inverters' disconnection time was within a 2 s interval in all conditions. Nijhawan and Singh [69] performed a feasibility analysis of the potential of PV–wind hybrid systems in Umrala and Haripar, Gujarat. They found that it was feasible due to the presence of adequate solar and wind potential [70,71]. Matai [72] analyzed the domestic plans for an architectural point of view; the work highlighted strategies for the implementation of these hybrid systems from design to the finishing stage.

Al-Mamun et al. [73] designed and analyzed a PV–wind hybrid system. After the stimulation of variables, the authors strongly recommended the need to use an efficient storage system for effective operation and use. Mohiuddin and Sheikh [74] used superconducting magnetic energy storage (SMES) for the stabilization of a renewable energy system. Superconducting magnetic energy storage (SMES) was introduced to reduce the fluctuations from generated electricity due to the intermittent nature of renewable energies. Their result showed an increased reliability of the hybrid system when using SMES than without it. Budiman et al. [75] performed research on the Internet of Things (IoT) technology, monitoring, controlling, and data logging for ATS on a PV–wind hybrid system connected to the grid. The work highlighted the importance of IoT technology in implementing hybrid systems by analyzing, monitoring, and controlling the major indicators by using sensors and other related devices in remote and real-time situations.

Al-Waeli et al. [76] assessed the potential of a PV–wind hybrid system in the Al-Muthana Governorate in Iraq, which was chosen due to the high wind speed in that area. Their results showed satisfactory performance, especially if it was connected to the national grid. Rafai et al. [77] designed the pole for a PV–wind hybrid system using Ansys 14.0 using the weather of Islamabad, Pakistan. Their model was tested, simulated, and analyzed under three different extreme loading conditions, using stainless steel as the material with a safety factor of 1.5. Their model was found to be safe for use.

3.2. Selected Recent Studies on Solar–Wind Hybrids

Mohammad et al. [78] constructed a nano off-grid hybrid solar-wind system, which was found to be adequate for supplying to rural households. The design architecture was divided into five subsystems for generation, monitoring, transmission, distribution, and house load, which consisted of a solar panel, wind turbine, converters, inverters, batteries, and the load. This design optimized and simulated the systems with HOMER Pro (Hybrid Optimization Model for Electric Renewables) and Simulink. They were declared adequate to meet the demands of rural and moderately urban households that fall within the range of 10–15 kWh per month, considering that the average Nigerian household uses between only 150 kWh per capita. Johnson et al. [67] studied a 200 kW solar–wind hybrid system for a newly constructed building in Uttarakhand, India, optimized using HOMER software [67]. The hybrid system was found to supply the load of the building location throughout the year while producing excess electricity of 430.409 kW h/year, which was 87.3% of the electricity supplied by the system.

Awasthi et al. [71] proposed a 500 kW alternating and direct current hybrid isolated microgrid energy storage system for solar–wind hybrid systems. Using PSCAD/EMTDC in isolated conditions, simulation studies were carried out to achieve an effective integration of renewable energy storage systems (RESS) to the microgrid [71]. A boost converter operated at maximum power point tracking (MPPT) was connected with a doubly fed induction generator (DFIG)-based) WTG system and an energy management control. The result showed that it was effectively achieved without giving away the power quality of the grid. Kumar and Kumar [68] researched anti-islanding protection for a 20 kW solar–wind hybrid inverter with a battery backup option. The research simulated three voltage levels and 31 conditions [68]. For the inverter tested for protection against islanding using a 200 kW RLC load system for different real and reactive power flow conditions, it was recorded, that in all cases, the inverters' disconnection time was within a 2 s interval as per the limit necessitated by IS standard 16169:2014.

Bakir and Kulaksiz [79], in their research on voltage control of a hybrid micro-grid with optimized STATCOM rated at 3 MVAR, a 2 MW wind generation system and a 0.4 MW solar system on the grid were examined. The voltage fluctuation at the end of the bus bar was observed to be reduced by 8% using a conventional PI controller [79]. Kose et al. [80], in their research on a hybrid solar–wind irrigation system in Turkey, used a solar–wind hybrid system for powering a 300 W DC-driven submersible pump 2.5 m from ground level. It was recorded to pump a minimum daily average of 44.1 m^3/day of water, which was enough to irrigate 3.1 acres of sugar beet, 3.25 acres of potatoes, 3.35 acres of maize, 3.4 acres of green bean, and 2.7 acres of sunflower [80]. This, they calculated, will save USD 10,410 on energy 20 years after the introductory payback period of 5.7 years.

Sikder and Pal [70] developed an intelligent battery controller for a standalone hybrid distributed generation system and proposed a modeled and simulated system using Simulink [70]. They recorded that the hybridization of solar (photovoltaic) and wind energy leads to an increased generating capacity without increasing the storage or battery capacity while maintaining a reliable electricity supply to the end user. Nyemba et al. [81] worked on designing and manufacturing streetlights powered by a solar–wind hybrid system. The study showed that the system reduced the energy storage requirement by a 38.75% and a 14.4% overall reduction in the cost compared with a standalone solar streetlight. They also recorded a 69.3% increase and a 50% decrease in turbine power output and energy storage requirements, respectively, when the diffuser effect on the turbine was being evaluated [81]. They recommended further research into the reliability of a standalone system. Bakir and Kulaksiz [79] studied the modeling and voltage control of a PV–wind micro-grid and contributed the optimization of four proportional–integral (PI) controllers in STATCOM based on a generic algorithm (GA) [54,80].

Some Principal Challenges of New Proposals

A careful analysis of studies by region was conducted, from which it was discovered that the challenges faced by research in this industry are sometimes region specific. Other prominent challenges are also noted in this section.

- Cost of parts and spares: The cost of parts for the fabrication and manufacturing of hybrid systems has cropped up as a significant setback to research in space. Unfortunately, most of the sites and regions where the PV–wind hybrid system can best achieve full potential are in areas with low purchasing power and medium purchasing power in rare cases. This was identified from studies conducted in Nigeria, Zimbabwe, Kenya, India, Pakistan, Malaysia, Iraq, Bangladesh, and Zimbabwe [63,66–68,70–74,76–78,81,82]. This affects the quality of research in these areas as researchers are forced to limit their research to simulations and theoretical analysis. The cost of parts also affects research to push scientists towards over-improvisation, which may be cheap but reduces the quality of research output. The PV–wind costing structure also needs to be simplified so that consumers understand the allocation of expenses. Mari and Nabona [83] provided a simplified framework for understanding wind–PV hybrid generation expenses by dividing them into five major parts: initial investment, operation, and maintenance (O&M) cost; equipment replacement cost; hybrid power generation; grid exchange cost; and utility regulation cost [83].

- Appropriate design implementation: Proper design implementation is a challenge as most studies to design prototypes either fail to implement these designs or resort to simulation. Unfortunately, simulations do not comprehensively mirror real-life situations. Design implementation is essential as it highlights paths for fabrication and challenges of specific designs in real life. Additionally, due to these simulation constraints, the solutions proposed in some studies do not adequately match the actual devices produced, possibly due to fabrication modifications.
- Scalability: Several proposed solutions face various challenges in design implementation for mass production. All research aims to solve real-life problems and improve people's lives; therefore, designs have to meet the criteria of functionality, ease of use, lightness in use (weight), durability, and aesthetics (optional). These are characteristics of most mass-produced goods. Therefore, designs should strive to meet the minimum for future implementation and possible usage.

Other challenges include:

- Streamlining research;
- Energy storage system;
- Cost of system components;
- Need for windmill poles at the appropriate height for proper utilization of wind energy;
- Possibility of grid connection to sell excess power to the grid and buy in times of low energy production;
- IoT enables PV panel sensitivity to tilt to the appropriate angle for proper solar energy utilization.

3.3. Major Challenges of Solar–Wind Hybrids

In the present review, we pinpointed the significant challenges of solar–wind hybrids. It is crucial to examine efforts to solve these problems. A holistic review of some studies that have significantly addressed the identified setbacks is provided in this section.

3.3.1. Policy Challenges

Several works examined policy structures around other renewables [84]. RE policies were extensively addressed in various studies. Indispensable policies and framework components covering various loopholes in existing policies and new angles have been proposed. These studies considered subsidies, long-term debt and financing, incentives, skilled labor, and policy implications [33,85,86]. RE price policies were thoroughly addressed as they are more influential than RE non-price policies. A price policy fixes a price tag and leaves quantity decisions to the market, whereas a non-price policy sets the quantity leaving the price to the market [7]. The authors highlighted various policy and regulatory challenges and opportunities for RE prosumers (consumers that also produce) in several European countries. The recurrent setbacks were among those already mentioned in the present work. According to the study, prosumers enjoy the most enabling regulatory conditions in Germany, Great Britain, France, and the Netherlands [87]. Some even argued that ambiguous regulatory frameworks are worse than no policy frameworks [88]. Some studies modeled the policies to select the best options. One such method is called a robustness analysis, which determines the required criteria (parameters) for validity; some statements say "Policy a outperforms policy b" [89,90]. The present work determined that RE policies have been (and continue to be) sufficiently studied in all the geographical regions [37,40,43]. Regardless of the interest in RE policies, there are few studies on solar–wind HPP policies in particular.

3.3.2. Overproduction or Over-Generation

The adoption of solar–wind hybrids and even solar energy, in general, continues to suffer thanks to the tendency for PV to overproduce energy that can be consumed in a given time frame. Auxiliary components, including converters, controllers, and storage units, affect overall generation [35]. Coupling PV and storage systems will alleviate over-generation. Government bodies and developers have used curtailment laws and solutions to mitigate this problem (as discussed in this study). Curtailing PV generation reduces its benefits both economically and environmentally, although it does not significantly impact the benefits of PV when occasionally implemented [91].

Overproduction has been modeled as the duck curve. Although the mainstream noticed this crucial problem recently, the US Department of Energy's Solar Energy Technologies Office (SETO) has been funding studies on the duck curve for years. In 2016, SETO paired researchers with utilities to provide solutions to curtailment [91]. Figure 10 is an illustration of the duck curve.

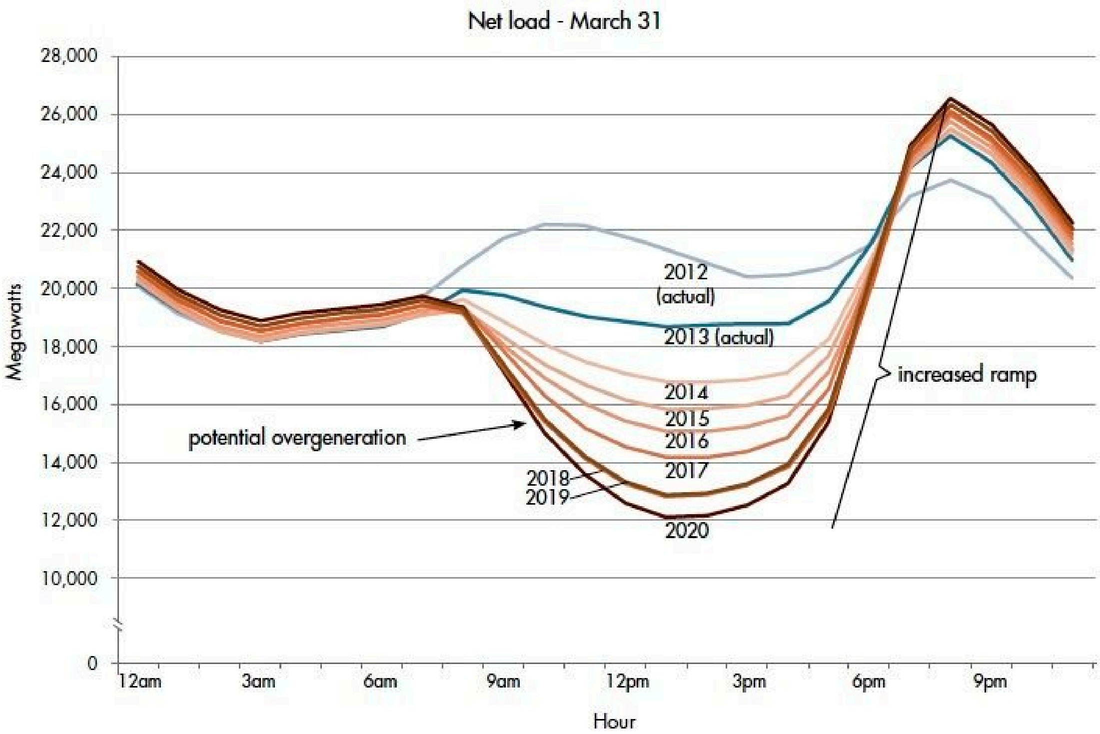

Figure 10. The overproduction duck curve [91].

Optimization techniques that determine the optimum size of generation systems to ensure full utilization of equipment at the lowest costs significantly impact generation capacities. Such techniques cover meteorological data, probabilistic approach, graphic construction method, iterative technique, artificial intelligence methods, energy flow and management controls, multiobjective design, and algorithms [92–94].

Altin et al. [95] proffered novel optimization solutions that implemented an algorithm to maximize the wind turbine's overproduction of energy. The authors also investigated the short-term impact of overproduction on wind turbine structural loading via aeroelastic simulations to point out the aerodynamic limitations. This impact analysis was also a novel angle in its time. The solutions proffered stemmed from three approaches to the genetic algorithm that considered the mechanical and electrical constraints.

The first approach covers the optimization of the duration of overproduction for a group of active power set points. The second extends the consideration of power set points to include the duration of response under two decision parameters. The third approach modeled the active power set point as a variable (not a constant), performing the optimization based on the frequency deviation measurements [95]. From the optimization results, the authors investigated some relevant aspects of consideration for developers and operators regarding synthetic inertia and fast frequency control components [95].

Some utilities and developers use forecasts and solar power predictions to discover generation layouts and avoid overproduction. IBM has developed a machine-learning technology that improves solar prediction accuracy by 30%. The success of forecasts in reducing production loss has been so significant that researchers trust that improving predictive accuracy will help reduce overproduction [91].

3.3.3. Storage: A Solution to Overproduction

Storage, a prominent solution to overproduction, is a challenge of its own [91]. Hybrid generation is usually integrated with storage units for the following purposes:

- To ensure more reliability [35];
- To close the energy gap between load demand and generation;
- To provide ample time for maintenance activities [91];
- To reduce the need to run PV–wind systems continuously as consumers can draw from storage systems during downtime;
- To eliminate the need for curtailment.

Some studies addressed the relevance of optimizing the size of storage units to enhance the reliability of power generation [96–98]. Other studies discussed the optimization of the charge and discharge states of storage systems. Studies also analyzed minimizing the total cost of the system [96].

There has been significant interest in the viability of hydrogen production solutions as a storage alternative. Maclay et al. [99] proposed a similar PV–hydrogen-powered system for standalone and grid connections. Their system utilized Simulink to examine the regenerative fuel cell (RFC) storage device for PV generation. The authors further discussed storage issues such as battery sizing, charge limitations, and charge and discharge rates [99].

Researchers refer to green hydrogen as the "missing link" in the energy transition from conventional to renewables. Green hydrogen is described as the use of excess renewable power to produce hydrogen, which can be used to reproduce electricity during downtimes [100]. Hydrogen is becoming more popular among engineers because it burns similarly to natural gas and does not release carbon dioxide emissions. It is also produced using a relatively straightforward process of electrically separating water molecules [101].

There are two sides to the coin, however. Some experts consider it "dumb" to generate hydrogen to generate more power. Their arguments are founded on all the losses involved in such cyclic systems. Additionally, green hydrogen is not cheap [102]. It is almost three times as costly as natural gas benchmarks in certain regions [101]. Nonetheless, the world cannot avoid that green hydrogen is sustainable and will reduce emissions [103]. It is predicted that an estimated 250 to 300 terawatt hours of excess PV and wind energy will be used in producing green hydrogen by 2030 [101]. Again, researchers mention the importance of policy and regulation to facilitate the adoption of green hydrogen [100].

This carbon-free energy solution is already employed in a USD 65 million project at Okeechobee built by NextEra Energy. The project, initially built for natural gas, was converted to produce hydrogen. In 2021, Mitsubishi entered into a partnership to build a green hydrogen storage facility to produce 150,000 MWh of electricity. Several other companies, such as New Fortress Energy in the US and Uniper in Germany, are also improving their facilities to enter the space [101]. Seasonal storage is also possible with hydrogen. In a nutshell, green hydrogen is a long-term, environmentally friendly solution that is much cheaper than batteries on a large scale [103].

3.4. Key Takeaways

Although these studies have helped the field in one way or another, the need for more viable large-scale solutions still exists. These critical problems of the hybrids, in particular, also need more research. Very few studies address the problems of overproduction, enabling policies, and adequate electricity storage. Furthermore, solutions can be better fitted to real-life operations if more studies merge implementation with simulation. This can be easily achieved when there is even more collaboration between researchers and developers. Institutions have to address the challenges faced by industry–academia collaborations [104,105].

4. Conclusions and Recommendations

Research and development (R&D) funds should focus more on technical and optimization challenges regarding the operation, development, and scaling of HPPs. More studies should address crucial implementation challenges. There should be more collaboration between developers and researchers (even though several developers have in-house research and development teams) to fully utilize the Earth's resources [1].

Revolutionary innovation is also needed to birth out-of-the-box designs for solar and wind turbines. This is because the solar–wind hybrid concept and the wind turbine concept, in particular, have changed slightly from the fundamental design concepts of their predecessors. The introduction of vertical axis wind turbines was a game-changer; more of such innovation is needed in the solar, wind, and solar–wind hybrid designs.

Optimizing the sizes and size ratios of the elements of a solar–wind hybrid is very crucial. Using their optimal sizes (while ensuring all loading and performance requirements are met) helps reduce costs [27]. Additionally, the battery (in cases of integrated storage) and wind turbine are the most significant components of the solar–wind hybrid system required to fulfill load requirements at night [27]. Extensive research is therefore required to introduce better storage solutions in this space. The industry needs more innovation surrounding the problems of overproduction, enabling policies, and adequate electricity storage.

Research has suggested several methods to solve the problem of overproduction. These include sector coupling, demand- or supply-side flexibility, transmission flexibility, and better storage solutions. Research has shown the setbacks of several of these methods especially those related to connected transmission. Electricity storage is a great solution to overproduction, and lithium-ion batteries remain the best choice for storage.

Policies should be enacted to standardize metering, grid supply requirements, and traceability procedures and permit flexible connection capacities. RE challenges can be solved or mitigated through proper policies [7]. Some governments are already at the forefront of events regarding renewables. A good example is the US Department of Energy's Solar Energy Technologies Office (SETO), which has enacted not only several initiatives to promote the adoption of renewables but also research programs to assist developers, utilities, and researchers in predicting not just when and where but also how much renewable power will be produced in such regions [91]. Governments should place subsidies on storage devices and other incentives to enable developers to move to better hybrid systems.

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