DTU Library

Research Challenges and Opportunities of Utility-Scale Hybrid Power Plants

Das, Kaushik; Hansen, Anca D.; Leon, Juan Pablo Murcia; Zhu, Rujie; Gupta, Megha; Pérez-Rúa, Juan-Andrés; Long, Qian; Pombo, Daniel V.; Barlas, Athanasios; Gocmen, Tuhfe

Total number of authors:
14

Published in:
Wiley Interdisciplinary Reviews: Energy and Environment

Link to article, DOI:
10.1002/wene.70001

Publication date:
2025

Document Version
Publisher's PDF, also known as Version of record

Wiley Interdisciplinary Reviews: Energy and Environment

WILEY

WIREs ENERGY AND ENVIRONMENT

OVERVIEW OPEN ACCESS

Research Challenges and Opportunities of Utility-Scale Hybrid Power Plants

Kaushik Das | Anca D. Hansen | Juan Pablo Murcia Leon | Rujie Zhu | Megha Gupta | Juan-Andrés Pérez-Rúa | Qian Long | Daniel V. Pombo | Athanasios Barlas | Tuhfe Gocmen | Andrey Sogachev | Matti Koivisto | Nicolaos A. Cutululis | Poul E. Sørensen

DTU Wind and Energy Systems, Technical University of Denmark, Roskilde, Denmark

Correspondence: Kaushik Das (kdas@dtu.dk)

Received: 9 February 2024 | **Revised:** 11 December 2024 | **Accepted:** 27 January 2025

Associate Editor: Damian Flynn | **Editor-in-Chief:** Peter Lund

Funding: This work is done as part of Danish project "IEA Wind Task 50 (hybrid-kraftværker) - Dansk Konsortium" funded by EUDP: 134-21024.

Keywords: design and operation | energy management systems | grid code | hybrid power plant | renewable hybrid power plant | uncertainty and forecast

ABSTRACT

Hybrid power plants (HPPs) combining multiple generation and/or storage sources behind a single connection point are becoming popular due to their capability to provide additional value for both plant owners and power systems compared to individual technology renewable power plants. However, the research on HPPs is still in nascent stage. This article comprehensively overviews utility-scale HPPs (power plants ranging from hundreds of MW to GW scale). It primarily addresses HPPs that combine renewable sources such as wind and solar (PV technology) with electrical energy storage (ESS), all connected behind a single grid connection and operated as a unified power plant by a single operator. This article covers various aspects such as HPPs' potential benefits, research challenges, and opportunities related to their design, operation, and development, from both societal and HPP owners' perspectives. It briefly discusses the advantages of HPPs compared to individual renewable technology-based power plants highlighting the potential added values of HPPs for owners, system operators, and society, while ensuring compliance with grid code requirements at the point of common coupling. The main focus is on identifying and clustering the research challenges associated with design and operation of HPPs. Topics such as energy management systems, sizing and siting, electrical design and control, uncertainties and forecasting, grid emulation and advanced testing, and multi-energy system integration are elaborated and reviewed. This article demonstrates that significant research is urgently needed to enhance renewable generation flexibility and improve grid services. Addressing these challenges will accelerate the development and deployment of HPPs.

1 | Introduction

Increasing concerns for climate change and energy security around the world motivate the green transition of power and energy systems allowing renewable energy sources (RES) not only to replace fossil-fuel-based generators but also to meet increasing demand. The RES technologies are typically variable and uncertain in nature and are predominantly hydro, wind or solar power. This increases the concern for the stability and security of the power system. However, these RES are either replacing the fossil-fuel-based generators or adding to the existing fleet of generators in a power system. However, one of the major constraints to adding more RES is the congestion of grids. An opportunity arises to integrate more renewable generations when combining multiple generators in such a congested grid behind a single connection point. This can be particularly achievable if the RES are anti-correlated in nature as in the case of wind and solar power. Additionally, decreasing costs of wind, solar, storage, and other technologies in recent times has increased the focus on combining the technologies into hybrid power plants (HPPs) to investigate whether such an HPP is techno-economically feasible. The economic feasibility of an HPP depends on multiple additional factors beyond cost, such as, correlation between weather-based resources, market price fluctuations, grid congestion, regulations, and so forth.

Wind-diesel hybrid configurations have been around for many decades, however, in recent times renewable-based HPPs have gained immense interest. Such a concept is gaining global relevance rapidly, due to the reduced cost of renewable and storage technologies, better utilization of grid infrastructure, anti-correlation between wind and solar resources, and so forth. However, there is not yet a clear consensus on the definition of HPP, since HPPs differ largely in terms of composition, regulation, connection either front or behind the meter, purpose (such as the provision of peak power, ancillary service provision, market participation), size, and so forth. For instance, Ahlstorm et al. (2019) has defined a hybrid resource as "a combination of multiple technologies that are physically and electronically controlled by the hybrid owner/operator behind the point of interconnection and offered to the grid operator (or to some other customer) as a single resource." As per WindEurope's position paper (WindEurope 2019), HPPs are defined as "Power-generating facility that converts primary energy into electrical energy and which consists of more than one power-generating module connected to a network at one connection point." Irish transmission system network, EIRGRID and ESB Networks (2021) have differentiated a hybrid site to be "any project that has multiple generating units or power generating modules which utilises multiple primary energy sources or technology types in generating/storing electricity and are electrically connected behind a single defined connection point to a licensed System Operator (SO)"; as opposed to a hybrid unit as "a single generating unit or power generating module which utilises multiple primary energy sources or technology types in generating/storing electricity and are electrically connected behind a single defined connection point to a licensed SO."

For the scope of this article, HPPs combine renewable sources like wind and solar (PV technology) with ESS which are connected behind a single grid connection, as shown in Figure 1, and operated as a single power plant by a single operator. It should also be noted that the focus of this article is on utility-scale HPPs, that is, power plants of size ranging from hundreds of MW to GW scale are taken into consideration.

It should also be highlighted that there is a clear and distinct differentiation between HPP and hybrid power systems such as microgrids, mini-grids, or islanded networks. The hybrid power systems comprise multiple generation sources and/or storage (typically owned by different parties) controlled either coordinated or independently to meet demands in the system to ascertain the security of supply. Whereas, HPPs are designed and operated with the objective of maximizing values for the power plant owner while meeting the grid code requirements at the point of common coupling.

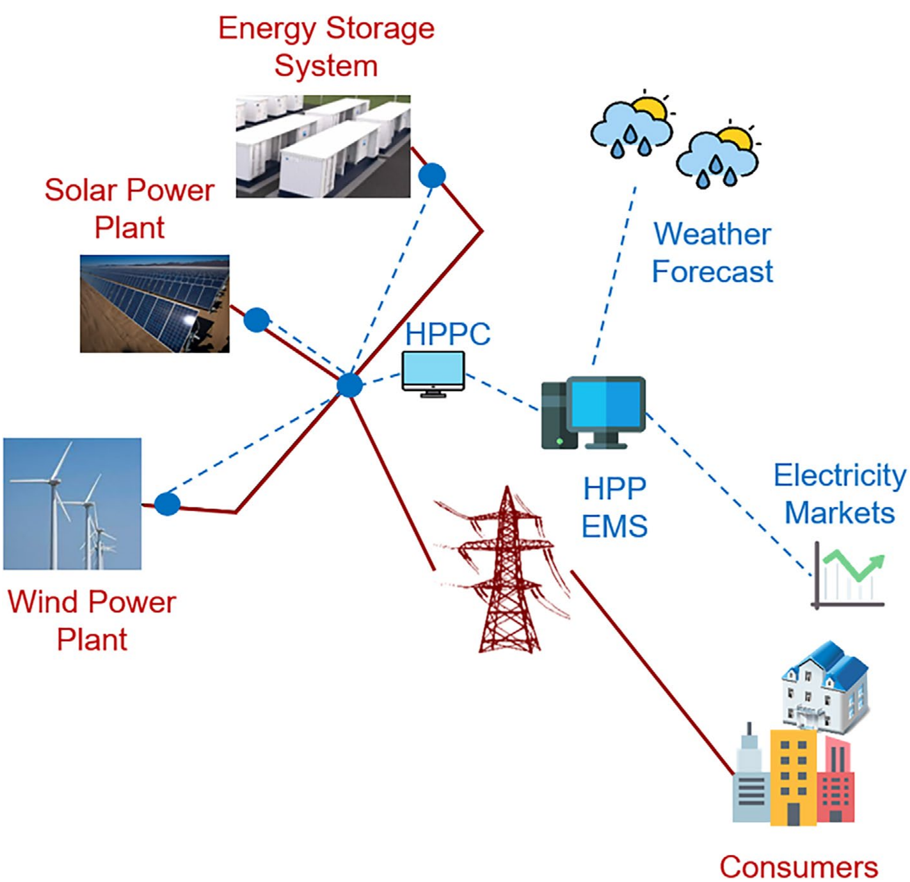

FIGURE 1 | Utility-scale co-located grid connected hybrid power plant.

There are several operating HPPs worldwide, for instance, Park Cynog in the United Kingdom was one of the first HPPs where an older 3.6 MW wind power plant (WPP) from 2001 was hybridized with a 4.95 MW PV plant. However, during the last few years, the interest has grown significantly toward multi-MW utility-scale HPPs, which have been developed all around the world such as the Kennedy Energy Park in Australia, Haringvliet in the Netherlands (Pombo et al. 2021), or the planned 26 GW hybrid wind/solar Asian Renewable Energy Hub in Western Australia (BP Australia 2023). Not only onshore, but offshore HPPs are also gaining attention. For example, in Hollandse Kust (noord), an offshore WPP has been hybridized with a floating solar plant, battery storage, and hydrogen electrolyzer (Eneco 2023). A detailed list of HPPs worldwide can be found in the WindEurope database in (WindEurope 2021).

HPPs are expected to provide advanced technical solutions that can drive and accelerate the wind power market growth even more in the near future (GWEC 2019), resulting in a higher level of predictability, reliability, flexibility, efficiency, and profitability through active participation in different energy and capacity markets. Higher predictability can be supposed through addition of a storage to a variable/intermittent technology, since storage can be used to reduce the forecast uncertainties and imbalances created due to these forecast uncertainties. An HPP consisting of wind and solar power has higher availability than the individual technology power plants. For example, a solar power plant is not available during night while an HPP can be available at night if the wind is blowing. HPPs are typically overplanted with respect to the grid connection capacity as shown in the simulation results in Das et al. (2022), Das et al. (2022), Murcia Leon et al. (2024). This implies that the amount of converters and power devices are higher than that of individual technology power plants without overplanting. This renders HPPs to be more reliable to provide grid services. Additional flexibility is achieved with the availability of storage which not only increases the dispatchability but also to provide flexibility to provide energy when required by the power systems such as a peak power plant. A wind solar HPP has higher capacity factor than an individual power plant thereby making them more efficient Das, Hansen, Vangari, et al. (2019). However, it should be noted that these features do not mean that HPPs will replace the need for individual technology power plants. The techno-economic feasibility of HPPs need to be assessed for individual cases as evidenced from the studies in León and Das (2023). For example, as a result, the Indian government came up with a national policy for HPPs in 2018 (Jethani 2018), and the Danish wind industry has mentioned that wind companies are moving toward HPPs for delivering energy at low cost to best meet demands in 2020s (Andersson et al. 2020). Nevertheless, even if the industry has paved the way for HPP deployment, the research within HPPs is still in the nascent phase, with major technological improvements being highly required if HPPs are to meet the expectations of the different agencies, companies and academia.

Apart from the potential value that HPPs bring to the power grid, many challenges and research gaps around the topic hinder HPPs from being commercially and widely utilized. There exist ample multidisciplinary research challenges which need to be addressed both by academia and industry in the near future, with respect to utility-scale co-located grid-connected HPPs, that is, development of energy management system (EMS), sizing and siting, electrical design and control, uncertainty and forecast, grid emulation and advanced tests, and multi-energy systems integration. For example, the development of advanced EMSs is highly needed to emerge market opportunities and quantify HPP profitability in electricity markets. The development of tools for technology selection, sizing, siting, and physical design of HPPs is also needed to increase their overall profitability and reliability. It is also vital to enhance the research on the electrical design and control of HPPs in supporting a stable, reliable, and resilient operation of the power system, that is, by providing advanced grid services. Many questions like, which service to prioritize, how to ensure that the common grid connection is not overloaded in case of overcapacity, grid code compliance, and which unit should be curtailed first, will be necessary to answer through thorough electrical design and control research to enhance the HPP capabilities as attractive sustainable energy solutions in the next few years. The complementarity of different energy sources inside HPPs can mitigate the variability of the power output potentially leading to lower imbalance costs. Investing in research on weather, market and hybrid power forecasts is therefore very important. Multi-energy coupling technologies and their combinations have the potential to provide larger flexibility services to the electricity system, supporting cost-effective RES integration and enhancing the security of supply. This requires thorough research and understanding of the technological and operational constraints of multi-energy systems integration.

In this respect, the overall objective of this article is to identify state-of-the-art and discuss the open research questions and challenges in the field of utility-scale HPPs.

This article is structured as follows. Section 2 provides a brief discussion on the potential values of HPPs both from societal as well as HPP owners' points of view. A state-of-the-art review and discussion on research challenges for utility-scale grid-connected HPPs are provided in Section 3. Finally, conclusive remarks are reported in Section 4, where the track for future work is also proposed.

2 | Value of Hybrid Power Plants

HPPs present numerous advantages when compared to individual renewable technology-based power plants both from societal/power systems/energy systems point of view as well as power plant owner's point of view.

Integration of large volumes of renewable generators in already congested power systems all over the world would require a huge investment in reinforcing the grid infrastructure. HPPs that combine wind and solar power behind a single grid connection point allow for the integration of a larger volume of RES, often with a total installed capacity higher than the grid connection capacity (called overplanting). This is possible since the wind and solar resources are negatively correlated (in the long term) to each other in many places in the world (Lave and Ellis 2016). Therefore, HPPs are not only potentially valuable to society due to the reduction in transmission reinforcement cost but also allow increased installation of RES. HPPs that combine wind and solar power have the opportunity to better utilize the land by using land available between wind turbines and are valuable to locations that have limited land availability (Stanley and King 2022). Another important point to note is that HPPs will not replace the requirement for individual technology plants. Most probably, individual technology plants will still have higher profitability than wind-solar HPPs at locations where the capacity factors of one of the technologies largely outweigh the other. However, in locations where the capacity factors of the wind and solar resources are comparable, combining these technologies can increase the capacity factor or grid utilization factor largely (Das, Hansen, Vangari, et al. 2019), which helps for the adequacy of the energy system. Owing to overplanting as well as negative correlation, the availability of the power plant increases substantially as compared to individual technology power plants with the same grid connection capacity. HPPs might also have storage together with wind and solar power especially with overplanting since it helps in reducing the curtailment. Having storage allows the HPPs to support the power systems with flexibility and ancillary service provision. With respect to power systems, HPPs may help to mitigate the RES variability, provide a better possibility of scheduled power dispatch and more stable power output over time (i.e., power smoothing), and reduce balancing needs and RES curtailment compared to individual RES-based power plants.

In addition to all the societal values mentioned above, the HPPs can be profitable businesses for power plant owners and developers through cost reduction and an increase in revenue (Asbeck 2018). From a project development point of view, one of the major benefits of hybridizing different resources is the reduction in financial losses and risk for the project developers due to delays in the permitting process, especially in congested power systems. Furthermore, HPPs allow for a reduction in the costs of project development in terms of performing joint resource assessment studies, permitting, site development, and so forth as it is possible to develop them for all the different resources (for wind and solar) as a joint venture. Particularly, land acquisition is a major challenge for the development of renewable plants around the globe (Dykes, King, and DiOrio 2019). Wind-solar HPP sites through co-location of technologies require less surface for the same capacity than their mono-technological (Dykes, King, and DiOrio 2019). Additionally, there is a potential to reduce development costs through sharing of infrastructure (e.g., access roads, substations) as well as electrical components (e.g., transformers, cables).

The utilization factor (capacity factor) for WPP is about 30%–45% for onshore WPP, while 40%–55% for offshore wind and 17%–27% for PV depending on the location (Pombo et al. 2021). Therefore, the equivalent full production hours (computed with respect to grid connection capacity) can be increased by overplanting capacity; which is further motivated by the existing anti-correlated relationship between wind and solar resources.

The HPP setup also allows to reduce the forecasting uncertainties in two ways, first relying both on wind and solar permits redundant capacity during some periods. While, including energy storage ensures no underproduction and minimizes the curtailment occurrence, as it facilitates the time displacement of energy from over- to under-production periods. In addition, storage also allows the HPP to better deal with RES-based fluctuation of electricity prices, this being an increasing issue in subsidy-free systems with high rates of renewable integration. In this context, WPPs tend to present low income during high production periods due to the low prices of electricity. There, an HPP will be able to perform energy arbitrage, namely storing energy during low prices and selling it during high prices, referred to as energy arbitrage (Pombo et al. 2021; Lindberg et al. 2021).

Regarding market services, systems with large RES shares present significant requirements in terms of balancing. This is caused by the generation capacity uncertainty of the weather-dependent resources. Such a situation reinforces of course the usefulness of HPP to contribute as a dispatchable resource and to provide frequency services such as synthetic inertia (Sørensen, Pombo, and Iglesias 2023), fast frequency response (Nguyen, Pombo, and Bindner 2021), frequency containment reserve (Sahin et al. 2022), and frequency restoration reserve. These services, which address different time horizons and require either power-based responses (short duration, large capacity) or energy-based (long duration, small capacity), can be provided not only based on energy storage but also using other techniques such as delta control or virtual inertia (Pombo, Sørensen, and Martinez-Rico 2022).

It should be noted that HPPs could also participate as specialized power plants, namely generation units with a particular role such as peak, round-the-clock, or load-following plants. This means for example that, in case of a catastrophic failure that would bring the power system to a total collapse, HPP could provide power restoration capabilities, that is, blackstart support. Briefly, storage could be thus used to gradually start the auxiliary equipment and control systems of the HPP. It is important to notice that in such situations, HPPs should be coordinated with other blackstart-capable units in the system to restore power. Given the higher risk of RES-based power systems collapsing, blackstart provision will potentially be a critical contribution of HPP to the reliability of near-future grids. Additionally, since HPPs are coupled via power electronics, it is relatively simple to provide reactive power support; and given the solar and storage inverters inclusion, their capacity will be higher than that of an individual WPP. While the reactive power support service is not generally paid attention to at the moment, this may become increasingly important in nearly saturated power systems as HPPs can be used to alleviate congestions, lower transmission losses, and so forth (Petersen 2020).

3 | Research Challenges and Opportunities of Utility-Scale Hybrid Power Plants

Figure 2 depicts an overview of different research areas for Utility-scale HPPs identified by the authors and discussed and reviewed by Danish Hybrid Wind Power Plant Forum (DTU 2023). Each of these categories is discussed in the following subsections.

3.1 | Energy Management System

The purpose of an EMS is to coordinate the different assets in an HPP to fulfill a specific objective. This objective is typically to maximize the profit from the different market participation possibilities of the plant while ensuring the fulfillment of all technical requirements from system operators. Depending on the complexity level, constraints like energy efficiency and equipment lifetime might be also considered. To do so, an EMS must integrate forecasts, available production, system operator requests, and safety constraints (Pombo, Bacher, et al. 2022). Other objectives may include maximization value for specific power purchase agreements and provision of energy in fit-to-purpose plants like peak power provision. Table 1 summarizes the challenges and opportunities of EMS. One of the main challenges for an EMS is to handle the uncertainties arising from RES, market prices and ancillary service requirements. This challenge is less pronounced in an individual technology power plant without storage technology and without the possibility of energy arbitrage and providing ancillary services.

The most important market for HPP operation is the *Spot Market*, which considers the one-day ahead power and energy schedules that already highlight the need for multi-time scale operation. Furthermore, flexible generation and storage integration enables the HPP to participate in *Reserve*, *Balancing* and *Ancillary services markets*. This provides on one hand secondary revenue streams, and on the other hand requires further coordination, and the integration of additional forecasts with different horizons and resolutions in the EMS (Martinez-Rico et al. 2021; Cao et al. 2020; Mohamed, Jin, and Su 2020).

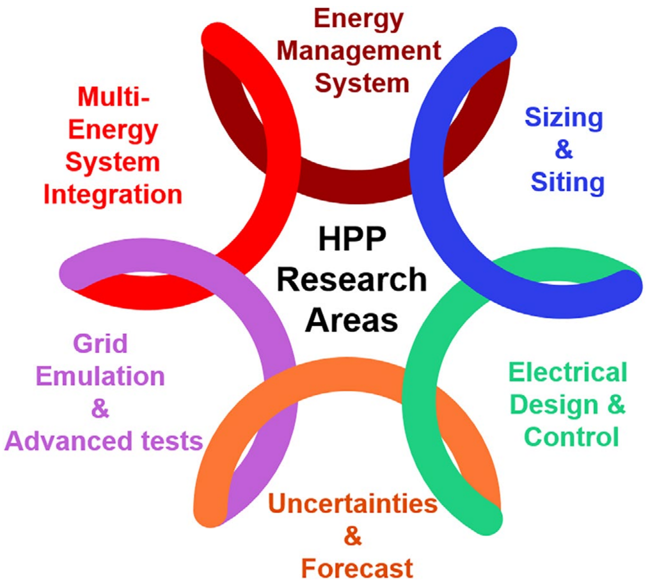

FIGURE 2 | Main research areas with respect to Utility-scale co-located grid connected HPPs.

There is already experience in a large variety of methods proposed to model the EMS, such as optimization techniques (Das et al. 2020), model predictive control (MPC) (Khalid et al. 2018), and machine learning methods (Cao et al. 2020). Yet, inadequate consideration of forecasting uncertainties results in unreliable power schedules and energy notifications in practice, causing advanced stochastic methods to be an upcoming research topic in academia. While the industry mostly uses optimization techniques for the market participation, maintaining rule-based methods for the internal HPP dispatch due to their robustness even if results in non-optimal operation.

Another research topic highly relevant and critical for a reliable EMS is battery degradation, as batteries lose capacity during their lifetime based on operational strategies. Thus, EMS must also consider and limit the expected degradation and properly estimate the battery's ability to support the HPP operation. However, battery degradation is a complex electro-chemical process, whose theoretical model presents strong non-convexity and non-linearity making it difficult to integrate into EMS (Xu et al. 2016). Alternatively, empirical models require fewer parameters and are easier to apply, while often performing badly in practice.

3.2 | Sizing and Siting

The development of an HPP project is a long process, consisting of the following distinct stages: site assessment, sizing, device selection, physical design, and electrical configuration. During the early stages, rough approximations for the HPP sizing are typically used for site selection and feasibility studies. Subsequently, sizing consists of estimating the capacity of the plant's connection point and its different components (wind, PV, storage). This of course is usually approached hand on hand with the device selection, for example, selecting specific wind turbines and PV tracking options, as well as quantifying the possible value produced. Subsequently, the complete and detailed physical design is performed, in order to specify the final type and location of each turbine, PV panel, storage unit and electrical components, with the main objective of maximizing the value generated by the HPP.

Sizing and design of HPP focus on value generation metrics that move away from the metrics used from WPP design, such as levelized cost of energy (LCOE) as they fail to capture the time-varying revenues resulting from the participation in merchant electricity markets, ancillary services and other revenue sources such as Power2X and sector integration. The two most important inputs in the estimation of the HPP value generation are each generation resource and the time-varying

TABLE 1 | Overview of challenges and opportunities of EMS.

Challenges
• The complexities of coordinating multiple markets and different PPAs
• The difficulties of considering multiple uncertainties such as RES, market prices, and ancillary service requirements
Opportunities
• The novel approaches of including battery degradation model into EMS

revenue potentials, that is, time series of the available power and market prices. The challenges and opportunities of HPP sizing and siting are summarized in Table 2 for ease of comparison. More detailed explanations are carried out in the following subsections.

3.2.1 | Resource Assessment

Independent analyses are to be conducted for each renewable resource, as their assessment is one of the most important inputs for HPP design. They provide the required information to estimate the energy generation for each generation technology, as well as their temporal correlation.

Traditionally, wind resource assessment focuses on estimating the wind speed distribution on a site area, which relies on combining on-site or near-by short-term wind speed measurements (1–2 years) with long-term mesoscale reanalysis data sets (10+ years) and detailed micro-scale modeling (Landberg et al. 2003). Yet, wind resource time series generated using mesoscale reanalysis tend to be too smooth, that is, it does not contain all the high-frequency oscillations (between 10 min and 5 h) across multiple locations (Sørensen, Hansen, and Rosas 2002). Several authors (Larsén et al. 2012; Larsén, Larsen, and Petersen 2016; Koivisto et al. 2020) rely on adding wind speed fluctuations and turbulence (within 10-min) based on a cross-spectral model, in order to capture the correlation between the wind speed time series on multiple locations within a plant at a desired high sampling frequency. On the other hand, solar resource assessment focuses on the selection of a typical meteorological year in order to estimate the time-varying generation (Vignola et al. 2012) in a process that relies on mesoscale reanalysis data sets (Jimenez et al. 2016) and, in very few cases, combination with local short-term measurements. Similarly to the wind resource, solar predictions using weather models tend to be too smooth because they do not model the dynamics of cloud formation, evolution and advection (Wang et al. 2016). This justifies the need for developing stochastic models capturing cloud-based high-frequency losses in irradiation. Then, the main difference between wind and solar resources is related to revenue estimation. In general, WPPs have been developed under fixed-price power purchase agreements and therefore focus only on estimating the mean generation or annual energy production (AEP), while early PV plants were developed by selling at the time-varying price of electricity, helped by governmental subsidies and loan programs (Grau, Huo, and Neuhoff 2012; Chowdhury et al. 2014). While similar revenue schemes might currently affect the development of HPPs, the near future subsidy-free market will eliminate such a caveat. In addition, HPPs are expected to participate in the merchant and regulation markets (Zhu et al. 2023). Furthermore, resource assessment focused on estimating the joint probability of wind and solar resources fails for HPP sizing and design, because storage and, to a lesser extent, the limited grid capacity introduces non-linearities that can only be modeled in time-series. In fact, it is a common practice in HPP design to use time series as a natural approach to capture the correlations across multiple locations for wind, solar and energy prices. Yet, if data sets from different sources are combined, the correlation structure tends to break. This phenomenon is particularly problematic if each analysis uses a different weather reanalysis data set, different weather models or different periods.

Lastly, the simulation of future scenarios (e.g., covering greenhouse gas concentration evolution) using weather models is crucial to understanding climate change. In addition, the inclusion of climate change effects on wind/solar resources are big open question for the renewable industry. Uncertainty reduction based on these available climate change models is essential and yet, there is no consensus across model results.

Resource assessment for HPPs requires the following:

- Higher resolution mesoscale models such as WRF-LES have been developed as a dynamic weather model that resolves all scales in the plant. These models are significantly more computationally expensive.
- Machine learning techniques such as convolutional neural networks can applied to databases of high-resolution weather models with the purpose of training transfer functions that will enable the simulation of high-resolution weather on the latest global reanalysis data sets such as ERA5.

3.2.2 | Optimal Sizing of HPP Technologies

The general approach for optimal sizing of HPP is to use simplified models of each component and an unsophisticated simple EMS to estimate curtailment, revenue, costs, and financial model (Duchaud et al. 2019). However, the complexity rises due to the interaction between different technologies, uncertainties not only coming from resources, cost, prices, and so forth but also considering uncertainties of the impact of changing power

TABLE 2 | Overview of challenges and opportunities of sizing and siting.

Challenges
• The complexities of sizing raised from high-fidelity models
• The obstacle of solving the collection system cable layout optimization, which is NP-hard
Opportunities
• The novel approaches of modeling wind and solar time series considering high-frequency fluctuations
• The novel approaches of modeling wind and solar time series considering the impact of climate changes
• The advancements of sizing optimization considering wind turbines of varied rotor diameter, hub height, and power ratings

and energy systems over the lifetime of the HPP (example—next 25–30 years).

Briefly, the optimization problem aims to maximize the profit as the difference between revenue and costs. This can be approached in different manners, one not requiring the use of electricity price signals relies on specifying other optimization goals such as minimizing the LCOE or the net present value (NPV) (Das et al. 2022). One byproduct of such a process is the maximization of the grid connection utilization through minimizing curtailment by exploiting the synergies among the different technologies. However, due to the change in revenue sources mentioned in the previous section, HPP requires higher fidelity modeling than their mono-technology counterparts. Stanley and King (2022) recommend considering hourly resolution over at least 2 years of data for a specific site. However, they focus on ensuring a minimum hourly production in the wholesale market. If other intra-hour services such as frequency support are targeted, higher time resolutions are required.

Most of the existing work focuses on microgrid and hybrid power systems, meaning that many of the methods and results can be extended or adapted for HPP (Anoune et al. 2018; Khan, Pal, and Saeed 2018; Ammari et al. 2021). Regarding work focused specifically on HPP, Dykes, King, and DiOrio (2019) highlight the research gaps related to design and optimization. Tripp et al. (2022) propose a tool for sizing HPP that takes into account the layout for wind-solar combinations thus including flickering and shading losses. In this direction, Stanley and King (2022) study the foreseeable shading of the turbines over the solar panels concluding that their impact will vary depending on the application, being more important for short-term, speed-based services such as FCR. Then, Martinez-Rico et al. (2021) use linear programming to size the battery of an HPP, based on its participation in aFFR markets while considering the state of health and degradation. Silva and Estanqueiro (2022) evaluate the repowering of WPP sites at the end of their life vs. overplanting wind or hybridizing them using NPV as the evaluation metric.

Furthermore, various tools have emerged in recent years specifically designed for sizing and optimizing the operation of HPPs. Hybrid Optimization of Multiple Energy Resources (HOMER), by UL, is an open-access tool designed to determine the least-cost configuration for HPP systems to meet energy and thermal demands. It supports diverse HPP components, including biomass, run-of-river hydropower, diesel engines, fuel cells, cogeneration, and standard renewables like wind, solar PV, and battery storage Bahramara, Moghaddam, and Haghifam (2016). Another tool, the Hybrid Optimization Performance Platform (HOPP), also by NREL, optimizes the sizing and layout of hybrid systems combining wind, solar, and storage, with detailed component-level modeling to achieve robust system configurations Guittet et al. (2022). HOPP provides various optimization objectives, such as NPV, AEP, capacity factor, payback period, and carbon payback time Tripp et al. (2022). In addition, HyDesign, an open-access tool from DTU Wind, facilitates the design and operation of utility-scale HPPs that integrate wind, solar, battery, and power-to-hydrogen components. HyDesign incorporates component degradation models over the plant's lifetime and offers flexibility in optimization objectives, including NPV/CAPEX and LCOE, while delivering key financial metrics to assess HPP feasibility and profitability Murcia Leon et al. (2024). *The availability of advanced HPP optimization tools like HOMER, HOPP, and HyDesign highlights the growing research focus on enhancing HPP design strategies, system configurations, and objective functions for optimized performance and commercial viability.* However, detailed review of the functionalities and comparison of proprietary and open-source tools is beyond the scope of the paper.

In general, sizing of HPP components involves optimization for maximizing the value of the considered HPP considering operations, uncertainties over the lifetime, reliability of components, limited grid connectivity, and land constraints, among others.

3.2.3 | Selection of Wind Turbines

Wind turbines are typically designed for specific site conditions, according to pre-defined design classes (International Electrotechnical Commission 2019a), with wind turbine manufacturers recently offering more site-specific customization through various platform options. The traditional WPP optimization studies look at the optimization of energy production accounting for the local wind resource conditions, type and number of wind turbines and the placement of those turbines in the plant, with the overall design objective typically focusing on the profitability and economic competitiveness of the plant over its lifetime. The types of turbines used are an important design parameter. Uniform or multiple turbine types can be considered as design choices for plant optimization Mustakerov and Borissova (2010); Graf et al. (2016). As the industry introduces platforms with potential for site-specific customization, there is an opportunity to consider the impact of WPPs with turbines of varied rotor diameter, hub height and power ratings. Moreover, potential turbine design variables can be associated with the power plant design optimization related to the balance of plant and operation.

Most wind plant design efforts (both in academia and in practice) focus on trade-offs between the balance of system costs (affecting capital expenditures) and energy production. Each of these subsystems involves several components and associated disciplines (Dykes, King, and DiOrio 2019). Shifting from single-generation technology power plants (solar or wind with or without storage) is motivated by the need to increase profitability by moving beyond LCOE to look at the time-varying revenues and costs for the power plant over its lifetime. Such an example would be a design of LowWind turbine based power plants (Swisher et al. 2022; Madsen et al. 2020). The challenge is that the design of these plants involves all the complexity described earlier with potential additional complexity of interactions if the technologies are collocated. Therefore, the selection of wind turbines of varied rotor diameter, hub height and power rating in the context of an optimized HPP, offers opportunities to move beyond WPP optimal selection types to an overall increased value for the HPP.

3.2.4 | Collection System Design

The electrical system of an HPP is a fundamental part of the Balance of Plants (BoPs), comprising the set of equipment to support its integration into the grid. This mainly includes inverters, power cables, and step-up transformers. Additional equipment for control, protection, and measures are required as well, however, a large part of the investment is associated with the aforementioned principal components of the HPP.

Initially, a group of decisions needs to be made regarding technology choices for the main components of the electrical system, such as PV system configurations (central inverter, string inverter, and so forth; Corporation 2015), cable type, energy storage technology, voltage levels at different zones of the system, and topology of the network to interconnect WTs and PV panels (radial without branching, radial with branching, radial with branching and with intermediate points of connections, closed-loop, and so forth; Pérez-Rúa and Cutululis 2019). Following the previous step, the task consists of formulating and solving an optimization problem to design the cable layout of the HPP collection system.

The collection system cable layout optimization problem is equivalent to specific groups of standard computer science problems categorized as NP-Hard (Non-Deterministic Polynomial time). Particularly, it maps to a Capacitated Minimum Spanning Tree (C-MST) problem (Gouveia and Martins 2005), when radial layouts are targeted, or to a multiple Travelling Salesmen Problem (mTSP) (González-Longatt et al. 2012) for closed-loop topology. Likewise, the operation of the HPP must be taken into account to exploit the shareability of electrical infrastructure in the function of the (negative) correlation between wind and solar resources. As a consequence, the greatest challenge resides in the ability to solve optimality (or to provide statistically significant improvement compared to baseline designs) large-scale problems within the framework of multistage optimization (investment and time-varying operation). Similar works from the offshore wind industry, such as (Fischetti and Pisinger 2018; Pérez-Rúa et al. 2019) demonstrate the complexity of even obtaining feasible points for single-stage problems in the order of a 100 WTs. Hence, formulation and solution algorithms with high tractability are demanded, as HPP projects are massive in terms of number of generator units.

In addition to scalability, other challenge arises regarding the capacity to incorporate relevant but non-linear factors in the optimization formulation such as electrical power losses, wake losses, and other types of aerodynamic interactions between WTs and PV panels, ultimately affecting power production. Finally, other research opportunities emerge within the context of multidisciplinary optimization, which defines efforts to design systems considering multiple aspects simultaneously, for instance, the optimal sizing of HPP technologies, selection of WTs, and the physical layout of generators and electrical networks. Hybrid solvers based on combinations between different philosophies (optimization heuristics, global optimization, evolutionary algorithms, computational learning methods), and the use of surrogate models for physics modeling, are promising techniques to tackle this type of integrated problem. The latest would allow for optimizing comprehensive high-level economic metrics; for example, NPV or internal rate of return. Which accounts not only for initial investment but also for HPP operation throughout its lifetime.

3.2.5 | Hybridization of Existing Renewable Power Plants

Hybridization of existing wind or solar power plants is being considered a viable option due to many factors. One of the major contributing factor is that toward the end of the lifetime of these individual technology power plants, the capacity factors of these plants can reduce substantially. In such situations, it might not be capable of meeting the capacity factor requirements as per the contract during installation. Hybridization with a complementary asset can help in improving the capacity factor and meet the contractual requirements. Another reason can be due to the congestion of the grid or unavailability of a new grid connection point due to different reasons. In such systems, hybridization can potentially provide the economic benefit since a major component of the HPP is already installed, so CAPEX is partially covered as well as complementarity of resources allows increased grid utilization and energy arbitrage (through storage).

There has been some recent studies on hybridization of existing WPPs with solar PV power plant. Silva and Estanqueiro (2022) have developed an optimization tool for feasibility assessment of an hybridized WPP. Cuoto and Estanqueiro Couto and Estanqueiro (2023) developed an AI based methodology and probabilistic forecasting based methodology Couto, Algarvio, and Estanqueiro (2024) for quantification of market value of an hybridized WPP. An assessment of complementarity of resources for a ase study in Portugal is performed in Couto and Estanqueiro (2021). Grossi et al. has extended the capability of HyDesign tool for hybridization of existing renewable power plants Grossi et al. (2024). It should be noted that hybridization of a PV power plant with storage is a well-researched topic and is out of scope for this discussion.

However, the research on this topic is still in nascent stage. Some futuristic aspects like planning for future hybridization of power plants. The hypothesis is to design an HPP in such a way that it starts as a singular technology power plant and can potentially be hybridized in the future with reducing cost of technology (especially storage). The electrical aspects of hybridization has also not been researched. The operation of grid connection transformer and cable are of particular importance. As per the existing design, the transformer and cable can be overloaded especially if the nature is generous, which might lead to curtailment. Dynamic overloading of the transformers can be impeded due to regulations as well as existing protection systems of the existing plants. Therefore, a holistic system engineering approach is needed for design of hybridization of an existing renewable power plant considering resources, financial aspects, market value, grid code requirements as well as existing electrical design, control and protection systems.

3.3 | Electrical Design and Control

There can be different kind of electrical configurations of an HPP, especially considering that HPPs are bespoke solutions to meet specific needs of each power system to which it is connected. The configuration can be broadly classified as either AC-coupled or DC-coupled as detailed in Das, Hansen, Adamou, et al. (2019). In the AC coupled HPP solution, each asset has their own point of connection, being connected to the external grid through the same transformer. WTs are connected through full-scale back-to-back converter. PVs are connected through a DC-DC converter and an inverter. The DC-DC converter is used to increase the panel's output voltage. The BESS are connected only through an inverter.

Whereas, the DC-coupled topology comprises of multiple DC-coupled hybrid units. A WT, a PV system, and a BESS are connected at the DC-link forming a hybrid unit. Each of these hybrid units are then connected through an inverter to the AC substation. The AC substation forms the interface that connects the hybrid units to the external grid. The WT is connected to the DC bus through a rectifier. The PV and the BESS are connected through DC-DC converters. The asset level controller communicates with the plant level controller for different control schemes.

AC-coupled topology is more matured and implementable as compared to DC-coupled topology, although DC-coupled topology has the potential to have additional cost savings. The maturity comes from availability of control strategies, controllers, and protection systems which are tested and validated in relevant environment (often referred as technology readiness level). Even though the AC coupled HPP are not fully matured in these previously mentioned aspects, however, they are still at a higher technology readiness level than the DC coupled HPPs. It should also be noted that there can also be different variants of HPP configurations in terms of grid connection, such as connection to AC grid, or HVDC grid or an energy island.

Control strategies and architecture for single-technology renewable power plants (i.e., WPP, SPP, and ESS) have been an active research area over the past decades. In general, as depicted in Figure 3, several control levels are usually involved for single technology renewable power plants (Hansen et al. 2006; Gevorgian and O'Neill 2016): the plant control level that manages power flows at the plant point of connection and dispatches control commands to each individual asset, and the asset control level that addresses local control function for each individual unit. In co-located HPP including wind, solar, and potentially energy storage, coordination issues arise across the different technologies, as presented in Table 3. It also highlights the opportunity to introduce and develop new control levels to allocate active and reactive power references among multi-technology plants in a real-time fashion, for one or more control objectives (Long et al. 2022). Besides active and reactive power dispatch, other technical challenges also need to be addressed, including ramp limiting control, state of the charge (SOC) management of the energy storage system, real, and reactive power reserve provision (Kim, Seok, et al. 2016), frequency response (Pombo, Iov, and Stroe 2019), and so on. Further work will also need to be performed to investigate stacked control or services for HPPs (Bullich-Massagué et al. 2017).

Coordination across hierarchical layers also arises in HPPs. For instance, in normal operations, time separation needs to be taken into account when one designs the controller for each level. The higher control level should have a slower control response, and vice versa, in order to decouple the response from the lower control level. Also, for time-critical services such as fast frequency response (FFR) or inertia response (Nanou, Papakonstantinou, and Papathanassiou 2015) and under/over voltage ride through (Kim, Muljadi, et al. 2016; Yang et al. 2017), a coordination strategy needs to be considered. This is because fast responses are mostly implemented at the asset control level, and can counteract control actions from a higher control level. Freezing PI controllers and adding compensation signals are two possible options. Furthermore, communication delays pose extra challenges to such control design that can guarantee robust performance under various operating conditions.

As already mentioned, HPP, due to the combination of different generation and/or storage technologies, can intrinsically overcome what is probably the main limitation in effectively providing ancillary services (common to all RESs): power and energy availability. This characteristic, combined with the flexibility offered by the highly controllable power electronics, paves the way for HPP to provide essential services like grid forming and restoration. Depending on the HPP's electrical topology, the functionality would be provided by the converters attached to each asset (wind, PV, battery, etc.) in an AC-based topology, while in

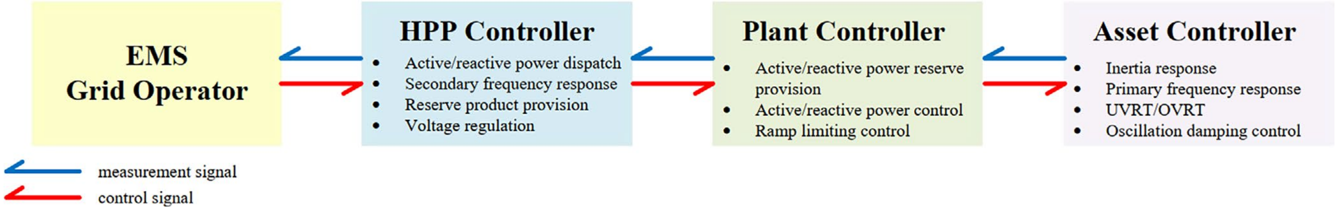

FIGURE 3 | HPP control hierarchies.

TABLE 3 | Overview of challenges and opportunities of electrical design and control.

Challenges
• The difficulties of coordination across multiple hierarchical control layers
Opportunities
• The requirement of developing a new control level to allocate active and reactive power references among multi-technology plants in a real-time fashion, for one or more control objectives

the DC base topology, this role will be played by the grid side converter (rectifier).

3.3.1 | Grid Codes

Generally, technology-agnostic grid codes are technical specifications defining requirements for any facility connected to power systems ensuring its integrity, high-level security of supply and reliability. These specifications have become increasingly elaborate as the share of RES has increased.

The recent development of combining various generation and energy conversion technologies inside utility-scale HPPs implies that there is a growing need to define, adapt and elaborate entire grid codes for HPPs in the near future. Hansen et al. (2021) provides a thorough review with insight and understanding of the salient features of the grid codes imposed today to the individual technologies conforming utility-scale wind HPPs; WPP, SPP, and so forth.

The basic assumption in grid codes for generating plants is that the maximum power of the plant and thus the occupied grid connection capacity and all requirements to the plant are based on the sum of nameplate capacities of the generating units in the plant. This assumption is not appreciating the fundamental advantage of HPPs compared to single technology plants, namely to allow overplanting controlling the power to a maximum value below the sum of unit capacities.

The inclusion of storage in the HPPs poses additional challenges in grid codes since the storage allows the bidirectional flow of power at the grid connection point. The European Requirements for Generators—RfG European Commission (2016) only considers generating modules and does not consider bidirectional flow. The Danish TSO has, as a first mover, published a grid code with technical requirements for battery plants Energinet (2019). But the existing Danish grid code portfolio still requires to treat generation and storage in a HPP as separate connections.

Thus, the majority of existing grid codes do not give room for utilizing the advantage of overplanting and for combining generation with storage as in HPPs. One exemption is the Indian Central Electricity Regulatory Commission, India (2023) which introduces the concept of "Maximum Continuous Rating" (MCR) to quantify grid code requirements instead of the "On-Bar Installed Capacity" which would be larger for an overplanted HPP. The Danish TSO Energinet is proposing to define 2×3 capacities for co-located and/or overplanted energy facilities Energinet, Denmark (2024). Those definitions distinguish between grid connection capacity and nameplate sums in a similar way as the Indian MCR definitions, and also allow bidirectional flow with capacities which can be different for production and consumption.

Table 4 suggests a categorization of the most common requirements. For each category, the introduction of maximum power definitions like MCR would affect HPPs in the following way:

- Operation ranges generally affect the individual units in the HPPs the same way as in single technology plants, so this category is not affected by existing grid codes.
- Fault ride through requirements are not only about the ability to stay connected during and after a fault, they also include requirements to support voltage recovery by reactive current control. The requirements to reactive current would be less if they refer to the grid connection capacity rather than the sum of nameplate capacities.
- Frequency response from a HPP can take advantage of dynamic dispatch between generation and storage unit contributions, which would not be possible if generation and storage is treated separately.
- Ramp rate capabilities of the units would be less demanding if they refer to the grid connection capacity rather than the sum of nameplate capacities.
- The reactive power capability and related control would be less demanding for the units if the requirements refer to the grid connection capacity rather than the sum of nameplate capacities.
- A HPP would have more capability for power oscillation damping and synthetic inertia if the capability refers to the grid connection capacity rather than the sum of nameplate capacities. Also, HPPs can dispatch dynamically between the technologies.
- A HPP can provide black start capability if only the storage provide grid forming control, whereas black start capability from single technology plants will require grid forming control from the chosen technology.

TABLE 4 | Suggested categorization of most common grid code requirements.

Operation ranges	Voltage, Frequency, and Rate of change of frequency (RoCoF) ranges
Fault ride through	Under voltage ride through (UVRT)
	Over voltage ride through (OVRT)
Active power control	Frequency response
	Ramp rate limit
Reactive power control	Reactive power capability
	Voltage control
	Reactive power control
	Power factor control
Advanced control	Power oscillation damping
	Synthetic inertia
	Black start capability
Models and data	Fundamental frequency models
	EMT models
	Fault recording
	Frequency domain models

- Modeling does become more complex in HPPs than in single technology plants, for example, because there are more control layers and because aggregation can be complicated, especially if the collection system is shared between technologies.

In summary, basing future grid code requirements on maximum power rather than sum of unit capacities would be an important step to incentivize co-located overplanted HPPs, which will allow to connect more renewables to existing grids because the HPP controls the maximum power.

3.4 | Uncertainties and Forecast

3.4.1 | Variability for Combined Wind-Solar-Storage

Variability in meteorological variables impacts the power output of an HPP. Key variables are wind speed, irradiance, but also, for example, wind direction and temperature impact on HPP generation. When operating an HPP, forecasting can be used to estimate the variability (e.g., day-ahead or hour-ahead). However, when planning an HPP, an estimate of the variability over the long term, covering the expected lifetime of the plant, is needed, as it impacts the optimal design. The difference between forecasting and long-term simulation is discussed in Koivisto et al. (2019).

Understanding the variability in meteorological variables includes their probability distributions, temporal dependencies and dependencies between variables. The distributions impact directly the AEP of an HPP, and describe the likelihood of experiencing very low or high generation values. The temporal dependencies describe how large changes in the variables are expected, for example, within 5 min, which can impact the battery design of an HPP. The dependency between irradiance and wind speed is important for the optimal sizing of an HPP, including overplanting. As HPP analysis is usually based on time series, the dependency between variables needs to be understood as a dependency between time series, using, for example, cross-correlation functions to describe also the time-lagged correlations (Ekström et al. 2018).

The main approaches for simulating long-term variability use either meteorological reanalysis data sets for generating the underlying meteorological data, or stochastic time series models for simulating the time series of interest (Koivisto et al. 2019). Modern meteorological reanalysis data sets cover tens of years, are available on hourly or even higher resolution and offer increasingly high temporal and spatial resolution (Murcia et al. 2022). As they are straightforward to apply for any location, they are potentially very suitable for analyzing HPP variability. Using reanalysis data to model both wind and solar variability is shown to work well in large-scale studies (Murcia et al. 2022). However, on the plant level, reanalysis data may show too low high-frequency variability (Murcia et al. 2021). This can impact, for example, HPP battery sizing. Therefore, it provides the potential to model high-frequency variability on top of large-scale reanalysis datasets, as shown in Table 5. Also, the relatively low spatial resolution of large-scale reanalysis data may not provide high enough resolution for plant-level analyses.

Reanalysis data may be supplemented with stochastic simulation and micro-scale resource data to mitigate the challenges mentioned above. Stochastic simulation provides the high-resolution variability missing in reanalysis data and enables sub-hourly simulations (Koivisto et al. 2020). High-resolution micro-scale wind data has been shown to enhance the resolution and accuracy of coarser reanalysis data (Murcia et al. 2021). However, the literature on similar enhancements of reanalysis data considering irradiance is less developed. A combined model enhancing the spatial and temporal resolution of both wind speed and irradiance (and potentially even more variables) would be needed to fully analyze HPP variability.

The impact of climate change on wind and solar resources and variability has been studied, but there are still significant uncertainties (Luzia, Koivisto, and Hahmann 2023). Even if the overall direction of change cannot be estimated accurately, the fact that there is uncertainty in how the resources are in the future may create additional risk to planning HPPs.

3.4.2 | Uncertainty in Resources

The interaction of wind turbines and solar panels raises several factors that can affect the performance of the HPP. These factors are (i) the shading of solar panels by wind turbines, (ii) the aerodynamic effect of PV panels on wind turbines, and (iii) the aerodynamic effect of wind turbines on PV panels. A short overview of to-date knowledge for each factor is provided in the following:

i. Substantial progress has been made in understanding how wind turbines' shade affects solar park performance. Researchers distinguish the slowly moving shadow caused by the turbine tower and the dynamic, rapidly

TABLE 5 | Overview of challenges and opportunities of renewable uncertainties and forecasts.

Challenges
• The limitations of low spatial resolution of large-scale reanalysis data set
• The difficulties of developing accurate and effective forecasting methodologies
Opportunities
• The novel approaches of modeling high-frequency variability for plant-level wind and solar time series
• The impacts of the interaction of wind turbines and solar panels on HPP performance

moving shadow caused by the turbine blades (known as shadow flickers) (Mamia and Appelbaum 2016). The slowly moving shadow can be easily incorporated into the plant design for resource assessment. This quasi-static effect can be a priori estimated from climatic factors, that is, latitude, and the layout of a wind farm, that is, wind turbines' size and their distribution. All such estimations primarily were done using numerical simulations with the assumption of infinite plant size. The simulations show that shadows from wind turbines can reduce solar energy production in the range of 1%–2% (Mamia and Appelbaum 2016; Ludwig 2013). However, relatively little is known about the dynamic, rapidly moving shadow. Recently, TNO (the Netherlands Organization for Applied Scientific Research) workers have investigated dynamic shading on a small scale and showed that a dynamic shadow could lead to greater energy loss than an equally large, slowly moving shadow (Newman et al. 2019; TNO 2021). They conclude that applying the right power electronics can reduce this effect and thus also limit the additional load on the installation. The shading issue is worthy of further consideration.

ii. Considerable research has been done in boundary-layer wind tunnels worldwide over the last 40 years to better understand the wind loads on various solar-energy collection devices on buildings and in the open field (Bienkiewicz and Sun 1992; Kopp, Farquhar, and Morrison 2012; Warsido et al. 2014; Abiola-Ogedengbe, Hangan, and Siddiqui 2015; Cochran 2015; Markousi, Fytanidis, and Soulis 2016; Aly 2016; Glick et al. 2020). Nowadays, researchers increasingly employ the computational fluid dynamics (CFD) approach to reduce the experimental effort investigating full-scale problems, for example, optimizing the array design of solar panels for wind load (Shademan et al. 2014; Jubayer and Hangan 2016; Reina and De Stefano 2017; Irtaza and Agarwal 2018) or dust deposition (Beattie et al. 2012; Lu and Zhang 2019; Chiteka, Arora, and Jain 2021). Numerous experimental and numerical studies have provided fundamental knowledge allowing us to estimate the dynamic response of PV panels on the wind. Still, they do not answer how solar panels affect airflow. There is a lack of data about wind and turbulence regimes in the atmospheric boundary layer above large solar farms (up to heights where wind turbines operate). Recently, numerical experiments have shown that installing PV panels can significantly increase the underlying surface roughness, reducing the approaching wind speed and, consequently, wind turbine performance (Sogachev 2021). The production loss can be about 1%–2%, depending on the hybrid farm design. Though these results are preliminary, they indicate the importance of this issue for the correct resource assessment of hybrid farms. We need more numerical and experimental investigations in this direction.

iii. According to the literature, the efficiency of PV panels reduces by approximately between 0.14% and 0.65% per each 1°C increase in panel surface temperature (Zaoui et al. 2015; Vasel and Iakovidis 2017; Cotfas, Cotfas, and Machidon 2018). The most cost-effective option to enhance the cooling of PV panels is taking advantage of natural wind to the highest possible extent. Gökmen et al. (2016) observed that when wind speed is not accounted for, the yearly energy of the PV plant located in Denmark is underestimated by 3.5%. This difference is emerging from overestimating PV module temperature by not considering the cooling effect of wind speed as in the traditional method (Markvart 2000; Mattei et al. 2006; Skoplaki and Palyvos 2009; Schwingshackl et al. 2013). Vasel and Iakovidis (2017) tested and confirmed the hypothesis that in the northern hemisphere, that is, where PV panels are facing the south, the power production of the solar PV plant should be greater in the event of southerly winds. Observations showed the power production of Hadley solar plant in the United Kingdom was higher by about 6% under southerly than other wind conditions provided that all other determining factors, such as solar irradiance, ambient temperature, and wind speed, were the same. The enhancement was attributed to better convection heat transfer from the surface of PV panels and, consequently, better cooling. Recently, Waterworth and Armstrong (2020) showed that PV outputs of Westmill Solar Park, Oxfordshire, UK were between 20% and 43% higher under southerly winds compared to northerly equivalents. These field studies demonstrated that the impact of different weather conditions (i.e., wind speed and direction) on solar panel efficiency had been very much overlooked and should be considered when the energy production is assessed, especially in the planning stage. The presence of wind turbines makes the estimation of airflow's impact on PV panel production more difficult. Wind turbines extracting energy from airflow generate turbulence (Porté-Agel, Bastankhah, and Shamsoddin 2020). Thus wind turbines, on the one hand, reduce the wind speed which can result in more heating of PV panels and lowering their output. On the other hand, the increased turbulence will provide the intensified exchange of PV panels' surface with ambient air and effectively cool them. That is, increasing panel efficiency. To investigate this two-sided effect, one should combine models for evaluating the temperature of PV modules from climatic data (i.e., ambient temperature, global solar irradiation in the plane of the array, and wind speed) (Mattei et al. 2006; Siddiqui et al. 2012; Kaplanis, Kaplani, and Kaldellis 2022) with models for assessing the wind and turbulent conditions inside wind clusters (Calaf, Meneveau, and Meyers 2010; Porté-Agel et al. 2011; Stevens, Gayme, and Meneveau 2016). New simulation data can be used for the estimation of the energy gain when two plants occupy the same location. Besides developing simulation tools, there is a need for field investigation. There are no experimental data available yet for the authors' knowledge regarding this effect.

Overall, the factors mentioned above (i–iii) that arose from the interaction of wind turbines and solar panels will be better understood as more combined sites will be developed. That will provide more data and allow the development of some formal guidance for better resource assessment.

3.4.3 | Forecast

The variability and the overall uncertainty of the resources add to the challenge of efficient integration of renewables into the power system operation and market trading, which highlights the significance of forecasting technology even further. Renewable power forecasting, with wind energy being the front-runner of the technology, started more than three decades ago (Brown, Katz, and Murphy 1984). It took another 10 years for the first operational forecasting tools to arrive at system operation level (Giebel et al. 2011) and since then, the field has grown exponentially; developing ever better tools and providing solutions to improve renewable power forecasting accuracy and reliability.

Given the chaotic nature of the atmosphere with temporal and spatial scales more than six orders of magnitude (Lorenz 1969; Slingo and Palmer 2011; Wyngaard 2010), it is not feasible to achieve perfect forecasts for HPPs. Climate change also has significant implications for renewable power resources, and supply and demand forecasting, which is an increasingly important research area where the impacts are still unclear (Chandramowli and Felder 2014). In addition to the complex weather patterns, the operational and conditional status of the generation units contribute to the non-linear and time-varying uncertainties in renewable power forecasting (Pombo, Bacher, et al. 2022). Accordingly, the identification of the uncertainty sources and quantification of these uncertainties for renewable power forecasting is of key importance in risk evaluation and decision-making for the optimum operation of HPPs.

HPP forecasting can be utilized for energy arbitrage (Das et al. 2020), short-term operation and control (Rodrguez et al. 2020), power balancing (Pombo, Rincón, et al. 2022), energy management (Pombo, Martinez-Rico, et al. 2022), and mitigation of variability (Quan et al. 2013). The forecast resolution and horizon can vary from seconds to days depending on the application and there are mainly two approaches studied in literature (Kumar et al. 2020; Santhosh, Venkaiah, and Vinod Kumar 2020). The first approach focuses on the weather forecast (e.g., the solar irradiance and wind speed forecasts, also referred to as the Numerical weather prediction model, NWP) and applies a predefined model or a look-up table for power conversion (Zhang et al. 2019). The principal limitation of this indirect approach is the potential disregard of the (non-linear) control actions implemented in the generation units; such as the actions of the solar tracking system, dynamic shadow effects, off-performance control of the turbine(s), and so forth. To overcome that, the second approach builds the forecasting framework directly on the power output (Sanjari, Gooi, and Nair 2020). Both of these approaches typically decouple the generation units and provide solar and wind power forecasts separately. However, since they harbor several levels of uncertainties propagated through the modeling chain, it should be noted that the combination of the individual uncertainties of wind and solar power forecasts depends on the correlation between wind and solar power forecast errors. This is a relatively significant research gap as the negative correlation reported in the literature (e.g., Zhang, Hodge, and Florita 2013) could potentially result in a lower forecast uncertainty of HPP than that of combined individual wind and solar power forecasts. This has the advantage of power system balancing in terms of reduced need for balancing and ramping reserves. It is also very relevant as the uncertainties in the forecast may determine the operation criteria for the HPP since the HPP owners need to use a single forecast of the whole plant (and not individually for solar and wind) for market trading and provision to system operators. This is more pronounced if the HPP also consists of storage assets thereby, decisions on storing energy are influenced by combined forecast error uncertainty. Therefore, the prominent challenge and research need for the HPP is the development of robust probabilistic forecasters that include uncertainty assessment as well as associated risk indices for robust decision-making.

3.5 | Grid Emulation and Advanced Tests

According to the European network code RfG, (European Commission 2016), the *compliance* of a power park module (PPM) with grid code requirements needs to be verified by a combination of tests and simulations of its electrical characteristics. A TSO and WPP developer survey published in (Sørensen, Marshall, and Kahlen 2020) shows that simulations are mostly required at an early stage to validate the plant in a specific case before it is built whereas tests are mainly required as part of the commissioning. Before using simulations to show compliance, it is crucial that the applied simulation models are validated against other tests. For instance, many authorities require that simulation models are validated against tests as part of a certification, for example, the German FGW technical guideline Part 8 (FGW e.V. 2019) which specifies requirements for certification of the electrical characteristics of power generating units, systems and storage systems as well as their components on the grid.

The wind power community has been the first mover in standardizing test methods for renewable generation. IEC published the first wind turbine power quality test standard in 2001, and today, more comprehensive tests of the electrical characteristics of a wind turbine are specified in IEC 61400-21-1 (International Electrotechnical Commission 2019b). Currently, a new standard IEC 61400-21-2 (International Electrotechnical Commission 2021b) is under development to specify test requirements at the WPP plant level after the WPP has been constructed, for example, as part of the certification.

The wind power community has also been the first mover in standardizing model validation methods for renewable generation. IEC published the first standard with validation procedures for wind turbine models in 2015, and the present IEC 61400-27-2 (International Electrotechnical Commission 2020b) is extended to also include validation procedures for WPP models. The scope of IEC 61400-27-2 is limited to the validation of fundamental frequency simulation models, also sometimes referred to as RMS models.

The wind power community has also specified generic models for wind turbines and WPPs. WECC published a 2 generation of wind turbine models in 2014 (Pourbeik 2016), and IEC 61400-27-1 (International Electrotechnical Commission 2020a) is the 2 edition of a standard for generic models for wind turbines and WPPs, published in 2019. The scope of the WECC and IEC 61400-27-1 is limited to fundamental frequency models that are applied in traditional power system stability studies.

The growing share of converter-based generation in power systems development of the power systems is not only affecting the definition of power system stability as mentioned in Section 3.3.1, it also calls for other types of models to analyze the power system stability. Therefore, using electromagnetic transient (EMT) models is increasingly important, especially when TSOs connect converter-based renewable generation to very weak points in the grid. EMT models include more details about the converter, and especially detailed models of the phase-lock loop (PLL) are essential to simulate voltage stability with converter-based generation in very weak grids.

Another class of models needed to study new stability issues is multi-frequency models, which are traditionally referred to as harmonic models. These typically use the frequency domain to quantify distortions outside the fundamental frequency, that is, sub-synchronous as well as super-synchronous. IEC 61400-21-3 (International Electrotechnical Commission 2021a) is a technical report describing wind turbine harmonic models and their application. Recent research has verified that non-linearities in power converters create strong couplings between frequencies and even between the positive and negative sequences. Present research and test procedures are focusing on characterizing single converters connected to the grid, but having multi-vendor converters in HPPs would suggest more research on how to ensure stable interoperability between the converters in HPPs, taking into account the resonances in the power collection and transmission systems.

To test and model HPPs, standards for solar PV and electricity storage are also needed, and for the high-level control of an HPP. The lack of comprehensive electrical test standards for solar PV and electricity storage technologies is still a challenge, as outlined in Table 6. However, most of the specifications in wind power standards could be extended to cover solar PV and electricity storage systems. The WPPs considered in the IEC 61400-21 series and IEC 61400-27 series already apply to WPPs with auxiliary reactive power compensation like STATCOM's and serial reactors, and electricity storage can be seen as an active power auxiliary equipment in this context.

3.6 | Multi-Energy System Integration

Electrification of sectors such as heating, transportation, and industry, along with coupling of these sectors is expected to significantly impact energy systems toward 2050 (Brown et al. 2018; Gea-Bermúdez et al. 2021). However, the transition to a low-carbon and sustainable energy future may need an increased focus on harnessing RES to decarbonize through electrification. Notably, hydrogen can serve as a vital bridge during the energy transition, with green hydrogen produced from RES holding significant potential for decarbonizing various sectors and achieving climate targets (Gielen 2018).

Utility-scale HPPs comprising wind, solar, and battery can potentially offer enhanced investment returns when combined with Power-to-Hydrogen (P2H) technologies WindEurope (2019). The incorporation of RE along with hydrogen production, generates synergies rooted in cross-market arbitrage involving electricity and hydrogen Mehrjerdi, Saboori, and Jadid (2022). The HPP owner/controller holds the ability to manage the assets and capitalize on fluctuations in electricity pricing. The electricity produced by RE can be supplied to the grid during high-energy prices and can be used to produce hydrogen during low energy prices. This approach can support improving the revenues from both electricity and hydrogen markets and can effectively compensate for the cost of hydrogen production.

A multi-technology multi-vendor HPP also can be called as a hybrid energy plant that not only generate electricity but other energy vectors like heat, hydrogen or another hydrogen byproduct—ammonia, methane, methanol. This section does not deal with large-scale energy system modeling; however, deals with design and operation of hybrid energy plants. Hydrogen, generated from renewable electricity through electrolysis, relies on electrolyzers that are critical for integrating variable RES into energy systems. These electrolyzers can adjust their electricity consumption based on the fluctuating output from wind and solar sources, significantly aiding in the reduction of RE curtailment and providing an additional revenue stream (Alahmad et al. 2023; Gupta et al. 2023). As a result, hydrogen and its derivatives can act as valuable storage mediums for renewable electricity, offering grid balancing services, including frequency regulation (ENTSO-E 2022). Liquid ammonia, for example, is a carbon-free and easily dispatchable hydrogen carrier, facilitating the cost-effective storage and distribution of significant amounts of renewable energy (Jackson et al. 2019).

Despite advancements in electrolyzer technology, operational challenges persist, particularly in modeling the non-linearities and dynamics associated with these technologies (ENTSO-E 2022). Moreover, the complexities involved in modeling ammonia and methanol reactors alongside integrated heat dynamics require further attention. It is also crucial to design operational strategies for hydrogen markets and their integration into energy systems to enable sector coupling and facilitate a smooth energy transition (Pombo et al. 2023). Furthermore, hybrid energy systems present the opportunity to operate in islanded mode, especially for offshore wind plants, enabling large-scale hydrogen production when grid connections are challenging Gupta et al. (2024).

TABLE 6 | Overview of challenges and opportunities of grid emulation and advanced tests.

Challenges
• The lack of comprehensive electrical test standards for solar PV and electricity storage technologies
Opportunities
• The novel approaches to ensure stable interoperability between the converters in HPPs, taking into account the resonances in the power collection and transmission systems

TABLE 7 | Overview of challenges and opportunities of multi-energy system integration.

Challenges
• The difficulties of modeling non-linearities and dynamics of electrolyzers
• Complexities in modeling ammonia and methanol reactors with integrated heat dynamics
• Developing operational strategies for integrating hydrogen markets into energy systems
Opportunities
• The potentials of HPPs under the sector coupling backgrounds
• The impacts of future energy market prices on the development of HPPs
• The viability of HPP operations in islanded mode for producing multiple energy vectors
• The feasibility of efficient, long-term storage options

Also, the development of energy systems toward 2050 will significantly influence the profitability of RES/hybrid energy plants, impacted by factors such as hydrogen demand and the expansion of transmission infrastructure. This indicates that analyzing HPP profitability based on current market prices should be complemented by evaluating the robustness of results using projections of future market prices over the expected lifespan of the plant (Pombo, Bindner, Spataru, Sørensen, and Rygaard 2022).

Thus, it is worthwhile to explore green hydrogen production utilizing RE of HPPs and considering multiple energy market participation. Integrating hydrogen production addresses fluctuations in non-dispatchable renewable energy output, minimizes curtailment, and enhances revenue potential from both electricity and hydrogen markets compared to direct grid connections. Additionally, determining the optimal sizing of components such as electrolyzers and storage units is crucial for maximizing investment efficiency and assessing the long-term profitability of these hybrid energy systems Gupta et al. (2023).

In summary, the challenges and opportunities of HPPs for multi-energy system integration are highlighted in Table 7.

4 | Conclusion

This article identifies significant opportunities for value provision from HPPs. It explores state-of-the-art advancements and addresses open research questions and challenges in the field of utility-scale HPPs.

This review explores the numerous anticipated benefits of HPPs over individual renewable technology-based power plants, showcasing the added value for owners, system operators, and society. The comprehensive analysis highlights the pivotal role of HPPs in advancing a sustainable and resilient energy future, offering significant advantages from societal, power systems, and energy systems perspectives, as well as for power plant owners. By combining wind and solar power behind a single grid connection point, HPPs facilitate the integration of larger volumes of RESs without requiring extensive grid infrastructure investments. This is possible due to the negative correlation between wind and solar resources, allowing for overplanting and better land utilization. HPPs enhance grid stability by mitigating RES variability, providing scheduled power dispatch, and reducing balancing needs and curtailment. For power plant owners, HPPs offer higher capacity factors, increased ancillary services support, and potential revenue growth through energy arbitrage and market services. Additionally, HPPs reduce development costs by sharing infrastructure and performing joint resource assessments, making them a cost-effective and resilient solution for the future energy landscape.

By highlighting research areas and challenges such as EMSs, sizing and siting, electrical design and control, uncertainties and forecasting, grid emulation, and multi-energy system integration, the authors emphasize the potential for academic and industrial research to reduce costs and accelerate the development of HPPs. Addressing these challenges involves developing robust EMSs, optimizing sizing and siting, designing advanced electrical systems, and ensuring accurate forecasting and grid emulation. Integrating HPPs with other energy systems requires sophisticated control and communication technologies. Focused research in these areas can significantly enhance the performance, reliability, and economic viability of HPPs in the future.

The identified research areas in this article are not exhaustive. Other relevant topics have not been deeply elaborated on yet, such as the impact of regulations on HPP design and operation, value quantification for larger power systems, coordination of assets within a HPP considering turbine loads and lifespan, integration of wind farm flow and wakes in operation and control and coordinated control between different HPPs.

Extensive research and development are urgently needed to enhance the flexibility of renewable generation and provide advanced system services for future grids. This review can be used by researchers, policymakers, and industry professionals to identify key areas for innovation and collaboration. By addressing the outlined challenges and leveraging the identified opportunities, stakeholders can drive the advancement and deployment of HPPs, ultimately contributing to a more sustainable and resilient energy future.

Author Contributions

Kaushik Das: conceptualization (lead), funding acquisition (lead), methodology (lead), writing – original draft (lead), writing – review and editing (lead). **Anca D. Hansen:** writing – original draft (equal),

writing – review and editing (equal). **Juan Pablo Murcia Leon:** writing – original draft (equal), writing – review and editing (equal). **Rujie Zhu:** writing – original draft (equal), writing – review and editing (equal). **Megha Gupta:** writing – original draft (equal), writing – review and editing (equal). **Juan-Andrés Pérez-Rúa:** writing – original draft (equal), writing – review and editing (equal). **Qian Long:** writing – original draft (equal), writing – review and editing (equal). **Daniel V. Pombo:** writing – review and editing (equal). **Athanasios Barlas:** writing – original draft (equal), writing – review and editing (equal). **Tuhfe Gocmen:** writing – original draft (equal), writing – review and editing (equal). **Andrey Sogachev:** writing – original draft (equal), writing – review and editing (equal). **Matti Koivisto:** writing – original draft (equal), writing – review and editing (equal). **Nicolaos A. Cutululis:** writing – original draft (equal), writing – review and editing (equal). **Poul E. Sørensen:** writing – original draft (equal), writing – review and editing (equal).

Acknowledgments

The authors would like to thank EUDP IEA Wind TCP Task 50—Hybrid Power Plants for the support of the work.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Using time series simulation tools for assessing the effects of variable renewable energy generation on power and energy systems

References

Abiola-Ogedengbe, A., H. Hangan, and K. Siddiqui. 2015. "Experimental Investigation of Wind Effects on a Standalone Photovoltaic (PV) Module." *Renewable Energy* 78: 657–665.

Ahlstorm, M., A. Gelston, J. Plew, and L. Kristov. 2019. "Hybrid Power Plants—Flexible Resources to Simplify Markets and Support Grid Operations." Technical Report. https://www.esig.energy/wp-content/uploads/2019/10/Hybrid-Power-Plants.pdf.

Alahmad, B., O. Sahin, N. Cassamo, et al. 2023. "Coordinated Control of Hydrogen Production Based on Wind Power Generation." In *7th International Hybrid Power Plants & Systems Workshop*, 41–49. IET.

Aly, A. M. 2016. "On the Evaluation of Wind Loads on Solar Panels: The Scale Issue." *Solar Energy* 135: 423–434.

Ammari, C., D. Belatrache, B. Touhami, and S. Makhloufi. 2021. "Sizing, Optimization, Control and Energy Management of Hybrid Renewable Energy System—A Review." *Energy and Built Environment* 3, no. 4: 399–411. https://doi.org/10.1016/j.enbenv.2021.04.002.

Andersson, M., P. H. Jensen, P. H. Lauritsen, et al. 2020. "Wind Power Annual Research and Innovation Agenda 2020." Technical Report. https://winddenmark.dk/sites/winddenmark.dk/files/media/document/Megavind%20Annual%20Research%20%26%20Innovation%20Agenda%202020%20-%20full%20report.pdf.

Anoune, K., M. Bouya, A. Astito, and A. B. Abdellah. 2018. "Sizing Methods and Optimization Techniques for Pv-Wind Based Hybrid Renewable Energy System: A Review." *Renewable and Sustainable Energy Reviews* 93: 652–673.

Asbeck, P. 2018. "Next-Gen Generation System: The Symbiotic Relationship of Solar, Wind & Storage Hybrid Power Plants." 17th Wind Integration Workshop, Stockholm.

Bahramara, S., M. P. Moghaddam, and M. Haghifam. 2016. "Optimal Planning of Hybrid Renewable Energy Systems Using Homer: A Review." *Renewable and Sustainable Energy Reviews* 62: 609–620.

Beattie, N. S., R. S. Moir, C. Chacko, G. Buffoni, S. H. Roberts, and N. M. Pearsall. 2012. "Understanding the Effects of Sand and Dust Accumulation on Photovoltaic Modules." *Renewable Energy* 48: 448–452.

Bienkiewicz, B., and Y. Sun. 1992. "Local Wind Loading on the Roof of a Low-Rise Building." *Journal of Wind Engineering and Industrial Aerodynamics* 45: 11–24.

BP Australia. 2023. "Renewable Energy Hub in Australia." https://www.bp.com/en_au/australia/home/who-we-are/reimagining-energy/decarbonizing-australias-energy-system/renewable-energy-hub-in-australia.html.

Brown, B. G., R. W. Katz, and A. H. Murphy. 1984. "Time Series Models to Simulate and Forecast Wind Speed and Wind Power." *Journal of Applied Meteorology and Climatology* 23: 1184–1195. https://journals.ametsoc.org/view/journals/apme/23/8/1520-0450_1984_023_1184_tsmtsa_2_0_co_2.xml.

Brown, T., D. Schlachtberger, A. Kies, S. Schramm, and M. Greiner. 2018. "Synergies of Sector Coupling and Transmission Reinforcement in a Cost-Optimised, Highly Renewable European Energy System." *Energy (Oxford)* 160: 720–739.

Bullich-Massagué, E., M. Aragüés-Peñalba, A. Sumper, and O. Boix-Aragones. 2017. "Active Power Control in a Hybrid PV-Storage Power Plant for Frequency Support." *Solar Energy* 144: 49–62.

Calaf, M., C. Meneveau, and J. Meyers. 2010. "Large Eddy Simulation Study of Fully Developed Wind-Turbine Array Boundary Layers." *Physics of Fluids* 22: 015110.

Cao, J., D. Harrold, Z. Fan, T. Morstyn, D. Healey, and K. Li. 2020. "Deep Reinforcement Learning-Based Energy Storage Arbitrage With Accurate Lithium-Ion Battery Degradation Model." *IEEE Transactions on Smart Grid* 11: 4513–4521.

Central Electricity Regulatory Commission, India. 2023. "180-Regulations. no. l-1/265/2022/cerc." https://cercind.gov.in/Regulations/180-Regulations.pdf.

Chandramowli, S. N., and F. A. Felder. 2014. "Impact of Climate Change on Electricity Systems and Markets—A Review of Models and Forecasts." *Sustainable Energy Technologies and Assessments* 5: 62–74. https://www.sciencedirect.com/science/article/pii/S2213138813000805.

Chiteka, K., R. Arora, and V. Jain. 2021. "Cfd Prediction of Dust Deposition and Installation Parametric Optimisation for Soiling Mitigation in Non-tracking Solar Pv Modules." *International Journal of Ambient Energy* 42: 1307–1320.

Chowdhury, S., U. Sumita, A. Islam, and I. Bedja. 2014. "Importance of Policy for Energy System Transformation: Diffusion of Pv Technology in Japan and Germany." *Energy Policy* 68: 285–293.

Cochran, L. S. 2015. "On Wind Load Reduction: Solar Arrays in the Field and Building Roofs." In *Proceedings of the SENG 2015 National Conference*, Adelaide, Australia. Sustainable Engineering Society.

Corporation, I. F. 2015. *Utility-Scale Solar Photovoltaic Power Plants*. Techical Report. Wolrd Bank Group. https://www.ifc.org/wps/wcm/connect/a1b3dbd3-983e-4ee3-a67b-cdc29ef900cb/IFC+Solar+Report_Web+_08+05.pdf?MOD=AJPERESCVID=kZePDPG.

Cotfas, D. T., P. A. Cotfas, and O. M. Machidon. 2018. "Study of Temperature Coefficients for Parameters of Photovoltaic Cells." *International Journal of Photoenergy* 2018. 2018: 1–12. https://doi.org/10.1155/2018/5945602.

Couto, A., H. Algarvio, and A. Estanqueiro. 2024. "An Optimized Probabilistic Forecasting Approach for Hybridized Wind Power Plants." 8th International Hybrid Power Plants & Systems Workshop (HYB 2024), IET.

Couto, A., and A. Estanqueiro. 2021. "Assessment of Wind and Solar Pv Local Complementarity for the Hybridization of the Wind Power Plants Installed in Portugal." *Journal of Cleaner Production* 319: 128728.

Couto, A., and A. Estanqueiro. 2023. "Wind Power Plants Hybridised With Solar Power: A Generation Forecast Perspective." *Journal of Cleaner Production* 423: 138793.

Das, K., A. Cossu, J. P. M. Leon, and P. E. Sørensen. 2022. "Component Sizing of an Utility-Scale Hybrid Power Plant." In *6th International Hybrid Power Systems Workshop*, IET.

Das, K., A. L. T. P. Grapperon, P. E. Sørensen, and A. D. Hansen. 2020. "Optimal Battery Operation for Revenue Maximization of Wind-Storage Hybrid Power Plant." *Electric Power Systems Research* 189: 106631.

Das, K., A. D. Hansen, P. Adamou, et al. 2019. "Dynamic Modelling of Wind-Solar-Storage Based Hybrid Power Plant." In *18th Wind Integration Workshop: International Workshop on Large-Scale Integration of Wind Power Into Power Systems as Well as on Transmission Networks for Offshore Wind Power Plants*. IEEE.

Das, K., A. D. Hansen, D. H. Vangari, M. J. Koivisto, P. E. Sørensen, and M. Altin. 2019. "Enhanced Features of Wind Based Hybrid Power Plants." In *4th International Hybrid Power Systems Workshop*, IET.

Das, K., J. M. Leon, H. Habbou, et al. 2022. "Hydesign: A Tool for Design and Operation of Renewable Hybrid Renewable Plants." In *21st Wind & Solar Integration Workshop (WIW 2022)*, vol. 2022, 85–91. IET.

DTU. 2023. "Danish Hybrid Wind Power Plant Forum." https://hybrid-vindenergi.dtu.dk/.

Duchaud, J.-L., G. Notton, C. Darras, and C. Voyant. 2019. "Multi-Objective Particle Swarm Optimal Sizing of a Renewable Hybrid Power Plant With Storage." *Renewable Energy* 131: 1156–1167.

Dykes, K. L., J. R. King, and N. A. DiOrio. 2019. *Research Opportunities in the Physical Design Optimization of Hybrid Power Plants*. Technical Report. National Renewable Energy Lab (NREL).

EIRGRID and ESB Networks. 2021. "Hybrid Working Group Multiple Legal Entities Response to Consultation." Technical Report. https://www.esbnetworks.ie/docs/default-source/default-document-library/flextech-multiple-legal-entity-response-to-consultation.pdf?sfvrsn=3d9502f0_0.

Ekström, J., M. Koivisto, I. Mellin, R. J. Millar, and M. Lehtonen. 2018. "A Statistical Modelling Methodology for Long-Term Wind Generation and Power Ramp Simulations in New Generation Locations." *Energies* 11, no. (9): 2442.

Eneco. 2023. "Hollandse Kust (Noord) Wind Farm." https://www.eneco.com/wat-we-doen/duurzame-bronnen/windpark-hollandse-kust-noord/.

Energinet. 2019. "Technical Regulation 3.3.1 for Electrical Energy Storage Facilities." https://en.energinet.dk/Electricity/Rules-and-Regulations/Regulations-for-grid-connection.

Energinet, Denmark. 2024. "Tekniske krav til samplacerede og/eller overplantede elproducerende og-forbrugende anlÆg samt energilageranlÆg." https://energinet.dk/media/upmoyooh/tekniske-krav-til-samplacerede-og-eller-overplantede-elproducerende-og-forbrugende-anlaeg-samt-energilageranlaeg-med-tc.pdf.

ENTSO-E. 2022. "A Potential of P2H Technologies to Provide System Services." https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/ENTSO-E_Study_on_Flexibility_from_Power-to-Hydrogen__P2H2_.pdf.

European Commission. 2016. "Network Code on Requirements for Grid Connection of Generators." https://www.entsoe.eu/network_codes/rfg/.

FGW e.V. 2019. "Technical Guidelines for Power Generating Units, Systems and Storage Systems as Well as for Their Components. Part 8: Certification of the Electrical Characteristics of Power Generating Units, Systems and Storage Systems as well as Their Components on the Grid." https://wind-fgw.de/wp-content/uploads/2019/05/TG_Part8_Rev9_EN_preview.pdf.

Fischetti, M., and D. Pisinger. 2018. "Optimizing Wind Farm Cable Routing Considering Power Losses." *European Journal of Operational Research* 270: 917–930.

Gea-Bermúdez, J., I. G. Jensen, M. Münster, et al. 2021. "The Role of Sector Coupling in the Green Transition: A Least-cost Energy System Development in Northern-Central Europe Towards 2050." *Applied Energy* 289: 116685.

Gevorgian, V., and B. O'Neill. 2016. *Advanced Grid-Friendly Controls Demonstration Project for Utility-Scale PV Power Plants*. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy16osti/65368.pdf.

Giebel, G., R. Brownsword, G. Kariniotakis, M. Denhard, and C. Draxl. 2011. *The State-Of-The-Art in Short-Term Prediction of Wind Power: A Literature Overview*. 2nd ed. ANEMOS.plus.

Gielen, D. 2018. *Hydrogen from Renewable Power Technology Outlook for the Energy Transition*. International Renewable Energy Agency.

Glick, A., N. Ali, J. Bossuyt, M. Calaf, and R. B. Cal. 2020. "Utility-Scale Solar Pv Performance Enhancements Through System-Level Modifications." *Scientific Reports* 10: 1–9.

Gökmen, N., W. Hu, P. Hou, Z. Chen, D. Sera, and S. Spataru. 2016. "Investigation of Wind Speed Cooling Effect on Pv Panels in Windy Locations." *Renewable Energy* 90: 283–290.

González-Longatt, F. M., P. Wall, P. Regulski, and V. Terzija. 2012. "Optimal Electric Network Design for a Large Offshore Wind Farm Based on a Modified Genetic Algorithm Approach." *IEEE Systems Journal* 6: 164–172.

Gouveia, L., and P. Martins. 2005. "The Capacitated Minimum Spanning Tree Problem: Revisiting Hop-Indexed Formulations." *Computers & Operations Research* 32: 2435–2452.

Graf, P., K. Dykes, G. Scott, et al. 2016. "Wind Farm Turbine Type and Placement Optimization." *Journal of Physics: Conference Series* 753: 062004.

Grau, T., M. Huo, and K. Neuhoff. 2012. "Survey of Photovoltaic Industry and Policy in Germany and China." *Energy Policy* 51: 20–37.

Grossi, M., J. P. M. Leon, M. Friis-Møller, and S. V. Spataru. 2024. "Hybridization of Wind Farms Using Hybrid Power Plant Sizing Optimization." In *8th International Hybrid Power Plants & Systems Workshop (HYB 2024)*, vol. 2024, 75–82. IET.

Guittet, D., P. Stanley, B. Hamilton, J. King, and A. Barker. 2022. *Hopp-Hybrid Optimization and Performance Platform*. Technical Report. National Renewable Energy Lab (NREL).

Gupta, M., K. Das, M. Friis-Møller, and J. P. M. Leon. 2023. "Assessment of Hybrid Power Plant Operation Including P2H in Future Energy Markets." In *22nd Wind and Solar Integration Workshop (WIW 2023)*, vol. 2023, 289–294. IET.

Gupta, M., J. P. Murcia Leon, M. Friis-Møller, and K. Das. 2024. "Evaluation of Grid-Connected and Off-Grid Operations of Hybrid Power Plant With p2h Integration." In *IET Conference Proceedings CP877*, 143–148. IET.

GWEC. 2019. "Global Wind Report 2019." Technical Report. https://gwec.net/wp-content/uploads/2020/08/Annual-Wind-Report_2019_digital_final_2r.pdf.

Hansen, A. D., K. Das, P. E. Sørensen, P. Singh, and A. Gavrilovic. 2021. "European and Indian Grid Codes for Utility Scale Wind Hybrid Power Plants." *Energies* 14: 4335.

Hansen, A. D., P. Sørensen, F. Iov, and F. Blaabjerg. 2006. "Centralised Power Control of Wind Farm With Doubly Fed Induction Generators." *Renewable Energy* 31: 935–951.

International Electrotechnical Commission. 2019a. "IEC 61400–1—Wind Energy Generation Systems—Part 1: Design Requirements." Technical Report.

International Electrotechnical Commission. 2019b. "IEC 61400–21-1—Wind Energy Generation Systems—Part 21–1: Measurement and Assessment of Electrical Characteristics—Wind Turbines." Technical Report.

International Electrotechnical Commission. 2020a. "IEC61400-27-1—Wind Energy Generation Systems—Part 27–1: Electrical Simulation Models—Generic Models." Technical Report.

International Electrotechnical Commission. 2020b. "Iec61400-27-2—Wind Energy Generation Systems—Part 27–2: Electrical Simulation Models—Model Validation." Technical Report.

International Electrotechnical Commission. 2021a. "IEC 61400–21-3—Wind Energy Generation Systems—Part 21–1: Measurement and Assessment of Electrical Characteristics—Wind Turbine Harmonic Model and Its Application." Technical Report.

International Electrotechnical Commission. 2021b. "IEC61400-21-2—Wind energy generation systems—Part 21–1: Measurement and Assessment of Electrical Characteristics—Wind Power Plants." Technical Report.

Irtaza, H., and A. Agarwal. 2018. "Cfd Simulation of Turbulent Wind Effect on an Array of Ground-Mounted Solar Pv Panels." *Journal of the Institution of Engineers: Series A* 99: 205–218.

Jackson, C., K. Fothergill, P. Gray, et al. 2019. *Ammonia to Green Hydrogen Project: Feasibility Study*. https://assets.publishing.service.gov.uk/media/5ea1705fd3bf7f7b4cadb7c5/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf.

Jethani, J. 2018. "National Wind-Solar Hybrid Policy." Technical Report.

Jimenez, P. A., J. P. Hacker, J. Dudhia, et al. 2016. "Wrf-Solar: Description and Clear-Sky Assessment of an Augmented Nwp Model for Solar Power Prediction." *Bulletin of the American Meteorological Society* 97: 1249–1264.

Jubayer, C. M., and H. Hangan. 2016. "A Numerical Approach to the Investigation of Wind Loading on an Array of Ground Mounted Solar Photovoltaic (PV) Panels." *Journal of Wind Engineering and Industrial Aerodynamics* 153: 60–70.

Kaplanis, S., E. Kaplani, and J. Kaldellis. 2022. "Pv Temperature and Performance Prediction in Free-Standing, Bipv and Bapv Incorporating the Effect of Temperature and Inclination on the Heat Transfer Coefficients and the Impact of Wind, Efficiency and Ageing." *Renewable Energy* 181: 235–249.

Khalid, M., R. P. Aguilera, A. V. Savkin, and V. G. Agelidis. 2018. "On Maximizing Profit of Wind-Battery Supported Power Station Based on Wind Power and Energy Price Forecasting." *Applied Energy* 211: 764–773.

Khan, F. A., N. Pal, and S. H. Saeed. 2018. "Review of Solar Photovoltaic and Wind Hybrid Energy Systems for Sizing Strategies Optimization Techniques and Cost Analysis Methodologies." *Renewable and Sustainable Energy Reviews* 92: 937–947.

Kim, J., E. Muljadi, J. W. Park, and Y. C. Kang. 2016. "Adaptive Hierarchical Voltage Control of a DFIG-Based Wind Power Plant for a Grid Fault." *IEEE Transactions on Smart Grid* 7: 2980–2990.

Kim, J., J. K. Seok, E. Muljadi, and Y. C. Kang. 2016. "Adaptive Q-V Scheme for the Voltage Control of a DFIG-Based Wind Power Plant." *IEEE Transactions on Power Electronics* 31: 3586–3599.

Koivisto, M., K. Das, F. Guo, et al. 2019. "Using Time Series Simulation Tools for Assessing the Effects of Variable Renewable Energy Generation on Power and Energy Systems." *Wiley Interdisciplinary Reviews: Energy and Environment* 8: e329.

Koivisto, M., G. M. Jónsdóttir, P. Sørensen, K. Plakas, and N. Cutululis. 2020. "Combination of Meteorological Reanalysis Data and Stochastic Simulation for Modelling Wind Generation Variability." *Renewable Energy* 159: 991–999. https://www.sciencedirect.com/science/article/pii/S0960148120309277.

Kopp, G. A., S. Farquhar, and M. J. Morrison. 2012. "Aerodynamic Mechanisms for Wind Loads on Tilted, Roof-Mounted, Solar Arrays." *Journal of Wind Engineering and Industrial Aerodynamics* 111: 40–52.

Kumar, D. S., G. M. Yagli, M. Kashyap, and D. Srinivasan. 2020. "Solar Irradiance Resource and Forecasting: A Comprehensive Review." *IET Renewable Power Generation* 14: 1641–1656. https://doi.org/10.1049/iet-rpg.2019.1227.

Landberg, L., L. Myllerup, O. Rathmann, et al. 2003. "Wind Resource Estimation—An Overview." *Wind Energy* 6: 261–271.

Larsén, X. G., S. E. Larsen, and E. L. Petersen. 2016. "Full-Scale Spectrum of Boundary-Layer Winds." *Boundary-Layer Meteorology* 159: 349–371.

Larsén, X. G., S. Ott, J. Badger, A. N. Hahmann, and J. Mann. 2012. "Recipes for Correcting the Impact of Effective Mesoscale Resolution on the Estimation of Extreme Winds." *Journal of Applied Meteorology and Climatology* 51: 521–533.

Lave, M., and A. Ellis. 2016. "Comparison of Solar and Wind Power Generation Impact on Net Load Across a Utility Balancing Area." In *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 1837–1842. IEEE.

León, J. M., and K. Das. 2023. "Profitability of Hybrid Power Plants in Europe."

Lindberg, O., J. Arnqvist, J. Munkhammar, and D. Lingfors. 2021. "Review on Power-Production Modeling of Hybrid Wind and Pv Power Parks." *Journal of Renewable and Sustainable Energy* 13: 042702.

Long, Q., K. Das, D. V. Pombo, and P. E. Sørensen. 2022. "Hierarchical Control Architecture of Co-Located Hybrid Power Plants." *International Journal of Electrical Power & Energy Systems* 143: 108407.

Lorenz, E. N. 1969. "The Predictability of a Flow Which Possesses Many Scales of Motion." *Tellus Series A: Dynamic Meteorology and Oceanography* 21: 289–307.

Lu, H., and L.-Z. Zhang. 2019. "Influences of Dust Deposition on Ground-Mounted Solar Photovoltaic Arrays: A Cfd Simulation Study." *Renewable Energy* 135: 21–31.

Ludwig, D. 2013. "Masterarbeit Photovoltaik und Windkraft als Integriertes Kraftwerk auf gleicher Fläche Master of Science." PhD thesis, Reiner Lemoine Institut, Germany.

Luzia, G., M. J. Koivisto, and A. N. Hahmann. 2023. "Validating Euro-Cordex Climate Simulations for Modelling European Wind Power Generation." *Renewable Energy* 217: 118989.

Madsen, H. A., F. Zahle, F. Meng, T. Barlas, F. Rasmussen, and R. Rudolf. 2020. "Initial Performance and Load Analysis of the Lowwind Turbine in Comparison With a Conventional Turbine." *Journal of Physics: Conference Series* 1618: 032011.

Mamia, I., and J. Appelbaum. 2016. "Shadow Analysis of Wind Turbines for Dual Use of Land for Combined Wind and Solar Photovoltaic Power Generation." *Renewable and Sustainable Energy Reviews* 55: 713–718.

Markousi, M., D. K. Fytanidis, and J. V. Soulis. 2016. "Wind Load Reduction in Hollow Panel Arrayed Set." *Modelling and Simulation in Engineering* 2016: 1–14. https://doi.org/10.1155/2016/1034539.

Markvart, T. 2000. *Solar Electricity*. Vol. 6. John Wiley & Sons.

Martinez-Rico, J., I. R. de Argandoña, E. Zulueta, U. Fernandez-Gamiz, and M. Armendia. 2021. "Energy Storage Sizing Based on Automatic Frequency Restoration Reserve Market Participation of Hybrid Renewable Power Plants." In *2021 International Conference on Smart Energy Systems and Technologies (SEST)*, 1–6. IEEE.

Mattei, M., G. Notton, C. Cristofari, M. Muselli, and P. Poggi. 2006. "Calculation of the Polycrystalline Pv Module Temperature Using a Simple Method of Energy Balance." *Renewable Energy* 31: 553–567.

Mehrjerdi, H., H. Saboori, and S. Jadid. 2022. "Power-To-Gas Utilization in Optimal Sizing of Hybrid Power, Water, and Hydrogen Microgrids With Energy and Gas Storage." *Journal of Energy Storage* 45: 103745.

Mohamed, M. A., T. Jin, and W. Su. 2020. "An Effective Stochastic Framework for Smart Coordinated Operation of Wind Park and Energy Storage Unit." *Applied Energy* 272: 115228.

Murcia, J., M. Koivisto, P. Sørensen, and P. Magnant. 2021. "Power Fluctuations in High Installation Density Offshore Wind Fleets." *Wind Energy Science* 6: 461–476.

Murcia, J. P., M. J. Koivisto, G. Luzia, et al. 2022. "Validation of European-Scale Simulated Wind Speed and Wind Generation Time Series." *Applied Energy* 305: 117794.

Murcia Leon, J. P., H. Habbou, M. Friis-Møller, M. Gupta, R. Zhu, and K. Das. 2024. "Hydesign: A Tool for Sizing Optimization of Grid-Connected Hybrid Power Plants Including Wind, Solar Photovoltaic, and Lithium-Ion Batteries." *Wind Energy Science* 9: 759–776.

Mustakerov, I., and D. Borissova. 2010. "Wind Turbines Type and Number Choice Using Combinatorial Optimization." *Renewable Energy* 35: 1887–1894.

Nanou, S. I., A. G. Papakonstantinou, and S. A. Papathanassiou. 2015. "A Generic Model of Two-Stage Grid-Connected PV Systems With Primary Frequency Response and Inertia Emulation." *Electric Power Systems Research* 127: 186–196. https://doi.org/10.1016/j.epsr.2015.06.011.

Newman, B., A. Burgers, N. Dekker, P. Manshanden, M. Jansen, and J. Kester. 2019. "Impact of Dynamic Shading in Csi Pv Modules and Systems for Novel Applications." In *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 3088–3092. IEEE.

Nguyen, H. T., D. V. Pombo, and H. W. Bindner. 2021. "Frequency Stability Assessment for the Future Power System of Sao Vicente Island." In *2021 IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, 1–5. IEEE.

Pérez-Rúa, J.-A., and N. A. Cutululis. 2019. "Electrical Cable Optimization in Offshore Wind Farms—A Review." *IEEE Access* 7: 85796–85811.

Pérez-Rúa, J.-A., M. Stolpe, K. Das, and N. A. Cutululis. 2019. "Global Optimization of Offshore Wind Farm Collection Systems." *IEEE Transactions on Power Systems* 35: 2256–2267.

Petersen, L. 2020. "Proof-of-Concept on Next Generation Hybrid Power Plant Control."

Pombo, D. V., P. Bacher, C. Ziras, H. W. Bindner, S. V. Spataru, and P. E. Sørensen. 2022. "Benchmarking Physics-Informed Machine Learning-Based Short Term Pv-Power Forecasting Tools." *Energy Reports* 8: 6512–6520.

Pombo, D. V., H. W. Bindner, S. V. Spataru, P. E. Sørensen, and M. Rygaard. 2022. "Machine Learning-Driven Energy Management of a Hybrid Nuclear-Wind-Solar-Desalination Plant." *Desalination* 537: 115871.

Pombo, D. V., F. Iov, and D. I. Stroe. 2019. "A Novel Control Architecture for Hybrid Power Plants to Provide Coordinated Frequency Reserves." *Energies* 12, no. 5: 919. https://doi.org/10.3390/en12050919.

Pombo, D. V., J. Martinez-Rico, M. Carrión, and M. Cañas-Carretón. 2022. "A Computationally Efficient Formulation for a Flexibility Enabling Generation Expansion Planning." *IEEE Transactions on Smart Grid* 14: 2723–2733.

Pombo, D. V., J. Martinez-Rico, S. V. Spataru, H. W. Bindner, and P. E. Sørensen. 2023. "Decarbonizing Energy Islands With Flexibility-Enabling Planning: The Case of Santiago, Cape Verde." *Renewable and Sustainable Energy Reviews* 176: 113151.

Pombo, D. V., A. G. Raducu, N. Styliaras, et al. 2021. "The First Utility Scale Hybrid Plant in Europe: The Case of Haringvliet." In *Virtual 5th International Hybrid Power Systems Workshop*, Energynautics GmbH.

Pombo, D. V., M. J. Rincón, P. Bacher, H. W. Bindner, S. V. Spataru, and P. E. Sørensen. 2022. "Assessing Stacked Physics-Informed Machine Learning Models for Co-Located Wind–Solar Power Forecasting." *Sustainable Energy, Grids and Networks* 32: 100943.

Pombo, D. V., D. A. Sørensen, and J. Martinez-Rico. 2022. "Is Real Inertia Always Better? Synchronous Condensers, Fast Frequency Response, and Virtual Inertia in Isolated Hybrid Power Systems." In *6th Hybrid Power Systems Workshop*. IEEE.

Porté-Agel, F., M. Bastankhah, and S. Shamsoddin. 2020. "Wind-Turbine and Wind-Farm Flows: A Review." *Boundary-Layer Meteorology* 174: 1–59.

Porté-Agel, F., Y.-T. Wu, H. Lu, and R. J. Conzemius. 2011. "Large-Eddy Simulation of Atmospheric Boundary Layer Flow Through Wind Turbines and Wind Farms." *Journal of Wind Engineering and Industrial Aerodynamics* 99: 154–168.

Pourbeik, P. 2016. "WECC Second Generation Wind Turbine Models." https://www.wecc.org/Reliability/WECC%20Second%20Generation%20Wind%20Turbine%20Models%20012314.pdf.

Quan, D. M., E. Ogliari, F. Grimaccia, S. Leva, and M. Mussetta. 2013. "Hybrid Model for Hourly Forecast of Photovoltaic and Wind Power." In *2013 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, 1–6. IEEE.

Reina, G. P., and G. De Stefano. 2017. "Computational Evaluation of Wind Loads on Sun-Tracking Ground-Mounted Photovoltaic Panel Arrays." *Journal of Wind Engineering and Industrial Aerodynamics* 170: 283–293.

Rodrguez, F., A. M. Florez-Tapia, L. Fontán, and A. Galarza. 2020. "Very Short-Term Wind Power Density Forecasting Through Artificial Neural Networks for Microgrid Control." *Renewable Energy* 145: 1517–1527.

Sahin, O., B. Alahmad, A. G. Raducu, D. V. Pombo, and S. Kanev. 2022. "New Frequency Control Philosophy for Future Hybrid Power Plants." In *6th Hybrid Power Systems Workshop*. IEEE.

Sanjari, M. J., H. B. Gooi, and N.-K. C. Nair. 2020. "Power Generation Forecast of Hybrid Pv–Wind System." *IEEE Transactions on Sustainable Energy* 11: 703–712.

Santhosh, M., C. Venkaiah, and D. M. Vinod Kumar. 2020. "Current Advances and Approaches in Wind Speed and Wind Power Forecasting for Improved Renewable Energy Integration: A Review." *Engineering Reports* 2: e12178. https://doi.org/10.1002/eng2.12178.

Schwingshackl, C., M. Petitta, J. E. Wagner, et al. 2013. "Wind Effect on Pv Module Temperature: Analysis of Different Techniques for an Accurate Estimation." *Energy Procedia* 40: 77–86.

Shademan, M., R. Barron, R. Balachandar, and H. Hangan. 2014. "Numerical Simulation of Wind Loading on Ground-Mounted Solar Panels at Different Flow Configurations." *Canadian Journal of Civil Engineering* 41: 728–738.

Siddiqui, M. U., A. F. Arif, L. Kelley, and S. Dubowsky. 2012. "Three-Dimensional Thermal Modeling of a Photovoltaic Module Under Varying Conditions." *Solar Energy* 86: 2620–2631.

Silva, A. R., and A. Estanqueiro. 2022. "From Wind to Hybrid: A Contribution to the Optimal Design of Utility-Scale Hybrid Power Plants." *Energies* 15: 2560.

Skoplaki, E., and J. A. Palyvos. 2009. "Operating Temperature of Photovoltaic Modules: A Survey of Pertinent Correlations." *Renewable Energy* 34: 23–29.

Slingo, J., and T. Palmer. 2011. "Uncertainty in Weather and Climate Prediction." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369: 4751–4767.

Sogachev, A. 2021. "Airflow Modelling Over Hybrid Solar/Wind Farm." In *Wind Energy Science Conference 2021*, 386–387. ForWind-Center for Wind Energy Research.

Sørensen, D. A., D. V. Pombo, and E. T. Iglesias. 2023. "Energy Storage Sizing for Virtual Inertia Contribution Based on Rocof and Local Frequency Dynamics." *Energy Strategy Reviews* 47: 101094.

Sørensen, P., A. D. Hansen, and P. A. C. Rosas. 2002. "Wind Models for Simulation of Power Fluctuations From Wind Farms." *Journal of Wind Engineering and Industrial Aerodynamics* 90: 1381–1402.

Sørensen, P., B. Marshall, and C. Kahlen. 2020. *Deliverable 11.5 Best Practice and Recommendations for Compliance Evaluation*. European Commission.

Stanley, A. P., and J. King. 2022. "Optimizing the Physical Design and Layout of a Resilient Wind, Solar, and Storage Hybrid Power Plant." *Applied Energy* 317: 119139.

Stevens, R. J., D. F. Gayme, and C. Meneveau. 2016. "Effects of Turbine Spacing on the Power Output of Extended Wind-Farms." *Wind Energy* 19: 359–370.

Swisher, P., J. P. M. Leon, J. Gea-Bermúdez, M. Koivisto, H. A. Madsen, and M. Münster. 2022. "Competitiveness of a Low Specific Power, Low Cut-Out Wind Speed Wind Turbine in North and Central Europe Towards 2050." *Applied Energy* 306: 118043.

TNO. 2021. "TNO Starts Multi-Annual Study on the Effects of Wind Turbine Shade on Solar Parks." https://www.tno.nl/en/about-tno/news/2021/2/tno-starts-multi-annual-study-on-the-effects-of-wind-turbine-shade-on-solar-parks/.

Tripp, C., D. Guittet, J. King, and A. Barker. 2022. "A Simplified, Efficient Approach to Hybrid Wind and Solar Plant Site Optimization." *Wind Energy Science* 7: 697–713.

Vasel, A., and F. Iakovidis. 2017. "The Effect of Wind Direction on the Performance of Solar Pv Plants." *Energy Conversion and Management* 153: 455–461.

Vignola, F., C. Grover, N. Lemon, and A. McMahan. 2012. "Building a Bankable Solar Radiation Dataset." *Solar Energy* 86: 2218–2229.

Wang, L., O. Kisi, M. Zounemat-Kermani, G. A. Salazar, Z. Zhu, and W. Gong. 2016. "Solar Radiation Prediction Using Different Techniques: Model Evaluation and Comparison." *Renewable and Sustainable Energy Reviews* 61: 384–397.

Warsido, W. P., G. T. Bitsuamlak, J. Barata, and A. G. Chowdhury. 2014. "Influence of Spacing Parameters on the Wind Loading of Solar Array." *Journal of Fluids and Structures* 48: 295–315.

Waterworth, D., and A. Armstrong. 2020. "Southerly Winds Increase the Electricity Generated by Solar Photovoltaic Systems." *Solar Energy* 202: 123–135.

WindEurope. 2019. "Renewable Hybrid Power Plants—Exploring the Benefits and Market Opportunities." Techical Report. https://windeurope.org/wp-content/uploads/files/policy/position-papers/WindEurope-renewable-hybrid-power-plants-benefits-and-market-opportunities.pdf.

WindEurope. 2021. "Database for Wind + Storage Co-Located Projects." https://windeurope.org/about-wind/database-for-wind-and-storage-colocated-projects/.

Wyngaard, J. C. 2010. *Turbulence in the Atmosphere*. Cambridge University Press.

Xu, B., A. Oudalov, A. Ulbig, G. Andersson, and D. S. Kirschen. 2016. "Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment." *IEEE Transactions on Smart Grid* 9: 1131–1140.

Yang, Y., A. Sangwongwanich, H. Liu, and F. Blaabjerg. 2017. "Low Voltage Ride-Through of Two-Stage Grid-Connected Photovoltaic Systems Through the Inherent Linear Power-Voltage Characteristic." In *IEEE Applied Power Electronics Conference and Exposition*, 3582–3588. IEEE. https://doi.org/10.1109/APEC.2017.7931212.

Zaoui, F., A. Titaouine, M. Becherif, M. Emziane, and A. Aboubou. 2015. "A Combined Experimental and Simulation Study on the Effects of Irradiance and Temperature on Photovoltaic Modules." *Energy Procedia* 75: 373–380.

Zhang, J., B.-M. Hodge, and A. Florita. 2013. "Investigating the Correlation Between Wind and Solar Power Forecast Errors in the Western Interconnection." In *ASME 2013 7th International Conference on Energy Sustainability of Energy Sustainability*, ASME. https://doi.org/10.1115/ES2013-18423.

Zhang, W., A. Maleki, M. A. Rosen, and J. Liu. 2019. "Sizing a Stand-Alone Solar-Wind-Hydrogen Energy System Using Weather Forecasting and a Hybrid Search Optimization Algorithm." *Energy Conversion and Management* 180: 609–621. https://www.sciencedirect.com/science/article/pii/S0196890418309671.

Zhu, R., K. Das, P. E. Sørensen, and A. D. Hansen. 2023. "Optimal Participation of Co-Located Wind–Battery Plants in Sequential Electricity Markets." *Energies* 16: 5597.