Research Opportunities in the Physical Design Optimization of Hybrid Power Plants

Preprint

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Research Opportunities in the Physical Design Optimization of Hybrid Power Plants

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***Abstract*—With renewable energy growing to 10%–20% or more of overall electricity generation, design objectives for renewable power plants are shifting from producing energy at the lowest levelized cost to maximizing profitability. Several research and commercial efforts have investigated how to size respective generation and storage assets together for hybrid power plant systems including wind, solar, battery storage, and other technologies. However, the physical design of hybrid power plants has yet to be considered in detail. Even the design of individual solar and wind power plants is complex with large numbers of design variables, constraints, and complex physical interactions across subsystems. Developing an integrated approach for the design of hybrid power plants that include several generation technologies compounds this complexity and requires domain knowledge across the technologies as well as new approaches for addressing the statistical representation of resource availability and revenue opportunities. To inform the research needs on physical design of these hybrid power plants, a workshop was held in December 2018 at the National Renewable Energy Laboratory. This paper summarizes the findings from the workshop on research needs for hybrid power plant design.**

Keywords—hybrid power plant; design; optimization; multidisciplinary

I. Introduction

Driven both by consideration of environmental impacts and significant cost reductions in wind, solar photovoltaic (PV), and energy storage (particularly battery) technologies, new installations of electricity generation have been dominated by renewables in the United States, Europe, and globally [1-2]. As we look toward the future grid system with ever-increasing shares of variable renewable energy, a paradigm shift is underway where the traditional model of fixed-price-energy-based revenue streams for wind and solar PV using power purchase agreements (PPAs) or feed-in tariffs is changing [3]. With renewable energy growing to 10%–20% or more of overall electricity generation [4], design objectives are shifting from producing energy at the lowest levelized cost of energy (LCOE) to also include other design objectives that maximize profitability. Future profitability for individual power plants will increasingly depend on time-varying energy pricing, capacity, and service markets [5]. Wind, solar, and storage technologies can take part in a limited way in some of these markets today but, due to their uncertainty and variability, not to the same degree as traditional power plants. To ensure profitability of these assets in the future, developers would like wind and solar plants to have the ability to operate more like traditional power plants in terms of capacity value, dispatchability, ancillary services, and reliability. To ensure profitability at an individual asset level, developer/owner/operators are designing "hybrid power plants" that combine wind, solar, and storage together.

By combining generation assets together, including storage, solar, and wind, into "hybrid power plants," an individual plant owner can 1) develop economies of scope in terms of land usage, electrical and physical infrastructure, and operational expenditures; and 2) increase their system value to capitalize on revenue streams through forward capacity markets (where present), "dispatchable" operation in markets with time-varying energy pricing, and ancillary service markets (where present).

This is a substantial shift from historical approaches to solar and wind energy power plant development and operation. Up until recently, renewable power plants in many markets had a design objective to produce as many kilowatt-hours as possible since all were awarded the same fixed income stream (whether through a PPA or other form of fixed energy payment, such as a feed-in tariff). In this case, such power plants only curtail when necessary, and commanded to, by the system operator to support the larger grid. Looking forward, hybrid power plants will act more like conventional generation where they consistently produce less than full capacity and focus on providing energy at specific times (i.e., dispatchable energy) as well as services that support the reliability and stability of the grid system. This new paradigm creates an opportunity to critically consider how hybrid power plants should be designed—with what technology assets and in what configuration— operated, and controlled.

To understand the current landscape of hybrid power plants and associated research and technology development needs, a workshop was held at the National Renewable Energy Laboratory (NREL) in December 2018 to bring together perspectives from across a large stakeholder group including original equipment manufacturers, developer/ owner/operators, utilities, consultancies, government, laboratories, and universities. Through a series of presentations and breakout sessions, speakers, and participants described current practice in hybrid power plant design and development and discussed gaps and challenges.

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Topics addressed included technology combinations, market opportunities and sizing of hybrid power plants, physical design considerations for hybrid power plants, and operation and control of hybrid power plants. The detailed results of the workshop are summarized in a technical report [6]. This paper focuses on the research opportunities related to physical design of hybrid power plants and summarizes some of the findings from the more detailed report with an emphasis on the physical design process.

II. Technology, Resource and Market Opportunities

A. Technology Combinations

Hybrid power plants are those that combine multiple generation assets in a single power plant. Storage technologies, like batteries, do not generate technology by themselves and instead can shift when energy is produced to provide more predictable and controllable generation, and to provide services to support grid system reliability. However, storage additions to a single-technology generation facility are not considered to create hybrid power plants.

Definition: Hybrid power plants are power plants that contain two or more energy generation sources such as wind turbines, solar PV, concentrating solar power (CSP), geothermal power, hydropower, biomass, natural gas, oil, coal, or nuclear power.

Throughout this paper, we will focus on hybrid power plants using only renewable generation and with emphasis on wind and solar PV hybrid power plants with and without additional storage technology. We also focus on hybrid power plants that produce electricity as their only output (versus producing fuels, hydrogen, or other energy products).

B. Resource Opportunities

Depending on the specific location in the world, there are different quantities of renewable resources (solar, wind, hydro, geothermal) at different timescales of interest. These will have varied levels of correlation at different timescales as well. The further you move away from a specific location, the more a resource profile for a given energy source will change, creating geospatial correlation characteristics both for a given resource as well as across different types of energy resources.

To understand the large-scale potential of hybrid power plants, more research is needed to understand the potential for different resources (wind, solar, hydro, geothermal) to complement each other, decreasing overall variability of the joint potential energy resource, and, as a result, increasing the predictability and controllability of the joint assets.

The joint probability distributions of different renewable resources at different geospatial and temporal scales (including autocorrelation within and across resources) is key to understanding the potential for hybrid power plants at a single location (if co-located) or virtually connected (if physically separated).

Moving to combined hybrid power plants with wind and solar assets with their inherent variability over time, the joint distribution of the resources is important to understand at a given site. In additional to annual correlation, the temporal correlation (including autocorrelation within and across assets) will be important to model to support sizing, design, operation, and control of hybrid power plants that include these combined assets.

C. Market Opportunities

Looking toward the future of the electricity system, there is a consensus within the grid integration community that there will likely be a shift in market structures as more variable and uncertain energy sources (such as wind and solar PV) are integrated in the electricity system [5,7]. In general, as the need to ensure capacity adequacy and sufficient provision of ancillary services at all times, and as more and more very low cost energy is added to the grid system in the form of wind and solar PV, the market structures may shift towards increasing revenue from capacity and adequacy markets and reduced revenues from energy markets (as indicated in Figure 1).

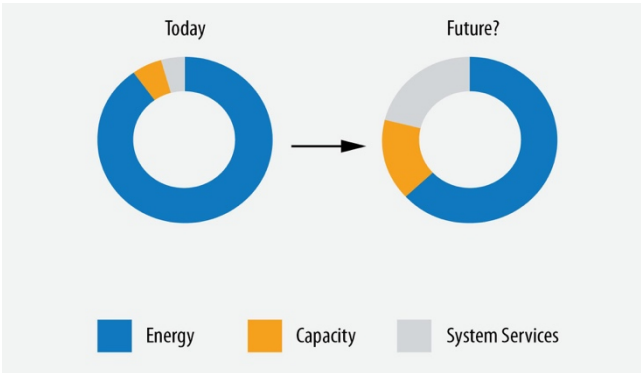

Figure 1: The morphing electricity market system (Source: NREL, based on a figure in [5])

Some markets, many of which have high wind and/or solar PV concentrations, are already shifting toward such models where the relative shares of revenue for energy sales have been declining and a larger share has been made up of capacity payments [8]. In places like Ireland and southern Australia where the systems are relatively isolated and not well-connected to other balancing areas, regulators and system operators have found that adapting markets (shorter time intervals for dispatch, encouraging renewable to participate in ancillary markets, among others) have supported higher and higher shares of renewable energy in those systems [9]. As markets evolve, the economic potential of hybrid power plants will change. A grid system with very small shares of variable renewable energy and a lot of gas or hydropower resources where the energy markets dominate would indicate that hybrid power plants will only benefit in terms of economies of scope that can be made through integration of some infrastructure and operational assets. On the other hand, a market that has very high shares of renewables where capacity and service markets are significant may mean that the profitability of a hybrid power plant may be better than individual technology plants or even possible individual technology plants with storage.

For evaluation of hybrid power plants, the market context in terms of what other generation assets are present and what revenue streams are available (and their expected value over the plant lifetime) are critical to assessing the relative performance of the relative sizing of technology assets in the plant and its overall physical design.

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The changing nature of markets means that from the development standpoint, there is a large amount of uncertainty and a need to directly address that uncertainty in the design process. Thus, the hybrid power plant developer has to contend with a complex choice of technology selection, including the relative sizing of assets as well as large uncertainties in not just the resource availability but also in the future available revenue opportunities as the technology mix within a given market changes or even the market structure itself changes over time.

III. Physical Design of Hybrid Power Plants

Several research and commercial efforts have explored the optimal selection of technology and sizing thereof for a large range of contexts and plant sizes, from microgrid scales to utility-scale (see [6] for a more detailed discussion). In this work, we focus on the physical design of these plants where selection and sizing of the assets may or may not have already been completed. We first look at the state of the art in wind and solar power plant designs and then at opportunities for their integrated design, potentially including storage technology as well.

A. Wind Power Plant Design

Historically, wind power plant designers have used an LCOE metric as a global objective for plant design. While the LCOE metric obfuscates details of the financing impacts, it is necessary to create an objective function that can be tractably computed within an optimization design loop. In practice, however, plant designers and developers perform detailed financial modeling of the plant and may adjust the design to a degree based on the results of those modeling efforts.

To estimate the LCOE for a given wind power plant design, designers use software packages that contain a combination of several models that represent different subsystems of the plant, each itself represented by one or more engineering and/or cost models. The primary subsystems considered for the plant design include energy production, balance of system (including plant infrastructure and installation), and operations and maintenance. In practice, the community still lacks detailed and accurate models for how plant design affects the latter subsystem, operations and maintenance, due to the very high uncertainty around the reliability of the turbine and balance of system equipment components over the lifetime of the plant. Thus, 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.

Combining wind plant design models includes models for the flow and the wakes, for the electrical system performance and cost, other infrastructure costs, the civil engineering of the foundation, and associated costs. Limiting the design to just this set of models already introduces many potential design variables for consideration (see [10] for a more detailed review). The most common design variables include:

- Turbine layout: the position of each turbine in the plant (either on a gridded, semiregular, or irregular layout formation) are the most common design variables for wind power plant design.
- Turbine number: the number of turbines is often a design variable and requires a discrete variable in the optimization.
- Topology and sizing of the electrical collection system: suboptimization of the topology of the electrical collection system and the sizing of various cables is often included.
- Foundation sizing: even for the same turbine, the location of the turbine in the plant will affect the loads on the foundation and its design.
- Types of turbines: a newer area of research has explored using different types of turbines in the same plant with varied hub heights, rotor diameters, and rated powers.
- Turbine control strategy: another novel area of research has focused on wind plant controls to affect the wakes that they produce to increase overall plant energy production or decrease loads and improve turbine component reliabilities as well as provide ancillary services to the grid.

Given the number of potential design variables and models that may be addressed in wind power plant design optimization, most research and commercial efforts reduce the design space by focusing on a subset of design variables as well as use simplified models (especially early in the design process). Models from different disciplines are connected into a workflow that may be monolithic (all disciplines are solved simultaneously with a single optimizer driving the workflow) or may include suboptimizations of certain disciplines or even more complex architectures. A more detailed review can be found in [10].

B. Solar Power Plant Design

Optimizing solar power plant design has the primary goal of maximizing the value of the plant, typically by maximizing the net-present value or internal rate of return, depending on the ownership structure [11]. For utility-scale plants operating under a PPA, the traditional source of revenue for a plant is to sell electricity produced by the system at a negotiated rate, which can be fixed or vary by time of day and season. Therefore, a full plant optimization would account for the structure of the PPA and producing electricity at times when it is most valuable within the limits of the system. As with wind energy, there are several variables involved in the solar power plant design process:

- Tracking system and inverter load ratios: the choice of tracking system and inverter load ratios are two factors to optimize in a PV system. The tracking system is designed to optimize the array tilt and azimuth angles to maximize power production.
- Module orientation (portrait vs landscape): The module orientation governs the length of each row and the length of the side of an array, which affects the shadow cast by the array into the next row.
- Row layout (1-up vs. 2-up): The row layout also affects the length of the side of an array. Rows with only one module will cast a smaller shadow, while rows with two or more modules along the length will have a larger shadow.

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- Bifacial vs. monofacial modules: Monofacial modules are those which produce electricity due to solar insolation on the front side of the module. Bifacial modules are configured to produce electricity from both the front side and rear side.
- Inverter selection: The inverter is power electronics which convert DC electricity to AC electricity. Each inverter is designed to accept inputs within certain voltage and power ranges; thus, the inverter must be selected with the module string layout in mind. The selection must also be made between different classes of inverters, such as string, central, and microinverters, which offer different benefits and cost tradeoffs.
- Module string wiring: PV modules can be wired in series to boost string voltage and added in parallel to boost total capacity. Strings must be designed to conform to the inverter input.

Optimal design of a solar power plant then proceeds often in a more manual approach than for wind power plants, where the designer iteratively considers design using knowledge about land area, cost targets and desired module and inverter combinations. Within each iteration, the designer then optimizes DC/AC ratio, tilt, azimuth, ground-coverage ratio and tracking system for that system size by iterating through options, evaluating energy production and value.

C. Hybrid Power Plant Design

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. 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 (integrated collection system design, shading of the PV by wind turbines, the interaction of storage with the two technologies, and more). Table 1 summarizes the key differences between general sizing of single technology or hybrid power plants, detailed physical design of single technology power plants, and detailed physical design of hybrid power plants.

The most critical design inputs for considering hybrid power plant design at a given site are a characterization of the potential resource from the different energy technologies and the potential revenue streams available based on the local market conditions. Significant work has gone into the characterization of solar and wind energy resources around the globe to produce both statistical data as well as to provide historical and synthetic time-series data that can be used for site resource assessment, but little work to date has been done to explicitly derive joint probability distributions across resources. Sizing tools use time-series data (at a range of temporal resolutions) and so implicitly account for the complementarities of the resources at a given site. Physical design often uses simplified statistical representations of the resource. For physical design of hybrid power plants that integrate wind, solar PV, and potentially storage, a harmonization across these approaches is needed. This could take the form of using joint probability density functions across the resources either annually or broken down by season or month. Such analysis could include auto-correlation aspects within or across the resources as well. Another approach could be to use time-series binning similar key parameters that are used in physical design of wind power plants. However, the resolution of such binning practices would need to be very low to limit the number of input cases to something tractable for the optimization. As an alternative, representative time slices could be used to book-end a range of exemplary performance cases, and again these could be subdivided by time of year. Finally, some combination of these approaches could be used: i.e., a general joint pdf for certain revenue streams and representative time slices to address others.

The time dependence of the resource availability is particularly important to hybrid power plant design when considering the revenue potential for the plant. Assuming the plant is small relative to the overall system, the market conditions can be treated as exogenous (though they will likely change over time, introducing a source of uncertainty into the optimization process as will be discussed later in the optimization problem formulation). The approach in hybrid power plant sizing tools which have historically focused more on distributed generation is to use actual time-series data for available capacity, energy, and service revenue streams [12]. For utility-scale solar and wind energy, a similar approach for distributed generation and for utility-scale systems assumes a PPA type of structure with potentially added revenues related to time-of-delivery factors [11]. Most wind power plant design optimization tools assume a very simple PPA structure with no variation in revenue over time, and often the objective function for the design is thus reduced to the LCOE, which still creates a complex optimization for the detailed design consideration (as in [13]). For hybrid power plant design, time slices of data may be intractable while the LCOE is oversimplified and would not lead to the optimal design from an overall profitability perspective. In conjunction with the resource data, the options again span from a completely statistical approach of complex joint pdfs for wind, solar and revenue opportunities to a completely time-series-driven approach (either with binning or representative time slices). The former may be very difficult to construct in and of itself and then be still difficult to apply within a design optimization context while the latter may produce to many cases to perform a tractable optimization. It is possible that some combined approach that uses a limited set of cases based on statistics and time-series data would be tractable from a computational standpoint and drive to designs that have significantly improved profitability over classic LCOE optimized power plants.

Hybrid power plant design optimization then requires decisions related to the extent of collocation and electrical coupling of the assets. On one extreme, a virtual hybrid power plant may have resources without a single common point of interconnection to the larger grid system. On the other, a fully DC-coupled collection system with solar and wind resources interwoven in a single land area is also possible. The physical and cost modeling of the assets depend on where the hybrid power plant falls in this spectrum. For the former, existing models are adequate while for the latter, new models will need to be developed to account for shading, an integrated collection system design, shared balance of plant and operational resources, and more.

An optimization problem formulation includes the specifics of design variables, nondesign input parameters,

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constraints and objectives as well as the overall architecture of the workflow and the algorithms used. Wind power plant design problems are multidisciplinary design optimization problems that are difficult due to the size of the problems (potential number of design variables and constraints) and their scope (number of different disciplines involved). Integrated wind and solar power plant design together (potentially with storage) further complicates this.

Technology selection and sizing of hybrid power plants typically have problem formulations that can be classified mixed integer linear programming like what is used by unit commitment and dispatch models at a systems operation level. These problems are typically solved as one monolithic workflow rather than involving embedded suboptimizations. On the other hand, wind plant layout design optimization is highly nonlinear and can thus be classified as nonlinear programming (NLP) or mixed integer nonlinear programming (MINLP). In addition, depending on the submodels involved, wind plant layout optimization problems are typically not fully differentiable across all models and gradient-free methods, including heuristic and metaheuristic methods are often used (though there is a growing body of research that applies gradient-based methods to wind plant design: see [10] for more detail on both). Finally, often there are design subprocesses in wind plant optimization that can be decoupled and allow for suboptimization of some subsystems (in that case, the electrical collection system design and the monopile sizing). For solar power plant design, approaches often do not use explicit optimization as the smaller number of design levers and the relative ease with which design subprocesses can be decoupled lends itself to a manual design approach.

For optimization problems, the most complex aspect of the problem formulation drives the design of the workflow and choice of algorithms. Thus, since wind power plant design problems are NLP or MINLP, then hybrid power plant physical design optimization will fall into one of those categories as well. Depending on whether discrete choices are included (number of turbines, solar panels, collection cable strings, etc.), then the problem will be MINLP and require either gradient-free techniques or some mixture of gradient-based and gradient-free techniques.

Finally, the entire earlier discussion assumes that the optimization involved deterministic information. However, uncertainty is rampant in almost all design optimization problems and highly relevant for technology selection, sizing, and physical design of hybrid power plants. Sources of uncertainty include the resources themselves, the potential revenue streams, and aspects of technology performance and cost over time. Including all sources of uncertainty would result in intractable problem formulations, but robust designs will likely require addressing some of the aspects of uncertainty in the design process. Such problems known as optimization under uncertainty or robust design optimization problems include an uncertainty analysis and quantification method within the optimization to produce statistics that can be used to evaluate the objective function and/or various system constraints. Optimization under uncertainty applied to design optimization for renewable systems is an active area of research and, while it is necessary to first address issues associated with hybrid power plant physical design from a deterministic perspective, it will be important to quickly bring uncertainty into the design process to ensure the overall success of the developed designs.

IV. Summary

Hybrid power plants show promise to provide significant value to the electric grid system especially as shares of renewable energy in systems increase. However, there still are many questions around when hybrid power plants make sense versus leaving it to the larger grid system to ensure low cost and reliable supply by engaging directly with all individual assets. This paper explored opportunities for research in the physical design optimization of hybrid power plants with emphasis on wind and solar PV hybrid power plants. The complexity and uncertainty involved in the physical design optimization of hybrid power plants goes beyond current practice for sizing of hybrid power plants or physical design of single technology power plants and creates opportunity for research and innovation to realize the full potential of future hybrid power plants with low cost and high value to the electric grid system.

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TABLE 1: OVERALL CHARACTERISTICS OF TECHNOLOGY SELECTION, SIZING, AND DESIGN OF WIND, SOLAR, AND WIND-SOLAR HYBRID POWER PLANTS.

Design Process Elements	**Current Practice for Single Technology and Hybrid Power Plant Sizing**	**Current Practice for Single Technology Physical Design Optimization**	**Potential Approach for Hybrid Power Plant Physical Design Optimization**
Input Data – Resource	Time-series data with variable bin resolution (for a representative year)	Statistical model of key resource parameters (i.e., for wind: speed and direction joint pdf)	Limited cases that reflect temporal dependencies but also bulk statistics
Input Data - Resource	Time-series data with variable bin resolution (for a representative year)	Single power purchase price (with limited options of extension)	Limited cases that reflect temporal dependencies but also bulk statistics
Technical Models – Solar, Storage, and Wind	Simplified parametric representations of technology performance and cost	Detailed physical models of the technologies for cost and performance	Detailed physical models of the technologies for cost and performance including interaction effects (i.e., turbine shading of panels)
Technical Models – Balance of Plant and Operations	No or highly simplified parametric representation of infrastructure and operational costs	Broad range of fidelity in terms of modeling the infrastructure and plant operations	Important to adapt existing single technology models for hybrid power plant implementations with various topologies of coupling in the plant collection system
Optimization Problem Formulation – Design Variables	Technology types, capacity sizing, and operational strategy	Technology types, number, placement, interconnection topology, control strategy, and more	Technology types, number, placement, interconnection topology, control strategy, and more (for all technologies)
Optimization Problem – Design Constraints and Objectives	Objectives on profitability (NPV, etc.) as well as potentially resiliency etc. Constraints on sizing and operation of the different technology components.	Objectives on LCOE typically. Locational and technology usage constraints.	Objectives on profitability (NPV, etc.). Locational and technology usage constraints.
Optimization Problem Formulation – Workflow Architecture and Algorithms	Monolithic mixed integer linear programming	Monolithic (mostly) NLP or MINLP (can include suboptimizations that are typically NLP) (both gradient-based and gradient-free)	Monolithic (mostly) NLP or MINLP (can include suboptimizations that are typically NLP) (both gradient-based and gradient-free)

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