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Optimal sizing of flexible nuclear hybrid energy system components considering wind volatility

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HIGHLIGHTS

- Volatility exponentially increases levelized cost for penalized energy systems.
- Flexibility stabilizes short and long term costs for energy systems.
- Flexible energy systems will enable higher levels of variable renewable energy.
- Battery investment only becomes justified with higher levels of renewable energy.

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ABSTRACT

This paper seeks to quantify the benefits of a flexible energy system in the context of enabling higher levels of variable renewable energy on the grid. We explore a nuclear hybrid energy system (NHES) consisting of a 300 MW small modular reactor, wind generation, battery storage, and a reverse osmosis desalination plant. A dispatch rule is constructed within the Risk Analysis Virtual Environment (RAVEN) to model the system. Stochastic optimization and parametric analysis are utilized to explore how increased volatility in the *net demand* resulting from higher levels of wind penetration affect the optimal solution, and the stability of the system's levelized cost of electricity (LCOE). In this study, net demand is the demand minus wind generation. This work contributes multi-objective analysis implemented through a supply-demand mismatch penalty to illustrate the financial stability and operational reliability benefits of the flexible energy system. In this context, we find that the additional up front cost of flexible loads and energy storage result in greater stability in LCOE as volatility in the demand increases. Additionally, the flexibility results in increased reliability in terms of meeting the demand. Although the analysis is conducted on a NHES, we emphasize the flexibility of the method applied here, in that the RAVEN platform and the multi-objective strategy are widely applicable to the analysis of energy systems faced with uncertainties in supply and demand.

1. Introduction

Improvements in energy systems are predicated on the achievement of reductions in the carbon intensity of electricity generation either through technological change, emissions-reduction policies, or both. At the forefront of technological change and the carbon reduction efforts are variable renewable energy (VRE) sources such as wind turbines, solar photovoltaic panels, and solar-thermal generators, which accounted for around 77% of new power plant capacity installed in 2015 [1]. However, despite their emissions reduction benefits, they also portend negative implications for system stability because of their intermittency. Thus, much effort has gone into increasing the flexibility of the electricity grid to mitigate the disruptive effects of increased intermittent VRE generators. Flexible loads and buffering systems such as battery electric storage (BES) show high potential for improving system stability. BES can act as both a load and source for electricity, but also adds to the system's operational complexity. With added complexity comes cost implications. This paper contributes a methodology to assess and quantify the value of flexibility, and identify the conditions which justify the increased costs. Specifically, this study considers the role of flexible loads and energy storage in nuclear hybrid energy system (NHES) to increase the overall system's ability to reliably meet demand under varying levels of wind penetration. It is imperative to note that variability exists on both the demand side and supply side of the energy

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balance equation, thus, injecting some appreciable levels of risk in system operation. BES systems in this context are evaluated for their stability contributions to the system.

The methodology is based on the application of simultaneous perturbation stochastic approximation (SPSA) optimization in the risk analysis virtual environment (RAVEN) platform. This process integrates a parametric analysis into the RAVEN architecture by evaluating the changes in optimal system component sizing as a result of increased volatility in the net load input. RAVEN is in part a flexible framework for statistical analysis, sampling, optimization, and data-mining. RAVEN communicates with external models, meaning that it is well suited to a wide variety of energy systems outside of the NHES focus area.

Thus far, RAVEN has been the primary platform for NHES research. Initially, parametric studies were used to characterize the levelized cost of electricity (LCOE) of an NHES using fixed dispatch rules [2,3]. More recently, the SPSA optimization algorithm has been applied to sizing the industrial process within an NHES [4,5]. As an extension of prior works regarding NHES, this study includes in the optimization the sizing of battery storage, as well as a penalty function for mismatches between supply and demand. The penalty function acts as an incentive for the energy system to meet as much of the demand as possible in its operation, effectively acting as a second attribute in the optimization.

This study offers a look into an integrated energy and water system, and how volatility in the demand profile affects the optimal sizing of system components. The system presented here includes small modular reactors (SMR), reverse osmosis desalination (ROD) plant, and BES. The SMR is chosen as the primary generating technology because nuclear power plants consistently have the highest capacity factor, around 90% in the U.S. [6]. Because most of nuclear power plant outages are planned for fuel replacement, they are easily accommodated by system operators, and therefore do not significantly impact our findings. The ROD plant and battery serve as flexible loads, while the battery also serves as a peaking generator when possible. An exponential penalty function driven by the mismatch between the system's electrical output and net demand is used to quantify the reliability of the overall system in meeting the demand. The net demand, defined as demand minus wind generation, is subject to varying levels of wind penetration to capture the effects of volatility. The model seeks to minimize levelized cost of electricity. This model represents the next step in a series of prior studies around NHES and, to the best of our knowledge, it is the first to integrate stochastic optimization, battery storage, and a demand mismatch penalty function. This study contributes a methodology that is readily adaptable to systems where the value of flexibility needs to be considered in the optimization cost function.

In the context of this study, the LCOE is defined as the cost of electricity required to make a fair market return on the initial investment of the system. LCOE as defined by the Energy Information Agency (EIA) "represents the costs of building and operating a plant per kilowatt hour of output over an assumed financial life and activity level" [7]. In the context of NHES, it is a useful metric because it can account for multiple revenue streams, such as those from a secondary industrial product like desalinated water. Despite the various project lifetimes, fuel costs, and operating costs, LCOE provides a single metric that quickly signals how an energy system compares to other generating technologies.

A contribution of this work is the finding that while flexible loads and energy buffering systems initially increase the LCOE, they can significantly stabilize the LCOE as net demand volatility increases with increasing wind penetration. Currently in energy markets, nuclear energy does not offer a promising value proposition due to long payback periods, and the risk associated with volatile electricity markets. Additionally, increases in the amount of VRE production have eroded the base-load fraction of energy demand, negatively impacting the economic viability of high capacity factor energy systems. An NHES including energy storage and renewable generation can provide reliable base-load capabilities as well as flexibility. In this sense, the flexibility applies to both the hourly supply, but also the ability to withstand both short and long-term changes in operational modes.

The rest of this paper is structured as follows. Extant literature is discussed in Section 2. Section 3 describes the model. Section 4 presents results from the modeling, optimization, and parametric analysis, and describes some of their implications. Finally, Section 5 concludes the study with a summary and discussion.

2. Background

The feasibility and benefits of flexible energy systems is an important area of research. This section provides an overview of the primary strategies for increasing the flexibility of energy systems, and the methods applied in the analysis of those systems.

BES systems are at the forefront of research around energy system flexibility given that they can operate as both flexible generators and loads, depending on the system needs. Lazard's Levelized Cost of Storage analysis shows that in addition to load following and peak shaving, a number of ancillary services can be supplied by storage systems such as frequency and voltage regulation, ramp rate reduction, and spinning reserves [8]. Electricity consumers can exploit time of use benefits by storing electricity when it is cheap, and producing it for use when electricity is more expensive. One study utilized an advanced multi-pass dynamic programming algorithm to optimize BES capacity and contract size for an industrial time of use (TOU) rate customer. The study indicates that peak shaving can substantially reduce electricity costs, and optimal sizing can be achieved [9]. A later study uses a multi-pass iteration based on particle swarm optimization algorithm to investigate the optimal dispatch of a BES over a month. The results indicate that BES performs both load shifting and penalty avoidance duties under an optimal dispatch schedule [10]. Mixed integer programming shows that optimally sizing a battery can have cost reduction benefits for utilities when operated as a peaking generator, as well as for customers when operated as a peak shaving energy supply where TOU rates apply [11]. Decision theory methods were also applied to solve a discretized battery sizing problem in which static load profiles were used, and it was found that variations between load profiles (representing possible future scenarios) had an impact on the optimal battery size [12]. These studies highlight the importance of including load characteristics in adequately valuing the contribution of BES systems.

Another segment of the literature explores the benefits of energy system integration in the context of microgrids. A linear program to optimally dispatch heat and electrical energy among residential and industrial customers showed reductions in cost and carbon emissions as compared to simply purchasing from the grid [13]. Linear programming was also applied to optimally size components in a microgrid, a design that includes wind, solar, and diesel generators coupled with a saltwater desalination plant and the residential grid [14]. The resulting design was actually implemented, and has demonstrated that while the system consistently meets the microgrid's demand, increases in load volatility leaves the system financially liable without the inclusion of a substantial safety margin in the design phase. The liability of the system may also be influenced by the policy changes or ambiguity [15], uncertainty in technological learning [16] or variability in technological performance [17,18]. These stochastic elements add up to influence overall system risk, market and competitive investment of firms employing these technologies.

This paper makes the argument for optimization methods that incorporate the volatility of system inputs into the modeling structure. RAVEN's SPSA optimizer has demonstrated that it can effectively size NHES subsystems subjected to stochastic inputs, and finds that under the right market conditions, substantial performance benefits can be achieved [4,5].

Several studies have looked at potential ways to improve system