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Investigating the impact of wind–solar complementarities on energy storage requirement and the corresponding supply reliability criteria

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HIGHLIGHTS

- Demonstrate advantages that wind–solar complementarities brings to the very high renewable grid.
- Highlight importance of new thinking regarding the role and use of energy storage.
- Emphasize the need for better approaches to very high penetration of renewables.
- Calls for new reliability criteria in transitioning to very high renewable grid.

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ABSTRACT

This paper explores various questions regarding very high penetration of intermittent renewable to electricity grid. The study was performed using one-year hourly demand data of California's electricity grid together with the hourly-simulated output of various solar and wind technologies distributed throughout the state. The result shows that wind–solar complementarities carry significant multidimensional benefits to the future grid as compared to a stand-alone wind/solar based grid. Specifically at 20% total energy loss, it was shown that their optimal complementarities lead to very high renewable penetration with smaller storage and backup requirement. Our study of system dispatch shows that storage provides flexible dispatch strategy, which makes it applicable for various services depending on season of the year including reduction of summer backup capacity need. We have also found that the existing peak load based long term planning reserve criteria may no longer be applicable to very high renewable grid. Finally, comparing our result to literature data, we conclude that some of the pessimistic views of storage technology are borne out of our lack of understanding about its role and design requirement.

1. Introduction

The most viable option for sustainable economic development and reduction of polluting emissions in electric power sector is the realization of very high energy-penetration of intermittent renewable. Several studies exploring integration of intermittent renewable to the electricity grid have identified various challenges to achieving very high penetrations [1–28]. The challenges relate to operational uncertainty created due to its intermittency and non dispatch-ability, mismatch between load and the intermittent renewable output, policy requirements for very high penetration of intermittent renewable and energy storage, technological advances needed to overcome some of the technical limitations as well as high system cost, etcetera.

Researchers put forward various solutions to overcome the diverse challenges emanating from resource intermittency [1–39]. For instance, demand response could be employed to ease the load following challenges of conventional power plants, while energy storage may serve to solve both load following challenge as well as the mismatch between demand and renewable systems output. A study based on simulated hourly output of wind and solar resources shows that, with appropriately sized energy storage and an energy dumping of about 20% annual demand, more than 85% of the annual electricity demand could come from Wind and Solar [1]. Energy dumping was also found to lead to a significant reduction in backup capacity need via increased use of energy storage and renewable [1,7]. This challenges the perception that

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we should not dump any excess energy, which is based up on our experience of a grid mainly composed of conventional thermal generators.

The supply of electricity with renewable sources has been a subject of several studies [1–35]. In [35–39] the feasibility of wind–solar-storage (with or without diesel) hybrid systems for an island micro-power systems were presented. Specifically, a study by [29] reported reduction of energy capacity (EC) of storage by relaxing their "loss of power supply probability" criteria while a report by [30] shows the variation of EC with resource complementarities, though clear relationship between the two was lacking. In the later paper [30], the use of predefined assumptions regarding the batteries power and energy capacity may have compromised the flexibility of evaluating the impact of complementarities; because storage design flexibility was reported to have significant role in determining the appropriate storage capacity (of both power and energy capacity) requirement for high renewable penetration [1–3]. Furthermore, for an obvious reason, these [29–35] off-grid micro-power system studies have limitations in addressing the case of grid-connected large geographically distributed deployment of energy storage and renewable energy resources (PV and wind). On the other hand, high penetration to power grids around the world was also the subject of several studies [1–29]. Some of these studies focus on demonstrating low-carbon grid using high renewable [8–29] while [2,3,17,23,27] presents high penetration of PV and wind with the support of energy storage, respectively. In the absence of storage, Solomon et al. [4] showed that wind–solar complementarities aids the achievement of higher penetration than what would be achieved by an equivalent capacities of wind or solar technologies alone. Similarly, an advantage of complementarities between wind, solar and wave power was reported in [24]. However, both [4,24] did not address relationship between storage requirement and their complementarities. In [5], it was suggested that resource complementarities could reduce energy storage requirement, which was also observed in Solomon et al. [1]. But no one has quantified the impact of resource complementarities on storage sizing and use. In the present paper, building on our novel approach presented in [1], we will make a detailed examination of the impact of wind solar complementarities on storage sizing and use.

Another important question about very high renewable grid relates to reliability criteria and its enforcement. In the present grid, regulators put a hard requirement that utilities plan for peak load plus 15% capacity need [36]. The future very high renewable grid involves large energy curtailment, significantly underutilized conventional backup capacity, and large storage technology that would render several flexible applications. Moreover, we also envision that demand response (DR) mechanism augments safe and efficient operation of our power systems [37,38]. DR resources were reported to play important role at lower penetrations [37,39], but at very high penetration when energy dumping starts to dominate, energy storage is considered essential part of DR resource [40,41]. Furthermore, to evaluate the benefit of DR, tools with a capability to model the actual operation are important [42]. Together with that, the advantage of energy storage over the load shifting/interruption technique or vice versa has not been demonstrated at very high penetration. However, it is possible to gain deeper understanding of very high renewable grid and the potential role of DR by closely examining the property of the year round hourly dispatch. Moreover, it is also instructive to investigate how the backup requirement depends on resource diversity. In the present paper, we will also examine issues of supply reliability and the role that resource complementarities could play in system design and operation. To the author's knowledge, this is the first enquiry into such questions that attempted to generate relevant empirical data. We hope that this study motivates such enquiries worldwide.

2. Focus of the study

2.1. Modeling frame work

In our previous study [1], we examined the case of very high penetration of renewable using large linear optimization model. The optimization was done using one-year hourly demand data of California's electricity grid together with the hourly-simulated output of various solar and wind technologies distributed throughout the state.

The hourly data's for the year 2011, total transmission networks thermal capacity and the corresponding losses between load-areas in the state are taken from the SWITCH database [13]. Following [13], we also divide the state into 12 load areas. To overcome the limits of the computational runtimes, we assume that we can represent the backup requirement in each load area as a set of conventional generators with 100% flexibility. This model has components exploring very high penetration renewable with and without energy storage. The objective functions for storage model was formulated in a way that would enable us to achieve multiple goals simultaneously i.e., optimize penetration, and minimize storage system properties and the conventional backup capacity. The detail of various component of the model construction is given in the appendix of Solomon et al. [1]. However, in the following, we provide a summary of the two-storage design models.

2.1.1. Stored energy to be transmitted (SET model)

In this model, the energy balance equation allows the power exchange between load areas under all circumstances only constrained by the total thermal capacity of the transmission lines connecting the load areas. The model can transmit excess energy and store in a neighboring load area if necessary while releasing power to the entire network, as needed, constrained by the power capacity of the storage.

2.1.2. Stored energy used only locally (SEUL model)

In the foregoing version of storage model, the storage design could be affected by many factors other than the seasonal and diurnal matching between demand profiles and intermittent renewable energy systems. The SEUL version could help us identify other factors that may affect the storage design requirement. It limits the stored energy use only to the load area where the storage is built, even though it allows direct transmission of the generated renewable energy between load areas. We also assume that the conventional backup is also built to meet the local energy need.

These models share the same objective function. In the preceding paper [1], we have shown that the SEUL version model better approximate the smallest energy storage. In the present study, we will use the SEUL model to assess the impact of complementarities on the storage design requirements. Then, we will use the SET model version to study the impact of energy dumping and resource complementarities for a fixed storage power and energy capacity. This study focuses on deeper examination of our findings and scenario analysis of some conditions. Therefore, we made minor modifications to assumptions and modeling strategies presented in that paper [1]. Specific cases relevant to the present study will be presented in the following sub-sections.

2.2. Impacts of wind and solar complementarities

The electrical output of wind and solar technologies substantially vary from time-to-time. The variability depends on geographic location, weather, time of the day, season and various topographic conditions. Fig. 1 presents the hourly profile of simulated output of wind and solar technologies, and the corresponding