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The dynamics of electricity grid operation with increasing renewables and the path toward maximum renewable deployment

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ABSTRACT

This paper presents an overview and analysis of the dynamics and unique impacts of variable renewables on the grid, and identifies the bottleneck problems and solutions associated with renewable integration.

Variability issues that concern many are not unique to variable renewables. Grid operators have been dealing with demand variability for over a century. With sufficiently accurate forecast for variable renewables, the grid operators can schedule dispatchable generation and/or storage resources to balance demand and supply on a nearly real-time basis. With state-of-the-art wind forecasting technologies and existing generation resources, wind integration has not caused major operational problems for grid systems with a penetration level of up to 37% during some time intervals.

Base load generators operate nearly constantly for days or longer and supply a larger share of the electricity mix than what is proportional to their capacity. This will be a limiting factor for high level variable renewables, if current operation continues.

The capability to at least partially follow electricity load should be a key performance measure of non-renewable plants if we are serious about high level variable renewables. Specific policy instruments are recommended to incentivize more flexible plant operation and ensure smooth integration of variable renewables.

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1. Introduction

Climate change has been increasingly recognized as a global challenge. Energy related GHG emissions including CO_2 and methane have been identified as the single largest contributor to the climate change effect [1]. Current energy systems also bring about other local or regional challenges such as energy security, environmental pollution, and potential political tensions or even international conflicts over fossil fuel resources. To address these issues, more and more governments are implementing various programs and energy policies to accelerate the deployment of renewable energy such as wind, solar, biomass, and geothermal in the electricity grid and other sectors. Some countries view the pursuit and realization of a high level renewable penetration as an opportunity for economic growth, since companies that produce renewable energy domestically will create jobs and revenue. A low-carbon economy with clean energy technologies and options is increasingly mentioned in government reports in countries such as the U.S., China, Germany, and Japan.

The penetration of renewable energy is still low in most countries, and some question the technical and economic feasibility of high level renewable penetration considering a variety of perceived constraints such as installation cost, transmission and distribution capacity limits, and the uncertainty and variability of wind and solar outputs [2]. Despite these doubts, there is wide consensus that renewable energy is more environmentally benign and that the diversified portfolio of renewables is better aligned with energy security requirements. As a result, many governments are developing policies that promote the deployment of renewables.

Targets for penetration levels of renewable energy are different in different countries or regions, and in different time periods. For example, the California Renewables Portfolio Standard (RPS) established in 2002 requires 33% of eligible renewable energy resources in its grid electricity mix by 2020, which is one of the most ambitious state regulations in the US. The 2012 version Renewable Energy Sources Act in Germany (Erneuerbare Energien Gesetz – EEG) requires 35% of renewable electricity production by 2020, 50% by 2030, 65% by 2040, and 80% by 2050 [3]. These energy policies probably reflect the renewable penetration level for the electricity grid that the legislators and policy makers believe to be politically and economically viable within a certain time frame. This paper does not intend to discuss what is considered a high and maximum renewable penetration level in a particular region within any given time frame. The focus is to better understand the impact of a high level (e.g., $>35\%$ in annual total generation) renewable penetration on the electricity grid, and to explore solutions to overcome the associated operational challenges to achieving such high level renewable deployment.

There has been a significant amount of research discussing the potential operational challenges of high level renewable penetration on the grid, and the intermittency and variability of wind and solar is widely considered a significant barrier. Many studies suggest energy storage could play an important role in addressing the variability issues [4,5]. These studies are a good start for addressing the issues, but a systematic and in-depth examination on the dynamics of electricity grid operation with increasing renewables is still to be performed. Some prior studies [6,7] have explored this area to some extent, but a lot remains to be done. In addition, there has been recent technology advances in wind and solar energy output forecasting, which may play a very important role in a high level renewable grid, and its impact on the grid operation needs to be considered.

The objective of this study is to provide a better understanding of the dynamics and unique impacts of high level integration of variable renewables such as wind and solar on the electricity grid, and to identify the bottleneck problems associated with grid operation that would hinder increasing renewable deployment. Potential ways to eliminate these limiting factors are also discussed.

This paper starts by describing how the grid is operated without and with variable renewables. It then analyzes what unique impacts increasing and high level renewable penetration has on the grid. The challenges and opportunities associated with high level renewable penetration are discussed next. Potential solutions to overcome the bottleneck issues are proposed and discussed. Policy implications of the analysis are explored and discussed at the end.

2. The dynamics of electricity grid operation with increasing renewables

The renewable energy resources commercially in use today include hydro, wind, solar, geothermal, and biomass (including biogas) [8]. Based on their operational characteristics, the renewable resources can be categorized as either dipatchable or non-dispatchable. The output of geothermal and biomass is controllable, and they are considered dispatchable renewables. Wind and solar outputs depend on real time availability of variable wind and solar resources, and they are considered non-dispatchable renewables (some solar technology such as concentrated solar power (CSP) can gain a certain level of dispatching capability when coupled with thermal storage; nevertheless, solar resources are not dispatchable). Hydro power can be either dispatchable or non-dispactable, depending on the capability of plant operators to regulate water flow.

"Variable" and "intermittent" have been frequently used to describe non-dispatchable renewable energy such as wind and solar, and often in a tone suggesting these characteristics bring insurmountable challenges to achieving high level renewable penetration [9]. However, variability is not unique to non-dispatchable renewable energy. The electricity demand varies with random switch-on and off of electrical appliances, and is constantly changing. Electricity grid operators have been dealing with the variability issues of demand for more than a century since the establishment of the first grid system.

2.1. Grid operation without variable renewables

Before the integration of non-dispatchable renewable electricity such as wind and photovoltaic (PV) based solar, grid operators scheduled and dispatched the output of available generation resources according to the forecasted demand, which constantly changes with uncertainty. More specifically, grid operators procured generation resources based on day-ahead, hourly, and minutes-ahead forecast of electricity demand, and dispatched adequate electricity supply every few minutes to meet the demand. Fig. 1 shows a 24-h snapshot of the hourly forecasted and actual demand, and supply capacity (available resources) for the California ISO grid system as an example. As can be seen in Fig. 1, the actual demand matches well with the day-ahead demand forecast for some hours of the day, and deviates within a small range for other hours. Hour-ahead demand forecast offers higher accuracy, and enables grid operators to provide the reliable electricity service that is currently available to Californians. Nevertheless, there is still uncertainty in even the hour-ahead demand forecast.

The common practice for the grid currently is to meet the forecasted electricity demand with three types of electricity generation resources: base load generators, intermediate load generators, and peak load generation resources. Base load generators meet the minimum level of demand (normally 35-40% of the peak demand) and run constantly over 24 h or longer periods. Intermediate, also called load following, generators adjust their power output as demand fluctuates throughout the day, and