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How low can you go? The importance of quantifying minimum generation levels for renewable integration

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ABSTRACT

One of the significant limitations of solar and wind deployment is declining value caused by the limited correlation of renewable energy supply and electricity demand as well as limited flexibility of the power system. Limited flexibility can result from thermal and hydro plants that cannot turn off or reduce output due to technical or economic limits. These limits include the operating range of conventional thermal power plants, the need for process heat from combined heat and power plants, and restrictions on hydro unit operation. To appropriately analyze regional and national energy policies related to renewable deployment, these limits must be accurately captured in grid planning models. In this work, we summarize data sources and methods for U.S. power plants that can be used to capture minimum generation levels in grid planning tools, such as production cost models. We also provide case studies for two locations in the U.S. (California and Texas) that demonstrate the sensitivity of variable generation (VG) curtailment to grid flexibility assumptions which shows the importance of analyzing (and documenting) minimum generation levels in studies of increased VG penetration.

1. Introduction

After two decades of grid integration studies and renewable deployment, the challenges of integrating large amounts of variable generation (VG) wind and solar resources on the bulk power system have converged on a specific subset of issues. One major concern is the economic limit to deployment that results from declining value of renewable generators as a function of penetration, which results in an "economic carrying capacity" of the power system (Cochran et al., 2015). The value of VG as a function of penetration depends on many factors, including renewable supply and electricity demand patterns and a variety of system constraints such as transmission capacity and the minimum production levels from hydro and thermal generation. The decreasing value of renewable energy (or increased costs depending on perspective) raises concerns about the contribution of VG resources to a decarbonized electric power system.

The constraint imposed by minimum generation levels from conventional generators is and will continue to be a critical factor for VG integration. While it is part of the more general issue of "grid flexibility," this specific issue has a set of drivers that include:

- The overall ramp range of thermal generators, their minimum up and down times, and start-up costs
- The need for process heat from combined heat and power (CHP) plants which requires them to generate electricity
- Minimum flow limits on hydro units.

In combination, these restrictions create significant technical and economic challenges to reaching increased levels of VG penetration. In this work, we examine the drivers behind minimum generation levels, and we examine how these levels may be determined. We discuss data sets available for the U.S. power system and provide examples of how these data sets are used in simulations to estimate the impact of minimum generation levels on VG integration. Finally, we demonstrate the importance of assessing minimum generation levels for estimating VG curtailment and the need for "enabling" technologies such as energy storage to achieve increasing levels of VG penetration.

2. Basic relationship between minimum generation levels and VG curtailment

The ability of a power grid to accommodate VG is often illustrated by the concept of "net load" (also known as "residual load"), which is the normal load minus the contribution of VG. Any increase in VG output is matched by a corresponding decrease in output of thermal and hydro units. The reduction in output of thermal and hydro units is limited by a large set of operational constraints on individual units as well as the fleet as a whole. The net effect is a limit to the instantaneous

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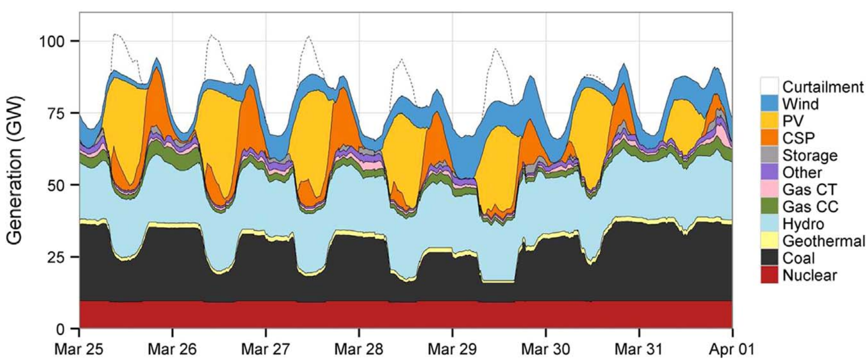

Fig. 1. Minimum generation levels resulting in renewable curtailment (Lew et al., 2013).

penetration of VG, and as a result, a limit to the overall contribution of renewable resources. Fig. 1 illustrates this limit using results from the Western Wind and Solar Integration Study Phase 2, which simulated grid operations under increased penetration of VG in the Western United States (Lew et al., 2013). The figure shows the system-wide dispatch (output of all generators) during a week with low net load in a scenario where 25% of annual load is met by solar and 8% from wind. During this week, there is substantial curtailment of solar generation—despite production from coal-fired and nuclear generators with higher operating costs—because the power system cannot reduce output of thermal and hydro generators.

Previous analysis has demonstrated that curtailment can increase dramatically as a function of penetration but also that curtailment is highly sensitive to assumptions about how much the conventional fleet can respond to variations in net load (Denholm and Hand, 2011). As a result, it is important that studies of increasing penetration of VG consider the impact of minimum generation levels when evaluating renewable portfolio standards, new generation mixes, and other elements of a changing power grid.

3. Sources of minimum generation level, quantification, and data sources

The potential role, costs, and integration challenges of VG in future power system is typically examined in utility planning and integration studies (Cochran et al., 2014). These studies are used for a variety of purposes, including estimating the optimal mix of generation resources, assessing system reliability, and calculating overall costs to utilities and ratepayers. A key element of these studies is the use of chronological grid simulation tools (production cost models) that simulate the hourly or subhourly operation of the power grid including individual power plants and major transmission elements while calculating operational costs and several basic metrics of system reliability. Additional models may be used to perform detailed studies of system stability and transmission adequacy (e.g., GE Energy, 2014a). Regardless of the modeling approach and specific tool employed, the studies typically start with a database of the existing power grid, including a detailed set of generator performance characteristics including size, efficiency (heat rate) curves, fuel costs, as well as transmission network topology. System studies then simulate various scenarios where the generators are committed and dispatched based on their marginal costs, resulting in a "least-cost" dispatch (FERC, 2015). System dispatch both in modeling studies and the real world must consider a large number of constraints including a variety of technical, economic, and policy factors that determine the minimum generation levels from individual generators. Some of these parameters are listed in Table 1. Many of these factors can be captured from readily available data, while others depend on data that may not be readily available (Lew et al., 2015; Younghein and Martinot, 2015). Each of these categories is discussed in detail in the following subsections.

Table 1
Minimum generation constraints.

Type of plant	Key techno-economic parameters/drivers
Fossil thermal	Minimum stable level and part load efficiency Minimum up and down time, start-up costs Individual plant emissions limits Local reliability must run units
Combined heat and power (CHP)	Plant schedule, process heat requirements
Non-fossil thermal	Ramping of nuclear plants Scheduling of planned maintenance/nuclear refueling Constraints on landfill gas flaring and leakage
Hydro	Physical constraints (e.g., water flow, water budgets) Social/environmental constraints (e.g., fish, recreation, and irrigation)

3.1. Fossil thermal plant limits

The general category of fossil thermal plant limits is probably the most important category of those listed in Table 1 because of the large number of such plants and the fraction of total generation that they represent. About 778 GW (nameplate rating) of fossil-fueled (electricity only) power plants were in operation in the United States (lower 48 states) in 2015, or about 67% of the total system capacity (EIA, 2016). Given the importance of these plants in system operation, many VG planning and integration studies place a substantial effort in obtaining and quantifying thermal generation performance data, including minimum generation levels.

The minimum output of fossil thermal plants is limited by two components: the ability of a plant to reduce output while still operating and the ability (and cost) of power plants to shut down and restart later (Kumar et al., 2014; Henderson, 2014). Both of these factors must be evaluated. Considering only an operating ramp range is unrealistic, as frequent daily generator starts and stops have always been part of the inherent operation of power systems. Fig. 2 illustrates an example, using historical data from 18 GW of combined-cycle generators in California (obtained from EPA, 2017) and market prices for the same time period. Power plants respond to variation in system demand (reflected in prices) by varying output. These variations include changing commitment status and ramping over committed range. The blue line in Fig. 2 represents online (committed) capacity, while the red line represents actual output.

Understanding the ability and costs associated with both ramping and turning on/off plants is critical to performing grid integration studies. Certain plant-level data are available to system planners and researchers from a variety of sources. Publicly available data sets are available from government agencies, including the Federal Energy Regulatory Commission (FERC), the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Energy's Energy Information Administration (EIA). One example is the EIA 860 database, which