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Modeling constraints to distributed generation solar photovoltaic capacity installation in the US Midwest

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HIGHLIGHTS

- A model is developed of impacts from increasing solar energy in the Midwest.
- Solar generation is accommodated by coal, natural gas, and hydroelectric changes.
- Constraints to increasing solar are mitigated when possible through curtailment.
- 22 GW and 28,843 GWh of solar can be accommodated without the need for curtailment.
- Existing technology can accommodate solar offsetting up to 13.7% of generation.

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ABSTRACT

This paper presents a model for estimating the amount of distributed generation solar photovoltaics (DGPV) that can be accommodated by an electrical system, limited by the ability of existing generation infrastructure to change output. The model is applied to a region of seven states in the U.S. Midwest, showing the potential for temporary curtailment of installed DGPV to mitigate those constraints, and the associated reductions in coal- and natural gas-fired electricity generation. Scenarios considered are those under which 100%, 99.5%, and 95% of available solar can be utilized, and the point at which DGPV curtailment can no longer mitigate constraints because of the inability of conventional generation to keep pace as solar output declines in the late afternoon.

The model is developed using historical hourly fuel use data for electricity generation, hourly solar capacity factor, and carbon emissions factors. The model includes a generalized linear model, constructed by regression analysis, used to allocate potential reductions in conventional generation in response to demand changes caused by DGPV. Limits on output and ramping of conventional generation are considered and initially mitigated, where possible, by changes in hydroelectric generation.

Results indicate that a substantial amount of DGPV can be accommodated without any changes to current generation infrastructure, and that small amounts of curtailment enable greater DGPV capacity and generation. In a scenario without curtailment, DGPV could provide about 6% of total generation in the modeled region. With just 0.5% curtailment at DGPV installations, roughly 9% of generation could be provided by DGPV. Ultimately, up to 14% of generation could be achieved through DGPV installation before technological limitations would diminish the ability to meet all demand with further increased DGPV.

1. Introduction

There are increasingly actions being taken around the world to reduce anthropogenic greenhouse gas (GHG) emissions due to concern about the severe threats to global health and welfare that result from long-lasting changes in the earth's climate. One of the primary such actions is to replace fossil fuel-fired electric generating stations, which are among the most significant sources of emissions (representing the largest single source of GHG emissions in the United States for example, primarily in the form of CO_2) [1], with lower- or zero-emission sources of electricity. Solar photovoltaic generation technology is one such zero-emission source that is being installed at a rapidly increasing rate globally.

In this paper, a model is developed for calculating constraints on

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increasing distributed generation photovoltaic (DGPV) capacity related to the ability of existing coal, natural gas, and hydroelectric generation infrastructure to change output. The model demonstrates the effects of differing generation characteristics on the ability for such an electrical generation system to accommodate high levels of DGPV installations, as well as the potential for temporary curtailment of installed DGPV to mitigate those constraints.

The extent to which a modeled electrical system will be able to utilize DGPV depends on the available solar resource and the ability of the current electrical generation mix to accommodate new DGPV generation. The model considers available solar resource, region-wide hourly historical fuel use data and characteristics, and existing capacity by state. In addition, to offset limitations of large-scale coal and natural gas generation (hereafter "gas") to quickly change output, hydroelectric generation (hereafter "hydro") is included in the model as a potential balancing factor.

The model is then applied to a region consisting of seven states in the US Midwest managed by the Midcontinent Independent System Operator (MISO): Iowa (IA), Illinois (IL), Indiana (IN), Michigan (MI), Minnesota (MN), North Dakota (ND), and Wisconsin (WI). Outcomes from the model include four specific scenarios for DGPV installation by state and across the region: the maximum DGPV capacity wherein all solar generation is utilized, the points at which 0.5% and 5% of potential solar generation must be curtailed, and the maximum amount of DGPV capacity feasible to install before causing disruptions in electricity supply due to the inability of other modeled generation sources to increase output when solar generation decreases as the sun sets.

These results are discussed in terms of the levels of DGPV capacity and generation corresponding to each scenario, reductions in generation for each fuel source (coal, natural gas, and hydro), carbon dioxide (CO_2) emissions, and electrical system peak demand. Factors which could increase the feasible levels of DGPV are also discussed, including smart inverter technology. The results hold implications and real applications for a number of stakeholders including electric grid operators, utilities, independent power producers, regulatory bodies (such as public utility or service commissions), and solar power researchers and industry.

The paper is organized as follows: the balance of this Section 1 will discuss background related to the model and to increasing DGPV capacity in the Midwest; Section 2 presents the framework of the model, with an explanation of the source data and methodology; Section 3 then presents the development of the model; results are presented and discussed in Section 4; finally, in Section 5, overall conclusions are presented. Nomenclature used throughout the paper is shown in Table 1.

Table 1
Nomenclature used throughout the paper.

Symbol	Description	Typical units
CF	Capacity factor	–
Δ	Change in	–
E^D	Energy demanded (consumption)[a]	MWh/GWh
E^G	Energy generated[a]	MWh/GWh
$fuel$	Generic fuel index	–
f	Fossil fuel (coal or natural gas) index	–
i,j	Generic indexes	–
$\mathbf{k}$	Modeled hour[b]	–
$\mathbf{K}$	Historical hour[b]	–
p	Generic proportion or scaling factor	–
P^D	Power demanded (load)[a]	MW/GW
P^G	Power generated[a]	MW/GW

[a] Subscripts on E and P variables used variously to indicate quantities by state, fuel source, power plant, etc.
[b] $\mathbf{K}$ and $\mathbf{k}$ are used instead of $t$and shown in brackets (like $P^G[\mathbf{k}]$) to indicate the discrete (rather than continuous) nature of the model.

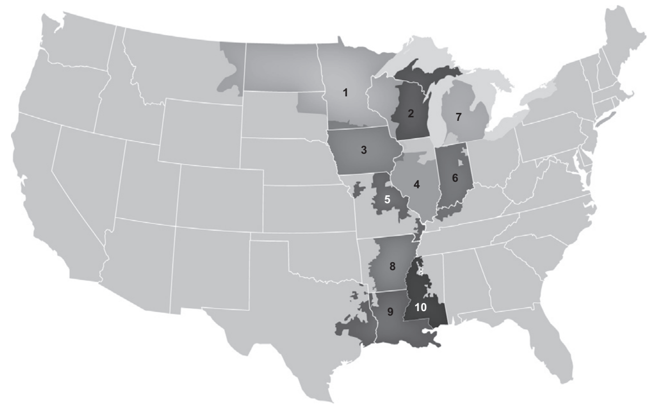

Fig. 1. MISO local resource zones (figure courtesy MISO).

1.1. Region under study

To ensure applicability to real-world electrical generation systems and minimize error associated with forecasting, historical hourly generation data is used to develop and evaluate the model. Specifically, the main input is hourly fuel use data obtained from the Midcontinent Independent System Operator (MISO) for the North and Central generating regions [2–5], and as a result the model is constrained to the areas in which MISO operates [6]. These areas are shown in the map in Fig. 1. The model considers each state in the study individually, and as a single combined region.

The North region is comprised of LRZs 1, 2, and 3, covering the entirety of Iowa, Minnesota, North Dakota, and Wisconsin. The South generating region, which is not included in this study, consists of LRZs 8, 9, and 10.

The Central region consists of LRZs 4, 5, 6, and 7. LRZ 5 covers a small portion of Missouri only, and has been excluded from the present study: annual generation from the MISO areas is less than 1% of the total generation for the state. The remaining LRZs cover the majority of Illinois, Indiana, and Michigan. Several counties in each state are not part of MISO territory (most notably Cook county, IL, which includes Chicago), and have been excluded from the present study. Details of the specific counties excluded, as well as a breakdown of the 2015 generation for the seven states in this study are given in the supplemental material.

1.2. Previous efforts

The present study was initially based on a pair of 2010 papers analyzing the impact of high DGPV penetration in Wisconsin, using 2002 hourly electric load data [7,8]. The authors estimated that due to minimum loading, DGPV could provide no more than 20% of total energy in Wisconsin, even with capacity at four times the level of conventional capacity. Minimum loading refers to the load which must be met at times when solar energy is not available. Because per-fuel source data was not available, the model used a flexibility factor of 60% for total generation. As DGPV capacity is increased, the authors found that additional capacity is providing generation during hours of the day in which the maximum load has already been met.

A more recent paper applies a similar method to an analysis of Illinois, but using more granular hourly solar estimates from the National Solar Radiation Database, and state-wide hourly demand data [9]. However, as the demand data does not indicate the ratio of sources used for generation, the authors calculate a value for "baseload power" and assume that this demand will be met by thermal generation, with the balance available to be served by solar PV. Results indicate that 7.3% of Illinois' energy can be provided by DGPV prior to the need for solar curtailment.

A large-scale model which can be used for similar analyses is