MODELING DISRUPTIONS IN POWER SYSTEM RELIABILITY USING A STATE CONTINGENT PRODUCTION FUNCTION APPROACH

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Overview

Using wind and solar photovoltaics (WPV) to generate electricity has long been cited as one potential solution to reduce carbon dioxide and other harmful greenhouse gas emissions. However, given the intermittent nature of WPVs, as the net generation of electricity supplied by them increases, so too do concerns over their impact on power system reliability. The objective of this paper is to provide a theoretical and empirical examination of how increasing the net generation of electricity supplied by WPVs impacts power system reliability. This paper makes two significant contributions to the literature.

First, while examinations of the reliability implications of transitioning an electrical power system to rely more heavily on WPVs have been conducted for other countries (Zaidi 2007; Chang and Wu 2011; Schmid, Pahle, and Knopf 2013; Abrell and Kunz 2015; Abrell and Rausch 2016; Pean, Pirouti, and Qadrdan 2016) to our knowledge, attempts to examine the impacts of such a transition for the United States have only been limited with the exception of Hibbard, Tierney, and Franklin (2017).

Second, this paper represents the first attempt to model power system reliability using a state-contingent production function approach. In its current state, the U.S. electrical grid operates as a one-way street where electrons are passed through the three phases of production sequentially (Gerrity and Lantero 2014). In addition, due to the lack of commercially available large-scale battery storage along the grid, electricity must be produced in real-time, the instant that it is needed. To ensure that supply (generation) equals demand (load) at all times an electrical power system operator must determine in advance, when and which generating units will be online (Federal Energy Regulatory Commission 2015; Blumsack 2018).

A troubling consequence of scheduling units to be online in advance of actual operations, is the future state-of-the-world is not yet known (Yang et al. 2017). Therefore, the power system operator faces uncertainty. Given the availability of WPVs depend largely on real-time weather conditions, if WPVs are scheduled to be online but conditions for WPVs are not favorable or as expected, then reliability of the power system could be negatively affected. Utilization of the state-contingent production function approach allows us to account for this uncertainty (Chambers and Quiggin 2000).

Methods

Following the state-contingent production function approach, we assume an electric utility company intends to produce only one output, electricity E_{it}, using a set of inputs, including capital (K_{it}) labor (L_{it}), and a combination energy resources which includes exhaustible, non-renewable fund resources (e.g., coal, oil, natural gas, and nuclear energy) (r_1), exhaustible, renewable fund resources (e.g., woody biomass) (r_2), storable, renewable, flow resources(e.g., geothermal energy and falling water for hydroelectricity) (r_3), and non-storable, renewable, flow resources also known as WPVs (r_4).

When scheulding resources to be onling, the power system operator considers the probability α_s that a random state of nature s will occur in the future. For ease of exposition we consider only two states of nature are possible $s \in \{1,2\}$ - state of nature $s = 1$ where conditions for WPV are favorable/as expected, and state of nature $s = 2$ where conditions for WPV are not favorable/as expected. The production function corresponding to the unit commitment problem can be expressed as follows:

(1) $E_{its} = E(K_{it}, L_{it}\ r_1, r_2, r_3, r_4) \qquad s \in \Omega = \{1,2\}.$

The production function in (1) is assumed to be well-behaved such that electricity production is continuous; strictly increasing in all inputs and all inputs are strictly necessary for production to occur. In the case where the state of nature $s = 2$ reveals itself, and the electric utility company has scheduled WPVs to be online, the utility can expect electricity E_{its} will not delivered to end consumers in a reliable manner – a power system disruption will occur. In the case of a power system disruption, equation (1) can be modified as follows:

(2) $E_{it2} = E(K_{it}, L_{it}, R[r_1, r_2, r_3, r_4]) \equiv OUT_{it}.$

In equation (2) power system outages OUT_{it} depend on many factors, including energy resource inputs, which are committed *ex ante* with the intention of producing electricity.

For our empirical analysis, the state-contingent theoretical approach discussed above suggests the need for a measure of disruptions in power system reliability. While there are many different definitions of electrical system reliability available in the literature, for the purposes of this study, we assumed electrical system reliability is defined as the ability of the electrical grid generating system and its components to provide a consistent, steady, uninterrupted supply of power to end-consumers. To this note, our empirical analysis focused on end-user interruptions as measured by two indices, namely the System Average Interruption Duration Index (*SAIDI*) and the System Average Interruption Frequency Index (*SAIFI*). Values for *SAIDI* and *SAIFI* have been reported on the U.S. Energy Information Agency (EIA)'s Survey Form EIA-860 since 2013.

Matching information reported on Survey Form EIA-860 with power plant operational data reported on Survey Form EIA-923 between 2013 and 2017, we estimate the impact of increasing the net generation of electricity supplied by WPV applying an random-effects model specification to an equation of the following form:

(3) $$OUT_{it} = \beta_0 + \beta_1 PrimeWPV_{it} + \beta_2 WPV_{it} + \beta_3 WPV_{it}^2 + \beta X_{it} + \delta Year_{t-1} + c_i + \mu_{it}.$$

In (3) , disruptions in power system reliability are measured by the dependent variable, OUT_{it} which is equal to inverse hyperbolic sine (IHS) transformation of *SAIDI* or *SAIFI* (Johnson 1949).The term X_{it} represents a vector of observable characteristics believed to influence the frequency and/or duration of power system disruptions experienced by end-consumers.

Variables of interest include $PrimeWPV_{it}$, an indicator for utilities who identified WPVs as a prime mover for at least one of the power plants they used to supply electricity to their end-consumers, WPV_{it} the net generation of electricity attributable to wind and solar photovoltaics, and WPV_{it}^2 which accounts for potential concavity in the relationship between net generation from WPV and disruptions experienced by end-consumers.

Results

The results from estimating (3) correcting for both heteroscedasticity and autocorrelation, indicated utilities who identified a WPVs as a prime mover for at least one of their power plants, experienced shorter and less frequent power system outages than utilities who did not. Net generation from WPV, on average, was found to have a significant positive impact on the duration of power system disruptions experienced, but only at low levels of net generation from WPV. Specifically, results suggested generating one additional giga-watt hour (GWh) of electricity from intermittent renewable resources results in only a 0.09% increase in the duration of disruptions experienced. However, as the net generation of electricity generated from WPVs increased, shorter disruptions in power system reliability, as measured by the IHS transformed values of *SAIDI*, were experienced. The effect of WPV on the duration of disruptions becomes negative when net generation from WPV 1,260 exceeds 1,300 GWh.

Only six of the 276 utility companies in our sample (about 2% of the sample) generated more than 1,000 GWh of their annual net generation from WPV between 2013 and 2017. However, with current renewable support policies in place, relatively significant, non-marginal increases in the amount of net generation supplied by renewables (including WPV) are expected (or in some cases mandated). Therefore, to provide some perspective on the policy implications of our results, we projected disruptions in power system reliability, for all states with active renewable support policies in place to determine how meeting future targets set by renewable support policies would impact reliability in these states.

Results suggest if WPV represented five percent of total net generation, then customers across states with active renewable support policies in place could expect, on average, to be without power for an additional 405 minutes (about 6 hours and 45 minutes) per year. If net generation supplied by WPV exceeded 50%, all else equal, customers could expect to be without power on average for an additional 248 minutes a year. This implies that as WPV penetration grows over time, utilities are likely becoming better equipped to manage power system disruptions resulting from their use.

Conclusions

Although our regression model results showed a statistically significant negative marginal effect of increasing WPV generation on power system reliability, further analysis is needed to control for potential endogeneity. For example, if increasing the net generation of electricity supplied by WPVs is known to lead to longer and/or more frequent power system disruptions, then utilities who already experience longer and/or more frequent power system disruptions may be less likely to install generation from WPVs, and vice versa. In addition, to account for differences in the impact of WPVs on the probability that a customer experienced a disturbance in power system reliability, as well as the intensity of disturbance given that it had occurred, we suggest exploring using a two-step Cragg-Hurdle Model (Cragg 1971; Greene 2012) to estimate equation (3). The Cragg Hurdle model is not only well-suited to handle the censored nature of our dependent variables but would also permit estimation of separate equations for the bounded and non-bounded outcomes. The study team is currently addressing both suggestions.