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Location matters: The impact of renewable power on transmission congestion and emissions

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HIGHLIGHTS

- Analyze the impact of renewable power plant location on congestion and emissions.
- Simulate optimal power flow in a test grid for over 10,000 configurations.
- Determine that emission reductions vary by a factor of 7.
- Find that renewable power is curtailed due to transmission congestion.
- Pricing emissions is most efficient since abatement potential varies across locations.

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ABSTRACT

Many governments offer subsidies for renewable power to reduce greenhouse gas emissions in the power sector. However, most support schemes for renewable power do not take into account that emissions depend on the location of renewable and conventional power plants within an electricity grid. I simulate optimal power flow in a test grid when 4 renewable power plants connect to the grid across 24 potential sites, amounting to over 10,000 configurations. Each configuration is associated with different levels of emissions and renewable power output. I find that emission reductions vary by a factor of 7 and that curtailment due to transmission congestion is more likely when renewable power plants are concentrated in an area of the grid with low demand. Large cost savings could be obtained by allowing subsidies for renewable power to vary across locations according to abatement potential or by replacing subsidies with a price on emissions.

1. Introduction

The United States (US) government has several policies in place, both at the federal and state level, that promote the production of electricity using renewable energy sources to mitigate climate change and improve energy security. While the US possesses an abundance of renewable energy sources, such as wind, solar, and geothermal, renewable power plants (RPPs) are not necessarily built in areas with high renewable energy potential, in part due to differences across states in the types of incentives offered (Hitaj, 2013).

The patchwork of state incentives for renewable power contributes to a certain distribution of RPPs across the electricity transmission grid that makes sub-optimal use of both renewable energy and transmission resources. RPPs cluster in areas that offer the most generous portfolio of government incentives, which can lead to transmission congestion and curtailment of renewable power. The developer of a new RPP takes the effect of congestion on its own output into account, but ignores the effect of its marginal contribution to congestion on output from existing plants. This externality can be corrected through congestion pricing, which is in effect in only some parts of the US electricity grid, to allow for efficient transmission capacity allocation among power producers.

A second externality at play concerns emissions from conventional power plants (CPPs). Without a price on emissions, the developers of CPPs do not internalize the costs society incurs through polluted air and water. Subsidies for renewable power are only an indirect way of addressing this externality, as they do not vary across locations according to the abatement achieved by RPPs. Output from a new RPP at a particular location substitutes for output from a specific set of existing power plants. The change in overall emissions induced by the new RPP depends on the emission rates of the substituted set of existing power plants. Thus, the abatement achieved by RPPs varies across locations, which a general subsidy for renewable power does not take into account.

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Understanding how RPPs contribute to reducing power sector emissions is vital to mitigating climate change in an efficient manner. Despite rapid growth in renewable power and growing evidence of transmission congestion affecting renewable power output, there is little research to date on the effect of the congestion externality and power plant location on power sector emissions.

Some studies focus on the relationship between transmission congestion and renewable power output. Førsund et al. (2008) determine that phasing in wind power in Norway contributes to transmission congestion and crowds-out hydropower. Phillips and Middleton (2012) develop an optimization model for the geospacial arrangement and cost minimization of wind power generation and transmission infrastructure. They find that the costs of integrating a certain amount of wind in the ERCOT electricity grid can be reduced by up to 50% by jointly optimizing investment in wind plants and transmission capacity.

Other studies directly link renewable power output to system-wide emissions. Blumsack et al. (2007) analyze the emission impacts of incremental investments in wind power in the Western US using a generation dispatch model that incorporates the impacts of transmission constraints. They find that the location of wind plants changes the utilization of transmission assets, which affects system-level emissions, with wind investment in *some* locations leading to slight increases in overall emissions. Kaffine et al. (2013), Novan (2015), and Cullen (2013) examine the emissions offset by wind generation in Texas and find substantial variation in emissions reductions over time driven by differences in the emission of the marginal generation plant. Only Callaway and Fowlie (2009) find that an abatement-specific subsidy does not significantly alter the order in which new wind power plants are developed in New York and New England as compared with a general renewable power subsidy. However, they do not employ a generation dispatch model, and so are unable to replicate actual system operations. In addition, their results are unlikely to hold for the entire US, as the region they consider is fairly homogeneous in terms of wind and transmission resources and the distribution of conventional power plants across the grid.

Subsidies for renewable power are not designed to account for variation in abatement potential across space and time. In addition, it is more efficient to tax rather than subsidize an environmental “bad,” such as power sector emissions. In a review of the literature, Borenstein (2012) determines that subsidies for renewable power are a poor substitute for pricing emissions from conventional power plants, since the timing and location of renewable generation impacts what generation is displaced. Fischer and Newell (2008), Fell and Linn (2013), Palmer et al. (2011), and Palmer and Burtraw (2005) compare the cost-effectiveness of various policy instruments for reducing emissions. They all conclude that a renewable power subsidy is a more costly instrument than an emission price for achieving a given level of emission reductions, because subsidies do not vary with the abatement achieved and because subsidies decrease electricity prices and thereby cause an increase rather than a reduction in electricity consumption.

This paper examines how the location of RPPs within a grid affects power plant output, transmission congestion, and emission levels in a series of simulations of optimal power flow in a stylized grid – the 30-bus test system of the Institute of Electrical and Electronics Engineers (IEEE). This grid consists of 30 nodes with 6 CPPs, and the simulation study investigates the effect of interconnecting 4 RPPs across the remaining 24 nodes. Each of the 10,626 configurations of 4 RPPs connected to the grid is associated with a different level of renewable and conventional power output, congestion and emissions. Power generation is dispatched in each simulation according to the generation dispatch model, replicating actual system operations.

While analyzing power flow in an actual rather than stylized grid would be more interesting, the data for that kind of a simulation analysis, including hourly generation data and most importantly grid data, are not publicly available. Indeed, the goal of this study is not to highlight the optimal RPP locations for a particular grid, whether actual or stylized, which would not be of much interest outside of the grid in question. Rather, the goal is to draw attention to the wide range of congestion and emission levels resulting from different RPP locations, for which a stylized grid is perfectly suitable.

First, I find that transmission congestion can have a significant effect on output from RPPs, when RPPs cluster together in more remote areas of the grid with low electricity demand. Second, the emission reductions achieved by an RPP depend on the emission rates of the CPPs its output substitutes for. Each potential RPP location is therefore associated with a different expected abatement potential. Given CPP emission rates that vary by a factor of 3, system-wide emissions are found to vary by a factor of 7 across configurations. In any grid where CPPs have significantly different emission rates, the degree of variation in the emission reductions achieved by RPPs across locations is considerable.

In sum, there are two effects at play. RPP location affects emissions through the substitution pattern with CPPs with differing emissions rates (quality effect) and through changes in output due to congestion (quantity effect). A more distributed arrangement of RPPs across the grid reduces congestion, increasing RPP output and (usually) reducing emissions. However, a more concentrated arrangement may result in greater overall emission reductions despite the diminished RPP output, because of particularly beneficial substitution patterns, such that the quality effect outweighs the quantity effect. For this reason, instituting a congestion price to increase RPP output does not guarantee emission reductions. Abatement at least cost requires subsidies for RPPs to vary across locations according to abatement potential or emissions to be priced at CPPs.

The great variation in emission reductions achieved by RPPs across locations means that large cost savings could be obtained by requiring subsidies for renewable power to vary according to the abatement potential of each location. However, the goal of guiding RPPs to the locations with the greatest abatement potential can be accomplished more readily with a price on emissions. A price on emissions ensures that air pollution externalities are appropriately internalized rather than through the roundabout method of subsidizing renewable power, disregarding each plant's contribution to emission reductions.

2. Background information

The location of an RPP affects both its power output and its abatement potential. Output can be negatively impacted by transmission congestion, which usually occurs when RPPs are located in areas of the grid with low electricity demand. Reductions in emissions likewise depend on where an RPP is located, as the configuration of the grid determines the size of the reductions (if any) in output of the CPPs, which have differing emission rates.

2.1. Electricity transmission congestion

Congestion occurs when the least-cost dispatch of generators would require power flow over a transmission line to exceed line capacity. This leads to higher local marginal electricity prices in the electricity demand center, since more electricity must be supplied by local generators rather than less expensive, distant generators. Expanding line capacity only temporarily eases