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Distribution system costs associated with the deployment of photovoltaic systems

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ABSTRACT

The broadening of our energy system to include increasing amounts of wind and solar has led to significant debate about the total costs and benefits associated with different types of generators—with potentially far-reaching policy implications. This has included debate about the cost associated with integrating these generators onto the electric grid. For photovoltaics (PV), this encompasses costs incurred on both the bulk power and distribution systems, as well as the value provided to them. These costs and benefits, in particular those associated with integrating PV onto the distribution system, are not well understood. We seek to advance the state of understanding of "grid integration costs" for the distribution system by reviewing prior literature and outlining a transparent, bottom-up approach that can be used to calculate these costs. We provide a clear delineation of costs to integrate PV in to the distribution system within the larger context of total costs and benefits associated with PV generators. We emphasize that these costs are situationally dependent, and that a single "cost of integration" cannot be obtained. We additionally emphasize that benefits must be considered when evaluating the competitiveness of the technology in a given situation.

1. Introduction

The cost of photovoltaic (PV) modules and systems are increasingly well known. However, the costs associated with integrating PV into the bulk power and distribution systems are not well understood, especially for very high penetration levels. Bulk power systems consist of centralized energy generators and high-voltage (≥ 69 kV) transmission lines that carry power from these generators over long distances. Distribution substations reduce the voltage from transmission lines and transfer power to the distribution systems, which consist of medium (typically 4–46 kV) and low voltage lines and constitute the final stage of energy delivery to the end user. There are multiple ways in which the presence of PV can affect both of these systems, potentially incurring a cost.

As penetrations of distributed PV (DPV) increase, uncertainty about the potential system impacts and their associated costs, in addition to concerns about utility business model disruption and cost-shifting of fixed costs associated with maintaining the electric grid from solar to non-solar customers, have contributed to debates around interconnection rules, net metering, and feed-in tariffs taking place across the globe. An enhanced understanding of the costs associated with—and value provided by—DPV is required to support the design of fair and efficient electricity tariffs, create policies that avoid market distortions, encourage low-cost solutions, help utilities plan more effectively for increasing penetrations of DPV, and compare different energy sources. An improved, more transparent approach for assessing these costs is also critical for reducing the uncertainty and cost of the interconnection process, which, in some cases, has presented a major hurdle to financing PV projects.

The costs associated with integrating PV into bulk power and distribution systems are both commonly referred to as "grid integration" costs; however, in general, modeling the cost of each of these systems involves distinct challenges. For the bulk system, past efforts to understand the costs and benefits of PV have highlighted "why calculating integration costs is such a difficult problem and should be undertaken carefully, if at all" ([1], pg. 1), largely due to complex, system-wide interactions. While system interactions at the distribution level are still quite complex, the localized nature of certain costs may make the definition of some distribution integration costs more tractable. Nevertheless, most past efforts in this area have been system-specific and have not attempted to extract generalizations. We begin to address this gap by surveying past work on PV integration costs at the distribution-level and then attempting to distill a more transparent and generalized framework for such evaluation.

Up to a certain penetration level, called the hosting capacity, PV may be incorporated onto the distribution system without requiring

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Table 1
Summary of prior work on distribution system costs associated with DPV.

Citation (year)	Scale and location	Methodology	Data included	Penetration levels	Key insights
[4] (2013)	Country, for a set of 11 countries in the EU	Imperial College distribution network planning tools	Distribution line costs, costs associated with distribution line losses	Varies between 2% and 18% (annual PV energy/annual energy demand), determined by projected levels for 2020 and 2030 scenarios in each country	● Costs associated with distribution line upgrades and losses may be positive (PV deployment results in a net cost compared to their base case) or negative (PV deployment results in a net benefit compared to their base case). ● Calculated costs of distribution lines with PV compared to the base case range from − 25 €/MWh to 9 €/MWh. ● Distribution line costs per MWh are not a monotonic function of PV penetration level; however, the highest cost per MWh does occur at the highest penetration level. ● Costs associated with distribution losses range between − 7.5 €/MWh and 1.8 €/MWh. ● When PV is present in the distribution system, the use of demand response results in lower distribution line costs as well as lower line losses.
[5] (2014)	Distribution circuit (feeder and substation), United States	Reported data from 90 SGIP reports for 3 utilities and one regional transmission operator	Total cost of mitigation and interconnection facilities required to safely and reliably connect PV	Varies, penetration in MW PV system sizes ranged from 2 to 20 MW, with most of them in the 2–10 MW range	● Costs for interconnection plus mitigation ranged from ~ $0/W to over $1.4/W. 50% identified total connection costs were less than $0.689/W ● Overvoltage impacts were the least expensive to mitigate, with almost half of the cases incurring no additional cost to the utility. Costs associated with mitigating voltage deviation and thermal overload effects (when present) were much higher, comprising 19–70% and 4–72% of total interconnection costs, respectively. ● Protection impacts were the most common, and, when present, cost 9–69% of total interconnection cost to mitigate.
[6] (2015)	Feeder, for 20 feeders in Atlantic City Electric Grid in the United States	PV impact study via hosting capacity analysis on the feeder level	Distribution system upgrade costs, including those associated with phase balancing, capacitor redesign, reduced voltage, dynamic voltage control, fixed power factor (PF) control, and battery storage	0–336.7%, depending on the feeder; (% PV capacity/ gross peak load)	● Every feeder has a different hosting capacity ● Distribution system upgrade costs per MW depend significantly on the feeder, loading, and PV placement. Costs ranged from ~ $0.23/kW to $118.7/kW. ● Distribution system upgrade costs are not necessarily higher for feeders with higher PV penetration levels. The feeder with the highest level of PV penetration had much lower cost than the feeder with the lowest non-zero penetration level ● Advanced communications and controls for dynamic Volt-Var operation will be required in some cases and for high penetrations ● Advanced inverters provide good, low-cost solutions, but uncertainty remains about their behavior at high penetrations

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