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COSTS of Upgrading Electric Distribution Grids to Integrate Increasing Solar PV Penetrations

As solar photovoltaic (PV) prices have fallen in recent years, the number of PV systems deployed on U.S. electricity distribution grids has grown dramatically.

The nation surpassed 1 million distributed PV systems in 2016—installed primarily on the rooftops of residential and commercial buildings—and rapid growth has continued. At the end of 2017, 16.2 giga watts (GW) of distributed PV was installed in the United States. Although distributed PV still provides a small fraction of the total U.S. electricity supply, its contribution to some utility systems has become large very quickly—highlighting the increasing need to develop strategies that maximize PV's benefits to distribution grids while minimizing grid-integration costs.

Challenges & Opportunities

Adding PV to distribution grids entails both costs and benefits. Costs may be incurred for distribution system upgrades when PV penetration reaches a level that causes deviations from acceptable operating conditions, such as voltages that are too high—requiring mitigation measures to ensure reliability, safety, and power quality. "Hosting capacity" is the PV penetration beyond which upgrades would be required on a given distribution feeder. Hosting capacity depends on the particular feeder and where PV is located within it. It can range from less than 5% penetration (PV capacity/peak load) to greater than 200% (*https://www.nrel.gov/docs/fy17osti/68681.pdf*). Additional costs are associated with connecting individual PV systems to the distribution grid, whereas PV can add costs or provide benefits by increasing or decreasing the electricity lost in transit through distribution lines. Finally, PV can benefit distribution systems in some cases by offsetting load growth and thus preempting the need for upgrades such as new transformers or distribution lines with higher ratings.

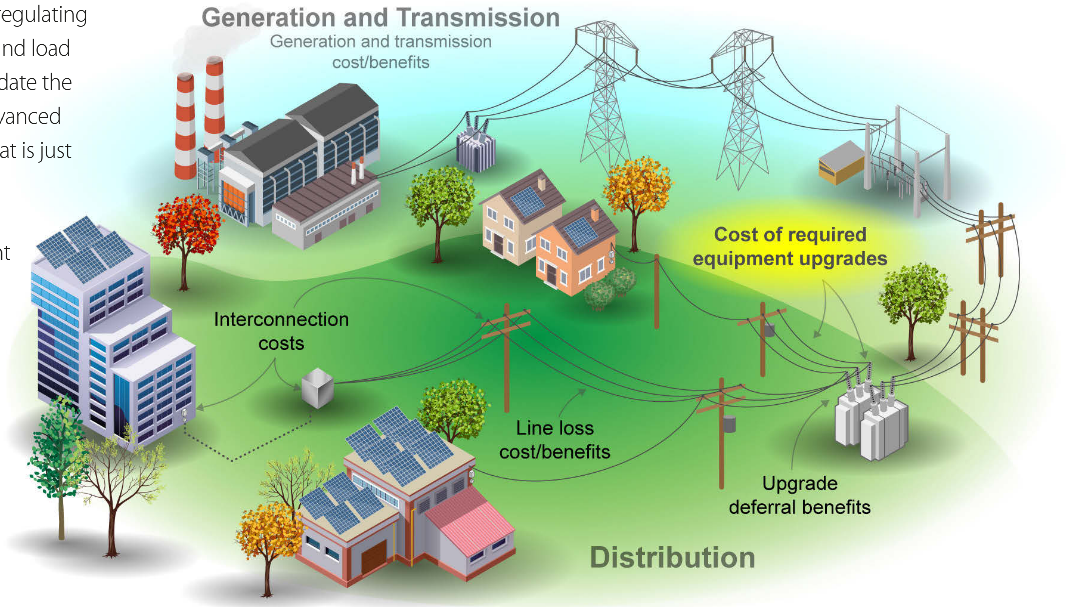
Grid-Integration Solutions

When the presence of PV necessitates distribution system upgrades, utilities typically choose from among various traditional options. At the lowest-cost end

For More Information

Download the report, *The Cost of Distribution System Upgrades to Accommodate Increasing Penetrations of Distributed Photovoltaic Systems on Real Feeders in the United States*, at **www.nrel.gov/docs/fy18osti/70710.pdf**.

of the spectrum, the settings of existing grid-regulating equipment—such as line voltage regulators and load tap changers—can be adjusted to accommodate the PV power inputs. Adjusting the settings of advanced PV inverters offers another low-cost option that is just beginning to be used in practice. When these measures are inadequate, traditional higher-cost options include installing new equipment such as capacitors, transformers, line voltage regulators, load tap changers, and upgraded distribution lines.



Grid-integration costs and benefits of PV across electric generation, transmission, and distribution systems, highlighting the distribution system costs analyzed in this study.

Cost Analysis

The National Renewable Energy Laboratory (NREL) has performed a bottom-up, engineering-based analysis to estimate the costs of distribution system upgrades as a function of PV penetration on three real U.S. distribution feeders. The adjacent figure shows how the analyzed costs relate to all the costs and benefits of integrating PV with electric grids. The other distribution system costs and benefits mentioned above (associated with interconnection, line losses, and upgrade deferral) were not assessed in this study, but they are being analyzed in ongoing work by NREL and other organizations.

The analysis assumes only limited advanced inverter functionality and traditional utility mitigation strategies are employed. It also uses the current utility practice for determining the need for system upgrades that involves power flow modeling for two static or snapshot scenarios: minimum load and PV production at its full-rated power and maximum load with no PV output. This method does not capture the time-varying behavior of loads, PV systems, or voltage-regulating devices on the feeder. Thus, the results reflect capital costs associated with upgrades for integrating PV in a "business as usual" case, which might overestimate the actual costs required to maintain distribution system reliability under increased PV penetration. Key findings include the following:

- PV capacities of 6%–88% of peak load can be integrated using advanced inverters plus traditional utility solutions, with cumulative distribution upgrade costs of \$0–\$0.07 per rated direct-current watt. At the high end, these costs are equal to approximately 3.8% and 2.5% of total installed costs for commercial and residential PV systems, respectively, in 2017. Higher penetration levels can be reached in some cases, at greater expense.
- In many cases where hosting capacity is limited by voltage issues, adjusting advanced inverter power factor set points at the time of installation can significantly expand the hosting capacity with no additional cost.
- Distribution grid integration costs depend significantly on how PV is spatially distributed, and costs could be minimized by guiding systems into low-cost or low-impact locations.
- Voltage constraints generally can be mitigated at relatively low cost using advanced inverters plus additional line voltage regulators or capacitors and/or adjusting the set points of existing voltage-regulating equipment: approximately zero cost for advanced inverters, hundreds to thousands of dollars for set point changes, and tens of thousands of dollars for new regulators. However, the expense increases substantially if a new substation load tap changer (several hundred thousand dollars) or distribution line upgrades (variable cost depending on line length) are required.
- Upgrades to mitigate thermal overloads (when the power through a line or transformer exceeds its rated power), including distribution line upgrades or transformer replacement, are generally expensive. Thermal constraints only limit the hosting capacity for one of the analyzed feeders.

Because hosting capacity and upgrade costs as a function of PV penetration depend on the particular feeder, spatial distribution of PV, and size of PV systems, additional research is required to validate the applicability of these results to other distribution systems.

Implications

Understanding the drivers of PV integration costs could help stakeholders estimate integration costs for specific distribution systems, and it could inform the design of electric rates and policies that promote low-cost PV integration and lower electricity costs. In addition, understanding these cost drivers could help guide R&D investments aimed at improving grid integration. Future approaches to grid integration that might lower costs and increase PV penetrations include dynamic PV curtailment, advanced communication and control schemes, battery storage, and new, forward-looking planning approaches. Ongoing research and analysis are evaluating these emerging options.

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