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TECHNICAL REPORT

FROM SUN TO ROOF TO GRID

Power Systems and Distributed PV



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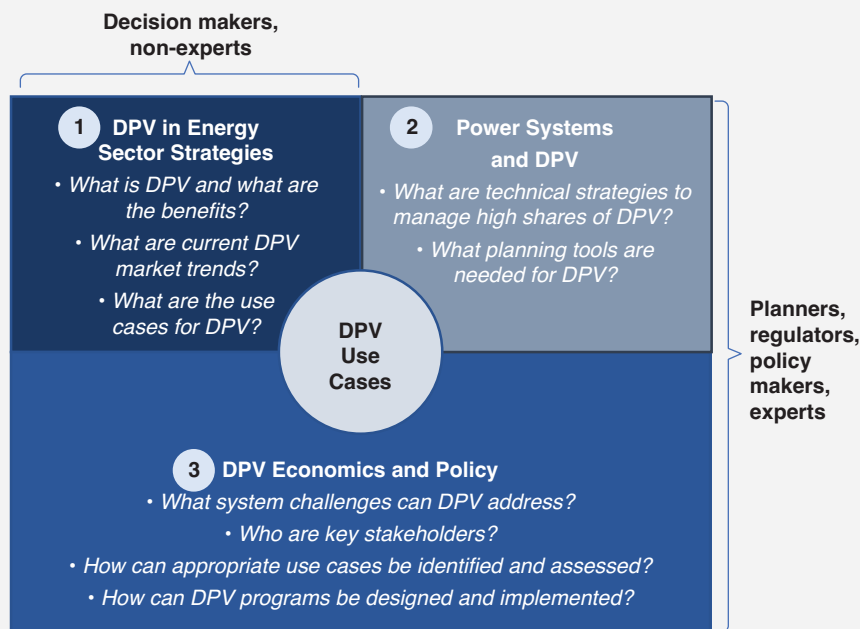
ABSTRACT

Rapid growth of distributed photovoltaics (DPV) has upended how engineers traditionally think about electric power systems. Consumers now increasingly generate their own power and feed it to the grid. Poorly managed DPV poses distinct risks for power systems as penetration increases. Yet, low- and middle-income countries can benefit from this clean distributed energy resource. How can DPV systems, distribution networks, and the power system be planned and operated to mitigate risks and reap technical benefits? This report, the second in a series of three, presents a menu of technical solutions applicable across diverse contexts. Balancing DPV supply with local loads, as far as practical, can help keep grid operations within technical limits. A grid's hosting capacity for DPV can also be enhanced on multiple fronts to cope with changed conditions. Many solutions are inexpensive. Inverter programming unlocks valuable services. Anticipating challenges and opportunities can avoid costly fixes. All countries can benefit from a grid code and planning approach that reflect expected growth of distributed resources. Prudent technical criteria can be used to streamline new approvals for grid-friendly DPV. Technical measures also require the timely capacity building of personnel. Examples of standards are provided for readers seeking more details.

ABOUT THIS SERIES: FROM SUN TO ROOF TO GRID

This report is the second in a series called “From Sun to Roof to Grid” produced by the World Bank’s Energy Sector Management Assistance Program (ESMAP). Distributed photovoltaics (DPV) is the world’s fastest-growing technology for local generation of electric power. This series shows how low- and middle-income countries can take full advantage of DPV as a low-cost, easy-to-install modular technology in diverse contexts from large stable power systems to small islands and regions marked by fragility. Interrelated topics across three reports target a range of readers—from non-expert decision makers to planners and regulators—to offer a menu of ideas, approaches, and examples to help demystify challenges encountered in deploying DPV. The series aims to help readers realize diverse potential benefits of DPV, whether on its own or paired with other distributed energy resources such as batteries, demand-side energy efficiency, and demand-response mechanisms. The relationship between the three reports and intended audiences is depicted below.

RELATIONSHIP OF REPORTS AND INTENDED AUDIENCES OF THE SERIES



As a relatively new technology with diverse applications, knowledge of how DPV can impact and interact with the grids varies greatly.

For this series, DPV is defined simply as any photovoltaics located with or near consumers connected to an electricity grid. This definition implies no minimum or maximum size. Systems can range from a single PV panel of 250 watts, for example, up to tens of megawatts (MW) capacity. DPV can be found on rooftops, as canopies above car parks or irrigation canals, and in floating arrays on industrial ponds. In advanced contexts, solar cells are now even being integrated into construction materials such as window glass, roof tiles, and the surfaces of sidewalks and highways. Different DPV systems feed all, some, or none of their electric output to the grid. Some grid-tied DPV systems provide backup electricity to consumers in countries

with frequent outages of grid power. Off-grid installations, that is, for consumers or facilities with no grid connection, are not the focus of this series except to the extent that access to grid electricity may become available within their economic lifetimes.

The first report in this series, “Distributed PV in Energy Sector Strategies” (ESMAP 2021), surveys DPV in different country contexts. Aimed at energy ministries and other decision makers, this report introduces key concepts, the DPV market, and nine use cases, or applications, of DPV to help solve different specific problems faced by various low- and middle-income countries.

Considerations from a power system perspective are the topic of this second report, “Power Systems and Distributed PV.” This report is aimed mainly at a technical audience—planners, distribution and transmission grid operators, and expert staff of energy authorities. However, the report also aims to introduce the issues simply enough for non-technical readers to become familiar with them.

The third report, “Distributed PV Economics and Policy,” details the strategic objectives, cost-benefit analyses, regulatory issues, and business models for DPV.

Taken together, these three reports (and their key messages for different stakeholders) aim to enable low- and middle-income countries to harness power from the sun to benefit all consumers connected to the grid.

For more information, visit www.worldbank.org/energy and www.esmap.org/esmap-from-sun-to-roof-to-grid-distributed-pv.

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Rooftops analyzed near substation in Dhaka, Bangladesh

KEY MESSAGES

Rapid growth of distributed photovoltaics (DPV) has upended how power system planners and operators think about electricity grids. Falling costs of solar electricity have made on-site generation and consumption a low-cost option for access to new, clean power globally. PV systems located close to consumers enable them to self-supply, and—if permitted—feed into the grid. DPV thus challenges how utilities traditionally generate, transmit, and distribute power as a one-way flow from central plants down discrete system levels to consumers. Many countries are learning to successfully manage DPV at increasing shares of total power generation. Low- and middle-income countries (LMICs) stand to benefit from emerging lessons. This report explains common technical challenges and opportunities to consider, and steps to take given the current and potential future levels of DPV. For technical readers wanting more details, the report points to examples of standards and technical procedures published by other institutions.

Well-managed DPV offers potential technical benefits to power grids in several distinct ways. DPV systems can, with other distributed energy resources (DER), help in LMICs to variously: (a) supply least-cost generation to the grid, especially where land is constrained; (b) defer certain transmission and distribution upgrades; (c) provide ancillary grid services; and (d) “bootstrap” or upgrade underperforming utilities by improving service and increasing bill collections for consumers in a microgrid.¹ These and other potential use cases, plus rapid installation times, enhance DPV’s value as a contribution to least-cost decarbonization or low-emissions development plans. Benefits from DPV, however, depend on appropriate power system planning, investments and operations, suited to the local context.

As DPV grows from low to higher levels of penetration, different technical risks typically emerge. These are summarized in Figure 1 (left column). Effects of DPV on power systems are gradual and the specific issues that arise as DPV grows can vary from place to place. At a low level of deployment, DPV may have negligible impacts, especially in larger grid systems. DPV power fed to the grid can usually be stepped up to higher voltage levels often without significant technical modifications to the distribution system. However, poorly managed DPV can cause system operating limits to be breached at certain times. Since DPV can be installed in a matter of weeks, at a much faster rate than bulk power plants, preparing for rising levels of penetration is imperative.

The amount of DPV that a grid can integrate safely, while keeping within specific operational limits, is not fixed. Hosting capacity for DPV is a dynamic, multi-faceted threshold. It can vary within a grid and over time, depending on the design and operation of the power system and of DPV systems—in aggregate and large individual systems.

A menu of potential technical solutions exist to help ensure DPV is grid-friendly. See Figure 1, middle and right columns, which correspond to two broad approaches as follows.

1. **Local load-balancing.** Matching DPV supply and local demand with each other as much as practical can help keep grids within specified system operating limits. This type of intervention aims to keep net load² relatively stable and certain, akin to load conditions without DPV or even, ideally, to improve upon them.

¹ “Bootstrap” here means using initial minimal resources to lift oneself up out of a bad situation.

² “Net load” here refers to demand for bulk grid electricity excluding demand for electricity served by distributed and/or bulk variable renewable sources. See Glossary for this and other key technical terms.

FIGURE 1: OVERVIEW OF POTENTIAL POWER SECTOR ISSUES AND SOLUTIONS FOR GRID-FRIENDLY DPV

| Power System Risks from DPV at Rising Levels | Solutions Menu 1: Local Load Balancing | Solutions Menu 2: Enhancing Hosting Capacity |
|---|---|---|
| <p><u>Low DPV penetration</u></p> <ul style="list-style-type: none"> • Breach of voltage limits <p><u>Medium DPV penetration</u></p> <ul style="list-style-type: none"> • Disruption to fault protection scheme • Breach of transformer capacities and conductor thermal ratings • Increased variability and uncertainty of net load • Poor response to grid disturbances <p><u>High DPV penetration*</u></p> <ul style="list-style-type: none"> • Power quality problems • Lack of synchronous generation | <p><u>Supply-demand coordination</u></p> <ul style="list-style-type: none"> • Promote efficient demand ahead of designing DPV • Analyze hosting capacity and grid congestion to inform strategic sites and DPV design • Favor large DPV close to substations • Use digital technologies to monitor and control DERs • Aggregate DERs into virtual power plants <p><u>Supply-side adjustments</u></p> <ul style="list-style-type: none"> • Calibrate PV sizes and angles to serve local peak loads and diversify production time • Design DPV systems with optimally high DC:AC ratio (inverter clipping) • Size DPV to match efficient projected local energy demand • Limit feed-in dynamically or statically <p><u>Demand-side adjustments</u></p> <ul style="list-style-type: none"> • Demand response • Energy storage | <p><u>DPV inverter programming</u></p> <ul style="list-style-type: none"> • Voltage management • Cope with grid disturbances • <i>Support power quality*</i> • <i>Grid-forming mode*</i> <p><u>Grid equipment adjustment or upgrade</u></p> <ul style="list-style-type: none"> • Voltage compensation equipment • On-load tap changing transformers • Protection scheme settings • <i>Harmonic filters*</i> <p><u>Enhance power system flexibility</u></p> <ul style="list-style-type: none"> • Improve forecasts • Automate operations • Expand balancing areas • Shorten dispatch intervals and schedule updates • <i>Fast-acting reserve*</i> • <i>Synchronous condensers*</i> |

Source: Original by the authors for this report.

Note: Solutions listed in the middle and right-hand column may address multiple risks in the left-hand column. Case-by-case appraisal is important to design and cost any intervention. *High DPV penetration is mostly relevant for small power systems. Hosting capacity enhancements marked with an asterisk are for high DPV penetration issues, which are rarely a constraint for DPV uptake in larger power systems. Thresholds for low and medium penetration are discussed in Chapter 1.

2. **Hosting capacity enhancements.** Load-balancing may not eliminate the need for a power system to cope with new pressures resulting from DPV deployment. A grid's hosting capacity can be enhanced by DPV inverter programming, grid equipment adjustments and upgrades, and flexibility resources in the power system overall.

In assessing interventions for grid-friendly DPV, some general principles apply. Consider a wide variety of options to address typical technical issues; consider if regulations need updating to allow new options; consider the value of ambitious investment options to accommodate long-term developments; and prioritize the most cost-efficient solutions. Costs can vary from one power system to another, so case-by-case appraisal is important.

Planning adequately ahead can avert the most costly solutions or blanket restrictions on DPV. Historically, DPV has encountered problems only when its deployment potential has been underestimated,

or when deployment has not been accompanied by a strategy to manage its integration. High costs result from needing to replace or upgrade grid assets before the end of their economic lifetime.

Most operational measures have very low costs while most DPV planning and investment solutions have low to moderate incremental costs. Some local conditions may enable a significant share of DPV to be integrated with purely operational measures such as inverter programming. Inverters need to have appropriate capabilities with the right settings at installation; retrofitting inverters is more expensive.

All countries should adopt a grid code that reflects expected future growth of distributed energy resources. DPV can become relevant for the overall power system, so technical rules must keep pace with installed DPV capacity. Countries with no grid code should develop one as soon as possible. Even in grids with low DPV penetration, specifying advanced inverter functions today can reduce the need to change systems in the future. It is important for grid codes to be easy to implement. Technical approvals for DPV installations to connect to the grid can be streamlined with prudent screening criteria for systems that meet certain specifications.

Integrated power system planning or a dedicated integration study are recommended where DPV may be deployed at high rates. Traditional capacity expansion and production cost models can be adjusted to account for DPV simply as a “negative load.” However, this may not capture enough detail to reflect important challenges and opportunities that emerge as renewables and distributed resources become more prevalent. Distributed energy resources spur new processes to analyze and design power systems accounting for alternative future scenarios.

For any approach to power system planning, engaging DPV stakeholders early can help foster convergence on key issues. Good principles include to set planning objectives that account for current and potential new use cases of DPV and a wide range of potential operating conditions. Consider the technical potential of distributed resources, deployment forecasts, distribution network performance indices, and options to enhance hosting capacity. Even in low-income countries or those marked by fragility, low-cost georeferenced datasets and data analysis tools may be helpful. Scenarios building on these can estimate current and enhanced hosting capacities with analysis to evaluate alternatives and optimize for the objectives. Planning outputs can inform DPV deployment targets, prioritize investments to enhance the network, and guide further site-specific analyses for key local projects.

LMIC governments would do well to seek adequate and ongoing technical and financial support for capacity building in DPV operations at the utility level, at the earliest opportunity. Technical measures alone are not enough. DPV integration also needs effective business models, regulation, financing, and timely capacity building of personnel.



Rooftops analyzed in Lagos, Nigeria

1: HOW IMPORTANT IS DPV FOR POWER SYSTEM PLANNERS AND OPERATORS?

This report explores the technical aspects of grid-tied distributed photovoltaics (DPV) to inform power system operators and planners especially in low- and middle-income countries (LMICs). DPV is a relatively new technology and has diverse applications across contexts. As such, DPV and its technical impacts are often misperceived. This report seeks to explain key issues so power system planners and operators can identify solutions to maximize DPV benefits while avoiding adverse outcomes for the grid.

This chapter establishes the importance of DPV, first, by highlighting its global growth and the roles the technology plays in energy sector priorities, especially in LMICs; second, by outlining DPV's incremental impacts on the power system over time.

Chapter 2 subsequently presents a menu of options for grid-friendly design and management of DPV systems, distribution grids, and the power system at large. Chapter 3 describes the importance of grid code connection standards to scale up grid-friendly DPV. Chapter 4 concludes with approaches to power system planning with DPV.

DPV HAS DISTINCT IMPLICATIONS FOR POWER SYSTEMS AROUND THE WORLD

DPV is irrevocably changing power systems around the world

DPV is irrevocably changing power systems around the world, including in diverse LMICs. Thin and modular, solar photovoltaic (PV) cells can be easily installed in myriad ways on or near sites of electricity consumption. These properties distinguish DPV from bulk generation sources—including large-scale ground-mounted PV power plants—and from other distributed generation technologies.

Bulk (centralized) power generation technologies occupy large parcels of land and usually transmit energy to consumers over long distances. Economies of scale mean that power stations for bulk generation of electricity may be enormous physical structures requiring large dedicated parcels of land, often located at a distance from centers of power demand (i.e., urban areas and industrial zones). Transmission systems are designed to convey power efficiently over relatively long distances and enhance reliability of supply from bulk power sources to local grids. However, many countries face land constraints, compounded by climate risks and environmental considerations around competing land uses. In contrast, DPV generates power from diverse locations, serving either its direct operators, or feeding electricity in to the power grid, without necessarily detracting from preexisting land uses.

DPV is also distinct from other distributed generation technologies, such as fuel-based generator sets or small-scale wind, as DPV does not rely on moving parts or feedstock. The cost to operate and maintain DPV is thus extremely low.

Integrated properly, DPV can actually support the local energy utility and the national grid. However, the resulting new network architecture has consequences that must be considered by power sector authorities.

Global Growth of DPV is Set to Continue

Global installed capacity of DPV exploded over the past two decades from just a few megawatts (MW) in 2000 to a cumulative total of over 383 gigawatts (GW) by the end of 2021. This includes 238 GW commercial and industrial PV and over 145 GW of residential PV (IEA 2022a). Much of this growth is occurring in China and India, although DPV is also expanding across small island-nations and low-income countries. DPV has grown steadily at a global level, rivaling utility-scale solar and overtaking coal and nuclear—combined—in net capacity added each year. Even as the COVID-19 pandemic slowed growth, new DPV installations offered a direct response to the global lockdowns by helping to power health clinics in regions with unreliable grid service. DPV is also boosting economic resilience and recovery strategies, including job creation. Recent rises in natural gas prices of several regions have prompted near-term forecasts of DPV deployment to revised upward. Over the longer term, even under a conservative scenario based on countries' recently stated policies, global installed capacity of PV (at all scales) is projected to reach an order of magnitude greater than any other single technology by the 2040s (IEA 2022b). A scenario of more ambitious decarbonization will only magnify this scale-up. As such, the rise of PV plus wind power are set to fundamentally reshape power systems and significantly increase the demand for power system flexibility.

DPV has Diverse Use Cases in Low- and Middle-Income Countries

For LMICs, DPV can contribute in distinct ways to the goal of reliable, affordable clean energy for all. Many LMICs are seeing steep but uncertain growth in demand, unreliable grids, and rapidly changing circumstances, especially in areas facing fragility, conflict, and violence. More than 50 million forcibly displaced people live in urban settings where grid capacity is strained. Globally, an estimated 350 to 500 GW of diesel generators supply temporary or backup power to consumers of grid electricity (IFC 2019). These are noisy generators that also create pollution. In addition, diesel is a costly fuel vulnerable to supply disruptions. Like these large urban settlements, many small islands rely on expensive oil imports for power, while they lack the land required to build ground-based power stations or transmission. For most communities, resilience to risks from climate change and crises is a high priority. The local nature of DPV, the fact that it can achieve high aggregate capacity from many individual plants, also adds to resilience. Even if a portion of systems fail, the overall output will not be affected as much as with fewer, large plants. In each of the above scenarios, DPV could provide significant benefits when deployed on its own or combined with other resources. Systems can be scaled to match available needs and budgets and operated with no fuel costs, no emissions, and minimal maintenance. DPV paired with battery storage is increasingly common and generally configured to provide backup power in the event of a power failure on the utility lines (ESMAP 2020b). There are several technical options for connecting batteries with a DPV system, and systems can also be configured, with the proper inverter, to charge the battery from the solar array as well as from the grid. When used in connection with batteries, DPV can power consumers independently when the grid, or sunshine, are unavailable. Grid-tied DPV schemes can also inform the design of off-grid systems that might later be connected to an expanded main grid.

DPV Can Provide Technical Benefits to Power Grids

Well-managed DPV offers potential technical benefits to power grids in several distinct ways. The first report in the present series (ESMAP 2021) introduced nine use cases, or applications, of DPV, which each respond to a specific problem found in LMICs. From a power system perspective, four of these uses cases stand out

BOX 1

DPV Use Cases with Technical Benefits for Power Systems

The following two use cases are already emerging in numerous countries.

- DPV may be part of the **least-cost generation** mix. Even before considering the value of avoided pollution and carbon emissions, DPV's proximity to loads can avoid transmission losses and help overcome grid infrastructure constraints or lack of land available for bulk power generation. This is true regardless of whether DPV systems feed all, some, or none of their output to the grid. High penetration of DPV can displace the need for generation from bulk power plants, such as in small islands. This is especially relevant in power systems that face periods of light demand.
- DPV can help utilities **defer certain transmission and distribution upgrades**. This is possible when peak demand occurs during the daytime and DPV helps meet local demand, planned with other DER such as demand-response, energy efficiency, and battery storage.

Two more use cases represent opportunities yet to be widely deployed.

- **Ancillary grid services** can be provided by inverters in DPV systems, in isolation and in aggregate. For example, inverters can control reactive power for voltage management or curtail active power for congestion management. More and more grid codes are being updated to require such capabilities of inverters before approving new DPV connections to the grid. Policy incentives to exploit more advanced ancillary services are a new frontier.
- Finally, utilities in a vicious cycle of chronic underperformance can use grid-connected microgrids with DPV as a **"bootstrap"** to improve service reliability, expand access, and increase bill collections.

See Annex A for technical description of these and other DPV use cases for LMICs.

for their technical implications: least-cost generation; transmission and distribution (T&D) alternative; ancillary grid services; and bootstrap³, as described in Box 1.

Annex A provides a technical description of all nine use cases including, for the most technical audience, electrical engineering diagrams to illustrate how each use case may be configured. Across the use cases, DPV's rapid installation times enhance its value as a contribution to least-cost decarbonization or low-emissions development plans. Across countries, all such plans call for an increase in electrification of end uses and in solar among other power sources.

³ "Bootstrap" here means using initial minimal resources to lift oneself up out of a bad situation.

Later sections of this report will refer to the above use cases, linking general concepts with real-life applications. In practice, two or more use cases may be combined to generate synergies in a single project or scheme or combined with other DER and schemes such as energy efficiency and microgrids.

All benefits from DPV, however, depend on appropriate planning, investments, and operations, suited to the local context, which in turn depends on the institutional capacity of energy agencies.

Enhancing the Institutional Capacity of Utilities

Investment in utility engineers' training in technical aspects of DPV is an important prerequisite for launching a decentralized generation program as part of a country's clean energy transition. Without sufficient numbers of adequately trained staff in the distribution utility, it is likely that DPV customers awaiting approval for their systems to be commissioned, will have to wait for many months. In some cases, they may also be paying interest on a loan for their installed but not-yet-commissioned DPV investment while receiving no benefits, not even from self-consumption. The resultant loss of reputation and consumer appetite for DPV will be hard to recover from. If consumer interest fades it will likewise be difficult to create a competitive ecosystem of the required service providers that underpin the DPV sector's growth. LMIC governments would do well to seek adequate and ongoing technical and financial support for capacity building in DPV operations at the utility level, at the earliest opportunity.

DIFFERENT DPV SYSTEMS FEED ALL, SOME OR NONE OF THEIR OUTPUT TO THE GRID

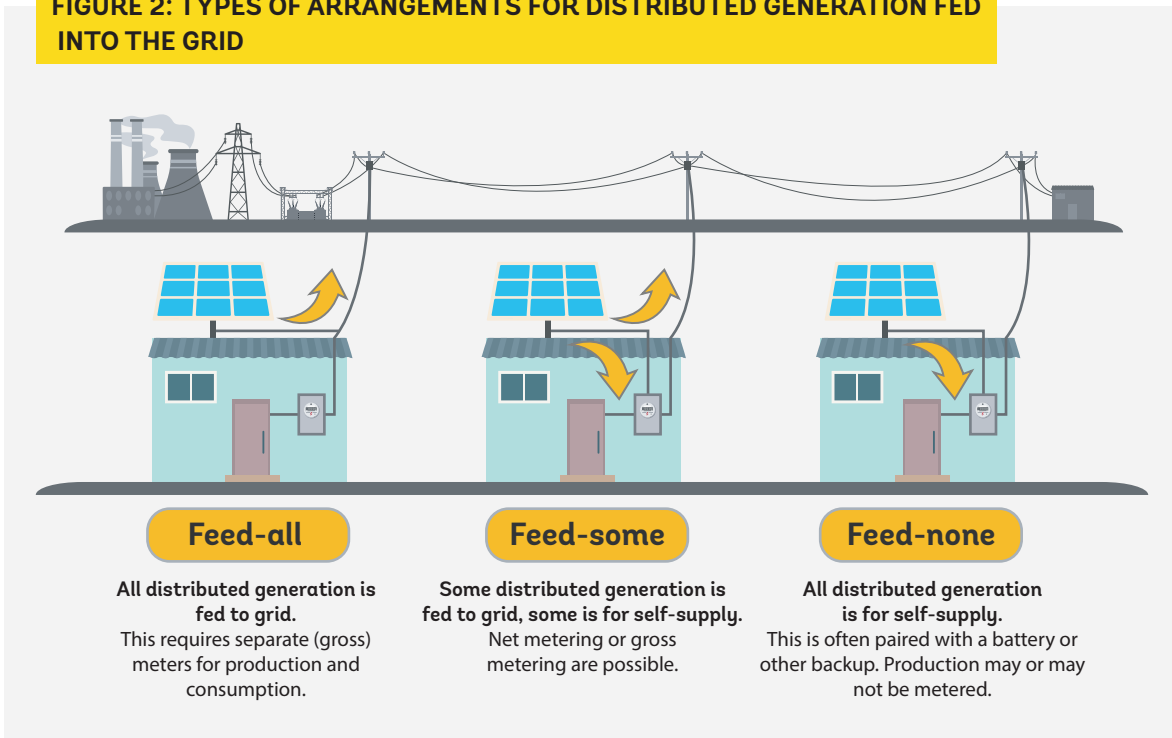
To Feed or Not to Feed the Grid?

Before discussing DPV in detail, it is important to recognize a fundamental configuration choice: whether all, some, or none of the DPV electric output is fed to the distribution grid, versus used for on-site self-supply. This report series uses a typology of feed-in arrangements, described below and illustrated in Figure 2. While described in terms of DPV, the typology applies to all sources of distributed generation.

- **Feed-all.** All DPV output is fed into the grid. This arrangement can further be categorized by whether DPV is connected to a consumer's power circuits (consumer side) or to a distribution grid directly (grid side). A feed-all DPV arrangement with an on-site consumer is known in some literature as "buy all, sell all" because the consumer buys all their power from the grid. Feed-all arrangements may alternatively be on a site with no to little grid consumption, such as ground-mounted DPV in an empty lot. Such arrangements resemble standard power plants but serve a distribution grid directly at lower voltage levels than bulk generation.
- **Feed-some.** Some of the DPV output is consumed on-site (or stored for later use) in lieu of consuming power from the grid. The remainder of the DPV output is fed into the grid. Feed-some models may involve a single (bidirectional) "net meter" that measures the net flow of power to or from the grid, or two (unidirectional) "gross meters," one for each direction of power flow.
- **Feed-none.** All DPV output self-supplies the consumer. Feed-none installations can still affect the grid by altering the customer's consumption profile. For example, passing clouds can disrupt DPV output and trigger variations in grid electricity consumption. In turn, these can affect grid voltage. Hence, planning and

operation for voltage management may need to factor in feed-none installations. Feed-none arrangements may have no need for a meter that measures DPV output. However, large feed-none arrangements might benefit from measuring output to inform the user or to help the utility forecast load. Systems designed for use without the grid typically also have a battery, charge controller, and a switch to disconnect the direct current (DC).

FIGURE 2: TYPES OF ARRANGEMENTS FOR DISTRIBUTED GENERATION FED INTO THE GRID



Source: Original figure by the authors for this report.

DPV systems that feed some or all electricity to the grid, connect (or interconnect) with the broader distribution network through a building-level service panel on smaller systems or through a dedicated transformer in larger installations. Meters typically serve as the point of common coupling, where the DPV system connects to the grid.

After installation of a DPV system that feeds the grid, in most cases inspection and approval from the distribution utility is required prior to commissioning. Connection standards in electrical grid codes inform rooftop installation companies on technical specifications and safety features that must be met for feed-in DPV systems to be approved. These are covered in Chapter 3. Connection standards do not apply for feed-none arrangements, though they may still be regulated.

DPV that Feeds the Grid has Distinct Implications

DPV that feeds into the grid challenges the classic rules governing distribution: that the substation is the sole source of power flowing from the substation to consumers downstream at feeder sections. At growing shares of feed-in DPV, periods of minimum load and reverse power flows up to higher voltage levels become important. Low demand periods can coincide with peak DPV output potential, such as on residential feeders on weekdays or at factories that shut down at lunchtime. This can lead to power flowing (or attempting to flow) from low-voltage to medium-voltage networks, and even from a distribution feeder to the transmission system.

All distribution systems are, technically speaking, bidirectional. Feeding power from a generator on the customer side, at higher voltage levels, is technically feasible. This is successfully managed in top DPV markets around the world and is not inherently dangerous. It requires no modifications, although in some cases it may require changes to protection equipment. In an AC-power system, the direction of current itself—as implied by the name “alternating current”—alternates in the system constantly, many times per second. Indeed, the change is not as fundamental as it may seem.

Nevertheless, reverse power flow can produce bottlenecks, depending on the condition of the infrastructure and associated operational capabilities. Optimizing or maximizing the amount of DPV in a distribution grid while maintaining high-quality service and reliability calls for understanding the hosting capacity limits and possible enhancements.

DPV IMPACTS ON POWER SYSTEMS EVOLVE AS DEPLOYMENT GROWS

DPV has been deployed at a large scale for more than a decade across many different countries and diverse grid topologies. This experience reveals various ways in which DPV challenges traditional power system planning and operations.

Energy Sector Agencies Need to Anticipate Incremental Impacts as DPV Grows

Deployment of DPV has a gradual, incremental effect on power systems. However, a key feature of DPV is that it can be installed rapidly, in a matter of weeks, much faster than traditional bulk generation plants. In many country contexts, DPV deployment rates have exceeded expectations, especially when developers and consumers respond to attractive feed-in tariffs. In Vietnam, for example, DPV capacity increased from 0.4 GW peak to 9.3 GW over the 12 months of 2020, with an estimated 6.7 GW connected in December alone.⁴

Proactively accounting for the likelihood and uncertainty of a high-growth scenario is thus important. DPV deployment projections also need to consider interactions with other trends. Growth in electric vehicles, for example, may incentivize DPV independently of feed-in tariffs.

Historically, DPV's main problems stem from being underestimated. Early management strategies were not well prepared for robust deployments a few years later. A well-designed DPV program should be strategic from the outset. Suitable attention to planning must therefore also be part of the capacity-building support sought for utility staff to familiarize them with DPV.

DPV shares properties of other variable renewable energy (VRE) technologies, namely large-scale PV and wind. For this reason, it is important to consider the deployment of DPV from both the perspective of local distribution grids as well as overall bulk power generation resources.

In broad terms, levels of penetration can be distinguished by the share of the power system's gross annual electricity generation coming from DPV on its own or in combination with other VRE. Low penetration is when this ratio is no more than a few percentage points. At this level, effects of DPV deployment are usually localized and relate only to the distribution grid. Certain distribution feeders may encounter high shares of DPV (i.e., nameplate DC panel capacity is multiple times the feeder peak capacity), although DPV is not yet a significant contributor to the overall power system. Medium penetration may be when the share is somewhere in the range of 5 to 10 percent, at which points effects may be seen throughout the power system. High penetration can occur around 10 percent, at which threshold there may be several

⁴ Vietnam's 25-fold increase was spurred by a time-limited program of generous feed-in tariffs, ranging from 7.00 to 9.35 US cents per kilowatt-hour (kWh), with 20-year contracts (Le and others 2022), though the rush of installations continued after the feed-in tariff deadline had expired (Le 2022). The unplanned boom, which also involved bulk renewable power plants, led to grid instability and curtailment (WBG 2022).

occasions during the year when VRE provides more than 50 percent of the load over at least one hour (Holttinen 2018). Specific thresholds depend on power system characteristics and can vary greatly.

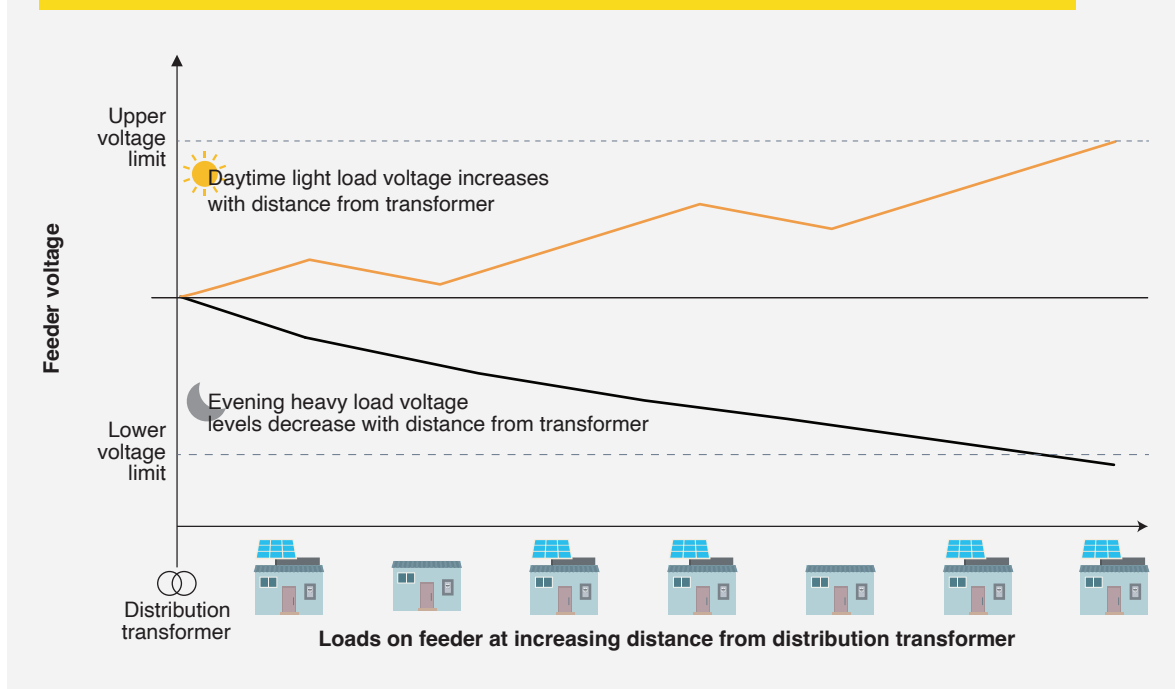
Different technical issues are associated with low, medium, and high levels of penetration. These issues are described below, while solutions to each of these issues are presented subsequently in Chapter 2. There are important implications for system operation once DPV generates reserve power flows frequently and in several locations to the transmission level. Broadly speaking, DPV capabilities must be matched to DPV reliability. The goal is to guarantee DPV generation that system operators can see and control. Moreover, DPV needs to provide more system services at higher penetration levels.

Low DPV penetration: Voltage issues

The earliest common risk to arise is the breach of voltage limits of a distribution feeder. Voltage issues may occur at early stages of DPV deployment even before DPV output exceeds local demand on a given feeder, for reasons explained below. Voltage issues may also occur at subsequent, higher penetration levels too. In rural grid areas or at weak grid connection points, DPV at low penetration levels may also cause local overloading or power quality issues as addressed under medium and high penetration levels, further below.

A general feature of distribution feeders, without DPV, is that customers far from a distribution transformer receive power at a lower voltage than those near the transformer. This is because voltage level along a feeder decreases with distance from the transformer, all the more so when electricity demand is high. In Figure 3, the lower (black) line shows voltage decline along a radial feeder with heavy loads and no DPV output, as

FIGURE 3: VOLTAGE ALONG A RADIAL FEEDER UNDER DIFFERENT CONDITIONS OF LOAD AND DPV OUTPUT FED TO GRID



Source: Original figure prepared by the authors for this report.

Note: The consumer furthest from the transformer (far right of the figure) risks overvoltage at times of high load and low DPV output, and risks undervoltage at times of high DPV output and light load. This figure assumes DPV without use of storage or demand response mechanism.

might occur on a typical evening in a residential area. Voltage drops are even more pronounced in locations where impedance is high, for example when the diameter of conductor cable is small. In rural areas with radial feeders, voltage at the distribution transformer is therefore set at the higher end of the allowed range, ensuring that sufficient voltage reaches the furthest customer under heavy-load conditions. Box 2 explains radial versus other types of distribution feeder.

Adding DPV to long feeders can exacerbate voltage issues. For DPV feed-in arrangements, the DPV inverter “lifts” the voltage at the point of interconnection, so that electricity can feed the grid. Any lifting effect has a range of consequences, which may be good or bad depending on load conditions. If total load from local consumption is high (matching or exceeding DPV fed into the grid), then the voltage at the DPV installation location will be relatively low. In this circumstance, DPV feed-in might even improve voltage levels by raising them to the target levels. However, problems may arise if local consumption is low—i.e., when DPV electricity is being fed all the way back to the substation transformer. In such cases, voltage surge can be significant with a risk of violating voltage limits on the feeder (see, e.g., Bazrafshan and others 2019; Islam and others 2017; Palmintier and others 2016). In Figure 3, the upper (orange) line shows the feeder voltage level increasing at each site with DPV when loads are light, as might occur in the daytime for a residential area. Voltage problems are riskier for long radial feeders with grid-feeding DPV systems located far from the distribution transformer.

Medium DPV penetration: Additional issues

At medium levels, thermal line ratings and transformer capacities may become constraints. Additional issues may include: maintaining fault protection capability; coping with the variability of net load, which will exhibit steeper and larger ramps during morning and evening hours; coping with output uncertainty, as forecasts for

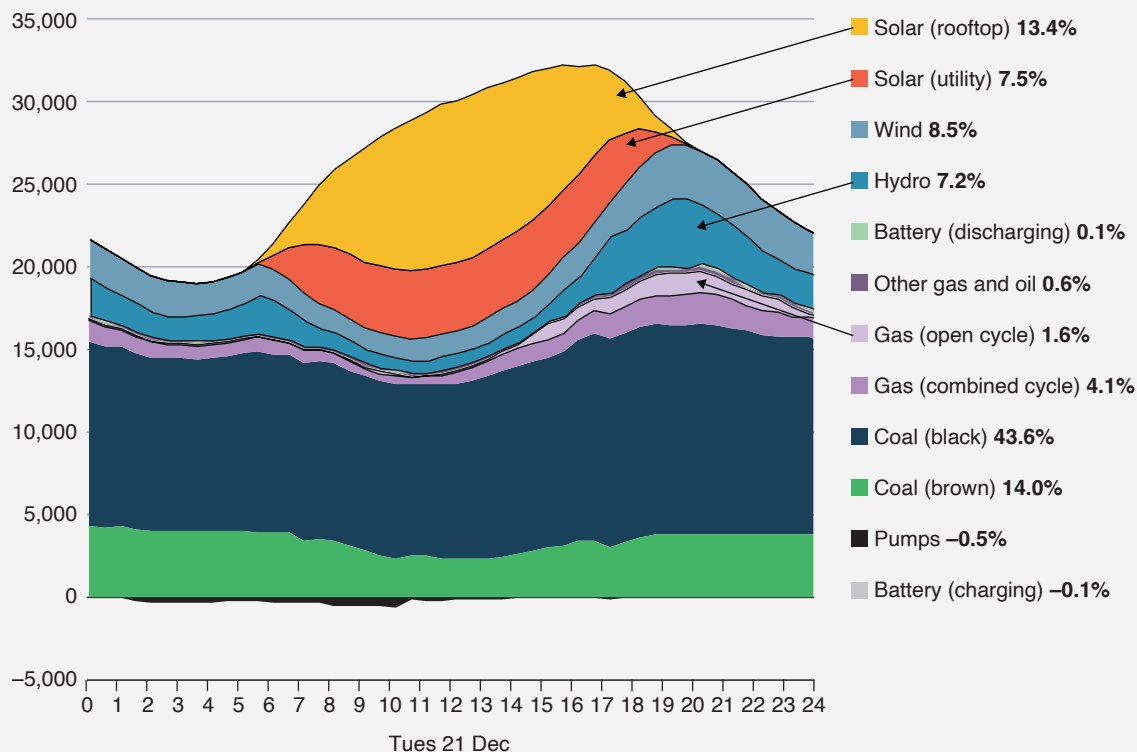
BOX 2

Radial versus Other Types of Distribution Feeder

The topology or layout of distribution feeders has implications for the effect of adding DPV. Distribution grids receive electricity from the high-voltage transmission system at substations where transformers step the electricity down to lower voltages. Each substation transformer typically features several circuits, or feeders, which use primary distribution lines to supply electricity to neighborhoods. Feeders in distribution systems may have radial, spot, looped, or mesh configurations.

- Radial networks are tree-like structures, with the higher-voltage power emanating from the trunk, at the base of the circuit, while primary feeders emanate like branches from the substation. They operate on a single path of current. Radial systems are typically used for light- and medium-density loads suited to residential and small commercial consumers. However, in countries with a weak grid environment, larger loads may also be connected via radial systems.
- Spot, looped, and meshed networks deliver concentrated or high-density loads typical in cities and for facilities that need highly reliable power, such as hospitals. These networks provide redundancy by having multiple sources of supply through a series of connected service transformers.

FIGURE 4: RAPID EVENING DROP IN DPV GENERATION WITH RAMP UP OF OTHER SOURCES, AUSTRALIAN EXAMPLE



Source: Australia National Electricity Market, data for December 21, 2021 (McConnell and others 2021).

PV output can be done only a few days or hours beforehand; and coping with exceptional conditions such as voltage dips. These issues are practically identical to those observed with large amounts of bulk PV or wind generation.

By reducing overall demand for grid electricity, DPV can dramatically change load curve hourly patterns. This is true even for backup arrangements that feed no output to the grid, and has implications for planning of bulk generation and network infrastructure, as well as for cost recovery.⁵ High penetration rates of DPV, regardless of the feed-in arrangement, typically lead to higher ramps between peak and off-peak loads. This points to the need for more flexibility in the power system at large to cope with abrupt changes in net load. The resulting load shape is often referred to as the “duck curve,” which can also be seen in relatively large systems with utility-scale PV.

For example, in Australia, which has some of the highest DPV penetration levels in the world, DPV is shaping the main national transmission grid load curve and technical operations. Figure 4 illustrates an actual summer day in Australia’s main electricity network, where a rapid evening drop of DPV generation is matched by a ramp up in other sources. As DPV changes the patterns of daily load curves for grid electricity, demand becomes harder to predict. This challenge can be all the more difficult when power flows become bidirectional

⁵ The third report in this series discusses broader implications of DPV for power sector financial viability and different business models.

or when consumers actively manage demand to reduce electricity bills. Rules of thumb and industry-standard calculations historically used to inform investment decisions are thus becoming outdated. Advanced communication infrastructure, such as SCADA⁶ connected to distributed energy resources (DER), can help.

High DPV penetration: Less common issues

At the extreme, DPV or other variable renewables may generate most of the power at some times. In such cases, additional issues may arise: power quality; and lack of synchronous generation. These issues are mostly relevant for small power systems and rarely a constraint for DPV uptake. High penetration of DPV may affect power quality by introducing harmonics. This can negatively impact sensitive equipment including that of other customers. Second, DPV is an inverter-based generation technology, connected to the grid via electronics, as distinct from thermal and hydropower plants, which have motors that directly produce alternating current (AC) electricity. Motors' frequency of rotation can be synchronized with the power of electricity transmitted and distributed throughout the grid. For this reason, these type of power plants are known as synchronous generators. A high share of inverter-based generation can affect the stability of grid electricity if not accompanied by solutions to compensate for the lack of synchronous generation.

Hosting Capacity for DPV is a Dynamic Concept

Hosting capacity here refers broadly to the estimated maximum amount of distributed generation that can be integrated into part of an electrical network while keeping within operational performance limits, before or after enhancement techniques. Hosting capacity is a critical concept for DPV and other forms of distributed generation that feed in to a grid. It is relevant for the purpose of planning, grid code connection screening and approval procedures, and power system operation. The concept of hosting capacity, first introduced in 2004, has seen starkly different applications across countries over time (Ismael and others 2019). Importantly, hosting capacity is particular for a given power system at a point in time and space. It is not one fixed exact value but rather determined by a probabilistic range of performance indices (e.g., overvoltage, thermal overloading, power quality, protection problems). This index values can vary by location (nodes and feeders) and by enhancement techniques (e.g., reactive power control, voltage control, active power curtailment, energy storage technologies, network reconfiguration and reinforcement and mitigation of harmonics). It is therefore important to consider why and how to define hosting capacity in a given context to apply the concept in practice. Chapter 2 discusses enhancement techniques, while Chapter 4 discusses approaches to hosting capacity analysis in the context of power system planning.

⁶ SCADA refers to supervisory control and data acquisition, a system of information and communication technology, with hardware and software, to assist system operators to automate and manage the network.

2: TECHNICAL SOLUTIONS FOR GRID-FRIENDLY DPV

Power systems are designed and operated with a general objective to instantaneously match demand for electricity across the grid by adjusting bulk electricity supply. Naturally, there are technical and economic limits to achieving this objective in full, especially in many LMICs. Power systems have thus evolved various mechanisms to help coordinate supply and demand and to cope with imbalances that occur over time in some part or all of the grid. Similar principles can be applied to manage DER, with certain differences. This chapter explores such solutions for DPV.

Characterizing Potential Technical Solutions for Grid-Friendly DPV

A wide range of potential technical solutions exist for grid-friendly DPV. These can be characterized in terms of two general approaches:

1. **Local load-balancing.** This type of intervention seeks to match DPV supply and local demand with each other as much as practical to help keep grids within a given hosting capacity or specified system operating limits. The aim of these interventions is to keep net load⁷ relatively stable and certain, akin to load conditions without DPV or even, ideally, to improve upon them. Such interventions can thus help defer or reduce, if not eliminate, the size and frequency of local imbalances that risk problems for the grid.
2. **Hosting capacity enhancement.** Even with load balancing, there will be a need for DPV systems and the power system to cope with changed grid conditions resulting from deployment of DER. Key options to this end include: DPV inverter programming; grid equipment adjustments and upgrades; and enhancing overall flexibility of the power system.

This chapter describes a menu of example solutions under each of these two categories. Some solutions are introduced briefly while others are elaborated in more detail, based on available information. Under both categories, different solutions can be implemented at different levels of the power system, namely: design and operation of DPV systems themselves on the consumer side or grid side; local distribution grids; and, in some cases, the power system overall including bulk generation and transmission. Inverters (within DPV systems) are emphasized given the wide range of low-cost system benefits they can provide, which remain as yet largely untapped in LMICs. Which solutions are relevant for a given context depends on local conditions including the current and future level of DPV penetration, noting actual growth rates often exceed expectations.

Grid-friendly DPV systems can avoid or mitigate negative impacts on the grid in the first place, and reduce the need for other fixes at the power system level. Developers of DPV system projects usually base designs on the impact for host consumers rather than for the power system. Certain design features can, however, affect large individual sites and power systems generally. To maximize synergies, developers can be encouraged to consider power system impacts of DPV system designs in aggregate and for large individual projects.

⁷ Net load here refers to gross demand for grid electricity less demand served by distributed and/or bulk variable renewable sources, also known as negative loads.

Table A summarizes technical solutions for DPV by mapping issues that arise across low to high penetration levels and their operational and planning or investment solutions.⁸ Solutions highlighted in italics involve load-balancing, while others aim to enhance hosting capacity. Some issues affect the distribution grid, while others concern the power system at large.

Cost is naturally a key consideration in assessing different solutions. In general, incremental DPV solutions usually have low to moderate costs when planned ahead. High costs result from needing to replace assets before the end of their economic lifetime. Figure 5 illustrates the potential range in cost of solutions for issues that may affect the distribution grid, if not otherwise avoided.

At the level of transmission systems, requirements for forecasting, visibility, and controllability of bulk PV can be applied to DPV in aggregate. Geographic dispersion of DPV systems should tend, on the one hand, to make aggregate output smoother at the system level than a few sites with a large concentration of DPV—easing integration. On the other hand, the accretion of many individual plants can hamper visibility and controllability—complicating integration. A pragmatic approach could be to prioritize visibility for all but the smallest installations, while ensuring control as required.

SOLUTIONS MENU 1: LOCAL LOAD BALANCING

Supply-Demand Coordination

Options to coordinate distributed resources include the following.

- (a) Avoid oversized PV capacity for self-consumption by ensuring local energy efficiency opportunities are identified before design and approval of DPV systems. In doing this, account for potential new sources of local electricity demand from buildings, industrial processes and vehicles.
- (b) Analyze hosting capacities of network locations to inform DPV siting and choice of optimal design parameters. Identify nodes or feeders where DPV could help ease congestion with or without storage.
- (c) Favor installation of large DPV systems close to distribution transformers to help mitigate voltage problems along long feeders where loads are inflexible;
- (d) Use digital technologies such as smart meters and inverters to enhance monitoring and control of DER.
- (e) Aggregate DER into virtual power plants or local balancing areas.

Coordinating DPV to provide system services

By default, bulk power plants are required to provide system services to maintain voltage and frequency within nominal ranges at all times (via response characteristics and reserves); they also provide capabilities to restart the power system following a large-scale blackout.

Using DPV to provide system services is technically possible but requires efficient coordination of a comparatively large number of resources to do so. The problem can be solved through the application of information and communication technology. This can be cost-effective by removing the need for bulk power plants to remain on the system and allowing DPV to substitute for their generation at zero marginal cost. Put differently: DPV is sometimes curtailed in favor of more expensive generation that can provide system services more easily under current conditions. Avoiding DPV curtailment may have economic benefits that outweigh the costs of enabling such functionalities. This can be achieved, for example, by aggregating DPV installations into a virtual power plant (Box 3). Invert programming for system services is discussed further below (page 30).

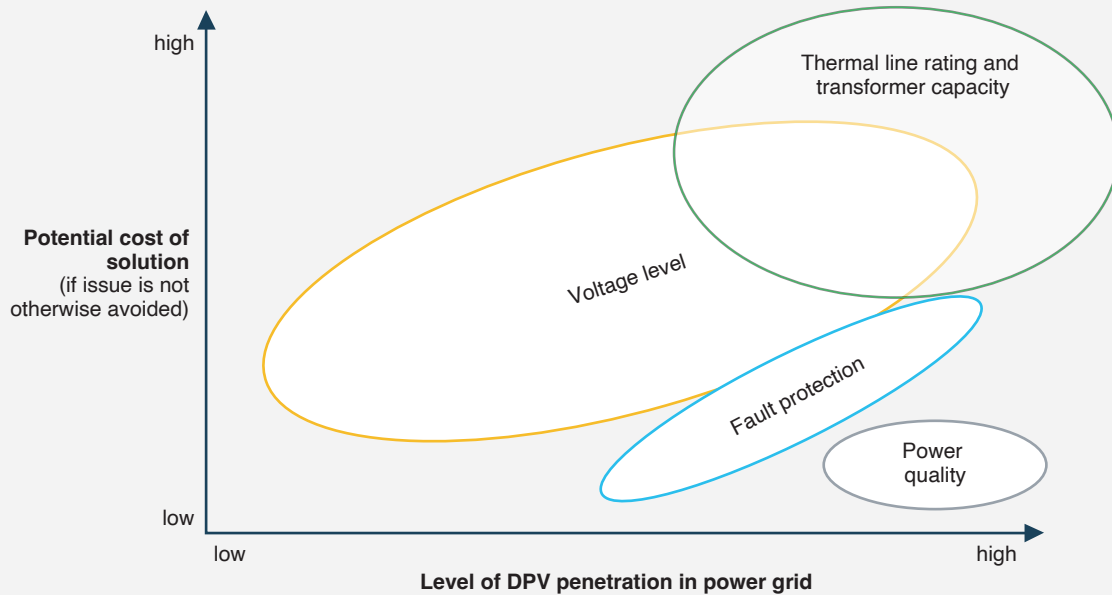
⁸ See Chapter 1 for an explanation of low, medium, and high DPV penetration levels.

TABLE A: POWER SYSTEM SOLUTIONS TO DPV ISSUES FROM LOW TO HIGH PENETRATION

| RISK ISSUE | OPERATIONAL SOLUTION | PLANNING OR INVESTMENT SOLUTION |
|---|---|--|
| Low penetration | | |
| Voltage levels. DPV can raise local voltage levels at times when PV output is high and local demand is low. This may cause voltage levels to exceed allowed maximum values. | <ul style="list-style-type: none"> • Program DPV inverters to contribute to grid voltage management • Adjust existing voltage compensation equipment, including transformer settings | <ul style="list-style-type: none"> • <i>Promote matching of DPV output and load through supply-side, demand-side, and coordination interventions</i> • Install on-load tap changing transformers to actively manage voltage in real time |
| Medium penetration | | |
| Fault protection. DPV may impact the efficacy of schemes to protect the spread of faults in distribution networks. | <ul style="list-style-type: none"> • Reconfigure settings of existing protection schemes | <ul style="list-style-type: none"> • Upgrade protection schemes to improve functionality |
| Transformer capacities and conductor thermal ratings. DPV output fed to grid may increase power flows in the distribution grid to the point of overloading thermal ratings and transformer capacities. | <ul style="list-style-type: none"> • <i>Dynamically curtail feed-in during times of system stress (if systems are technically capable to do this)</i> | <ul style="list-style-type: none"> • <i>Promote matching of DPV output and load</i> • Plan, and if needed upgrade, transformers and conductors with higher ratings |
| Output variability Across the power system, net load (i.e., power demand minus DPV output) will exhibit steeper and larger ramp-ups during morning and evening hours. | <ul style="list-style-type: none"> • <i>Incentivize demand response</i> • <i>Aggregate DPV into controllable, virtual power plants</i> • Dispatch other power plants more flexibly | <ul style="list-style-type: none"> • <i>Increase power system flexibility (demand response, storage, flexible generation, automate system operations with digital technologies)</i> |
| Output uncertainty. Across the power system, accurate forecasts of DPV output can be obtained only a few days to a few hours beforehand. | <ul style="list-style-type: none"> • Forecast DPV output and measure real-time output at enough DPV sites to inform system operations | <ul style="list-style-type: none"> • <i>Limit rapid DPV output changes using energy storage</i> |
| Exceptional conditions (e.g., voltage dips) in the power system. DPV must behave in a well-defined, system-friendly way during grid disturbances. | <ul style="list-style-type: none"> • Use DPV inverters to provide low-voltage ride-through and other system services | <ul style="list-style-type: none"> • Ensure grid codes require inverters to have the capability for high DPV shares |
| High penetration | | |
| Power quality. DPV may affect power quality in distribution networks by introducing harmonics, which can negatively impact sensitive equipment including that of other customers. | <ul style="list-style-type: none"> • Maximize use of existing inverters to support power quality • Adjust harmonic filters and other power quality management equipment | <ul style="list-style-type: none"> • Install harmonic filters and other power quality management equipment |
| Lack of synchronous generation in the power system. DPV connects to the grid via power electronics rather than a synchronous generator. | <ul style="list-style-type: none"> • Introduce fast-acting reserve services | <ul style="list-style-type: none"> • Use grid-forming inverters • Install synchronous condensers |

Note: *Text highlighted in italics* indicates load-balancing solutions that help match DPV output with local demand. In contrast, other solutions aim to enhance hosting capacity by adapting systems to cope with changed grid conditions. Case-by-case appraisal is important for the design and cost of any intervention.

FIGURE 5: DISTRIBUTION GRID EFFECTS FROM DPV BY LEVEL OF PENETRATION AND COST RANGE OF SOLUTIONS



Source: Original figure prepared by the authors for this report.

Note: This figure is indicative and based on general experience across countries. Specific costs of different interventions will vary from country to country and should be assessed case by case.

Supply-Side Adjustments

On the supply side, DPV systems can be designed and operated to better align with local load patterns. Supply side solutions may increase generation costs somewhat, so consider the costs and benefit of introducing general rules on this.

Options include the following.

- (a) Calibrate DPV panel sizes and angles to serve known peak loads and to diversify peak production times.
- (b) Size a PV array's DC capacity to exceed the inverter's AC capacity for an optimal DC:AC ratio (greater than one), so peak output is clipped while output during non-peak periods is maintained or maximized.
- (c) Size DPV system output capacity to serve only efficient local energy demand while accounting for potential new sources of demand such as electric vehicles.
- (d) Limit feed-in through dynamic curtailment or arrangements that feed none of the output to the grid.

Optimizing DPV panel sizes and angles across the grid

The solar PV array is the primary component of a DPV system. It comprises one or more modules, or panels, that convert incidental sunlight into DC electricity. Generally mounted as fixed panels, DPV

BOX 3

Aggregation of DPV into Virtual Power Plants

A virtual power plant (VPP) is an aggregation of various distributed energy resources (DER), using information and communications technology to provide power system operators with services like those provided by a bulk power plant. But information and communication technology would deliver these services with greater precision, flexibility, and efficiency than individual, uncoordinated DERs. VPPs have an important role to play in a future that features greater penetration of DPV technologies. Also, VPPs would ease planning for the dispatchable generation or system-level reserves required to balance variable renewable energy. A VPP's objectives usually arise from the system or market environment in which it operates.

Although VPPs are relatively new, commercial initiatives have already emerged in the United States, Australia, and Europe. In 2019, the company Sunrun won the first contract to supply capacity to the US wholesale power market from a VPP, providing 20 MW of capacity from solar energy and storage aggregated from homes, via the Independent System Operator of New England's Forward Capacity Market. In Australia, the Australian Energy Market Operator (AEMO) conducted a demonstration project for VPPs from 2019 to 2022. Although participation was open to any technology, all registered VPPs used batteries in their portfolios. Various state-based incentives program collectively targeted up to 700 MW of VPP-capable residential battery storage by 2022. As of June 2021, almost 168 MW across about 31,000 connections had registered. The project demonstrated VPPs' capability to deliver frequency-control ancillary services and other support to the grid, and informed determination of a market ancillary services specification in 2021.

Sources: Microgrid Knowledge (2019); AEMO (2021), and Maisch (2019). See also IEA (2022c) for recommendations on market development opportunities for DERs more generally.

modules are installed at a fixed angle to capture solar irradiation.⁹ A fixed panel may be mounted directly on a surface, if the angle of that surface (e.g., a tilted roof) is suitable, or mounted on frames allowing the panel to be set at a different angle.

Panel positions have implications for the power system. Power density is always greatest when the PV panel is perpendicular to the sun. But panels can still generate electricity from diffuse and indirect irradiation. Bifacial panels can capture sunlight from either side, a feature well suited to solar-reflective rooftops, where the panels help buildings with passive cooling (ESMAP 2020a).

⁹ PV systems can also be designed to move along one or two axes either manually, e.g., twice a year to optimize for seasonal variation, or automatically to track the sun over the course of each day. Tracking arrays have higher capital and operational expenses and occur rarely in DPV installations.

In most cases, panel angles (orientation and tilt) are chosen to maximize total annual energy production. This means positioning panels for peak production to occur around noon (i.e. north-facing in southern latitudes and south-facing in northern latitudes). This approach naturally suits the least-cost generation and bill reduction use cases, if feed in is allowed. However, if all DPV systems in a district peak at the same hour of a day, their aggregate effect on net load peaks and troughs is magnified. The risk of supply-demand imbalance in this situation may be moderate if peak demand in those distribution feeders also occurs around noon on average (e.g., commercial buildings with high cooling needs around noon on summer days), or if demand can be flexibly shifted to match the hour of peak production (e.g., air conditioners programmed to increase work earlier than they might otherwise to cool buildings efficiently in advance of peak cooling demand). Alternatively, panels can be oriented with an eastward or westward bias to shift peak power output to the mornings or evenings, to match the average hour of peak demand on site or on the local distribution feeder. In other words, panel position can be designed to reflect the time value of production. For example, when DPV design analyses reveal thermal overloading of distribution lines, other positions can be explored to yield a more consistent output profile. While orienting systems east or west can result in lower total annual outputs than installations, the trade-off can be considered strategically by DPV system designers, ideally in coordination with distribution system planners and operators, and reflected in connection standards and incentive programs.

Sizing inverters for a high DC:AC ratio

Almost all DPV systems deliver DC power through electrical cables to an inverter, which is a software-controlled power electronics device that changes the DC electricity input to an AC output.¹⁰ Inverters may be wired to PV panels in different ways: (i) a single PV panel may have its own inverter, known as a “microinverter”; (ii) more commonly, a line of PV panels together feed one inverter, known as a “string inverter”; (iii) in some large installations, an array of several PV panel lines may be served by a single “central” inverter.

DPV system inverters involve two key design parameters:

- DC:AC ratio of inverter capacity relative to the PV array output, discussed below; and
- Programmable electronic functions of inverter, discussed later under hosting capacity enhancements.

The DC:AC ratio, also known as inverter load ratio (ILR), is the ratio of the DC capacity of a PV array’s peak output to the AC output capacity of its inverter. The cost of inverters increases with the size of their capacity. As such, systems are generally designed to use the smallest appropriate inverter capacity, all else being equal. PV systems generate output at their peak DC capacity only for some hours of any given year, and less than 1 percent of the energy produced will be at a power above 80 percent capacity (Pulumbarit 2023). As such, it is often not cost effective to size an AC inverter to capture all of the PV output, i.e., with a DC:AC ratio of around 1, unless more PV can be connected to the inverter in the future.

An optimal ratio for DPV systems may be in the range of around 1.1 to 1.5 or even higher depending on the specific circumstances.¹¹ A system with a high DC:AC ratio (>1), and no DC-connected battery storage,

¹⁰ DC output from PV panels can, in limited cases, be used directly for DC loads or circuits, and for certain isolated settings such as rural microgrids (Tomar 2020; Papadimitrou and others 2018; Hailu and others 2015). But DC circuits and grids are not common. For practically all electricity grids, large and small, and for consumer circuits, the standard is AC. Inverters are also known as converters in some countries and in some literature.

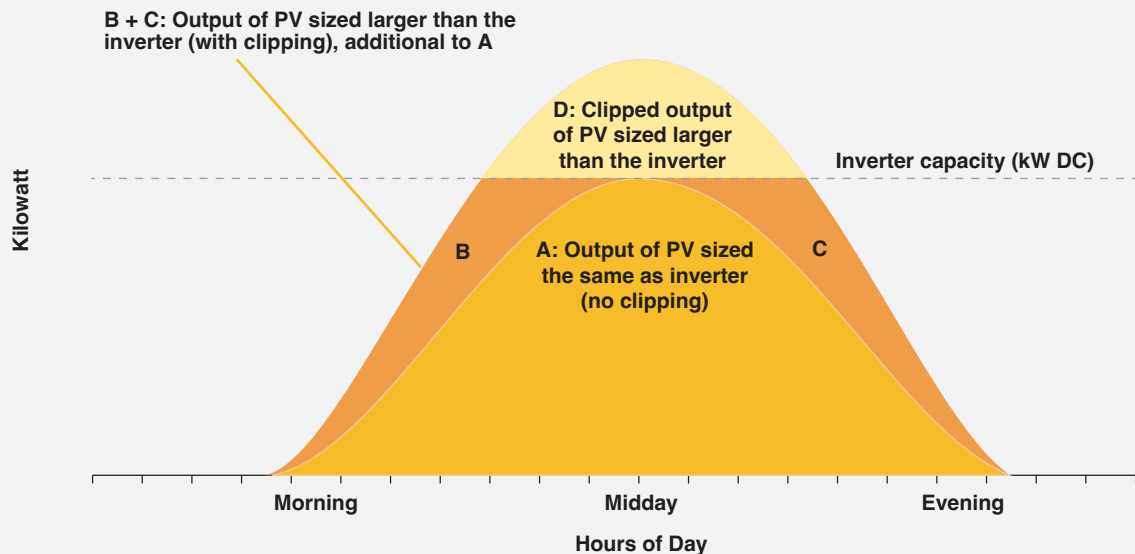
¹¹ Inverters are typically less than 100 percent efficient. This should be taken into account when considering the DC:AC ratio. In different literature, the practice of designing systems with a DC:AC ratio greater than 1 may be known variously as inverter clipping, peak shaving, overclipping, overloading, oversizing (of PV relative to inverter), or undersizing (of the inverter). Some literature also express the ratio as a percentage.

shaves or clips PV output during time periods of peak (potential) production (Figure 6). However, it does this without constraining solar generation at times of non-peak production, including the mornings and evenings of days with peak irradiance. In this way, PV sized greater than the inverter capacity can increase non-peak output (see Figure 6). Because the PV panels reach their maximum output for a limited amount of time, it is possible to have a strong reduction in peak feed-in capacity while reducing the overall amount of useful energy only modestly.

Typically, a ratio of 1.5 may lead to a reduction in annual energy output of just 2 to 5 percent (compared to a unit ratio inverter for a given PV capacity), while having a pronounced impact on peak reduction (Pulumbarit 2023). This approach can enhance the distribution grid hosting capacity of DPV. Experience to date in various countries suggests that optimizing the DC:AC ratio can facilitate the total installed capacity of DPV connected to a distribution feeder to exceed 75 percent of the feeder’s peak capacity, while keeping within system operating limits.

Common practice is to set the DC:AC ratio as high as possible without significant clipping loss. However, optimal DC:AC ratios are best assessed case by case. Generic rules of thumb for inverter sizing may be inaccurate or incorrect as they depend on a number of parameters. These include: the system’s location, array orientation, size, feed arrangement, technology costs (modules, inverter, storage), voltage level, and feeder reactive power support needs. The time resolution of analysis also matters (10-minute intervals can provide significantly more accuracy than hourly intervals). NREL’s *PVWatt* software gives a default

FIGURE 6: PV SIZED GREATER THAN THE INVERTER CAPACITY CLIPS PEAK BUT INCREASES NON-PEAK OUTPUT



Source: Original figure prepared by the authors for this report.

Note: The lower curve (area A) represents power output on a day of peak production for a PV system (without batteries) where all DC output is inverted to AC output, i.e., DC:AC ratio is 1 (disregarding inverter efficiency). The upper curve represents additional potential output of a larger PV system. With the same inverter capacity, this results in a DC:AC ratio exceeding one: peak output is clipped (area D), while non-peak output (areas B and C) is unconstrained.

ratio of 1.2.¹² An optimal ratio may be higher than 1.2 for larger PV plants, systems with DC-connected storage to store peak output that would otherwise be clipped, and plants with non-orthodox angles.¹³

Setting feed-in limits

One way to match load is to curtail DPV output during times of high output and low load. There are different ways to do curtailment. The simplest solution is a static feed-in limit, such as a feed-none arrangement, or a cap set as part of the connection agreement. Inexpensive inverters can be programmed to dispatch battery-equipped DPV at set times to ensure smooth system operations. This solution has been applied even in low-income countries marked by fragility. However, this can also be simplistic. A static limit is generally based on a worst-case scenario that may rarely occur, resulting in unnecessary curtailment and missed opportunities to feed the grid during times of day or times of the year when more distributed generation is desirable. A more sophisticated solution is to use control systems to curtail output dynamically when needed. This is further discussed under DPV inverter programming below.

Demand-Side Adjustments

Flexible demand can also help match DPV output patterns. Demand-response measures can directly reduce or increase final uses of electricity at different times of days as needed. Further flexibility comes from energy storage: plug-in electric vehicles; or battery systems connected either to consumers or directly to the grid.

SOLUTIONS MENU 2: ENHANCING HOSTING CAPACITY

DPV Inverter Programming

The programmable electronics of inverters offer a range of valuable services. The behavior and programming of inverters determine how generators behave on the grid during normal and exceptional operating conditions. Inverters can be programmed to keep voltage within system operating limits and cope with exceptional grid conditions by providing services such as low-voltage ride-through.

A standard typology for inverter functions is lacking in the literature. Figure 7 captures a sample of technical services that inverters in DPV systems may provide. Here, services are grouped according to the distributed system's capabilities to: (a) control only reactive power;¹⁴ (b) control both reactive and active power; or (c) additionally operate in grid-forming mode to substitute functions usually provided by synchronous generators.

DPV inverter settings for autonomous regulation in response to local grid conditions

Automated inverter settings can turn down the active power in response to local feeder conditions. All modern inverters can also provide static reactive power. While this requires slightly higher inverter ratings

¹² NREL (2023). This tool gives a default 3.33 AC kW inverter with 4 DC kW array at standard test conditions.

¹³ See Marcy (2018) and Weaver (2019). A study in the United Kingdom identified an extreme case of 1.7 for a north-facing PV system without storage (Balouktsis and others 2008).

¹⁴ Reactive power, measured in volt-ampere reactive (VAR), is a fundamental feature of AC electricity, in contrast with and complementary to active power (measured in watts). Reactive power can be injected and absorbed by certain types of electrical generators and other power system equipment including inverters, such as in DPV systems.

FIGURE 7: TECHNICAL SERVICES THAT DPV INVERTERS MAY PROVIDE BASED ON AVAILABLE CHARACTERISTICS

| Control characteristic | Services able to be provided |
|------------------------|--|
| Reactive power control | <ol style="list-style-type: none"> 1. Compensate reactive power (static voltage support) 2. Fault ride through (dynamic voltage support) 3. Improve power quality (e.g. voltage profile) |
| Active power control | <ol style="list-style-type: none"> 4. Limit feed in to grid (static voltage support and congestion management) 5. Provide operating reserves 6. Provide firm capacity |
| Grid forming control | <ol style="list-style-type: none"> 7. System stability services (synthetic inertia, frequency droop control) 8. Operate as intentional islands during outages 9. Support black start after systemwide outages |

Source: Original figure prepared by the authors for this report, drawing on Stetz and others (2014). See also: Magal and others (2014), Ding and others (2020), Lin and others (2020), Kraiczy (2021).

Note: All services require reactive power control from the inverter. In addition, services 5 through 9 require active power output, which could be from PV, battery, or another connected power source.

and boosts the electricity flow (that is, the reactive power component of the flow) on the grid, it moderates voltage increases due to DPV. The technical specifications in the grid code (discussed in Chapter 3) provide one pathway for mandating the provision of default static reactive power. Some advanced inverters can also absorb or inject reactive power dynamically in response to local feeder conditions.

When DPV use greatly exceeds local electricity demand, reactive power properties may be affected, with circuits exhibiting higher reactive power consumption during the day, owing to high active power flows from DPV generation, and more reactive power generation at night. Under these circumstances, management of the reactive power of the system may require adjustment. In order to avoid the challenges surrounding voltage surges during rapid uptake, DPV connection standards should contain provisions for disconnecting from the grid if voltage exceeds a certain threshold, addressed in interconnection standards like the Institute of Electrical and Electronics Engineers (IEEE) 1547–2018, discussed below.

Where larger DPV systems are connected to medium-voltage levels of the distribution grid, they may be required to contribute to dynamic reactive power management—including low-voltage ride-through circumstances—by remaining connected to the grid during voltage dips. This capability becomes more important as DPV penetrates the system. Low-voltage ride-through has been standard for wind turbines for over a decade and can also be implemented for DPV using appropriate inverters.

At high levels of penetration, poorly managed DPV systems may negatively impact the frequency of AC bulk grid power. Yet, as an inverter-based generation, properly configured DPV can actually help regulate frequency and other disruptions to the bulk power system. The response of feed-in DPV to such disturbances should

be considered to ensure constant grid reliability. Ride-through capabilities and protections against under- and over-frequency, among other problems, are especially important for larger DPV installations such as those above 30 kW capacity. Even for smaller systems, however, frequency ranges and voltage operation settings need to be defined and regulated, ideally through revisions of the grid code (e.g., adapting IEEE 1547 to reflect local characteristics), as discussed in Chapter 3.

High penetration levels of inverter-based generation call for innovative frequency controls. More advanced functions of DPV inverters, especially grid-forming controls, are still under development.

Grid-forming DPV systems

For several years now, solar-based mini grids have been rapidly deployed in remote areas around the world. Also known as “third-generation mini grids” (ESMAP 2022), they are generally owned and operated by private companies that leverage transformative technologies and innovative strategies to build portfolios of projects instead of single projects. The typical third-generation mini grid is ready to become grid-connected and uses remote management systems, prepay smart meters, and the latest solar-hybrid technologies. Companies may incorporate into their business model energy-efficient appliances for productive uses of electricity and provide reliable, resilient, and high-quality electricity supply to users at the end of service lines. Puerto Rico, for example, is utilizing solar-based, third-generation mini grids as a foundation for its recovery from the devastation of Hurricane Maria. The island’s integrated resource plan (IRP) has taken a grid that was once part of centralized generation and segmented it into eight mini grids incorporating PV with battery energy storage (Siemens 2019). Such systems rely on advanced DPV technology, including inverters that can fully substitute the functions usually provided by synchronous generators (Box 4).

Grid Equipment Adjustments and Upgrades

Hosting capacity can be maintained or enhanced through distribution grid infrastructure, whether adjusting operational settings of existing grid equipment, ensuring new grid investments are carefully designed, or as a last resort, upgrading existing grid equipment before the end of its economic lifetime.

Technology options include the following.

- (a) Voltage compensation equipment, including transformer settings.
- (b) On-load tap changing transformers to actively manage voltage in real time.
- (c) Fault protection equipment settings.
- (d) In cases where DPV adds enough value to justify the cost, grid equipment can also be upgraded to expand the capacity of transformers and the thermal line rating of conductors. Larger conductors yield greater hosting capacity thanks to fewer voltage issues and higher thermal limits.
- (e) The adjustment or installation of harmonic filters and other power quality management equipment. This is relevant only for high DPV penetration levels.

Voltage control equipment

When DPV output supplies local demand for grid consumers, it reduces or displaces load on the local distribution feeder, even if none of the DPV output is fed to the grid. DPV production occurring toward the end of a radial feeder line (as introduced in Chapter 1), may need special measures to maintain voltage levels

Grid-Following and Grid-Forming Inverters

Inverters can provide a distribution system with a suite of flexible services. These include fault ride-through, dynamic reactive and active power output, ramp rate control, and anti-islanding protection. Inverters come in several fundamentally different types. One class of inverters are grid-following, another class are grid forming, and some inverters have the ability to switch between grid-following and grid forming modes.

An inverter in **grid-following** mode operates as a current source (i.e., alternating current). In this mode, the inverter can adjust output and phase-angle relative to the broader distribution grid. However, the reference voltage and frequency regulation will depend on an external voltage source (i.e., the grid or a diesel generator). Grid-following inverters can be connected to an intermittent DC current source like PV without battery storage. As such, the inverter can inject available PV power into the AC network, up to the level of PV output or up to the level of inverter capacity, whichever is lesser. In general today, most grid-connected DPV systems' inverters operate in grid-following mode.

An inverter in **grid-forming** mode operates as an AC voltage source and controls the frequency to loads served by the inverter. Grid-forming as a function applies to both main distribution grids and to local loads such as in microgrids operating in island mode. For most power grids today, the grid-forming function is provided by large-scale rotating synchronous generators from central power plants connected to the transmission system. However, as inverter-based generation grows to larger shares of a power system, inverters will also need to begin contributing grid-forming for the network. An inverter with grid-forming functionality is required for a microgrid to operate in an island mode, independent of the main grid network. Grid-forming inverters rely on battery storage or another active power source such as a diesel backup generator to provide power necessary to dynamically increase or decrease output to balance loads and maintain local frequency and voltage.

Inverters that are able to operate in both grid-following and grid-forming modes often have two separate sets of AC terminals. The grid-following set of terminals is connected to an AC source like grid power. The grid-forming terminals are connected to local loads (or a subset of local loads that are identified as priority loads). When grid power is available, the inverter operates in a grid-following mode, routing AC grid power from the grid-following terminals through the inverter to the load. In this mode, the inverter is operating as a current source and, if there is a feed-some arrangement with the utility, the inverter feeds unconsumed DPV output into the grid via the inverter's grid-following terminals. In the event that the grid goes down, the inverter switches to grid-forming mode, internally disconnecting from the grid-following terminals and operating as a voltage source to supply connected loads with the inverter's own AC waveform. For an illustrated example, see Figure A2 in Annex A.

Source: Original based on Eto and others (2018), IEEE (2018), Lin and others (2020), Kroposki (2021), McAllister and others (2019), IRENA (2022).

within an acceptable range. For DPV fed to the grid, even when DPV generation exceeds local demand, power can be stepped up to feed the higher voltage grid without necessarily having to change cables, as long as the magnitude of the flow does not exceed the peak load for that distribution grid (called “feeder peak capacity”). At or near this limit, a transformer with a fixed turns ratio might need to be exchanged for one with variable tap settings (auto-tap) so that the transformer can accommodate the daily cycles from a daytime injected current to nighttime load without voltage falling out of an acceptable range.

Installation of an on-load tap changer at the distribution transformer is a common solution to manage voltage on feeders with DPV. These allow dynamic adjustment of voltage at the transformer. A lower setting avoids surges on the customer side under low-load conditions or reverse power flows. A higher voltage setting ensures that there are no under-voltages, for example, during the night and under high loads. By dynamically adjusting to low-load/high feed-in or high-load/low feed-in situations, on-load tap changing transformers can mitigate voltage issues.

Where other voltage compensation equipment is present in the distribution grid, its settings can also be adjusted to account for DPV. But voltage regulators may need to account for fluctuations in DPV output caused, for example, by passing clouds. Equipment upgrades may be needed.

Voltage control equipment may include: DPV units controlled by smart inverters; shunt and series capacitor banks, static VAR compensators (SVC), and static synchronous compensators (STATCOM).

Fault protection equipment

Large cumulative capacities of DPV responding to abnormal grid conditions can have system-wide impacts. For example, if there is a fault somewhere in the network, a DPV system may shut itself off, and in so doing it doesn't contribute fault current that overcurrent protection relies on to detect and isolate the fault. Another scenario may be if a lot of DPV is programmed to disconnect immediately when grid AC frequency is above or below nominal values. Loss of one generator could trigger all the PV to shut down immediately, contributing to further cascading outages, as discussed further below. At high penetration levels, reconfiguring or upgrading underfrequency load-shedding relays can become a priority. Substations often use relays as a last line of defense against the threat of a system-wide blackout. The traditional rationale for configuring such relays assumes that distribution grids are always loads and do not contribute to generation at the transmission level. But if the relay disconnects the system while it is feeding power up to the transmission level, the problem may be exacerbated. Existing relays may thus need to be reprogrammed or set differently or replaced by new ones altogether.

These impacts can also be mitigated by connection standards, such as the IEEE 1547-2018, that specify functions of DPV system inverters to cope with abnormal grid conditions.

Changes to protection schemes might also be required at higher shares of DPV, once power flows to higher voltage levels become common. Protection schemes prevent power flow during fault conditions by separating (“sectionalizing”) problematic circuit segments from the broader system. The function of these schemes is to detect current surges during a fault and then to isolate the problematic line section until normal conditions can be restored. Modern protection schemes can operate reliably at high shares of DPV but may require configuration. Grid operators will require training to ensure correct configuration.

Conductors and transformers

DPV deployment could at some point require upgrades to lines and transformers. Thermal capacity can become relevant, for example, if there is a large installation at the end of a smaller radial feeder line. A larger-diameter conductor (or similar interventions like an additional circuit) may be needed in the event electricity is to be fed back to the transmission level or to consumers closer to the transformer.

Enhancing Power System Flexibility

At the power system level, DPV shares many action areas and solutions with bulk PV and wind power plants. As a type of VRE, variability and uncertainty of DPV output call for system flexibility. Options include the following.

- (a) Improve operational forecasts for variable renewable resources.
- (b) Automate power system operations to respond quickly and efficiently to net load fluctuation and to resource forecasts.
- (c) Expand balancing areas of grids such as by increasing interconnections.
- (d) Dispatch other power plants more flexibly with frequent schedule updates close to real time and at short dispatch intervals.
- (e) Introduce fast-acting reserve services and/or install synchronous condensers to compensate for a lack of synchronous generation at high penetration levels of inverter-based generation.

System-wide DPV generation forecasts

In many parts of the world, forecasts for solar PV generation have become a commodity. If centralized PV forecasts are available, then system-level DPV forecasts can also be obtained. Calculating system-wide DPV forecasts depends, however, on accurate data on the location and size of DPV installations. System-wide forecasts will be more accurate the more details are available about, for example, orientation and tilt. For detailed guidance on using forecasting systems to reduce cost and improve dispatch of variable renewable energy, see ESMAP (2019).

Centralized, system-wide forecasts should be implemented in any case, integrating the forecasts of different providers. This is especially useful in cases of high uncertainty, as different forecast models tend to diverge under such conditions. A centralized forecast complements plant- or portfolio-level predictions. The latter may be used for scheduling DPV generation. But subjecting DPV to strict balancing requirements would be consequential only for larger installations. Small rooftop systems tend to aggregate output and achieve balancing through the system operator—like balancing electricity demand itself in many systems. That said, where DPV is paired with a battery system, more stringent scheduling requirements are advisable. This is because incentives for greater self-consumption create a less predictable interplay between load and DPV. While each can be forecast accurately in isolation, their interplay is more complex when linked via a storage system.

ESMAP offers a simplified PV forecasting tool to inform the decisions that utilities make regarding basic electricity dispatch. This is illustrated in Figure 8. In one mode, the tool provides a daily solar PV generation forecast with hourly resolution for a PV system or portfolio of systems.

Real-time visibility and controllability

Visibility and controllability are foundational to power system operations, and they remain valid at high shares of DPV. Indeed, they become even more important as DPV shares grow, because accurate, well-visualized data and reliable control may be required when many more individual assets are involved.¹⁵

¹⁵ See IEA (2022c) for further recommended practices on increasing the visibility of a distribution system and consumer dynamics.

FIGURE 8: USER INTERFACE, ESMAP'S SIMPLIFIED SOLAR PV FORECASTING TOOL



Source: World Bank (2021).

Note: The Solar PV Forecast Tool is a free, web-based application developed and operated by the company Nnergix Energy Management SL on behalf of the World Bank, utilizing Nnergix knowledge and weather forecasts publicly available from the US National Oceanic and Atmospheric Administration (NOAA), with funding provided by ESMAP.

But DPV installations are different from large, central plants. For example, connecting them to a transmission-level SCADA system would be unnecessary and expensive. More useful would be a layered approach, differentiated by visibility and controllability requirements.

This approach starts with a mechanism, and appropriate incentives, for registering DPV installations alongside basic plant data. With samples from real-time, metered generation sites, forecasting can create accurate generation data and reliable, system-wide estimates. This way of attaining visibility is sufficient when DPV is not the grid's major electricity source.

Utilities can improve power system operations by deploying production meters systematically and, where DPV penetration levels are high, by installing smart meters that enhance visibility and allow a wider range of operations. Also, utilities can ask consumers willing to install DPV to seek their approval and install specific control hardware (e.g., ripple control).

It is generally advisable, however, to ensure that DPV systems can be readily adapted to perform more complex functionalities when and if these may be needed. The first step in this direction is monitoring with smart meters and real-time generation. Another step would be to adjust generation—which can range from a simple on/off command to discrete steps, or even a detailed setpoint. Cost and proportionality should be primary concerns, together with reliability.

For control strategies to work as designed (especially in active control cases) utilities will need telemetry and sensors to render power flows visible in the distribution network. These visibility instruments may require investments in methods to monitor and manage the many devices used at the endpoints of the low-voltage network. Utilities are exploring centralized management systems to monitor and control DPV assets as inputs into system operations (for example, a distributed energy resource management system, or DERMS) or in coordination with scheduling responsibilities and operating equipment and protection

systems (e.g., advanced distribution management system, ADMS; or active network management, ANM). These systems help to develop a coordinated and collaborative distribution, where assets participate on both sides of the service transformer. Investments in ANM or ADMS focus on the entire distribution system, utilizing top-down strategies to monitor and control myriad assets on low-voltage secondary networks as part of a larger fleet. There is some devolution to subsets of DPV systems, so incremental adjustments can be made at the local level. Given the capital investments in these systems—notably, a fully integrated ADMS—utilities and system operators are examining phased rollouts, beginning with DERMS. DPV and DER asset management could then be merged with system-outage management or protection automation (Hanson and others 2019).

Systematizing Solutions

This chapter has highlighted a menu of potential solutions for grid-friendly DPV at growing levels of penetration, and how DPV can contribute to reliable system operations. Achieving these outcomes, however, depends on having a grid code, which is the focus of Chapter 3, and good planning, the topic of Chapter 4.



Illustrative analysis of rooftops in Grenada

3: GRID CODES FOR GRID-FRIENDLY DPV

Large-scale deployment of grid-friendly DPV depends on a grid code: the full set of operational and technical rules governing a power system. Connection standards are an important part of a grid code. Connection standards are technical requirements that DPV systems must meet to be permitted to connect and feed some or all of their output to the grid. Connection standards do not necessarily apply to DPV systems that feed none of their output to the grid. Feed-none systems (explained in Chapter 1) may nevertheless need to comply with safety regulations, equipment standards, or monitoring schemes. Although connection standards are just one part of the grid code, both terms are sometimes used interchangeably in literature on DER.

For DPV systems, connection standards establish how they must respond to certain power grid conditions, such as abnormal frequency and voltage parameters, and under which conditions to disconnect or “ride through,” remaining connected during mild or temporary abnormal conditions to help support the overall grid.

Successful deployment of DPV depends on streamlined connection standards that lessen the administrative and analytical burden for each DPV plant. For DPV, connection standards may require minimum responses under normal operating conditions and during contingencies, giving utilities a standardized means to enforce operational requirements.

SUGGESTED GRID CODE ELEMENTS FOR DPV

Grid codes can help address a wide set of potential problems and solutions associated with DPV, as introduced in Chapters 1 and 2. For grid codes to fully account for DPV system issues, many specific elements can be considered. These elements are itemized in Table B. Some elements relate to the connection of DPV systems to the grid, while others concern DPV communications and control. Most of the elements relate to functions of the inverter, as discussed further below.

Countries with no grid code should develop one as soon as possible, while countries with a grid code may need to update it to reflect expected future scenarios. An initial grid code may be developed quickly based on international experience to ensure minimum functionality for secure operations (IRENA 2022). However, it is important to stress that grid codes must be consistent with the specifics of a given power system. Copying values from a different system can produce inconsistent rules that are incompatible with the reliable operation of the system. Nevertheless, an imperfect grid code is, in many cases, better than no grid code at all, especially when DPV or other technologies are rapidly deployed.

Appropriate grid code elements for VRE, including DPV, will vary depending on how small or large is the power system and how low or high is the level of penetration. Figure 9 provides suggestions from a recent study by IRENA.

Successful implementation of grid codes critically depends on the availability of utility staff with adequate skills and training as well as schemes to monitor and enforce compliance. In many countries, maintenance of power systems is already a major challenge even before considering the increased complexity of distributed resources with more varied, independent actors. In such cases, it is important for grid code authorities to think

TABLE B: RELEVANT GRID CODE ITEMS FOR DPV SYSTEM REQUIREMENTS

| GRID CODE ITEM | DESCRIPTION |
|---|--|
| DPV CONNECTION REQUIREMENTS | |
| Classification of generator size per connection voltage level | Categorizes DPV or DER by size to define groups and provide requirements for each category. Each category will vary country to country according to size of the system and the different voltage levels. Please see Annex 1 for an example. |
| Normal operating conditions—voltage level | Sets permissible voltage levels to be defined for each category as voltage ranges would differ depending on the connection point. The operation ranges aren't defined in some distribution grid codes for DPV or DER but would need to be defined to avoid undesired situations in the grid. |
| Normal operating conditions—frequency | Sets permissible frequency levels and requirements to disconnect after a certain duration of frequency above a certain range. DPV must also remain connected to the system below a defined rate of change of frequency and disconnect above a certain rate. The operation ranges aren't defined in some distribution grid codes for DPV or DER but would need to be defined to avoid undesired situations in the grid. |
| Anti-islanding and intentional islanding | Ensure that all inverters have capabilities to detect outages and stop active power supply to protect equipment from damage. Bimodal inverters may, however, operate in stand-alone mode when disconnected from the utility. |
| Behavior during abnormal operating conditions—voltage ride-through | Defines voltage ride-through capabilities differently for different sizes of DPV where they are required to stay online. Some utilities may set an additional optional range. |
| Behavior during abnormal operating conditions—frequency ride-through | Defines the frequency ride-through requirements by the frequency range of operation where DPV or DER must sustain operation for a defined minimum time. |
| Protection time settings | Define protection time settings in the grid code, permitting reasonable delays for over/undervoltage and over/underfrequency events in light of voltage and frequency ranges. |
| Protection and fault levels | Ensure that the protection system is set to prevent faults and stays connected in noncritical situations, such as small variations in the system (bidirectional). |
| Reconnection after fault (synchronization to the grid) | State the conditions in the grid code under which DPV may reconnect (i.e., voltage and frequency levels sustained over a certain period). |
| Power quality—rapid voltage changes | Maintain voltage below a predefined threshold to prevent voltage fluctuations due to switching operations of DPV or DER. |
| Reactive power capabilities | Mandates the operation of DPV or DER above a certain voltage level (or size) at any power factor within the defined capable operation ranges agreed through the grid code. Inverters need to be sized considering the capability to provide voltage regulation. |
| Dynamic voltage support | Prioritizes DPV or DER above a certain voltage level (or size) to supply reactive power for grid support during abnormal conditions. |
| Active power control | Sets a size threshold for DPV or DER to be capable of controlling the supplied active power at the connection point when requested. |
| Ramp control/spinning reserves | Identifies DPV or DER above a certain size that are required to control output fluctuations (ramp control) or even provide frequency control reserves (spinning reserves) when needed by the system operator. |
| Frequency response | Requires DPV to reduce active power output above a certain frequency threshold according to a defined frequency—power-output curve defined by the grid code |
| Synthetic inertia | Require DPV or DER above a certain size to provide inertial response. |
| Power quality—flicker | Comply with the limits for DPV defined in the grid code when enforced—more relevant to wind power. |

TABLE B: RELEVANT GRID CODE ITEMS FOR DPV SYSTEM REQUIREMENTS (Continued)

| GRID CODE ITEM | DESCRIPTION |
|--|--|
| Harmonics | High levels of harmonics will damage equipment. DPV to comply with harmonic limits enforced in the grid code at the point of connection where the limits vary from country to country. |
| DPV COMMUNICATION AND CONTROL | |
| Remote control by system operator | Specify system operator control over system balancing above a certain size of DPV or DER, to adjust levels of active power operation |
| Forecasting requirements | Require forecasting for DPV or DER above a certain size (i.e., DPV in the MW range). |

Source: Original by authors for this report.

through the risk and consequences of potential non-compliance with certain provision. For example, even a small number of DPV systems can pose a safety risk to power system technicians if they do not comply with anti-islanding (or intentional islanding) requirements during a grid outage.

Over time, power system studies (as described in Chapter 4 on planning) can evaluate the adequacy of existing requirements and identify points to improve so that grid codes reflect the needs of the power system today as well as expected future development scenarios. Standards around the world are being revised to incorporate new capabilities offered from DPV systems (AEMO 2019). Notable past examples include Germany's expansion of fault ride-through capabilities in 2012, and updates in the United States led by California and Hawaii in 2018 (IEEE 2018).

THE RATIONALE FOR SPECIFYING DPV INVERTER BEHAVIOR IN GRID CODES

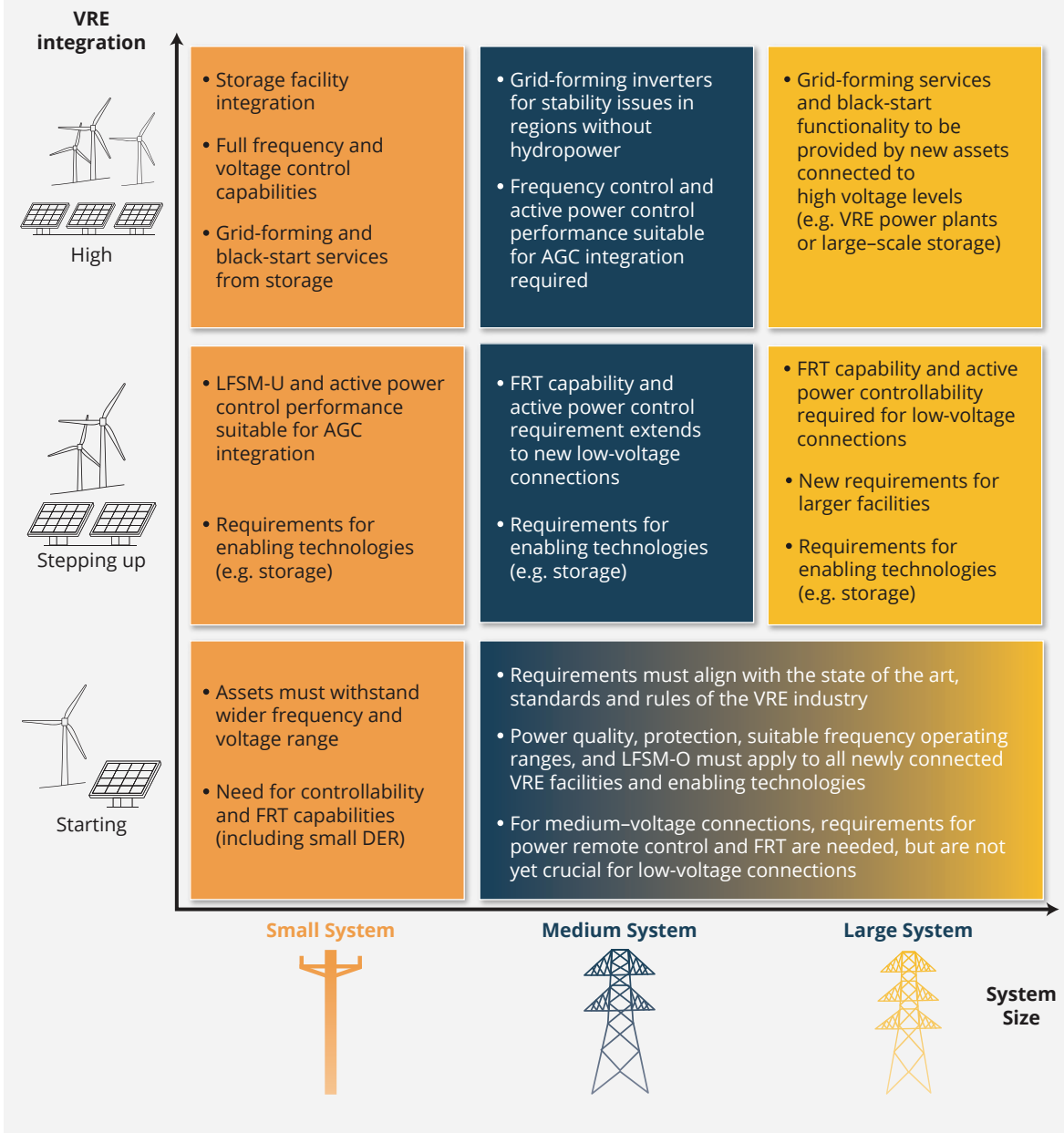
Inverter standards are key for high shares of DPV to cope with and avoid system disturbances from a bulk power system, as discussed in Chapter 2. Inverter settings for grid interaction can and should be mandated by grid code connection standards. They can define how DPV inverters interact with key distribution operational functions, including the regulation of voltage and frequency, the monitoring of power quality, and the functioning of protection systems needed for reliability and safety (Aznar and Stout 2018; IRENA 2022).

DPV that adheres to the grid code connection standards can benefit power systems. Even in grids with low DER penetration, requiring advanced inverter functions today could reduce the need to change systems in the future (IEA 2022c). For example, it is generally not possible to retrofit grid-following inverters to have grid-forming capability.

Initial approaches to DPV configuration followed the principles by which distribution systems were originally planned and operated: “fit and forget” and “do no harm.” Experience in countries with rising DPV shares has shown, however, that DPV integration requires a more nuanced approach.

For example, the German grid code used to mandate that DPV installations disconnect from the grid when system AC frequency reaches 50.2 hertz (Hz), or cycles per second. This would lead, the thinking was, to a do-no-harm response to surplus generation. Toward the end of 2020, however, Germany had an installed PV capacity of approximately 70 percent of peak demand, most of which was DPV, meaning that disconnecting all DPV at 50.2 Hz would have plunged the country into a system-wide blackout. Germany has since revised its grid code, and each DPV system now disconnects at a randomly chosen value within frequency intervals that deliver a smooth, system-stabilizing response (BDEW 2016).

FIGURE 9: GRID CODE FORMULATION GUIDANCE BY GRID SIZE AND LEVEL OF VARIABLE RENEWABLE PENETRATION



Source: IRENA (2022).

Note: AGC = automatic generation control; DER = distributed energy resources; FRT = fault ride through; LFSM-O = limited frequency sensitive mode for over-frequency; LFSM-U = limited frequency sensitive mode for under-frequency; VRE = variable renewable energy.

This example highlights two important points: first, DPV can become relevant for the overall power system, so technical rules must keep pace with installed DPV capacity. Second, such rules should be pragmatic and easy to implement, with few requirements for costly monitoring and control equipment.

In regions with high DPV penetration, inadequate responses to system-wide disturbances (e.g., the automatic disconnection of DPV units) risk worsening system conditions rather than improving them. To avoid this, transmission and distribution planners should coordinate closely to inform and comply with appropriate grid codes to specify and reflect the functional capabilities of DPV.

New functionalities can be tested in pilot programs. Autonomous control settings, for example, can allow stakeholders to gain experience with automated DPV management of grid operations. California and Hawaii (and elsewhere in the United States) have begun incorporating autonomous control settings into connection agreements, notably for circuits nearing the limits of capacity.

During the connection process, utilities and DPV users can develop custom setpoint-based curves that autonomously adjust reactive, or real, power output based on terminal voltages to limit the need for conventional DPV integration measures such as curtailment (AEMO 2019; Horowitz and others 2019; Palmintier and others 2016).

Over time, with greater investment in monitoring systems, DPV can expand beyond energy generation into reliability and capacity distribution services such as black-start functionalities or providing firm capacity.

DPV SYSTEM EQUIPMENT STANDARDS AND CERTIFICATION ARE IMPORTANT FOR ENFORCEMENT OF GRID CODES

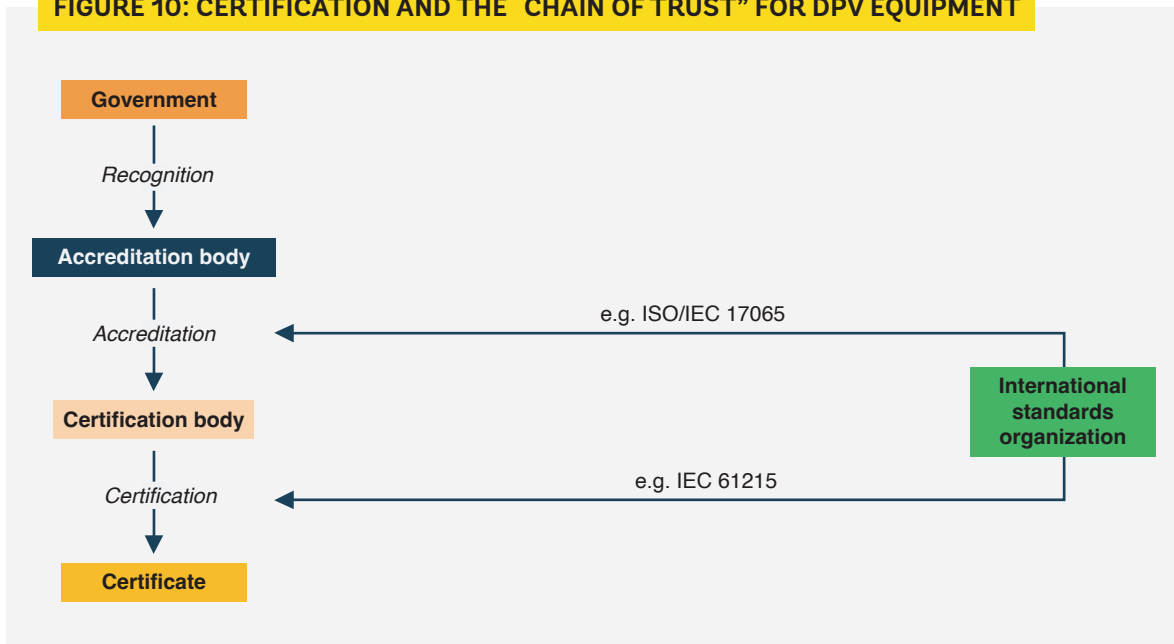
Equipment standards define capabilities and sometimes parameters of components in DPV systems for quality performance. In the case of DPV inverters, standards provide for the manufacture, programming, and testing of inverters to safely perform listed functions, including active support for distribution system operations (Energy Transition Initiative 2017). At the consumer level, dedicated standards regulate the safety and installation of DPV systems on consumer premises. In the United States and Latin America, the National Electrical Code (NEC) provides the building code to which all DPV systems must be designed, built, installed, and used for power systems operated at 60 Hz. The International Electrotechnical Commission (IEC) tests the safety requirements for DPV systems connecting to power systems based on a 50 Hz operation.

Financers' evaluations of DPV projects rely not only on standards but also the certification of systems, credible installers, appropriate insurance, and operations and maintenance packages (IFC 2014).

Certification bodies review documents to verify that equipment complies with standards. The certification process depends on a chain of trust (Figure 10). An internationally recognized accreditation body must also endorse the certifier to assure their competence and integrity. The International Organisation for Standardization (ISO)/IEC 17065 standard concerns bodies certifying products, processes, and services. Examples of certifying bodies include American National Standards Institute (ANSI), Joint Accreditation System of Australia and New Zealand (JAS-ANZ), and DAkkS (*Deutsche Akkreditierungsstelle* [German Accreditation Body]).

Certification of DPV equipment can be time-consuming and expensive, but is important to assure the integrity of the system by requiring that all components are adequate. Countries that have insufficient resources to certify equipment domestically, may be prompted to borrow an international certification from elsewhere. To be valid, following an international certification granted in another location requires a grid code similar to the one in use where the certification was granted.

FIGURE 10: CERTIFICATION AND THE “CHAIN OF TRUST” FOR DPV EQUIPMENT



Source: Original figure prepared by the authors for this report.

PROCEDURES FOR DPV CONNECTION SHOULD BE SIMPLE AND PRAGMATIC

Connection agreements (also known as interconnection agreements) provide the technical and regulatory basis for DPV systems to be connected to the grid. Connection standards are established by regional bodies worldwide: the Institute of Electrical and Electronics Engineers’ IEEE 1547 (North America and internationally), Technical Standards for Connectivity to the Grid (India), EN 50438:2013 (Europe-wide technical specification), VDE-AR-N 4100 (Germany), and AS/NZ 4777 (Australia and New Zealand).

A connection process generally involves the following steps.

- 1) **Application.** A service company or consumer applies to the relevant authority (e.g., distribution company or utility) to install a DPV system at a specific location in the distribution grid. The applicant submits documents detailing system capacity, feed arrangement, inverter specifications, and other specifics of the design. The applicant might rely on known standards or consult the authority or other experts on how to meet requirements in designing and procuring equipment for the system.
- 2) **Review.** The relevant authority reviews the application against technical standards and grid code requirements, including for basic safety and reliability and known hosting capacity of the local distribution network, to determine if the application complies as submitted or requires modifications to become compliant. Connection agreements can be streamlined to approve systems designed to keep within specific parameters such as a capacity threshold for smaller DPV systems and where ample hosting capacity of the local distribution network exists. This can avoid the need for a specific study to ensure the system is grid-friendly. However, technical screens may mischaracterize potential impacts especially in aggregate (Box 5). Detailed assessments, on the other hand, can be time-consuming and costly, but may be necessary and beneficial for large or complex projects to optimize designs including to potentially provide grid services.

- 3) **Issuance.** The authority issues the connection agreement, authorizing the project developer to proceed with installation and connection of the system as specified. The agreement typically also documents the permissible operational behavior of the DPV system.
- 4) **Connection.** The developer installs the projects and the process is complete when a DPV plant starts operation (commissioning). Audits may be carried out to ensure compliance.

At low DPV penetrations (regardless of configuration), utilities, distribution companies, regulators, DPV users, and developers have some discretion over design and criteria in the connection review. This flexibility can be used to balance technical rigor with a forward-looking perspective focused on system integration. As penetration grows, stakeholders should review and update connection procedures so processes balance deployment with the technical requirements of distribution. Box 5 discusses pros and cons of technical screening criteria.

BOX 5

Technical Screening Criteria: Helpful or Not?

Some countries use technical screens during DPV connection reviews to determine the potential safety and reliability impacts of a proposed installation. Technical screens fast-track the review of innocuous systems (i.e., those unlikely to induce impacts), considering that utility reviews can often be the most time-consuming part of the connection process and most DPV connection requests are insignificant.

They generally focus on (1) the risk of unintentional electrical islands (i.e., distributed generation unsafely feeding the grid during a system outage); and (2) the impacts on voltage control programs.

Technical screens commonly rely on hosting capacity calculations to estimate the point where DPV would induce technical impacts on system operations. Such screening criteria are widely used, for example, in India and the United States. In India, for example, regulations for many states specify that DPV installation size will be limited to a given percentage (e.g., 80 percent) of the customer's peak load. Authorities in Germany and Australia impose no general limits on feeder penetration.

Technical screens and hosting capacity thresholds often understate the capability of DPV systems to avoid unintentional islanding through preprogrammed clearing times or the availability of control modes to limit voltage impacts.

To improve the use, if any, of technical screening criteria, utilities and system operators can consider metrics relevant to the impacts of DPV on low-voltage distribution grids, such as DPV capacity penetration relative to minimum feeder daytime load.

Source: Based on Aznar and Stout (2018); Energy Transition Initiative (2017); Horowitz and others (2019); Palmintier and others (2016); Rylander and others (2015); Singh and others (2019).



Analysis of rooftops in İzmir, Türkiye

4: APPROACHES TO POWER SYSTEM PLANNING WITH DPV

This chapter describes various possible approaches to power system planning with DPV, and key issues to consider in choosing an approach. DPV can be relevant for power system plans at different levels: distribution; bulk generation; and even transmission, depending on the level of DPV and other variable renewables in the system. Where relevant, power system planning can also take DPV into account in different ways. No single approach will suit all countries, just as power system planning itself varies from country to country.

Until recently, most countries around the world have taken a rudimentary approach to DPV in power system plans. Utilities have historically responded to DPV-related changes on the grid in a manner that is reactive and *ad hoc*, rather than proactive or strategic. Rapid DPV growth has revealed the need for planning to evolve.

Many regions with high DPV penetration rates are updating their methodologies for power system planning to better reflect the characteristics of DPV and to improve overall hosting capacities. More advanced approaches are emerging. While new approaches are not yet well established, there are some general steps, principles, and common tools to consider. These are the focus of this chapter.

TRADITIONAL POWER SYSTEM PLANNING APPROACHES VARY BY COUNTRY AND ARE EVOLVING

Even before considering DPV, it is important to recognize how general approaches to power system planning can vary significantly across different countries. In general, power system planning involves projecting future demand for electricity, and identifying investments needed for generation and grid infrastructure to economically meet this demand, taking into account key constraints and assumptions. These may be technical, such as reliability and safety, or policy related, such as environmental standards and target years for electrification and emissions reduction.

Power system planning can involve various data and analysis tools, models and processes, to address different specific questions (Boyd 2016). Traditionally, the main model in power system planning is **capacity expansion**. Capacity expansion models simulate bulk generation and transmission capacity investments to identify the least-cost mix of power plants that should be built to meet demand in coming years and decades (e.g., 5 to 30 years). Typically, these models use a sample of representative days for each year for simplicity (rather than simulate all 8,760 hours of a year).

A capacity expansion model may be supplemented by other models such as:

- **Production cost model**, also known as **unit commitment and economic dispatch**. This typically takes the outputs of a capacity expansion model and simulate the power system's operation at higher temporal resolution (hours to 5-minute intervals) for all hours of relatively short time periods (e.g., one week to one year) to identify least-cost dispatch of bulk power plants.

- **Network reliability model.** These simulate transmission network operations over very short time periods (e.g., 30 seconds to 1 minute) to assess grid adequacy under normal operation conditions and contingencies (steady states with all or most assets available) and dynamic events such as fault conditions. Outputs of a production cost model may serve as inputs to network reliability model and vice versa.
- **Electrification planning.** In countries where the population lacks universal access to access, a least-cost geospatial electrification plan may identify which communities to prioritize for grid densification and extension, and which may be more cost-effectively served by non-grid electricity solutions such as community mini grids or standalone household PV and battery systems.¹⁶

Planning practices vary from country to country in important ways. Variations include: the extent to which generation, transmission, and distribution are planned together or separately; time horizon, geographic coverage, and temporal and spatial resolutions; the sophistication of data and methods of analysis that inform the plans; the roles and involvement of different stakeholders; the degree to which plans are followed in practice to guide actual investments; and how frequently plans are updated.

The particular approach pursued in a given country context depends of the availability of data, technology, expertise, and funding. Regulation and institutions are also important. Some low-income countries lack any formal power system plans due to resource constraints and limited institutional capacity. While all models require experts to manage inputs, run the model, and interpret the outputs, some advanced methods for power system planning require sophisticated computational resources for probabilistic analysis.

Historically, planning has involved discrete tracks for generation, transmission, and distribution. For small power systems without a transmission network, generation and distribution are often planned separately even though they are closely linked. Within this traditional approach, integration across planning tracks may not be seen as important, given the assumptions that power flows in one direction and that demand is inflexible.

Globally, the development trend is toward more integrated planning. For large power systems, more integrated approaches generally require higher levels of resources, and greater coordination among stakeholders. Such an approach is already evident in middle-income countries (e.g., Latin America). In countries with many separate (horizontally unbundled) distribution companies, technologies such as advanced meters and SCADA can help facilitate common approaches to coordinate with planning bulk generation and transmission.

A key element of the planning process is to analyze the current demand for electricity and project future demand based on population growth, economic activity, and other factors. Traditionally, demand is exogenous to power system models, and is assumed to follow predictable daily load curves that are modulated by weekday and perhaps season. So, the capacity of the entire power system—from bulk generation stations to the grid—is built out to meet peak demand across all end uses.¹⁷ In many LMICs, distribution planning typically involves constructing or upgrading substations and feeders to meet future demand and access targets at least cost (Georgilakis and Hatziargyriou 2015). This process tends

¹⁶ For an example of this approach, for Myanmar, see World Bank (2016).

¹⁷ This is true for capacity-constrained power systems—that is, the limiting factor is generation capacity while fuel itself is generally always available (fossil- and nuclear-dominated systems). By contrast, systems with a large share of hydro generation can also be energy-constrained: demand can be met at any given moment, but total production may not be able meet all demand over a longer period.

to overlook DER. Some demand-side flexibility may be achieved through, for example, contracts with industrial consumers to shift production during system peaks or extreme events like storms or prolonged cold spells.

Power system plans in LMICs are typically updated every 5–10 years or even longer in some cases. Most high-income countries, for comparison, update plans more frequently, such as every 3–5 years. Periodic review and updating of plans is important to optimize the use of available resources and account for emerging issues.

The integration of renewable energy sources and pursuit of decarbonization are also prompting power system plans to be updated more frequently than in the past. Vietnam, for example, was recently recommended to use power system planning as a dynamic investment decision tool through a continuous process that periodically, perhaps even annually, examines the changes in market conditions—demand, costs, technological progress—while increasingly factoring in (currently uncaptured) local and global externalities. Such an approach can avoid a potential long-term carbon lock-in that is not aligned with policy goals while also shielding the economy from import reliance on and price volatility of fossil fuels (WBG 2022).

POWER SYSTEM PLANNING CAN ADDRESS DPV IN A VARIETY OF WAYS

Where traditional power system planning has serious limitations for DPV, a variety of alternative approaches are possible. These include the following three archetypes.

1. **Adjust traditional power system models** to account for DPV. Planners need not wait for entirely new models to start accounting for DPV. Most traditional models can incorporate variable renewables and distributed resources, including DPV, to a degree. However, legacy models may not capture enough detail to reflect important challenges and opportunities that emerge as renewables and distributed resources become more prevalent.
2. **Conduct discrete integration studies** specifically for variable renewables and/or distributed resources, supplementary to conventional power system plans. Discrete studies may take conventional plans as an input then model the behavior of DPV in that context to assess impacts on power system reliability, stability, and cost. This is typically beyond the scope of conventional grid adequacy assessment for countries where all generation is dispatchable. The time horizon for analysis in discrete integration studies can vary significantly. New or updated studies may be needed each time significant new investments or changes to the power system are expected.
3. **Do integrated planning.** An integrated approach aims to explicitly consider the interdependence of different components of the power system and the impact of different types of generation and demand on each other. The role of variable renewables and distributed resources to help meet electricity demand can be analyzed in detail as part of power system planning from the outset. Linking and iterating analyses can co-optimize power system components that would otherwise be planned independently. Integrated planning thus represents an evolution beyond traditional approaches.

The above three archetypal approaches are not exclusive. A spectrum of variations are possible between traditional and fully integrated approaches at either extreme. Furthermore, even an integrated plan may still require supplementary discrete studies. Capturing the complexity and diversity within distribution systems can be difficult to generalize across an entire system. Therefore, planners may supplement or iterate system-wide

BOX 6

Assessing Integration of Renewables for Thailand's Power System

Thailand's 2015 Power Development Plan provided power demand forecasts and a generation and transmission capacity expansion plan to 2036. In 2018, this plan was used as the basis for a production cost model that simulated various scenarios of variable renewable deployment through to 2036. The model analyzed and compared the operational and economic impacts of different levels of variable renewables in the power system, as well as the efficacy of different flexibility options. The analysis found that Thailand's power system, as planned for in 2036 via the 2015 plan, would be technically capable of accommodating substantially higher shares of variable renewables. It also found that measures to improve supply-side and demand-side flexibility could reduce operating costs in a reliable manner.

Source: IEA (2018).

plans with analyses specific to representative sites for key projects. Each successive plan or study can build on the findings of past analyses and on experience gained in implementation.

Simply adjusting traditional models may suffice in contexts where forecasts show only low levels of DPV deployment, or where DPV is expected to serve mostly as a backup (i.e., feed-in arrangements). This may be the case for power systems suffering from frequent or severe outages and that have low prospects of improving over the planning period. DPV deployment can still be assessed feeder by feeder as needs arise. Even in such cases, utilities in a vicious cycle of chronic underperformance can plan bottom-up to use grid-connected microgrids with DPV as a “bootstrap” to improve service reliability, and increase bill collections.¹⁸

For power systems with high forecast rates of DPV deployment, good practice is to undertake integrated planning or else an integration study. This includes for countries where DPV is a source of least-cost generation, such as in small or land-constrained countries. In such contexts, simply adjusting traditional power system models may not suffice. Integrated planning and integration studies can help to ensure that the power system is more reliable and resilient while also minimizing costs and environmental impacts. They can identify ways to enhance hosting capacities to match the forecast growth level or to maximize DPV as a least-cost generation source and avoid overinvestment in bulk generation or grid upgrades that may be less efficient.

Experts convened by the IEA have recommended a detailed set of practices for renewable integration studies, including specifically for PV.¹⁹ Key findings from this work are reflected below.

In the United States, the Western Wind and Solar Integration Study from 2010 to 2015 broke ground to demonstrate how existing power system plans can accommodate larger shares of variable renewables (NREL 2015). Box 6 provides a more recent example from Thailand.

18 “Bootstrap” here means using initial minimal resources to lift oneself up out of a bad situation. This and other DPV use cases are detailed in ESMAP (2021), *Distributed PV in Energy Sector Strategies*, the first report in the present series.

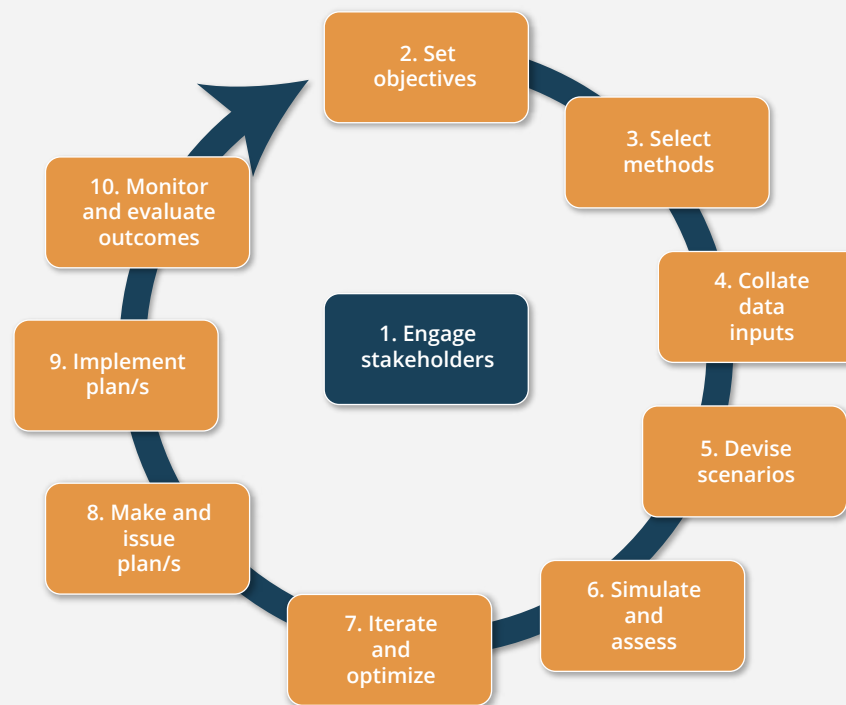
19 See Holttinen (2018), and related resources of the IEA (2023) Photovoltaic Power Systems Programme (PVPS) at <https://iea-pvps.org/>

GENERAL STEPS AND PRINCIPLES FOR POWER SYSTEM PLANNING WITH DPV

The remainder of this chapter describes a set of steps generally applicable for power system planning with DPV (Figure 11).²⁰ Some steps will differ in the detail of how they would apply in a traditional model versus a discrete integration study or integrated planning approach. However, since those three archetypal approaches can be combined or varied, the distinction between them can be blurry. As a result, the focus here is on what steps apply to any or all approaches in general, while noting specific issues that may apply to a certain approach.

The steps presented include considerations relevant for distribution level planning, as well as considerations for the broader power system, including transmission. Distribution planning may occur as part of integrated power planning, or as a standalone exercise based on existing power system plans. In a vertically unbundled power sector, an integration study with DPV would typically be the responsibility of distribution utilities or distribution system operators. In large power systems with a high or rapidly rising share of distributed resources, coordination between transmission and distribution system operators is important for the grid to obtain the full value from services potentially provided by DPV.

FIGURE 11: GENERAL STEPS RELEVANT FOR DIFFERENT APPROACHES TO PLANNING



Source: Original figure prepared by the authors for this report.

Note: These steps can be applied generally to traditional or integrated power system planning or to a supplementary discrete integration study for variable renewables and/or distributed energy resources. The steps may not be strictly sequential or discrete. Stakeholder engagement can occur throughout the entire process.

²⁰ This section draws on Stanfield and others (2021), Ismael and others (2019), Holttinen (2018), Stanfield and Safdi (2017), and Lindl and others (2013).

Steps may be altered and simplified or elaborated to suit local circumstances and needs. In all cases, the scope and detail of approach should account for institutional resource constraints and opportunities: data, technology, expertise, potential collaboration with regional partners; internal funding; and availability of technical and financial support from development partners. Utilities in some LMICs lack advanced tools and methodologies to plan expansion of DPV. Planning done with external support should consider opportunities to cultivate expertise and build institutional capacity among local personnel to at least help design and interpret modelling results. This may require investments in geographic information systems (GIS), modeling software licenses, data acquisition, and technical training such as on inverter capabilities and hosting capacity analysis techniques. If data are unavailable to support a chosen analytic scope, methods and plans may need to be simplified.

Step 1: Engage stakeholders

From the outset it is important to consider which stakeholders are relevant for the planning process, and engage them strategically throughout. Early and consistent engagement can help to build and maintain consensus on critical decisions to be made in subsequent steps and to participate in monitoring and evaluation. Principles for good practice include open membership, open access, neutral facilitation and reporting, and active involvement of utilities. Stakeholders to consider specifically for DPV include: distribution utilities, electricity retailers, consumer representatives, project developers, and energy service companies.

Step 2: Set objective

The first critical decision to make is establishing the objective of a planning exercise and specific questions to be answered. For example, the focus of planning may be on minimizing cost of service for a target level of DPV deployment, or on identifying how much DPV can be deployed within a fixed cost of service. In deciding the objective of planning, consider relevant policies, strategy, codes and standards.

Consider the range of potential uses cases for DER and DPV feed arrangements (see Box 1 on page 15, and Annex A). A focus on one or other use cases may have a bearing on the overall objective of planning. Exploring the potential application of DPV as a T&D alternative and for ancillary services may require different analysis than for use of DPV for least-cost generation. For example, where displaced generation from DPV might be significant, planners need to consider flexible generation options—that is, dispatchable generation that would fulfill the balancing needs of the system.

For cases of DPV as least-cost generation and T&D alternative, coordination between planning entities is key to ensure that DPV resources are reflected in both generation and transmission planning. Moreover, coordinated management of DPV, such as VPPs, can help limit the need for dispatchable generation (see Box 3 on page 28).

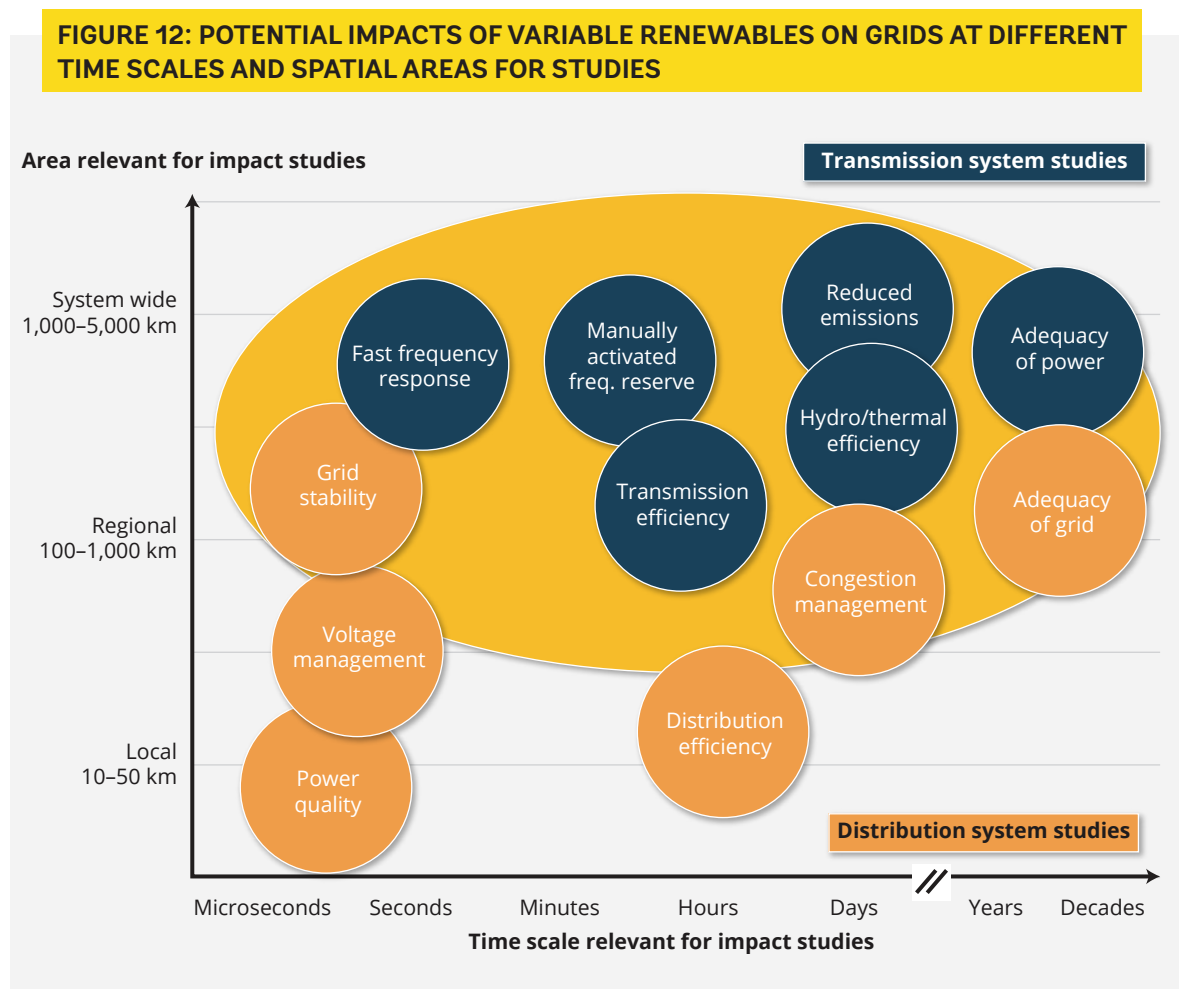
Step 3: Select methods

Once the planning objective has been decided, then select the models or tool for analysis to suit. It is important for the choice of tools to be guided by the objective rather than the other way around, since different tools provide different information. The choice of method is a critical decision because it is shaped by the kind and quality of data available in the given country (Step 4). In some cases, available data may constrain the method. In other cases, the choice of method may prompt collection of new data. Key questions for method include: what types of grid impacts to study; how to project DPV deployment; and how to reflect DPV in studies.

What types of grid impacts to study?

Parameters of scope to consider for power system analysis include which energy sector components to focus on (e.g., grid electricity only or also space heating, water heating, etc.) and the time horizon, geographic area, and spatial resolution. Figure 12 shows potential issues to study for the impact of variable renewables at the distribution level and at the transmission or power system level, differentiated by time scale and relevant geographical area. Not all planning processes need to look at all aspects presented here. Analyses can be done in phases. For example, a first phase for lower shares of variable renewables may look at short-term impacts on current power plants in production cost simulations, or on local distribution networks. Subsequent studies for higher shares over the longer term may look at network adequacy and congestion, as well as generation capacity adequacy, including the capacity value of DPV.

Consider the choice of method for hosting capacity analysis. Three archetypal methods are streamlined, iterative, or stochastic (Stanfield and Safdi 2017, Stanfield and others 2021):



Source: Based on Holttinen (2018).

Note: The yellow area and dark blue bubbles indicate issues of regional scale at the transmission and power system level. The light orange bubbles are issues relevant for more local, distribution system studies. Transmission and distribution efficiency refers to grid losses. Hydro/thermal efficiency refers to losses in generation. “Freq. reserve” is frequency reserve. km = kilometer.

- A **streamlined method** applies a set of simplified algorithms for each power system limitation to approximate the DER capacity limit at nodes across the distribution circuit.
- An **iterative method** (also sometimes known as the detailed method) directly models DERs on the distribution grid to identify hosting capacity limitations. A power flow simulation is run iteratively at each node on the distribution system until a violation of a power system limitation is identified.
- A **stochastic method** starts with a model of the existing distribution system, then adds new DPV (or other DER) of varying sizes to a feeder at randomly selected locations. The feeder is then evaluated for any adverse effects that arise from this random allocation, to derive a hosting capacity range.

Issues relevant for assessing DPV hosting capacity may include, as shown in Figure 12: voltage management, distribution efficiency, congestion management, power quality, grid stability, and grid adequacy. Consider details like minimum number and type of load hours to be analyzed. Probabilistic analyses, or else multiple scenarios, help make distribution planning robust to future uncertainties.

Power flow dynamics is a specific area to study to identify nodes where DPV can ease existing congestion and where DPV feed in risks contributing to congestion. Planners need to account for power flow dynamics under a wide range of operating conditions to ensure that the power system can operate reliably and efficiently with DPV. Planners need to consider the aggregate impacts of DPV on power flow dynamics in determining the placement and sizing of generation, transmission, and distribution infrastructure, as well as the development of control and protection schemes, accounting for region-specific characteristics.

How to project DPV deployment?

All planning approaches with DPV require projections of aggregate DPV output. The temporal and spatial resolution and accuracy of these estimates can vary greatly. Projections entail assumptions about the size and number of future DPV systems. Ideally, the locations of DPV systems should also be taken into account. Solar profiles appropriate for DPV systems can then be applied to project output for the hours of representative days of a year.

Projecting DPV deployment is more challenging compared with load forecasts (a well-known exercise for utilities). However, accurate DPV deployment projections are important as inaccurate projections can result in high costs for utility investments that could otherwise be avoided. Under-estimating DPV deployment can lead to needless capital expenditures on utility-scale generation and underinvestment in flexibility options, threatening the reliability of the grid. Over-estimating DPV deployment could lead the utility to fill generation shortfalls with energy from costly sources such as emergency rental generators. While the exact net load shape depends on the demand structure and the aggregate PV generation profile, increased ramping requirements for other power plants during the morning and evening hours are typical for systems with larger PV contributions.

DPV deployment estimates can comprise several interrelated analyses.

- Typically, utilities or planners first assess the maximum possible DPV deployment given any technical limitations, such as available roof space, orientation, and shading at required detailed geospatial resolutions. Box 7 showcases techniques to map this **technical potential** of DPV.
- Following from this, the **economic potential** can be determined—i.e., the maximum amount of viable DPV deployment according to economic criteria (such as net present value).
- Then, future DPV deployment can be estimated based on user-level realities such as market conditions, regulatory limits, and user preferences (**market potential**).

Mapping DPV's Technical Potential

Determining the technical potential for distributed photovoltaic (DPV) development can provide an analytic foundation for policy ambitions and program design. Techniques generally combine satellite and meteorological data with digital surface models.

The World Bank's ESMAP has created a free web-based tool—the Global Solar Atlas—that can help identify potential sites for solar power generation virtually anywhere in the world. The tool enables users to determine solar energy potential for a specific site, how much electricity will be generated, and in what time frame. Users can include developers, utilities, planners within utilities, or energy ministries. Solar energy projects can be planned and evaluated with site analyses, which determine average solar radiation at specific locations. Figure 13 shows a screenshot of the tool in use.

FIGURE 13: A SITE ANALYSIS USING THE GLOBAL SOLAR ATLAS



Source: <https://globalsolaratlas.info/map>.

ESMAP developed and is piloting another tool that estimates the solar power potential of individual rooftops. The Rooftop Solar Mapping tool (rooftopsolar.energydata.info) would help cities determine the potential of rooftop DPV, taking into consideration building structures, categories of building ownership and use, and neighborhood layouts. Users would be able to determine how much solar capacity can be installed on rooftops and how much power each installation can generate according to available rooftop space, angles, and solar irradiation. Individual buildings are mapped out on a footprint polygon extracted from high-resolution stereo-satellite imagery, which enables the measurement of installable capacity. (See the images used on the cover and between chapters of this report as examples). For each building rooftop, the geographic kWh/year output value that corresponds to the rooftop's tilt and azimuth is multiplied by installable capacity. The results are aggregated by geographic location, building category (commercial, industrial, single/multifamily residential), and other category clusters that provide insights to DPV planning.

How to reflect DPV in studies?

Most capacity expansion models treat DPV as a “negative load” that meets part of gross demand for electricity, leaving a “net load” or residual demand for grid electricity from other sources.²¹ In this approach, DPV output is deducted from the curve of the load that needs to be supplied by grid electricity. The expansion model is then run using this adjusted demand.²² This approach is pragmatic where the focus is primarily on the transmission system analysis, and where distribution level issues are expected to be negligible or of secondary importance. However, this approach implicitly assumes that DPV can feed in to the grid with no congestion and without any active contribution to system management. If no further analysis is done, the power plan will not capture the full range of potential benefits or challenges from DPV including its potential interaction with other distributed energy resources (like electric vehicles and demand response) and the power system more broadly. Utilities in LMICs often lack data or operational guidance on minimum load periods. Power system plans thus need to account for a broader spectrum of possible operating conditions.

Historically, distribution grid planning has often involved heuristics or rules of thumb for hosting capacity as a fixed value, for example, based on a substation’s transformer capacity. System models may then use this rule of thumb to impute how much DPV will be maximally deployed in aggregate. More detailed analysis can, in contrast, identify more meaningful hosting capacity estimates by examining what happens to voltage at select feeders under different scenarios.

Recent studies by electric utility companies show that siting and sizing of DPV systems can be optimized to maximize their benefits. Three emerging approaches to such optimization analysis, in order of increasing complexity and accuracy, are: (1) approximate procedures; (2) heuristic or metaheuristic approaches; and (3) mixed-integer programming techniques (Bazrafshan & others 2019). Box 8 describes common distribution system planning tools that go beyond a negative load approach.

Step 4: Collate data inputs

Collect available relevant data. Inputs will vary depending on the type of study being done and the choice of method or tool, but could include: system data on loads, the grid, and existing power plants; plus data on available energy resources, technologies, and projected deployment for DPV and other DER (efficiency, storage, EV, grid services) among other new generation sources. Where possible, map geospatial variation. Check the data quality and identify any notable gaps to fill or work around.

Data scarcity and poor data quality are pressing challenges in many LMICs. Utilities may have inadequate georeferenced information about their grids obtained through GIS. In some cases, distribution grids are extended on an ad hoc basis without proper planning. In such situations, planning for DPV penetration may become more challenging since the utilities do not know exactly where the feeders are and which customers they serve. Data scarcity is particularly problematic for load forecasting analyses. Together, the lack of data and improperly planned DPV deployment can have negative consequences for grid reliability, including power outages. Utilities with limited resources can make near-term DPV deployment forecasts

²¹ Net load can have different meanings depending on the context. Here it refers to demand for bulk grid electricity excluding demand for electricity served by distributed sources and bulk variable renewable sources. Gross load refers to total end-user demand for electricity from any source, including DPV or other “negative loads.” Storage, and demand-response measures may also be treated as negative loads. It is important to note that DPV and consumer-side storage reduce demand not only for grid electricity in general but from bulk renewables too.

²² For an example of this methodology in use, for Pakistan, see World Bank (2020).

BOX 8

Distribution System Planning Tools

Most available commercial tools for distribution system planning provide for analyses of power flow, power quality, and fault protection. Common distribution planning tools include ETAP, CYME, PSS Sincal, Milsoft, Powerfactory, and Synergi. Some of these, specifically CYME, Synergi, and Milsoft, can be used to assess hosting capacity for DPV. A specialized tool for hosting capacity analysis is Distribution Resource Integration and Value Estimation (DRIVE) which uses a streamlined hosting capacity method developed by the Electric Power Research Institute (EPRI 2015). This method identifies optimal DER locations, maps DER impacts across the distribution system, improves interconnection screening, and eventually informs distribution resource plans with DPV data. This method identifies locations where DPV is more (or less) likely to challenge grid operations and node-, feeder-, and system-level hosting capacity. DRIVE can be used in conjunction with other distribution planning tools.

Commercial tools such as those described above are the most common. Beyond these, open-source tools have additional functionalities being developed such as smart inverter controls and distribution system management applications. One example is EPRI's OpenDSS tool, which supports DER integration and grid modernization. Further advancements of distribution system planning tools underway include increasing hosting capacities through smart inverters and inverter settings guidance.

Note: This does not comprise an exhaustive list of available products and services and should not be read as an endorsement of any tool.

by extrapolating historical trends and using open geospatial planning tools such as the Global Solar Atlas. Several utilities have started incorporating GIS mapping of their grid and identifying the hosting capacity of each node to facilitate connection and streamline approval processes.

To improve data collection, power system planners can adopt relatively simple GIS-based methods. For example, staff can follow physical lines with a mapping tool (such as a global positioning system) or use satellite imagery (e.g., of existing or planned consumer locations) to gather inputs for their databases. Utilities can also conduct surveys. To monitor PV production, utilities can mandate meters that capture, at a minimum, monthly PV production to help with distribution network planning. More sophisticated approaches rely on the application of a SCADA system to the distribution grid and grid-mapping tools.

Due to DPV's ability to grow rapidly, deployment forecasts may need regular updating to reflect changes in key factors. Factors that can impact DPV projections include: historical DPV connection requests; DPV system costs; government DPV procurement programs; policies such as emissions targets or incentive schemes; pricing reforms; and shifts in demand patterns from electrification and urbanization. Assumptions about allowable DPV feed-in arrangements may affect projections.

For hosting capacity analysis, the choice of performance index or indices is critical. An index may be based on: overvoltage, thermal overloading, power quality, and/or fault protection. Determine limits for the indices according to local codes or applicable standards. Identify a menu of potential options to enhance hosting capacity (per Chapter 2).

Make appropriate assumptions to match the agreed scope for current and projected loads; energy resources; demand-side opportunities, bulk generation plants; and networks.

Step 5: Devise scenarios

Inputs are used to set up scenarios to illustrate different alternative futures. These may include: energy portfolio development, covering all generation sources, demand response, and storage; networks; and alternatives for system management (e.g., reserves, operational methods, and markets). In a production cost model, scenarios may differ in terms of system flexibility levels. In a system expansion study, scenarios may vary for fuel prices, technology costs, etc. Consider base case and alternatives for comparison. Apply forecasts for DPV deployment.

Since distribution feeder characteristics can vary significantly within a power system, planning for DPV at the distribution level relies heavily on scenarios based on many assumptions. For this reason, distribution level studies generally take the level of variable renewable generation, and load, as an input for scenarios rather than a result of optimization. At the transmission level, by contrast, it is easier to assess and co-optimize the capacities and locations of transmission networks with bulk variable renewables together.

Select hosting capacity enhancement options to include in simulations. In identifying options to enhance hosting capacity, a few general principles to keep in mind include:

- (i) Consider a wide variety of options;
- (ii) Consider which options are allowed by regulation and whether regulations need updating;
- (iii) Consider the value of ambitious investment options to accommodate long-term developments, versus incremental changes based on only short-term conditions; and
- (iv) Prioritize the most cost-efficient solutions beginning with grid optimization first, then grid reinforcement, then grid expansion, also known as the NOVA principle.²³

The third and fourth of the above principles need to be balanced against each other. Grid optimization may seem like the least-cost option in the short term to accommodate incremental changes. However, in some cases, grid reinforcement and expansion are more cost-effective than grid optimization from a long-term perspective. This consideration is particularly important for grid infrastructure given the length of time it can take to plan and build (years), its economic lifetime (decades), and the expense and complication of retrofitting as compared to new build.

²³ This term NOVA is from the German language: “*Netz Optimierung Verstärkung Ausbau*” (grid optimization reinforcement enhancement). Germany’s renewable energy law introduced the NOVA principle as a cost-progressive process for upgrading existing electricity grids (Wagner and others 2020).

Step 6: Simulate and assess scenarios

Scenarios can then be used for simulations to assess: (i) resource adequacy and capacity value (firmness); (ii) production cost and system flexibility; (iii) network adequacy at the transmission level and distribution level; and (iv) system dynamics for grid stability. These simulations can be conducted in any sequence, however the order as listed above is recommended (Holtinen 2018). Analysis may include: statistical data analysis for the impact of DPV power on short term reserves; adequacy of generation resources to assess the capacity value of DPV; production cost simulations to see how DPV impacts the scheduling and dispatch of conventional generation and system operational costs; and network adequacy.

Calculate the distribution performance indices as a function of the amount of distributed generation. Run a suitable load flow calculation for the model with increasing amounts of distributed generation by pre-defined steps until performance index results exceed allowable limits. The “restricted” (uncontrolled) hosting capacity is the maximum amount of distributed generation modeled with results not exceeding allowable limits before enhancements.

Planning at the transmission level can account for opportunities to promote a larger and more interconnected system, which can provide greater options and flexibility. Grid strengthening and regional interconnections can expand the balancing area to smooth the net load curve and provide more flexibility, leveraging the geographic diversity of loads and generation sources, such as connecting areas with high and low levels of DPV installation.

Step 7: Iterate and optimize

Explore how plans perform under different assumptions. If any simulation gives unacceptable results, the setup can be varied and simulations run again. Iterations can identify system enhancements that lead to acceptable results across the range of assumptions. Planners can estimate the impacts of varying input parameters (e.g., changes in regulations) on DPV deployment to optimize the power system analysis. Enhancement techniques can be chosen according to the defined performance index limit and applied considering the optimum rating and location. Load flow calculations can be re-run considering the enhancements to find the controlled (enhanced) hosting capacity, and on this basis determine the remaining capacity available on a distribution grid. The utility can also limit DPV deployment where appropriate. Options include to limit feed-in through dynamic curtailment, where remote control technologies are available, or else by approving only arrangements that feed none of the output to the grid. Inexpensive inverters can be programmed to dispatch battery-equipped DPV at set times to ensure smooth system operations. This solution has been applied even in low-income countries marked by fragility.

Step 8: Make and issue plans

Once all simulations return acceptable results, then the data analysis and output synthesis can inform conclusions about costs, reinforcement needs, stability constraints, as well as potential improvements for rules and regulations. Identify and evaluate cost-effective interventions to avoid or defer specific equipment upgrades, expedite interconnection procedures, and enhance hosting capacity.

Publish and validate results. The output of an integrated planning approach may be in the form of an Integrated Distribution Plan or, for the power system at large, an Integrated Resource Plan. Planning results and deployment plans should ideally be shared on user-friendly platforms, such as an online portal

on relevant agencies' websites. This information can then inform the design and timing of new projects. Depending on confidentiality and critical infrastructure considerations, the information might be made public or provided at the request of DPV developers.

Step 9: Implement plans

For DPV scale-up, plan implementation may typically involve proposing, soliciting and procuring identified investments to enhance hosting capacity. Plans may also point to the need for just-in-time studies for specific DPV installations, such as to analyze the benefits and costs of proposed projects at specific locations. This may involve outreach programs and materials, such as a user guide for hosting capacity analysis, to guide consumers' and developers' preparation of new DPV projects to align with overall plans.

Step 10: Monitor and evaluate outcomes

During plan implementation, monitor the effect of changes to the system to validate expected impacts or identify unexpected results. Power system operators and other stakeholders can provide valuable data to learn from evolving experience and inform future efforts. Consider how frequently an update to plans should occur and what types of changes might trigger an update, such as new energy sector or emissions reduction policies, an update to the grid code, or significant changes related to DER deployment.

CONCLUSION: BEYOND TECHNICAL ISSUES

This report has focused on the technical dimensions of grid operation and planning with DPV. But to implement a DPV rollout program, it is essential to evaluate the costs and benefits of different DPV scenarios. Moreover, policies are needed to clear barriers to deployment, ensure the economic viability of projects, and provide a sound financial basis for infrastructure and other relevant generation assets. Importantly, planning should not be done in isolation from regulation and policy making. If analysis for planning finds that DPV should be constrained in some areas to limit the technical or financial impacts on the power system, this can inform policy settings. If DPV is economically viable for a country or region, then incentives to develop DPV should be set in place and plans made accordingly. These aspects are covered in the third report of the series: "Distributed PV Economics and Policy."

ANNEX A: TECHNICAL DESCRIPTIONS OF NINE DPV USE CASES FOR LMICs

This annex provides technical descriptions of nine use cases, or applications, of DPV relevant for low- and middle-income countries. The first report of this series (ESMAP 2021) introduced these use cases with country examples. Table C summarizes the definition of each use case and their prevalence across countries, as well as the different feed arrangements possible. Figures A1 through A9, further below, present single-line diagrams to illustrate how each use case may be configured in an electrical engineering framework. A brief explanation accompanies each figure. Within a given use case, technical parameters may vary from one installation to another, and should be designed according to local circumstances. Key parameters include the type of equipment and wiring configurations, as well as feed arrangement and meters. Each diagram illustrates one conceivable configuration for a use case. In practice, many different configurations are possible.

USE CASE 1: BILL REDUCTION

Figure A1 shows a feed-some arrangement of DPV plus battery installed on the consumer side of a net meter. Feed-all and feed-none arrangements are also possible. The system can help consumers reduce the money they are charged in their electricity bills in several ways, compared to a case without DPV and battery (assuming the tariff structure is the same in all cases). First, DPV is used to help reduce the overall amount of grid electricity consumed. Second, the consumer may be compensated for surplus DPV output fed to the grid during times when DPV output exceeds demand on site (assuming the battery is fully charged). Third, the battery is used to adjust when and how much grid electricity is consumed during certain times of day to respond to time-of-use tariffs or demand charges. This arrangement cannot be used for backup power in the event of a power outage, as the direct connection of the inverter output to the utility-energized lines requires that the inverter is a grid-following type, which ceases producing power in the event of a utility power outage.

USE CASE 2: LEAST-COST BACKUP

Figure A2 shows a feed-none arrangement of solar plus battery and diesel generator differentiating priority loads such as computers, lighting, medical equipment, or refrigeration. Non-priority loads remain connected to the utility grid and powered when grid electricity is available. When utility power is available, all loads are supplied by utility electricity with priority loads powered by utility electricity routed through the inverter,²⁴ supplemented by electricity from the PV array if the sun is shining and batteries are full.

In the event of a power outage, electricity to priority loads is automatically switched over to inverter power (in grid-forming mode) using electricity stored in the batteries and, if the sun is shining, electricity from the solar panels. Typically, the transition to inverter power with loss of grid power happens within about 40 milliseconds, fast enough that there is little or no disruption.

²⁴ See Box 4 for a description of this functionality.

TABLE C: NINE DPV USE CASES AND THEIR PREVALENCE IN LOW- AND MIDDLE-INCOME COUNTRIES

| USE CASE | DEFINITION | PREVALENCE* | POSSIBLE FEED ARRANGEMENT |
|--|---|-------------|---------------------------|
| 1. Bill reduction | DPV offers affordable electricity bills to consumers by displacing electricity that would otherwise be purchased from the grid. | Common | Any [†] |
| 2. Least-cost backup | Consumers facing grid electricity outages have DPV, typically with batteries, to provide improved service while foregoing costs and dependence on fuel for backup generators. | Common | Feed-none or feed-some |
| 3. Least-cost generation | DPV may be consistent with least-cost generation planning for the power system, especially in places with land constraints, given the short timeline for installation and low levelized cost of electricity. | Emerging | Any (typically feed-all) |
| 4. Transmission & distribution alternative | DPV helps avoid or defer the more costly expansion of new power lines (also known as “non-wire alternative”). This use case depends on careful grid planning coordinated with DPV system location and design. | Emerging | Any |
| 5. Utility bootstrap | A utility installs DPV, with batteries and/or backup generators (e.g., as a microgrid), to improve service for a targeted set of consumers as part of a strategy to build trust and increase bill collection. | Opportunity | Any |
| 6. Ancillary services | DPV, especially in combination with inverters and batteries, can provide a range of services to the grid, such as frequency regulation and voltage support. This use case implies close coordination of DPV systems with grid operations. | Opportunity | Feed-some or feed-all |
| 7. Community social support | Medium-to-large DPV systems can benefit a large number of low-income consumers through direct connections and/or subscriptions. | Emerging | Any |
| 8. Financial loss reduction | DPV reduces grid sales to customers in chronic arrears and whose supply cannot be cut off. | Emerging | Any (typically feed-none) |
| 9. Box solution | Preassembled DPV system, quick and easy to install, typically with a battery or other backup, addresses urgent power needs (e.g., when the grid becomes unavailable following a disaster) | Common | Any |

Source: Original by authors for this report. See ESMAP (2021).

Note: * Well-established deployments of DPV are called “common” use cases. Those deployed in only a few circumstances are called “emerging.” “Opportunity” use cases are those that are yet to be deployed.

[†]“Any” feed arrangement means a DPV system in the given use case could be designed to feed all, some, or none of its generated electricity to the grid.

FIGURE A1: BILL REDUCTION CASE

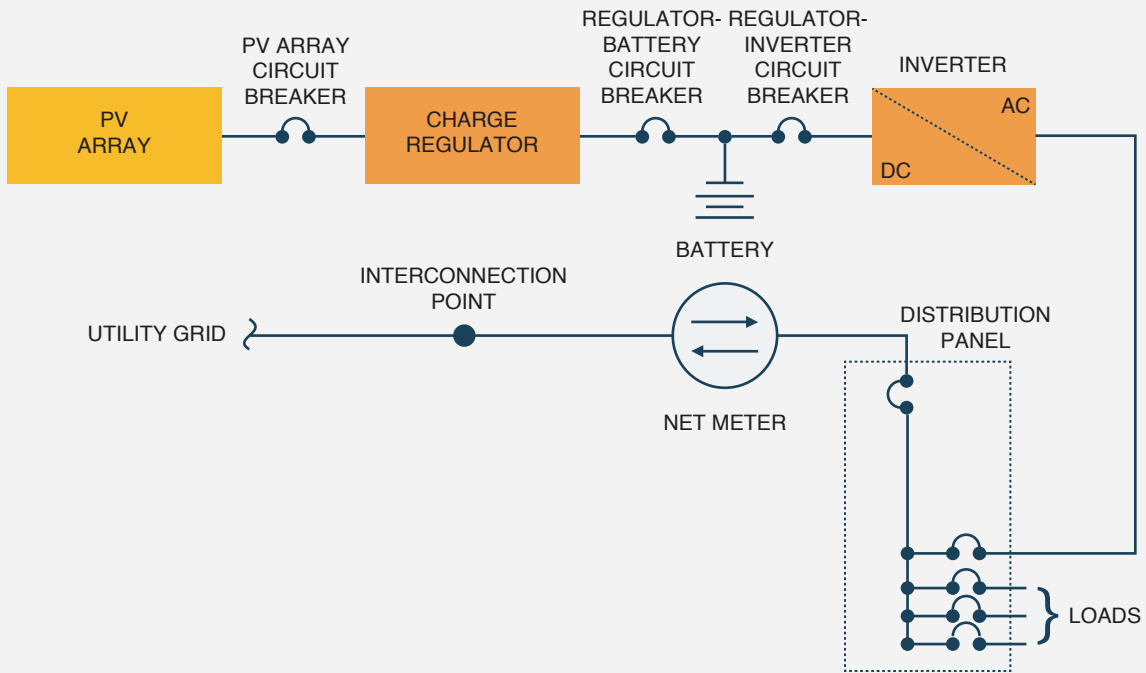
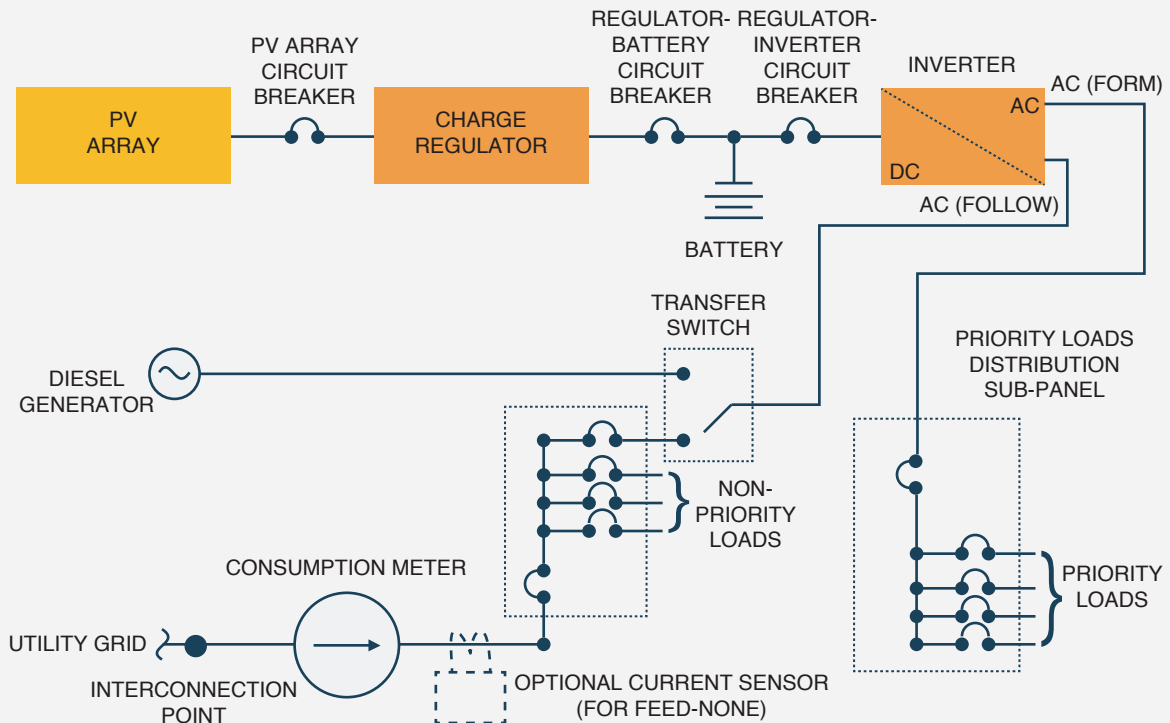


FIGURE A2: LEAST-COST BACKUP CASE



Loss of main power can be used to trigger a transfer switch (or the transfer switch could be manually operated), connecting the inverter's AC input to the diesel generator. If the battery discharges below a programmed threshold, the inverter can send a signal—typically by a wire from the inverter (not shown)—to start the diesel generator. Bidirectional functionality of most inverters allows for the batteries to be charged by AC electricity from the utility grid or diesel generator when energized. This can be useful for ensuring adequate backup battery reserves, and for equalization charging (controlled over-charging) which can help extend the lifetime of certain types of lead acid batteries. The inverter can allow the diesel generator to simultaneously power loads and charge the battery, operating the diesel engine at more efficient, higher power output levels.

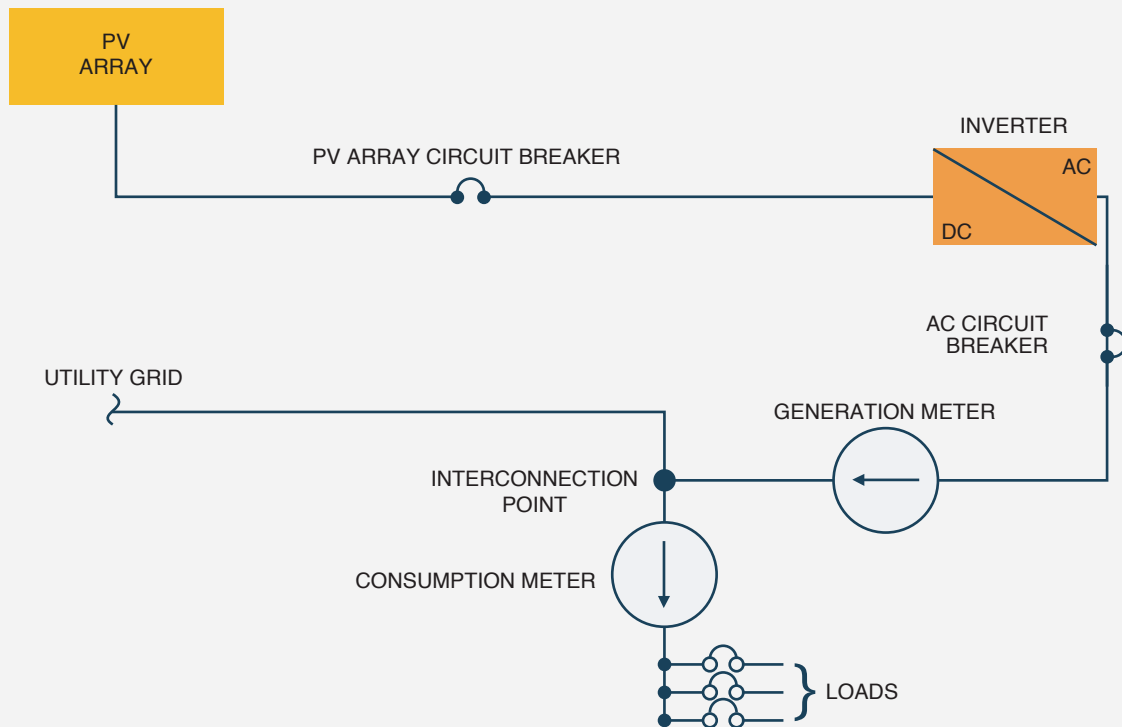
In practice, this configuration is convenient to retrofit into existing grid-connected buildings as it keeps much of the existing wiring largely intact, with the building's pre-existing distribution panel repurposed as a non-priority load panel and supplying the inverter and priority loads subpanel from a dedicated circuit in the non-priority load panel.

During periods when the utility grid is operational and solar supply exceeds demand from all loads, an energy management device is required to measure utility current and curtail inverter output as necessary to maintain the feed-none arrangement. Such a device typically communicates with the inverter via Bluetooth or ethernet cable. A “feed-some” arrangement is also possible with net metering, in which case the current sensor is not required.

USE CASE 3: LEAST-COST GENERATION

Figure A3 shows a feed-all arrangement of utility-side PV next to a grid electricity consumer. The PV system feeds all generated electricity into the grid, bypassing building-level electrical connections. Even if the system

FIGURE A3: LEAST-COST GENERATION CASE

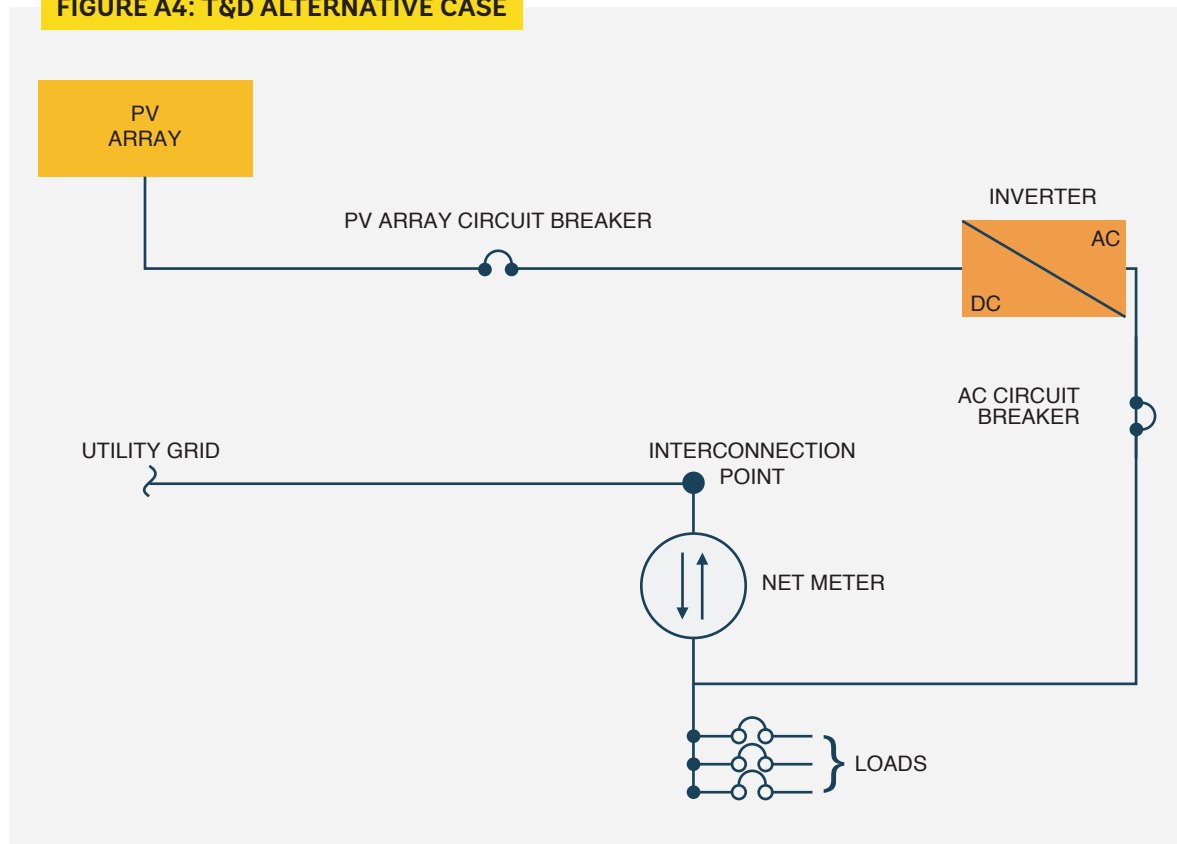


is installed on or nearby a building (which serves as a host to the PV system), the PV system is not a part of the building's electrical system. There is no direct electrical connection between the PV system and any building infrastructure other than through the grid. The configuration requires two meters, one for the electricity fed from PV into the grid and the other on the customer side measuring the customer's electricity use.

USE CASE 4: TRANSMISSION & DISTRIBUTION ALTERNATIVE

Figure A4 shows a feed-some arrangement of DPV with net metering. This may suit a site where grid electricity is reliable but a large midday peak demand (e.g. air conditioning) cannot be fully met by the local distribution grid capacity. In this scenario, production of electricity on the site of the consumer helps the grid to defer network upgrades that would otherwise be required to supply all electricity from the grid. During times when DPV output exceeds demand on site, surplus DPV output is fed to the grid.

FIGURE A4: T&D ALTERNATIVE CASE



USE CASE 5: UTILITY BOOTSTRAP

Figure A5 shows a feed-all arrangement of DPV plus battery installed on the grid side of existing regular consumption meters to improve service for targeted consumers in the hopes of improving collections. In this scenario, the targeted consumers enjoy less grid outages than before thanks to the DPV and battery system, which uses a similar architecture to the *least-cost backup* use case samples above. The system may be owned by the utility. (If owned by a third party, a generation meter would be needed to measure electricity production from the DPV).

USE CASE 6: ANCILLARY SERVICES

Figure A6 shows a feed-some arrangement identical to Figure A1 of DPV plus battery and inverter to provide ancillary services to the grid, such as frequency regulation, voltage support (including reactive power), and demand response (including ramping). A smart inverter allows this configuration to respond within milliseconds to maintain the proper flow and direction of electricity, address imbalances between supply and demand, and help the system recover after a power system event.

FIGURE A5: UTILITY BOOTSTRAP CASE

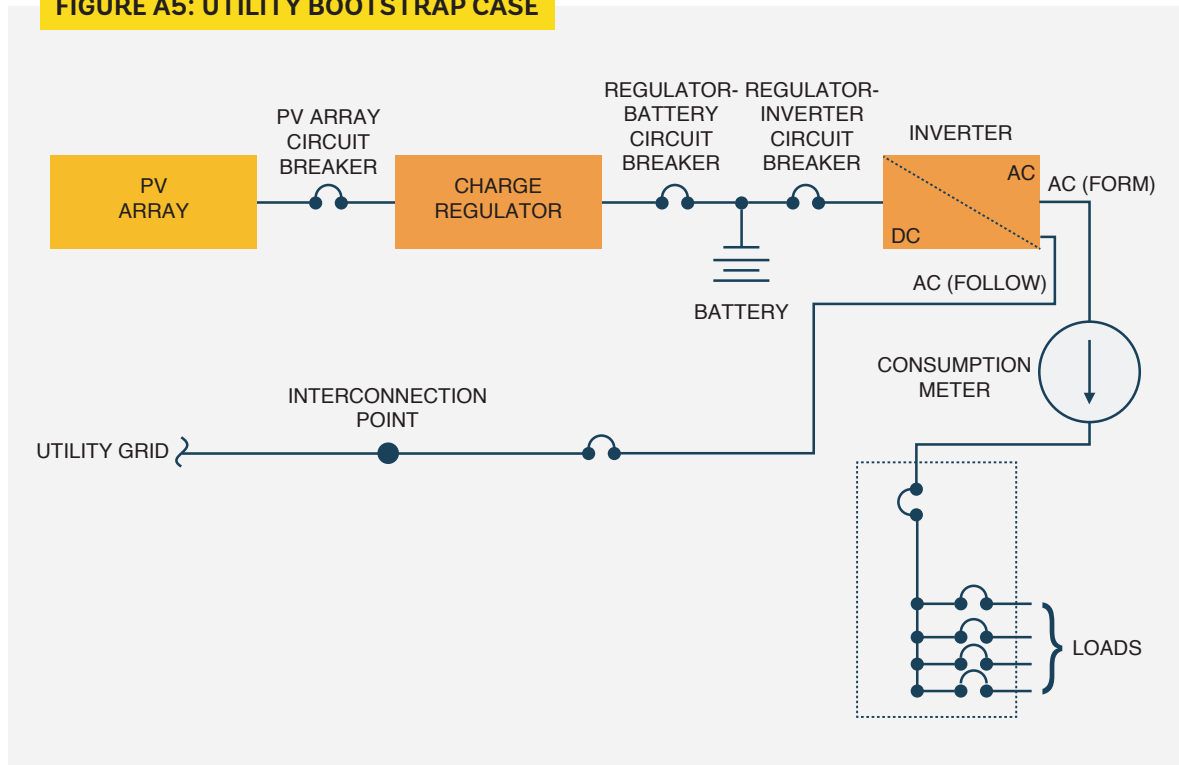
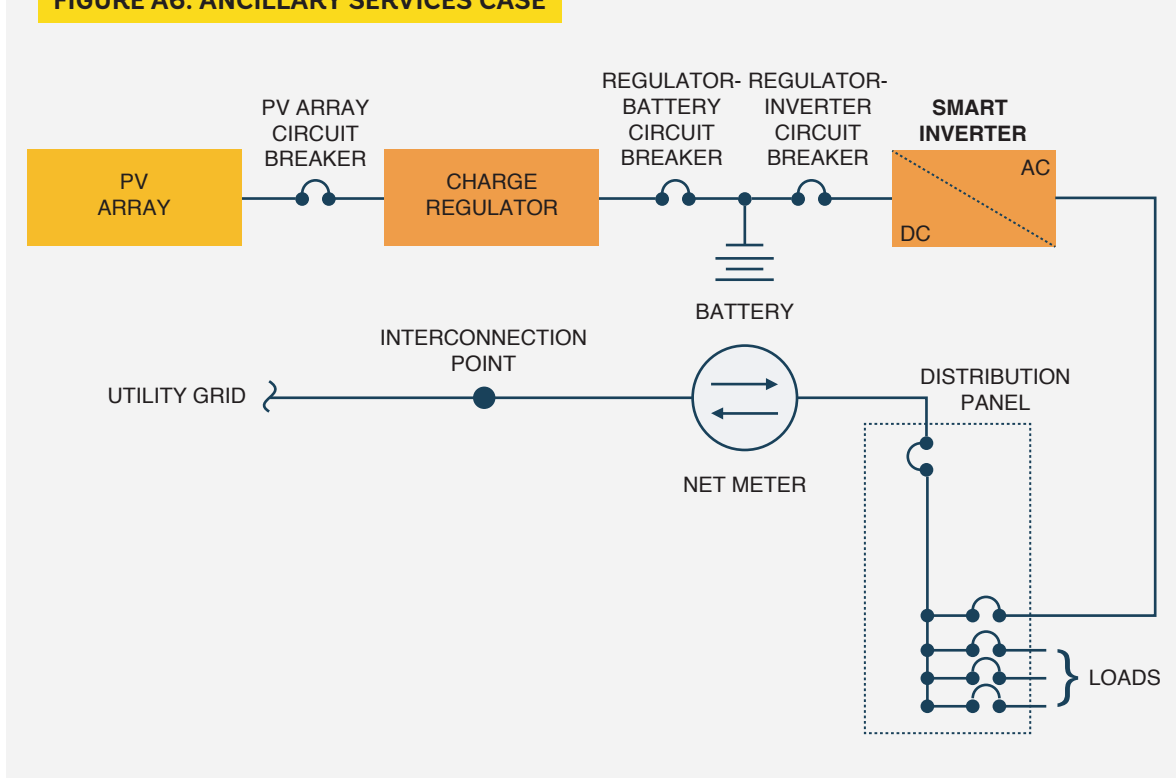


FIGURE A6: ANCILLARY SERVICES CASE

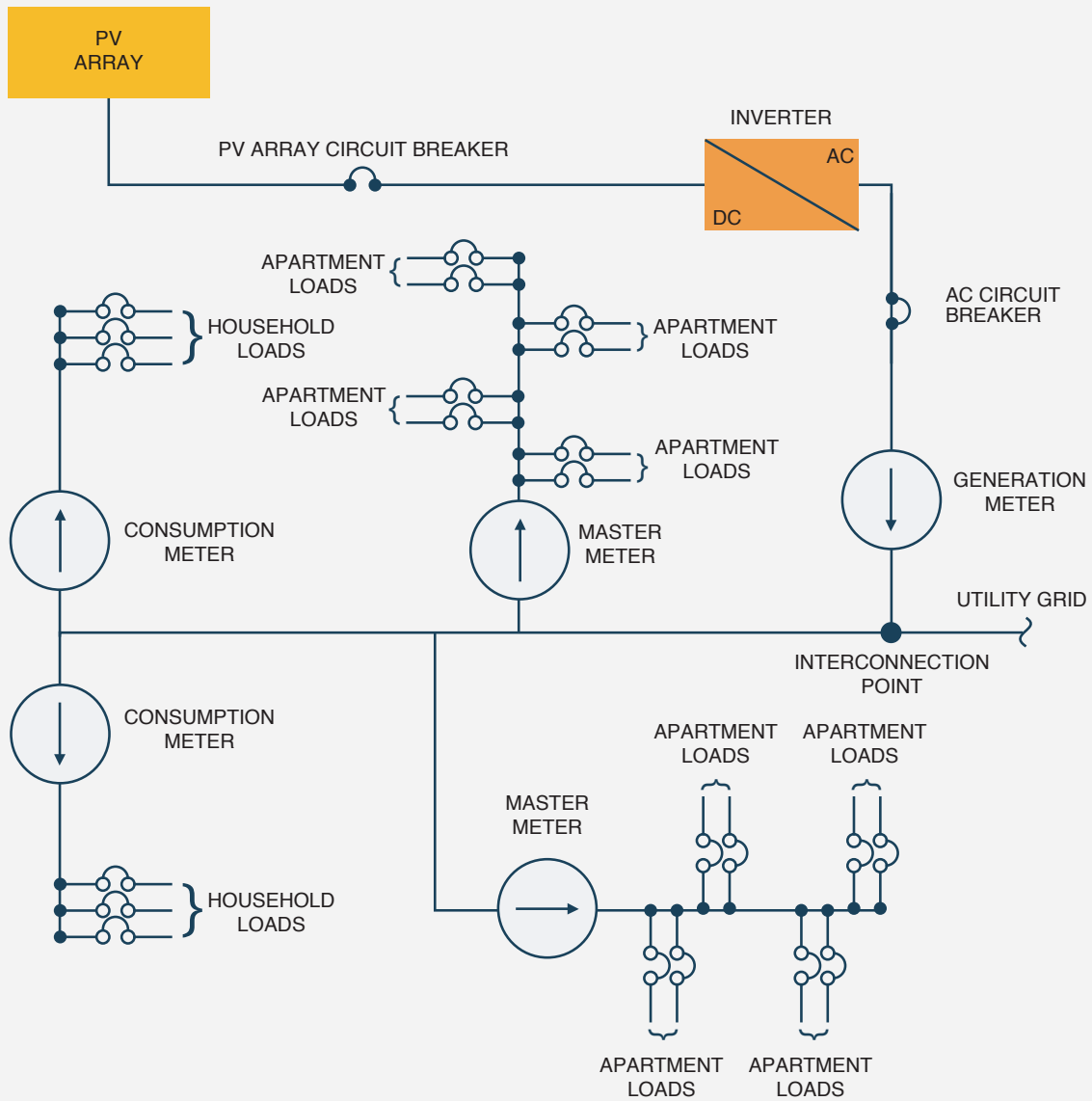


USE CASE 7: COMMUNITY SOCIAL SUPPORT

Figure A7 shows a grid-side feed-all arrangement of DPV as a community scheme near a number of consumers, including apartments that have only a master consumption meter. In this scenario, apartment households pay for their electricity based on some measure other than their specific use (e.g. floor area). A generation meter measures all the electricity produced by the PV installation. This arrangement typically requires cooperation with the utility to implement subscription mode for billing (also known as virtual net metering), in which the PV production is measured and the equivalent total amount of energy is divided up and applied to offset energy amounts in the utility bills of each subscribing customer according to their distribution of ownership of shares in the community solar facility.

In principle, the solar array could be anywhere in the utility's service territory; it need not be located in the beneficiary community. The program may prioritize low-income users as a form of social support.

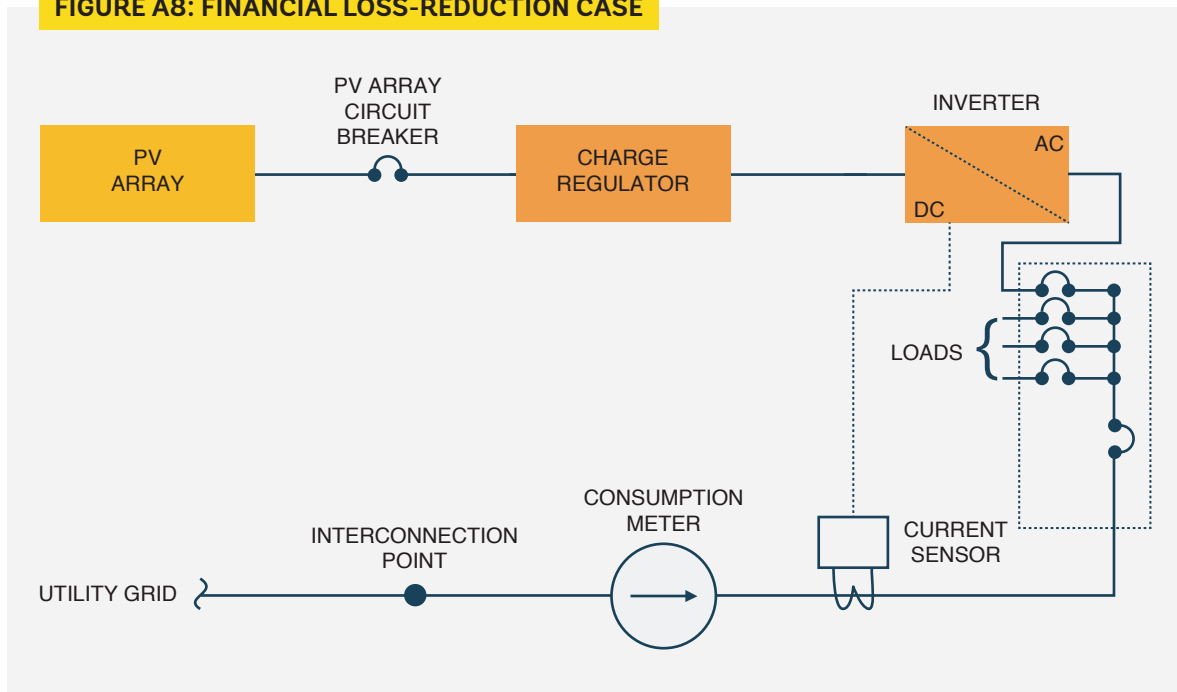
FIGURE A7: COMMUNITY SOCIAL SUPPORT CASE



USE CASE 8: FINANCIAL LOSS REDUCTION

Figure A8 shows a feed-none arrangement of DPV as may be used to reduce consumption of grid electricity for consumers in chronic arrears. Assuming the utility cannot disconnect service to these delinquent consumers, their use of DPV helps reduce the financial losses incurred by the utility from selling them grid electricity. In this configuration, all the electricity produced by the installation is supplied to the consumer. No output is fed to the grid. A current sensor communicates via Bluetooth or ethernet cable to curtail solar output to prevent the PV array output from exceeding the local load. (Feed-some or feed-all arrangements are possible with different configurations).

FIGURE A8: FINANCIAL LOSS-REDUCTION CASE

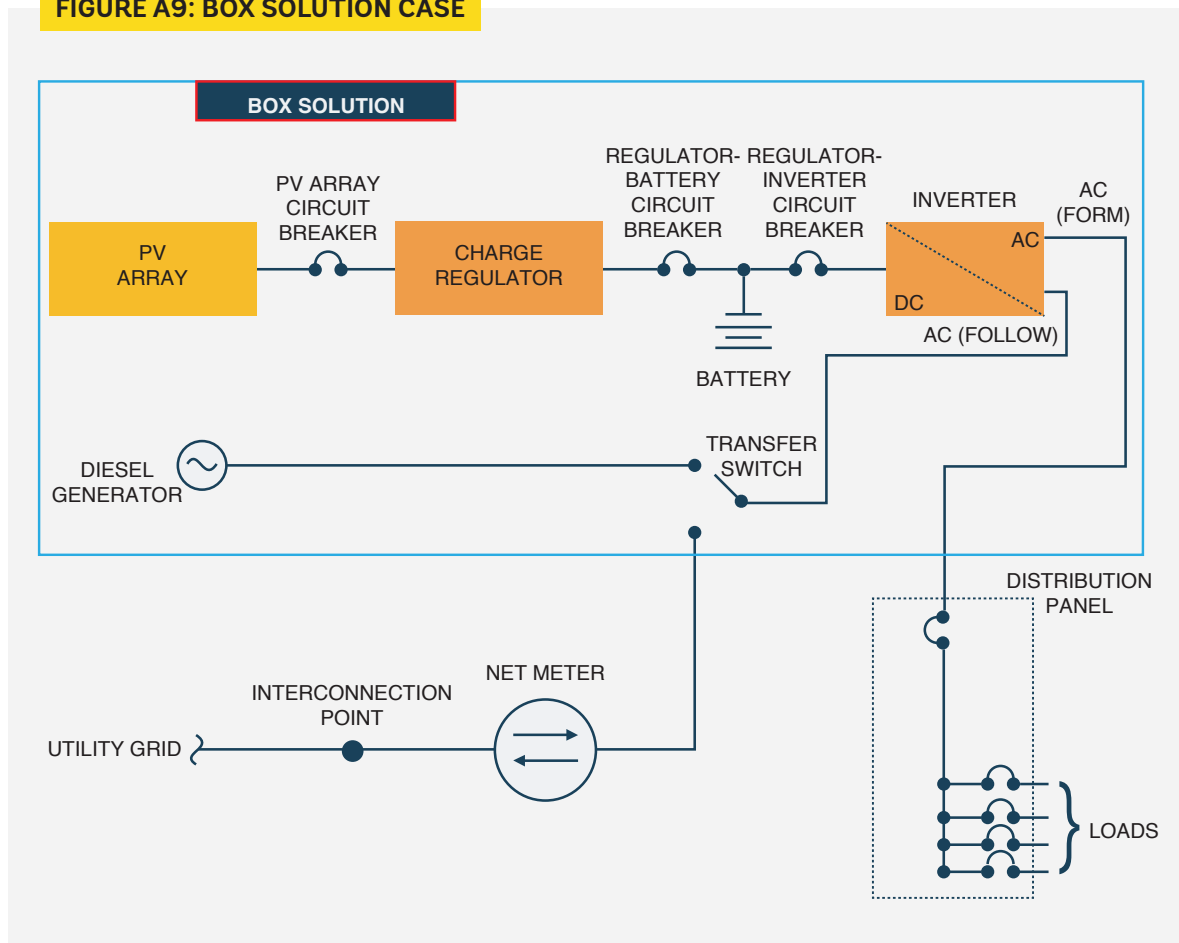


USE CASE 9: BOX SOLUTION

Figure A9 shows a feed-some arrangement of DPV plus battery and diesel generator as backup in a pre-assembled box solution, i.e., a metal cabinet, or in large cases a shipping container, for ease of transportation and installation. This serves as an uninterruptible power supply for a site with a connection to unreliable grid electricity, providing the ability to switch over to backup power within tens of milliseconds after grid power goes down. A box solution like this can be deployed quickly, improving resilience in case of natural disaster.

The bidirectional inverter supplies electricity to loads when the grid power is out, supported by a backup diesel generator. When utility grid power is available, the inverter can use grid electricity to charge the battery if needed. If the batteries are fully charged and PV panels produce electricity in excess of load then electricity can flow out to the utility lines. (Feed-all and feed-none arrangements are also possible).

FIGURE A9: BOX SOLUTION CASE



ANNEX B: DISTRIBUTION GRID TECHNICAL STANDARDS

Key recent standards on distributed PV and other distributed energy resources are listed below, as published by the Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC). This list is not intended to be exhaustive. Standards are updated periodically to reflect advances in technology and practical experience. Consult relevant authorities for latest developments.

IEEE 1547 series on interconnection of distributed energy resources: <https://standards.ieee.org/products-services/icap/programs/der/>

- IEEE 1547-2018, Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- IEEE 1547, Standard for Interconnecting Distributed Resources with Electric Power Systems
- IEEE 1547.1-2020, Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces
- IEEE 1547.2, Application Guide for IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
- IEEE 1547.3, Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems
- IEEE 1547.4-2011, Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems
- IEEE 1547.6-2011, Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks
- IEEE P1547.7-2013, Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection

IEEE power electronics and distribution system–related standards

- IEEE 2030–2011, Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads
- IEEE 1826-2020, Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW
- IEEE 1676-2010, Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems

Regarding battery storage, IEC has several committees working on documents (standards, guides) addressing battery energy storage implementation issues, either directly, under the general heading of DER technology or microgrid deployment. For example, IEC 62933.

IEC 61850 is an important smart-grids standard relating to substation automation. TC 57 has been preparing a document on how IEC 61850 can be used and extended for electrical battery energy storage for several use cases. The document is related to IEC 61850-7-420, which includes the extension of object models for energy storage, by itself and in combination with distributed generation.

ABBREVIATIONS

| | |
|---------|--|
| AC | alternating current |
| AEMO | Australian Energy Market Operator |
| ANSI | American National Standards Institute |
| DAkKS | <i>Deutsche Akkreditierungsstelle</i> [German Accreditation Body] |
| DC | direct current |
| DER | distributed energy resource(s) |
| DPV | distributed photovoltaic(s) |
| DRIVE | Distribution Resource Integration and Value Estimation |
| EPRI | Electric Power Research Institute |
| ESMAP | Energy Sector Management Assistance Program |
| GIS | geographic information system |
| GW | gigawatt(s) |
| Hz | hertz |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| ILR | Inverter load ratio |
| IRP | Integrated Resource Plan |
| ISO | International Organization for Standardization |
| JAS-ANZ | Joint Accreditation System of Australia and New Zealand |
| km | kilometer |
| kW | kilowatt |
| kWh | kilowatt-hour |
| LMICs | low- and middle-income countries |
| MW | megawatt |
| NEC | National Electrical Code |
| NOVA | <i>Netz Optimierung Verstärkung Ausbau</i> [grid optimization reinforcement enhancement] |
| SCADA | supervisory control and data acquisition |
| STATCOM | static synchronous compensator |
| T&D | transmission and distribution |
| VAr | volt-ampere reactive |
| VPP | virtual power plant |
| VRE | variable renewable energy |

GLOSSARY

active power The proportion of electricity flowing in an AC network that results in a net transfer of energy. (Compare reactive power).

ancillary services This is an umbrella term for all the capabilities required in a power system, apart from active power generation, to reliably meet demand. These comprise tools and procedures to maintain frequency and voltage within nominal ranges, and restart the system after a major blackout. Ancillary services can be provided across all levels of the power system by generation sources, storage systems, inverters, and other equipment. In different contexts, provision of some services may be mandatory (e.g., grid code connection requirements for DPV inverters), or optional and incentivized by remuneration. For example, DPV may be able to provide several distribution system services, including targeted load reduction in capacity-constrained areas of the network (distribution capacity), feeder-level voltage management (voltage support), reductions in the frequency and duration of outages (reliability or back-tie), and improved recovery time from outages or system disturbances.

anti-islanding For the protection of utility workers, generation resources (including distributed generation resources) must be able to detect blackouts and disconnect so as not to form an isolated island. This capability is referred to as anti-islanding.

bidirectional meter A device that measures both energy fed to a grid and energy consumed. Meter designs vary. Meters that measure two separate gross volumes can be used for gross metering, net metering, or net billing. In contrast, a bidirectional meter that only measures net energy fed to the grid and net energy consumed from the grid can be used only for net metering or net billing.

black start The capability of a generator to commence operations without relying on an external power source for starting up.

controllability The possibility to intervene in a system that is in a state of deviance from a target range. This is a fundamental concept of control theory (i.e., the science of managing dynamic systems) along with “visibility.”

distributed PV Any photovoltaics located with or near consumers connected to an electricity grid. This definition implies no minimum or maximum size. Systems can range from a single PV panel of 250 watts, for example, up to tens of megawatts (MW) capacity. In other literature, the term may refer to off-grid PV systems.

feed-in arrangement Denotes whether a DPV or other distributed generation system is configured to feed some, none, or all its power output to the grid, versus use of the output on site for self-supply.

feeder Segment of the distribution grid that connects individual smaller consumers to a larger power line.

grid code The full set of operational and technical rules governing a power system, including standards for DPV systems to connect to the grid.

grid-forming The function of an inverter to actively control frequency and voltage output, without need for an external AC source. This function may be served by a grid-forming inverter or a multimodal inverter in grid-forming mode.

grid-following The function of an inverter to track the voltage angle of an external source (e.g., the grid) to control the output so that it synchronizes to the external source, injecting current in sync with the

external waveform. This function may be provided by a grid-following inverter or a multimodal inverter in grid-following mode.

gross metering Measurement of all energy fed to the grid, with separate measurement of all energy consumed from the grid. A feed-all arrangement necessarily has gross metering of energy produced, since it is all fed to the grid. In a feed-all arrangement, a production meter serves this purpose. Gross metering is also an option for feed-some arrangements and can be achieved with dual metering, implying the use of two separate meter devices, or with a single bidirectional meter. Gross metering facilitates net billing for feed-some arrangements.

harmonics AC grid voltage and current ideally follow a sinusoidal waveform at a stable frequency (50 Hz or 60 Hz depending on the power system). Certain devices—including inverters—can distort this ideal shape. The effect of such distortions can be described by overlaying a set of waveforms that are integer multiples of the target system frequency. These additional waveforms are called harmonics. Harmonics can negatively impact equipment, such as increased heating of conductors or transformers.

hosting capacity The estimated maximum amount or range of distributed generation possible to integrate into an electrical network while keeping within specified operational performance limits (e.g., overvoltage, thermal overloading, power quality, protection problems) before or after enhancement techniques (e.g., reactive power and voltage control, active power curtailment, energy storage technologies, network reconfiguration, grid reinforcements, and harmonics mitigation).

islanding Capability of a distributed generator to maintain service in a small portion of the grid even if the main grid experiences an outage. Islanding is usually undesired because it can harm utility workers striving to reestablish service. Microgrids are designed deliberately to have islanding capabilities, but in a way that does not negatively influence the main grid.

load balancing Measures to match in time the demand for and supply of power. For DPV, this can involve optimizing DPV panel size, panel angles, and inverter shaving, so that DPV output coincides with the expected time and level of loads. It can also involve calibrating loads to better match DPV output (e.g. flexible coolers or heaters). Energy storage systems can perform load matching as part of a DPV system or alone.

microgrid A small grid system with its own power generation sources to serve one or more consumer facilities, typically with an interconnection to a main grid and capable of operating independently during an outage of the main grid.

mini grid A small grid system to serve one or more consumer facilities, typically in an off-grid setting.

net billing Separate measurement and pricing of energy consumed from the grid and energy fed to the grid under a feed-some arrangement (that is, some DPV energy is fed to the grid, and some DPV energy is consumed), each net of self-supply. Typically accounted with a bidirectional meter.

net energy The vector sum of energy consumed and energy fed by the consumer to the grid over a given period (for example, hour, day, month, or billing cycle). The sum for the given period may be a net feed-in (“credits” from the consumers’ perspective, sometimes called “excess” energy), net consumption, or zero (if the feed-in and grid consumption amounts happen to be equal).

net load Net load may have different specific meanings but refers here generally to demand for grid electricity excluding demand served by distributed and/or bulk variable renewable sources. Gross load refers to total end-user demand for electricity from any source, including DPV or other “negative loads.” Storage, and demand-response measures may also be treated as negative loads. DPV and consumer-side storage reduce demand not only for grid electricity in general but from bulk renewables too.

net meter A meter of net energy. The simplest version of a net meter is a common retail meter that spins forward for each unit of energy consumed from the grid and that can spin backwards when energy is fed to the grid. With such a meter, calculating net energy involves comparing the meter reading at two different points in time (e.g., once each month). The more frequently such a meter is read, the more information is available to inform billing options. Such a meter can theoretically be used to estimate total energy consumed from the grid or total energy fed to the grid when readings are taken continuously in real time.

net metering The process of accounting for DPV generation fed to a grid using a net meter or equivalent, such that energy fed to the grid is compensated at the same rate as the energy component of the retail electricity tariff for the given period (retail parity compensation). In practice, there are many forms of net metering, and different jurisdictions apply the term in different ways.

non-synchronous generation Production of electricity that is not synchronized to the grid, namely DC power (e.g., from PV), or AC power at a frequency other than the grid's frequency. Inverters convert non-synchronized AC or DC power into synchronized AC power. By contrast, synchronous generation (such as from thermal power plants) produce AC electricity at the grid's frequency without the need for an inverter.

penetration The amount of a particular generation connected to a power system.

reactive power The proportion of electricity flowing in an AC power network that is needed to continuously charge and discharge the electromagnetic fields in and around electrical equipment. Reactive power oscillates back and forth in the grid and does not contribute to a net transfer of energy.

ride-through The capability of an electric generator to stay connected to the grid and to continue operating during system disturbances, within a range of conditions, to help avoid power outages. For DPV, this capability is provided by a grid-connected inverter. Grid codes may require DPV inverters to be able to ride through short-term low-voltage events, for example, which may occur at the moment when large loads are connected to the grid.

underfrequency load-shedding relays Device that automatically disconnects a portion of a distribution grid during periods of generation shortfall to avoid a large-scale blackout. If frequency falls below a set threshold, the relay measures locally and disconnects.

utility Electricity service company. For DPV, a utility typically refers to a distribution company or a vertically integrated utility, being a company that owns assets across the electricity supply chain (generation, transmission, distribution and retail) within a given service area.

virtual power plant (VPP) A virtual power plant is a network of decentralized generating units, consumers of flexible power, and storage systems, all interconnected and dispatched through central control as if they were one power plant yet independent in operation and ownership.

visibility The ability to know the state of a system or process, as a fundamental concept of control theory (i.e., the science of managing dynamic systems) along with "controllability."

See also US Energy Information Administration (EIA) glossary at <https://www.eia.gov/tools/glossary/>.

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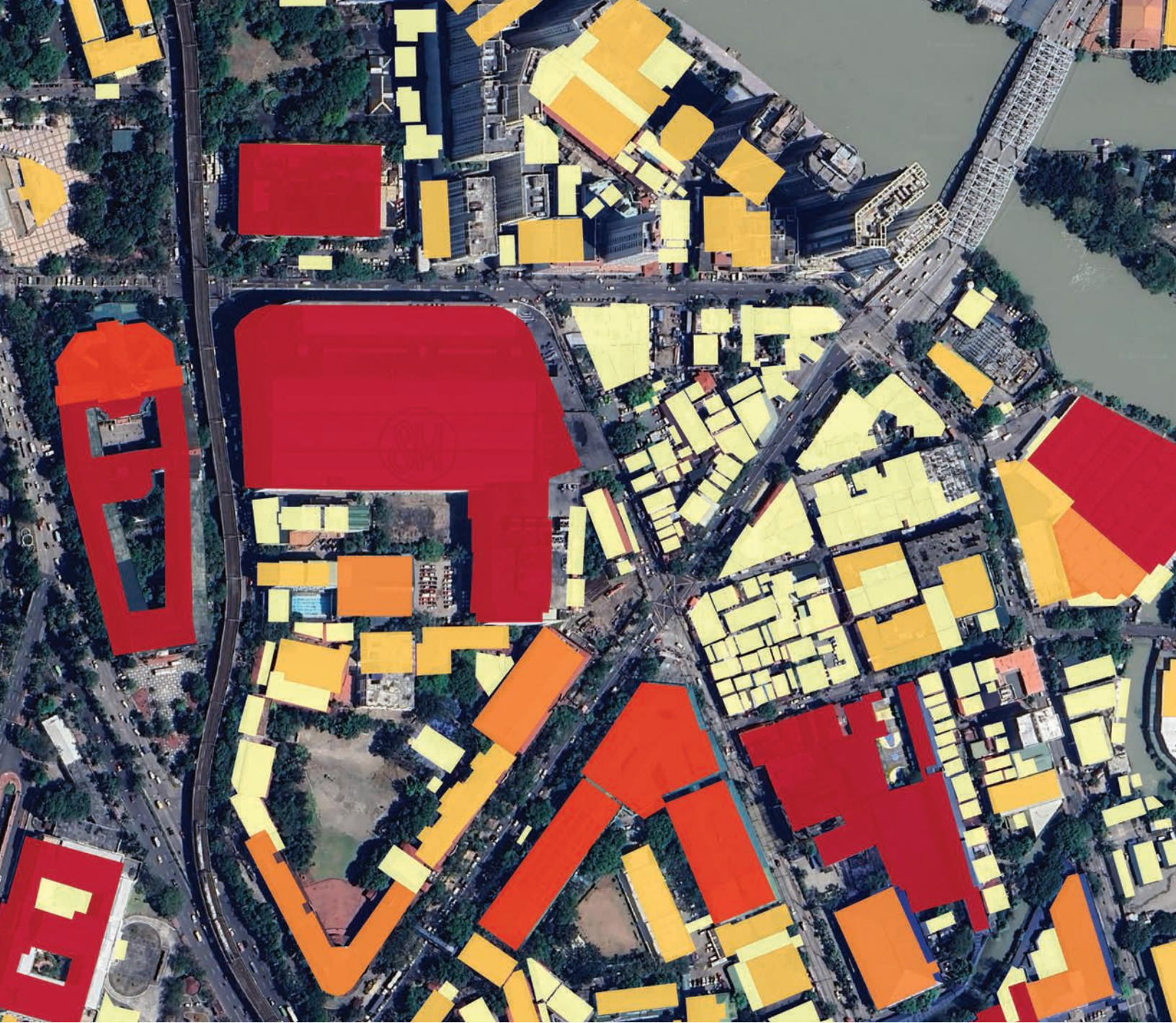
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Rooftops analyzed near substation in Manila, Philippines

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