PV Forecasting in Distribution System Operation - Requirements and Applications

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***Abstract*—PV forecasting applications can become increasingly relevant for the operation and the operational planning of distribution systems with a high PV penetration. This paper analyzes and discusses possible use cases for PV forecasting applications within the distribution level and their expected forecasting requirements. Furthermore, the paper introduces the planned case studies for the assessment of advanced PV forecasting applications in an active distribution system management in the MetPVNet project.**

Keywords: PV integration; PV forecasting; operational planning, GLDPM, SO-GL, Congestion management, Reactive power management

I. INTRODUCTION

In the MetPVNet project [1], innovative energy-meteorological methods for forecasts of irradiation and photovoltaic (PV) performance are further developed for use in the distribution grid. While the use of PV forecasting in transmission system (TS) operation and on the energy market is already state of the art, PV forecasting in German distribution system management (DSM) is solely limited to a few larger Distribution System Operators [1] (DSO) and R&D projects. However, an increasing use of PV forecasting in distribution system management is expected in the upcoming years, because of the following trends in the European power system:

- **Decarbonization**: increased variable and intermittent renewables, such as PV in the power system, which require more accurate forecasting to handle the massive fluctuations of renewables.
- **Decentralization:** increased generation and flexibility potential at the distribution level, which increases the importance of the distribution level for bulk system operation.
- **Deregulation:** increased number of relevant stakeholders, such as Transmission System Operators (TSOs), DSOs, energy suppliers and several market players, which can require forward coordination between stakeholders.
- **Digitalization:** improved observability and controllability at distribution level, which enables an active distribution system management.

In conclusion, these trends highlight major challenges but also opportunities for the distribution and bulk power system operation, which can require the integration of operational planning procedures and PV forecasting applications at distribution level. In the interdisciplinary project MetPVNet, experts from the field of atmospheric science, renewables energies, energy economics and energy system technology are working together to improve the forecasting of solar irradiation and the modeling of PV generators in a real distribution system environment [1].

This paper covers the grid integration aspects of advanced PV forecasting applications within the MetPVNet project. In Section II, use cases for PV forecasting applications at the distribution level are identified and their relevance and forecasting requirements are discussed. In Section III current developments for data provision from the distribution level for the transmission system operation are summarized, which can encompass the provision of forecasting information from the distribution level. Section IV describes the planned case studies for the assessment of benefits and constraints of PV forecasting applications in an active distribution system management and Section V is the summary.

II. FORECASTING APPLICATIONS AND THEIR REQUIREMENTS AT THE DISTRIBUTION LEVEL

This Section discusses the relevance and requirements of PV forecasting applications for different use cases at the distribution level. The focus is set on PV forecasting

[1] In Germany, also the high voltage level (73 kV to 125 kV) is mainly considered as part of the distribution grid.

applications for an active distribution system management by the DSO. PV forecasting applications for energy suppliers, consumers and other stakeholders are partly also discussed in this Section, but not in the main scope of the paper.

A. Overview of Use Cases

- **Balancing services[2]:** PV forecasts are already widely used in market trading, scheduling and the unit commitment of flexible power plants. Improved PV forecasts can further optimize market operations and power plant scheduling and can reduce the demand for frequency control reserves in the bulk power system. For example, PV forecasts for distribution grid sections can help to predict unintended interaction between system-wide balancing services and regional grid congestions. *Relevance*: Generally high, but usually not as part of the DSO's responsibility in Germany[3].
- **Congestion management:** A congestion forecast is of interest because grid operators should inform operators of renewable energy sources (RES) *"at the latest on the day before, otherwise without delay, of the expected […] curtailment to the extent that the execution of the measure is predictable."* (German Renewable Energy Sources Act [3], Section 14). *Relevance*: High, due to increased congestion measures in the German power system over the last years (see [6], p. 141). Furthermore, the new Grid Expansion Acceleration Act (NABEG 2.0) [4] considers the extension of comprehensive redispatch measures also for distributed RES with installed capacity above 100 kW and smaller dispatchable RES by October 2021 [5]. Therefore, congestion forecasting will become increasingly important also at the distribution level.
- **Multi-use case storage:** Better forecasts at distribution level can further optimize the storage dimensioning and usage, i.e. the storage can find the optimal state of charges for the upcoming hours. Furthermore, the best time for recharge and operation to extend its lifetime and profitability can be determined. Besides, a more precise forecast minimizes the storage size due to reduced backup capacity. *Relevance:* Medium to high, as the storage capacity in the German distribution level has increased over the last years. The main purpose of storage systems are balancing services. Here, especially the application of additional ancillary services for distribution system operation, such as congestion management can be of interest.
- **Reactive power management at grid interfaces (i.e. TSO/DSO interface)**: Distributed energy resources (DER) can provide reactive power flexibility for distribution system operation and the upstream transmission level. However, the DER reactive power capability usually depends on the DER active power feed-in. Forecasts of reactive power demand and reactive power flexibility potential at distribution level can be of interest for the operational planning of reactive power sources and reactive power procurement between TSO, DSO and other relevant stakeholders. *Relevance*: Medium, regulatory framework for reactive power procurement from DER is still under discussion in Germany [7].
- **Maintenance management:** PV forecasts can be used to identify optimal periods for maintenance measures. *Relevance:* Low to Medium, partly already applied at the distribution level. Maintenance management may not require detailed PV forecasts.
- **Grid restoration:** For example, PV now-casting and forecasting for individual distribution grid sections can help to predict the feed-in behavior of non-dispatchable PV systems during a grid restoration process. *Relevance:* Low to medium, distribution grids play currently and in near future (< 5 years) prospectively a rather passive role in grid restoration procedures.
- **Voltage control in the distribution level:** For example, forecasts can identify very short-term voltage variations, and thus may avoid unnecessary and frequent switching of voltage regulators at the distribution level. *Relevance*: rather low, voltage control on actual values widely sufficient.

B. Forecasting horizons

State of the art forecasting models are mostly classified into short or long-term horizon models. While short-term forecasts include latest measurements, long-term forecasts usually do not. Horizons of short-term forecasts reach up to around eight hours, while long-term forecasts easily cover more than a week, based on a numerical weather prediction model horizon used as input. Figure 1 shows the expected forecasting horizons for the different use cases.

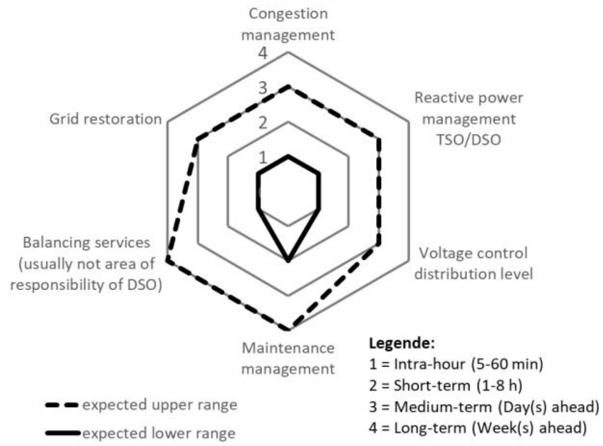

Figure 1: Expected relevant PV forecasting horizons for different applications in distribution network operation. For the multi-use case storage, the requirements dependent on the selected use cases.

Short-term (1 to 8 hours) and intra-hour forecasting horizons can be especially of interest for voltage-related services such as voltage control in the distribution network and reactive power management between the TSO and DSO. The voltage magnitude within the distribution level however can

[2] This system service is usually not in the area of responsibility of the DSO, due to unbundling reasons.

[3] The Balancing Responsible Party (BRP), i.e. energy suppliers, are responsible for the balancing of energy supply and demand for their portfolio of consumers, prosumers and producers (see also [2]). The respective TSO is responsible for the coordination of the balancing services.

fluctuate strongly regionally and temporally at the distribution level. Thus, the grid voltage is rather hard to predict in medium (day(s) ahead) and long-term (week(s) ahead) forecasts. Another use case for short-term and intra-hour forecasting horizons is a very time and system critical grid restoration process; here also short-term variations in PV generation can be of interest. Balancing services cover a wide range of services. In case of market-clearing [9] and real-time economic dispatch of DER intra-hour forecasts can be of high interest, whereas in power plant scheduling (e.g. refilling power plant stocks or the charging of long-term storage capacities) also long-term forecasting horizons are required. However, mainly short-term (1 h to 8 h) and medium-term forecasts (day(s) ahead) are prospectively sufficient for the majority of the described use cases.

C. Temporal forecasting resolution

The temporal resolution of forecasts can be designed to fit the application at hand. Prerequisites are usually some data providing historical information about the forecasting target in the needed resolution. Typical timesteps are hourly or quarter-hourly in size. Temporal forecasting resolutions of 10 or 15 minutes are expected to be sufficient for the majority of the described use cases. However, for very time-critical system services, such as grid restoration, frequency control (balancing service) or voltage regulation, a higher temporal resolution (≤ 5 minutes) can be of interest to consider short-term power and voltage fluctuations in the operational planning.

D. Spatial forecasting resolution

Generally spoken almost any spatial resolution can be forecasted on. Single sites, on the one hand, use onsite measurements and more or less close Numerical Weather Prediction (NWP) data interpolated to the site of interest. Forecasting regions, on the other hand, need a trade-off between available input data resolution and calculation efforts. NWP grids, as well as regional forecasting models, may have typical resolutions down to a few kilometers. The distribution grids are very heterogeneous and cover the low voltage (LV), medium voltage (MV) and high voltage (HV) levels in the German power system. LV grids often have line lengths of only a few 100 meters, whereas HV networks can also reach line lengths of more than 100 km. In particular, the voltage level of the forecasting application can therefore have a considerable influence on the spatial PV forecasting requirements. Increasing demand for forecasting applications in distribution system management are especially expected for the HV-level and pursuing the MV-level.

E. Summary and Outlook

For the case studies within the MetPVNet project, the use cases congestion management, reactive power management, and Multi-use case storage are identified as being the most relevant. Operational planning procedures and forecasting applications at the HV-level are already studied in several R&D projects (i.e. IMOWEN [10], SysDL 2.0 [11]) and are partly applied by larger DSOs. In addition, the focus of the MetPVNet case studies is set on PV forecasting applications for the MV-level and the prediction of vertical power flows and flexibility potential at the HV/MV interfaces. Therefore, also appropriate forecasts of the vertical power flow from the underlaid LV grids are of interest. For the selected use cases, a focus is set on day-ahead forecasts, which are especially of interest for the coordination between different stakeholders, such as DSOs, TSOs, DER operators and relevant market players. A temporal forecasting resolution of 15 minutes is considered adequate for the applied use cases.

III. Data Provision for transmission system Operation

In addition to the discussed use cases in the previous Section, also the TSO can require forecasting information on distributed generation and power flows within the distribution level for their operational security analysis. In the European power system, the respective requirements on data provision for the TSO are specified in the "Generation and load data provision methodology" (GLDPM) [12] and the "System Operation Guideline" [14], which are briefly described in the following Subsections.

A. Generation Load and Data Provision Methodology

To facilitate a capacity determination on inter TSO level, the Generation Load and Data Provision Methodology (GLDPM) which is based on European regulation [12], [13] has been introduced in Germany between the years 2017 and 2018. A process is described for building a model of the European interconnected electricity grid (common grid model, CGM) for large area load flow calculations. This model will frequently be updated with structure information and generation and load data in order to determine cross border congestions and to allocate capacities. It is the responsibility of the TSO to collect basic claims data, planning data and operational data of relevant generators and customers respectively loads for its control area. Under GLDPM, only power plants connected to the transmission grid as well as large conventional generation units connected to the distribution level need to provide operational data. Renewable generators are still out of the scope at this stage and are to be integrated in a further step. But in order to predict vertical power flows at interconnection points between TSO and DSO, not only large conventional generation must be considered. For sufficient accuracy, precise predictions of all generation and consumption within a HV-level and underlaid grids have to be used.

B. System Operation Guideline

As a logical continuation of GLDPM, the process is gaining extended acc. to the System Operation Guideline (SO-GL) [14]. A common framework for the operation of the interconnected system has been developed to facilitate European energy trade, to ensure system security, to the improve integration of distributed generators and to standardize data transmission between TSO, DSO and relevant grid users. With the implementation of SO-GL, distributed generators will have to submit data to the related network operator as well. The types of data in relation to the installed capacity as well as the types of primary power are displayed in Table 1.

According to Table 1, PV plants with an installed capacity of more than 1 MW will have to provide real-time operational data in Germany, and only plants connected to the transmission system need to provide planning data that have to be forecasted. In 2015, PV plants with a total capacity of more than 23 GW were connected to the German low voltage grid, while not even 100 MW are connected to the transmission system in Germany [16]. Low voltage PV plants have an installed capacity far below 1 MW, therefore only a few PV plants will provide real-time data and planning data will not be available at all. This lack of information will not lead to an optimal basis, which is necessary to reach the goals of SO-GL. Furthermore, if PV installations reach a relevant share in LV and MV grids, PV forecast data have to be taken into account to calculate two and one day(s)-ahead exchange power with the next higher network level which have to be reported to the upstream network operator. Combining PV forecasts with information of grid topology can help to close this gap and to ease network operation planning.

Table 1: Overview of required data provision for DG [15][1)]

power\criterion	Biomass	PV/Wind	Riverrun	Storage
P ≥ 0.8 kW	BCD	BCD RTD[2)]	BCD	BCD
P ≥ 135 kW	OD	--	--	--
P ≥ 1 MW	RTD	RTD OD	RTD	RTD
P ≥ 10 MW	PD	---	PD OD	PD OD
TS connection	--	PD	--	--

BCD: basic claims data; OD: outage data; RTD: real-time data; PD: planning data

[1)] If one class of data is required for power call, it is also required for higher power classes

[2)] if reference PV plant

C. Conclusion

As part of the operation security analysis and the capacity planning in the European transmission system, predicting the PV generation and power flows within the distribution level becomes increasingly necessary. The extra high voltage level and some parts of the HV-level (observability area) are usually modeled in detail in order for the TSO to conduct security analysis. Furthermore large generators, storage units and consumers have to provide planning data to the respective grid operators. Nevertheless, a major share of renewable energy sources and about 90 % of PV generation are connected to the German MV and LV levels. This distributed generation has a significant impact on the power flow, the grid security and the capacity calculations in the upstream voltage levels. Therefore, a relevant R&D demand is identified in predicting the vertical power flows from the underlaid MV and LV levels.

IV. Planned Case Studies

This Section describes the planned case studies for the assessment of advanced PV applications in an active distribution system management in the MetPVNet project.

A. Selected use cases

As outlined in Section II.E and III.C, there is a relevant R&D demand in the prediction of power flow and flexibility potential within the distribution level. The focus of the study is set on day-ahead forecasts of the power flow at a HV/MV interface and the corresponding flexibility potentials of large PV plants at the MV level. The identified use cases can be summarized as follows:

- **Use case 1 – Passive distribution network:** Forecast of PV generation in the selected grid section, followed by a forecast of active and reactive power flow at the HV/MV interface.
- **Use case 2 – Congestion management:** Forecast of active power feed-in and flexibility potential of large PV plants (> 500 kWp) and storage systems on MV level. Congestion measures in the investigated grid section are defined day-ahead.
- **Use case 3 – Reactive power management:** Forecast of reactive power flexibility potential at the HV/MV interface by reactive power control of large PV plants (> 500 kWp) and storage systems on MV level.

B. Identified case study region

The case study is performed in detail for one particular MV grid of the German DSO *AllgäuNetz GmbH*. The MV grid Ursulasried is selected for the detailed study based on the following criteria:

- High PV penetration level of approximately 126 % (installed PV capacity over peak load demand),
- Five large PV plants (P_N > 500 kW) for an active distribution system management in the grid section,
- Comprehensive grid data and measurement data from the HV/MV transformers. Furthermore, measured data of large PV plants (P_N >500 kW) are mostly available,
- Large battery storage system of 500 kW and 350 kWh in the investigated grid section.

Furthermore, the MetPVNet measurement campaign provides detailed meteorological information from the investigated grid section. This information is used in the MetPVNet project to further improve the PV forecasting models on distribution level (for further information see [1]). Table 2 provides an overview of the installed DER capacity and the peak load demand and Figure 2 shows a single line diagram of the investigated grid section.

Table 2: Installed DER capacity and peak load in the case study area

Capacity in MW	PV DER	Wind DER	Hydro DER	Bio DER & CHP	Peak load
MV level	11.4	3.5	0.0	14.1	23.1
LV level	17.9	0.0	0.1	0.5	

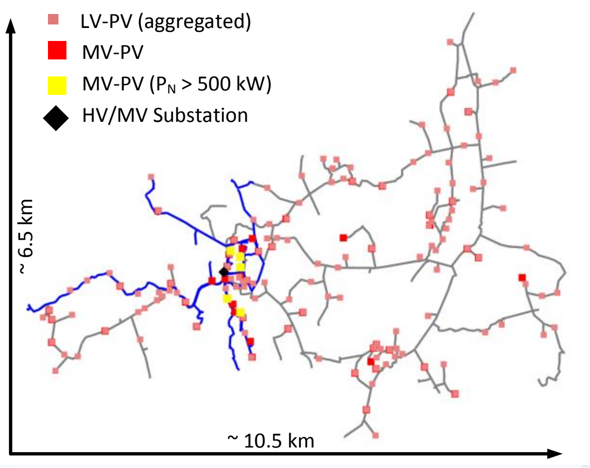

Figure 2: MV grid Ursulasried

The MV grid Ursulasried contains two HV/MV transformers (Tr122 and Tr121) and two main supply areas. Tr121 supplies mainly a commercial area including large commercial PV plants (blue lines in Figure 2) and Tr122 supplies a wide rural area with mainly residential PV (grey lines in Figure 2).

C. Pre-Assessment of PV Forecasting applications in the case study region

The application of characteristic day profiles, such as standard load profiles (SLP), is widely applied in the energy sector, i.e. for load forecasting. However, for predicting the residual load demand in a distribution section (distributed demand minus distributed generation) also changing metrological conditions, such as solar irradiation, can have a significant impact on the power flow at the distribution level.

In the pre-assessment, the power measurements at the two HV/MV transformers in the investigated grid section are analyzed for the year 2017 and the impact of PV generation on the power flow is investigated. Figure 3 shows selected percentiles (blue scale) of the active power flow at HV/MV transformer Tr122 (top) and Tr121 (bottom).

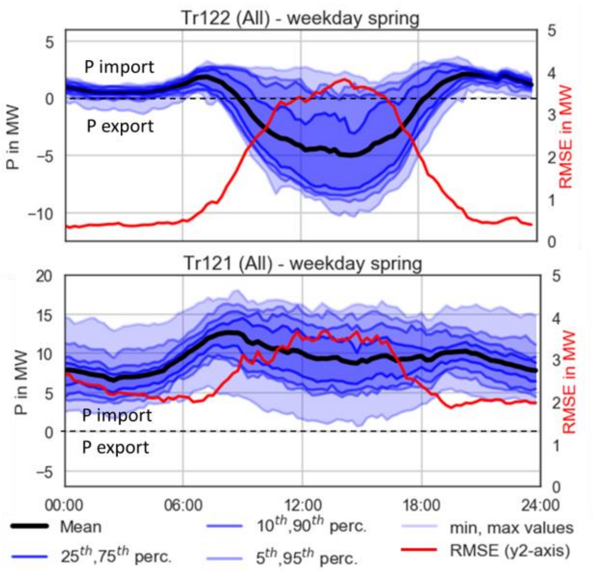

Figure 3: Statistic evaluation of active power transfer at HV/MV transformer Tr122 (top) and Tr121 (bottom) for all spring weekdays in 2017

The figure summarizes all spring weekdays in 2017 (excluding all holidays, Saturdays and Sundays) and the black line defines the mean power flow at the HV/MV transformers. This mean curve could be considered as a characteristic day curve for the particular HV/MV transformer classifying them as typical day profiles of a spring weekday in 2017. However, one needs to consider, that depending on the time of day the introduced errors might be severe with the application of characteristic day profiles. This is highlighted by the red line describing the root mean square error RMSE (Figure 3, right y-axis) of the derived mean profile with the actual power flow at the HV/MV transformer. At nighttime and without PV generation, the active power flow at Tr122 (Figure 3, top) has a low variation and the power flow can be well predicted by a characteristic profile. However, with PV generation between 7 am and 8 pm, the power flow at the HV/MV transformer achieves a large variation and the application of characteristic day profiles can lead to relevant inaccuracies. For Tr121 (Figure 3, bottom, commercial area) also a significant impact of the load demand and large power flow variations at nighttime without PV generation are determined. Hence, besides PV forecasting also load forecasting is expected to be a major challenge in the investigated grid section.

D. Simulation environment

Besides accurately forecasting PV generation, forecasting the load demand and other distributed generation present a challenge for forward operational planning procedures at the distribution level. In the applied case study, standard load profiles (SLP) are applied for forecasting the load demand. Therefore, detailed information on the SLP type and energy consumption are collected for each load and MV/LV substation. For other distributed energy resources, such as wind power plants (Wind DER), bio power plants (Bio DER), combined heat and power plants (CHP) and hydro power plants (Hydro DER), coincident measurement data are provided by the DSO and characteristic seasonal profiles for the individual DER types are developed and applied as forecast data. If, no sufficient measurement data in the grid region is available for a DER type, generation data from the R&D project Simbench [16] is applied. For day-ahead operation planning in the grid section, different day-ahead simulation approaches are developed (see Table 3).

Table 3: Overview of planned forecasting scenarios

	Loads	Generators (not PV)	PV generators
Reference simulation (now-casting simulation)	Based on actual measurement data from the investigated grid section and representative measurement profiles from the SimBench project. PV systems without measurement data are modelled by now casting satellite derived data.		
Day ahead simulation characteristic day	Standard load profiles DSO	Seasonal characteristic generator profiles	Seasonal characteristic PV profiles
Day ahead simulation advanced characteristic days PV	Standard load profiles DSO	Seasonal characteristic generator profiles	Advanced characteristic PV profiles
Day ahead simulation with standard PV forecast	Standard load profiles DSO	Seasonal characteristic generator profiles	Standard day-ahead forecast
Day ahead simulation with advanced PV forecast	Standard load profiles DSO	Seasonal characteristic generator profiles	Advanced day-ahead forecast

Different simple and advanced prediction models of PV generation characterize the simulation approaches:

- **Seasonal characteristic PV profiles:** based on historical measurement data retrieved in the grid section, average seasonal profiles are applied.
- **Advanced characteristic PV profiles:** based on historical measurement data retrieved in the grid section, average seasonal profiles for different cloudiness day types (i.e. clear sky, overcast or partly cloudy day) are applied.
- **Standard day-ahead forecast:** based on numerical weather prediction data standard day-ahead PV forecasts are applied. The forecasts are not optimized for the grid section (i.e. PV orientation and tilt) and the improvements in irradiation and PV modeling within the MetPVNet project are not considered.

- **Advanced day-ahead forecast:** based on numerical weather prediction data advanced day-ahead PV forecasts are applied. The forecasts are optimized for the grid section (i.e. PV orientation and tilt) and selected improvements within the MetPVNet project are considered.

As a reference for the day-ahead simulations and the different PV forecasting approaches, a now-casting simulation is performed, which is based on actual measurement data from the grid section and representative measurement data from the Simbench Project. PV systems without measurement data are modeled by now-casting data for the grid section. Annual power flow simulations of one year are planned to cover different seasonal effects and various atmospheric conditions.

E. Outlook

In the next step, an active distribution network management with day-ahead operational planning procedures for DER feed-in management and reactive power management are implemented in the simulation environment. For the use case congestion management, appropriate congestion scenarios for the grid section are further defined. The focus of the case studies is the assessment of benefits and constraints of PV forecasting applications in an active distribution system management at the MV level. As an example, the following research questions are addressed:

- What are the forecast accuracies of P and Q transits at the HV/MV interface for the different PV forecasting approaches? What is the benefit of advanced PV forecasting approaches?
- How accurate is the forecast of active power feed-in and reactive power flexibility potential by large PV-plants (>500 kW) in the case study region?
- What are benefits and constraints of day-ahead operational planning in the distribution level in the case studies?
- What is the impact of PV forecasting errors on operational planning procedures, i.e. required safety margins in day-ahead congestion planning?

V. Conclusion

In the MetPVNet project, advanced PV forecasting approaches and methods for the distribution level are (further) developed. This paper analyzes and discusses different use cases for PV forecasting applications and the expected PV forecasting requirements at the distribution level. In general, increasing demand for PV forecasting at the distribution level and an active distribution system management is expected. A major driver can be new requirements for operation security analysis and capacity planning at the transmission level, which can require the prediction of the power flow, DER feed-in and consumption in the distribution level. Furthermore, in a smart grid environment, day(s)-ahead operational planning and coordination between different stakeholders, such as TSO, DSO, DER operators, and other market players becomes increasingly relevant. In the planned case studies in the MetPVNet project the benefits of advanced PV forecasting applications for distribution system operation are assessed. The focus is set on forecasts of active and reactive power flows at the distribution level and operational planning in congestion management, reactive power management and procurement.

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