The case for better PV forecasting

Grid integration | Rising levels of PV penetration mean increasingly sophisticated forecasting technologies are needed to maintain grid stability and maximise the economic value of PV systems. The Grid Integration working group of the European Technology and Innovation Platform – Photovoltaics (ETIP PV) shares the results of its ongoing research into the advantages and limitations of current forecasting technologies.

Forecasting and monitoring technologies for PV are required on different spatial and temporal scales by multiple actors, from the owners of PV systems to transmission system operators. Power system operators require a real-time view of PV production for managing power reserves and networks. They also require forecasts on timescales from the short (for dispatching purposes) to the very long (for infrastructure planning), where physics-based models are more accurate. For PV system operators, accurate forecasting is also critical to maximising the commercial value of the electricity they produce.

In its review of the challenges and opportunities associated with massive deployment of solar PV generation [1], the Grid Integration working group of the European PV Technology Platform (now ETIP PV) identified forecasting and observability as critical technologies for the planning and operations of the power system with high PV penetration. In this article we spell out in more detail what features are needed from these technologies and, after an assessment of their current status, how they need to be developed.

Some very good reviews of forecasting techniques have been published in recent years [2,3]. We have built on these by taking a step back and analysing the different use cases for forecasting in relation to PV.

To estimate the economic value of further improvements in forecasting, we linked the effect of forecasting errors on the current imbalance settlement prices charged by balancing authorities in Europe.

Power system dynamics

At all times in all power systems, consumption (including charging of storage systems, and, in the future, demand) and production (including discharging of storage systems) need to be equal. In a conventional power system operating in alternating current (AC), frequency is a real-time indicator of that balance. To ensure that balance is maintained any fluctuation of production or consumption needs to be anticipated as much as possible before it translates into frequency deviations.

Indeed, any corrective action will be limited by the speed at which power system components can move to new set points. The characteristic time constants of power system components range from less than a second to 10 years or more, as summarised in Table 1. Prior to the introduction of variable renewable sources such as wind and PV, power consumption was the only variable component in the power system balance. The ability to forecast these variations was introduced in the 1950s. It has since been refined to take into account seasonal variations (day of the year, day of the week, hour of the day, and the specific characteristics of different electricity uses – heating and cooling, industrial equipment, lighting, etc.) [7]. However, the focus has always remained on regional or national aggregates.

Table 1: Characteristic time constant of power system components

<table>
<thead>
<tr>
<th>Time Constant</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10 s</td>
<td>Inertia response</td>
</tr>
<tr>
<td>1 min</td>
<td>Protection system operation, switching of power electronics</td>
</tr>
<tr>
<td>1 h</td>
<td>Start-up of pumped hydro power plant</td>
</tr>
<tr>
<td>1 year</td>
<td>Maintenance planning</td>
</tr>
<tr>
<td>10 years</td>
<td>Expanding transmission infrastructure</td>
</tr>
<tr>
<td>25 years</td>
<td>Economic lifetime of grid assets</td>
</tr>
</tbody>
</table>

Floating premium

- Market price
- Premium
- Reference price

Fixed premium

- Market price
- Premium
- Reference price

For PV to play its full part in the grid of tomorrow, further work is needed to improve forecast techniques.

Drivers for PV forecasting

An important concept when dealing with forecasting in the power system is the balance group. Balance groups can include generation units, consumption units, or be "virtual" when operated by financial actors who only trade. Forming a balance group is a requirement to participate in wholesale electricity markets. All balance groups report to a balancing authority, which in Europe is generally the transmission system operator (TSO). This authority ensures that trades on the electricity market are balanced and that contracted generation matches forecast consumption. Balancing group managers are responsible for ensuring that at each time step of market operations their contracted production and/or consumption matches the realized values. In case of mismatch between prediction and realization, balance group managers are penalized based on intraday market prices. If the imbalance is in the same direction as the whole system (i.e., a producer under-delivering when there is a shortage in production), the penalty will be above the intraday market price and if the imbalance is in the opposite direction the penalty will be below.

PV generation was until recently shielded from this balancing responsibility in Germany (for example, TSOs carry the responsibility and operate a balance group but the fees are modulated to take into account the inherent volatility of the different sources) [11], the resulting cost for PV generation is estimated around €5 MW/h, which is significantly lower than imbalance prices applied to regular balance groups in Europe [13,14].

In addition, support mechanisms for large PV generators are evolving from feed-in tariffs to market premiums in France, Germany and the UK [15] under which these MW scale plants may be exposed to market trades, and microgrid operators with self-consumed PV electricity require forecasts at the building or district level. Such granularity increases the forecasting difficulty: the standard deviation of PV power production is reduced as 1/√S and 1/√N, where S is the surface area of a PV power plant and N is the number of aggregated plants [9,10].

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generators receive a regulated payment on top of market prices. As illustrated in Figure 1, these premiums can be fixed, or floating, i.e. cover the difference between the average market price over a certain period of time — generally one month — and a reference price set by the regulators. In both cases, generators have a direct interest in maintaining a high market price on the market for the electricity they produce and, in this way, they can effectively sell. Since a generator can only commit to the market power it can produce, accurate forecasts are essential to maximising these wholesale volumes. Finally, the development of micro-grids and the expansion of PV-plus-storage systems requires local energy management, which, for optimal operations, relies on predictive control. Single-site or neighbourhood-level power forecasts are feasible to several timescales from a few minutes to 24 hours are therefore necessary. These drivers and the dynamics of power system components described earlier together create a range of use cases for forecasts on time horizons ranging from 15 minutes or less to a day, and on geographical scales ranging from the single site to an entire region or country. These use cases are summarised in Table 1, which shows in particular the central role of day-ahead forecasting.

Forecasting approaches and performance

Performance criteria
Because the use cases are so diverse, there is no single metric to characterise an "absolutely good"/"good" forecast. Instead, any approach can build on existing weather forecasting tools. The most appropriate tool to predict irradiance depends on the desired time horizon. For resource assessment — i.e., to predict patterns of energy generation over the lifetime of the system — statistically representative time series of weather parameters are generated based on interpretation of ground-level measurements (weather stations) or satellite images to produce the "typical meteorological year". For time horizons between four hours and three days, numerical weather prediction (NWP) is preferred. NWP data are generated by global or regional-scale simulation models that provide the numerical integration of the coupled differential equations describing the dynamics of the atmosphere and radiation transport mechanisms [16]. The initial conditions are given by satellite, radar, radiosonde and ground station measurements. NWP data are then corrected by post-processing algorithms called Model Output Statistics (MOS) which use historical ground measurements to partially remove systematic errors [17]. For time horizons between two hours and six hours, visible and/or infrared images are acquired by satellite-based sensors. A cloud index is computed based on reflectance measurements and is typically used to derive ground-level global and direct irradiances [18]. As compared to NWP, only a few relatively simple modelling assumptions have to be applied to derive the solar resource. Persistence of cloud speed and direction (as derived from the last two images, if they are generally assumed. The dynamic nature of clouds challenges cloud-motion vector approaches, as cloud distribution can change substantially within the typical 30-minute interval between two images. It is indeed challenging to account for cloud convective, formation, dissipation and deformation, however, since large-scale cloud systems (such as those associated with a cold front) are more persistent, satellite-based forecasts typically perform more accurately than NWP-based forecasting models up to six hours ahead, mostly because of ingestion, data assimilation and latency of calculations required to "spin up" NWP-based forecasts.

For time horizons below 30 minutes, total sky imaging is the preferred method. It consists of four steps:
1. Acquisition of the sky image from a ground-based, wide angle camera;
2. Analysis of the sky image to identify clouds;
3. Estimation of cloud motion vectors;
4. Prediction of future cloud cover and ground irradiance.

The maximum accuracy with this method is generally obtained between five and 20 minutes with low-cost and non-sun-sensing clouds; it can be reduced to three minutes for high and sun-sensing clouds and can be extended to 30 minutes. The state-of-the-art accuracy for all these physical forecasting methods is summarised in Figure 2.

Models for computing PV power from irradiance and environmental parameters also carry their own uncertainty, which compounds the error on forecasted irradiance. In a review of major modelling tools, the hourly root-mean-square error (RMSE) on AC power output was found to be below 6% in all situations [19]. To avoid this amplification of errors and to deal with time horizons between 30 minutes and two hours where there is no satisfactory physical forecasting technique for irradiance, stochastic learning techniques are used. These methods can be separated between:

Univariate methods: methods where only time series of the target variable (here, PV power) are fed into the model. These include:
- Persistence (P = Yt-1);
- STL: season decomposition by Loess;
- Holt-Winters seasonal method;
- TSPL: linear model fit with time series components;
- ARIMA: autoregressive integrated moving average;
- STARS: exponential smoothing state-space model with Box-Cox transformation, ARIMA errors, Trend and Seasonal components;
- Nnset: Feed-forward neural networks with a single hidden layer and lagged inputs for forecasting univariate time series.

- Single site
- PV distribution grid
- Transmission system
<table>
<thead>
<tr>
<th>Time horizon</th>
<th>Single site (5 m - 100 m)</th>
<th>PV plant owners</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 min</td>
<td>Management of storage system</td>
<td>Management of active/reactive power</td>
</tr>
<tr>
<td></td>
<td>Storage and load management</td>
<td>Activation of reserves</td>
</tr>
<tr>
<td></td>
<td>Day-ahead trades</td>
<td>Capacity adequacy</td>
</tr>
<tr>
<td>1 year</td>
<td>COM (contract)</td>
<td>Operation optimization</td>
</tr>
<tr>
<td>20+ years</td>
<td>Investment case</td>
<td>Infrastructure planning</td>
</tr>
</tbody>
</table>

Table 2: Summary of use cases for PV power forecasting

<table>
<thead>
<tr>
<th>Metric</th>
<th>Formula</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean bias error</td>
<td>$MBE = \frac{1}{N} \sum_{i=1}^{N} (Y_{i, forecast} - Y_{i, realised})$</td>
<td>Investment decision</td>
</tr>
<tr>
<td>Mean absolute error</td>
<td>$MAE = \frac{1}{N} \sum_{i=1}^{N}</td>
<td>Y_{i, forecast} - Y_{i, realised}</td>
</tr>
<tr>
<td>Root mean square error</td>
<td>$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (Y_{i, forecast} - Y_{i, realised})^2}$</td>
<td>Optimisation of generation reserves</td>
</tr>
</tbody>
</table>

Table 3: Main performance metrics used to assess forecasting methods

Figure 2: Error obtained with state-of-the-art physical forecasting methods for irradiance.
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