Impact of PV forecasting errors
Introduction

- 4% of UK’s power from PV
- System integration costs are a significant issue for renewable energy generation
- Examine the integration costs of PV systems
  - What is the financial (system) cost of forecast errors?
  - Impact of location & PV penetration
  - Optimal distribution of solar PV fleet
System Integration Costs

Shape Losses

- The change in value of the generation electricity generated based on the shape of the generation profile relative to baseload (constant) generation
- I.e. Generation-weighted price / average price

\[ \text{Value Factor} = 1 - \text{Shape losses} = \frac{s_a \cdot p_f}{s_a \cdot p_f} \]

Forecast Losses

- Generators must **forecast** generation
- Lowest risk strategy is to sell forecast power day-ahead
- **Errors** in forecast must be purchased in the real-time market

\[ I = s_f \cdot p_f + (s_a - s_f) \cdot p_{rt} \]
\[ = s_a p_f + s_f p_f - s_a p_f + (s_a - s_f) p_{rt} \]
\[ = s_a p_f + (s_f - s_a)(p_f - p_{rt}) \]
\[ = s_a p_f + \Delta s \Delta p \]

\[ \Delta s = (s_f - s_a) \] is the error in the forecast of solar energy generation,
\[ \Delta p = (p_f - p_{rt}) \] is how far the real-time settlement price differed from the market expectation a day ahead.
Method

- Used generation data from:
  - Over 20,000 PV systems
  - Distributed over GB
  - 2015-2022

- Created day ahead forecasts using NWPs & ML model (xg_boost) of hourly generation for each system

- Combined with prices from Nordpool & balancing market
Observe much greater forecast losses in centre of country
- Up to 5% of revenues
- Current loss is £24.7m p.a.
  - By 2035 - with PV targets, this will be ~£125M p.a.
- Can we understand this better?
Components of Forecast Impacts

Forecast impact can be rearranged:

\[
E[Forecast\, Impact] = E[\Delta s \Delta p] 
\approx \text{Cov}(\Delta s, \Delta p) 
= \rho \sigma \Delta p \sigma \Delta s 
\]

\[
\frac{\bar{\Delta s}}{\sigma \Delta s} = -0.006 \quad \text{&} \quad \frac{\bar{\Delta p}}{\sigma \Delta p} = 0.02 
\]

Unbiased forecast

Unbiased markets

Standard deviation of PV site forecast error (RMSE)

Correlation between the site’s forecast error and the price difference

Standard deviation of price difference between day ahead and real-time
Direct observable correlation

\[ \sigma_{\Delta s} \]

Standard deviation of PV site forecast error (RMSE)

\[ \rho \]

Correlation between the site’s forecast error and the price difference

\[ \sigma_{\Delta p} \]

Standard deviation of price difference between day ahead and real-time
Create National Forecast Error

Site level forecast error, $\Delta_s$

$\sigma_{\Delta s}$

Properties of system & sites together

National forecast error, $\Delta S$

$c_{\Delta s\Delta S}$

$\sigma_{\Delta S}$

Properties of the market

Price deviation, $\Delta p$

$c_{\Delta S\Delta p}$

$\sigma_{\Delta p}$

Site-level property: error (RMSE)
Components

Forecast Impact (%)

Standard deviation of site-level Errors

Correlation of site-level errors with national error

Correlation of National error with Price difference:

$\Delta S \Delta p = -13.5\%$
How do shape losses compare?

\[ \text{Value Factor} = 1 - \text{Shape losses} = \frac{\overline{s^a P^f}}{\overline{s^a P f}} \]

- Driven by the correlation of **outturns**
- Site-level correlations of actual generation are geographically flat
- Correlation is nationally high & even
Optimising PV Fleet

- We can take advantage of the lack of correlation of forecast errors across regions
- National forecast error (sigma) can be minimised
- Minimise weights across covariance of forecast errors

\[ \sigma^2_{\Delta S} = C \text{Cov}(S) C^T \]
Optimal Fleet - Reduces Costs by 25%

Current fleet
Sigma = 3.6%

Optimal fleet
Sigma = 2.8%

Worst fleet
(E.g. small island)
Sigma = 7.6%
Losses as PV penetration increases

- Examine correlation for hours where PV makes up a greater share of the energy mix
- Quartiles: PV as % of generation

<table>
<thead>
<tr>
<th>Quartile</th>
<th>Price - Error Correlation</th>
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<tbody>
<tr>
<td>1st</td>
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Further Work

- Consider forecast errors in other markets
- Wind and interconnection impacts
- Further understand impact of PV penetration
Thank You!

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