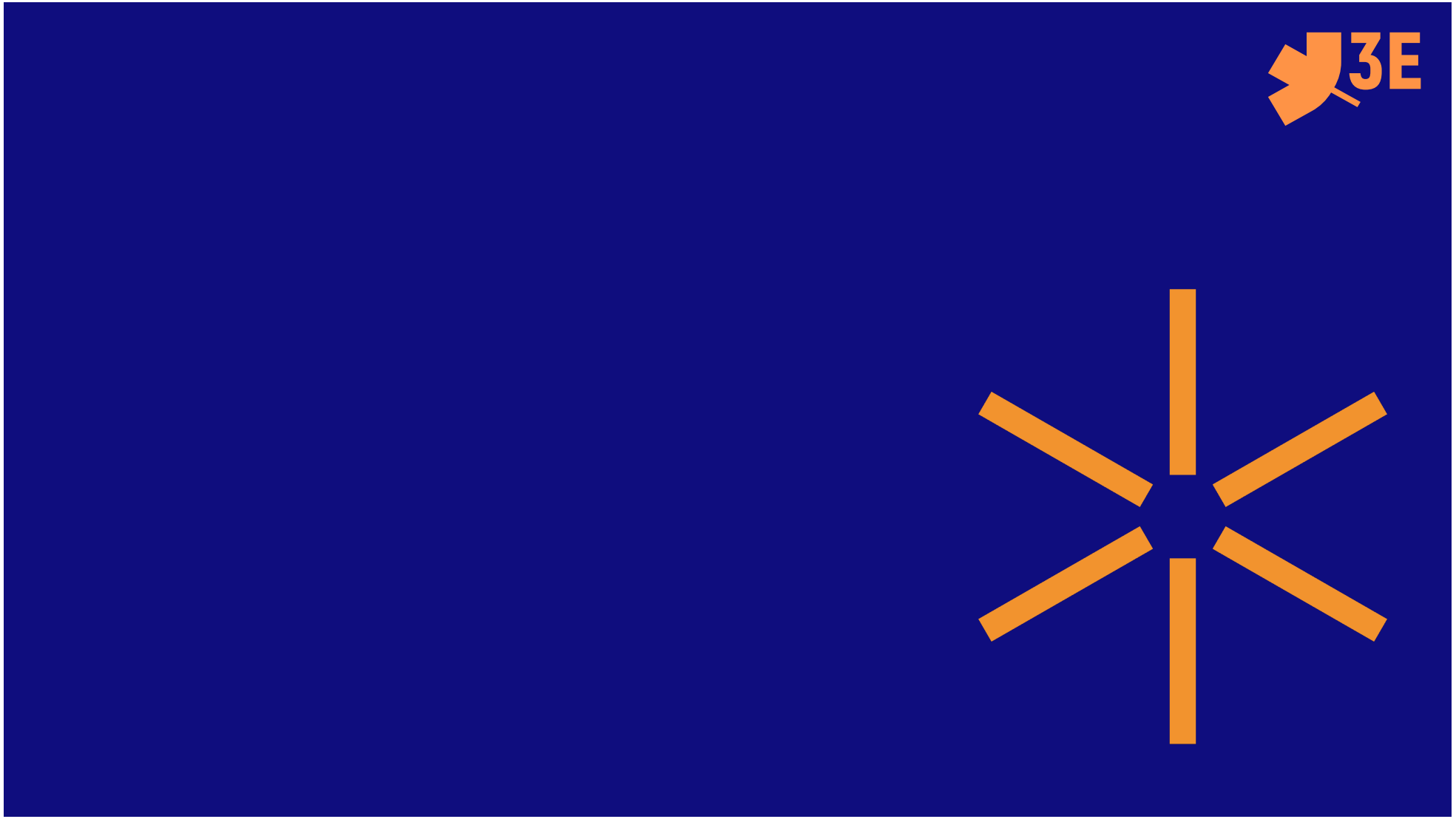
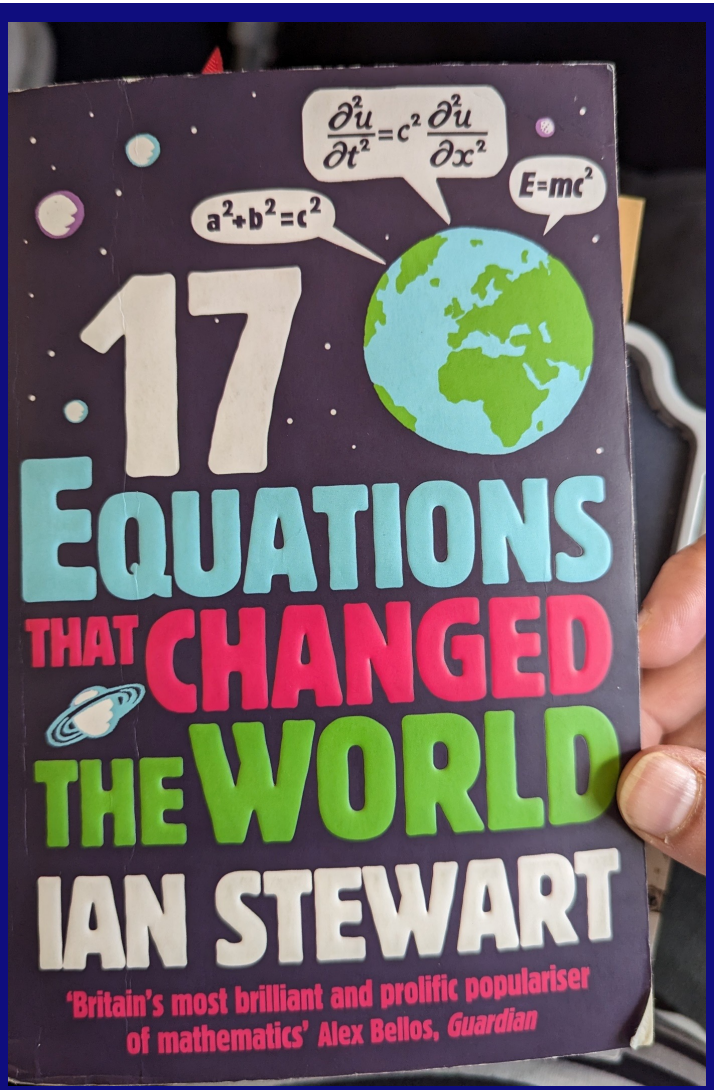

3E


$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$
$E=mc^2$
$a^2+b^2=c^2$
17
EQUATIONS
THAT CHANGED
THE WORLD
IAN STEWART
'Britain's most brilliant and prolific populariser of mathematics' Alex Bellos, Guardian

Curtailment !

Reliable and Actionable Performance Metrics for Heavily Curtailed Plants

PV Performance Modeling Collaborative Workshop

Albuquerque, NM

Dr. Gofran Chowdhury

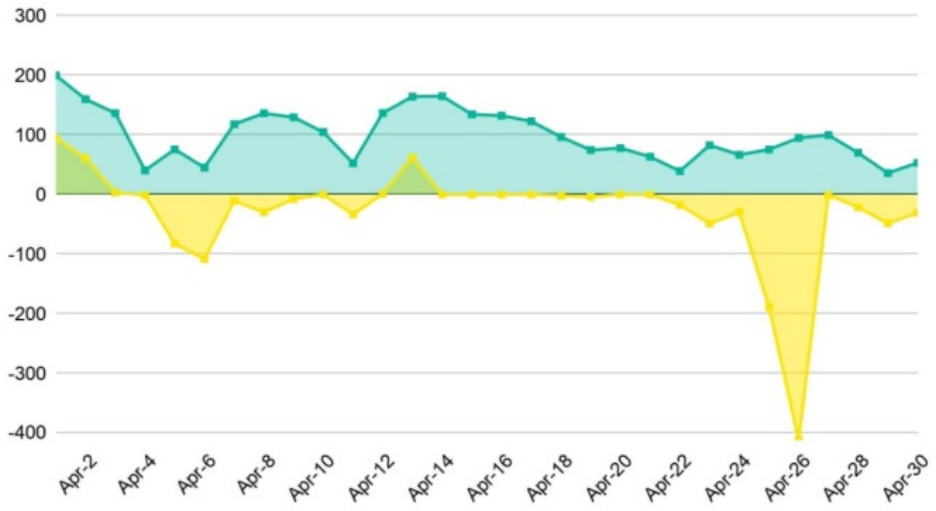
2026-05-13

Negative electricity prices in France hit a new record

Negative electricity prices are making a strong comeback in the French energy market. Driven by rising photovoltaic output and reduced nuclear flexibility, they dominated much of April, often falling close to the regulatory floor.

MAY 7, 2026 GWÉNAËLLE DEBOUTTE

HIGHLIGHTS MARKETS UTILITY SCALE PV FRANCE



April 2026 Statistics: average price (€40/MWh); average daily maximum price (€111/MWh); average daily minimum price (-€33/MWh); and average spread (€143/MWh).

e: Strommarkt-App

Negative power prices high on the Iberian Pe

Spain and Portugal recorded a surge in negativ strong solar generation and relatively low dem records are likely in 2026 as solar capacity grov expected across Europe.

APRIL 20, 2026 PILAR SÁNCHEZ MOLINA

GRIDS & INTEGRATION MARKETS UTILITY SCALE PV EUROPE

An Enel Green Power PV plant in Spain

Image: Enel Green Power.

Curtailment, nega small- and mediu owners toward ba

Continuous negative and zero wholes inadequate energy storage policy are exposed, despite abundant solar reso

MAY 7, 2026 ILIAS TSAGAS

ENERGY STORAGE HIGHLIGHTS MARKETS UTILIT

Image: pv magazine/AI generated

Negative electricity prices in France, G

AleaSoft Energy Fo returned to the Fre Nordic markets reg Belgian market saw

APRIL 9, 2026 PATRI

MARKETS EUROPE FRA

European ele

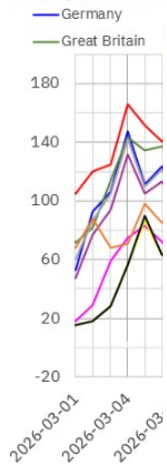


Image: AleaSoft Energ

Negative prices on the rise

Europe faces a lot of negative prices, and thus a lot of curtailment

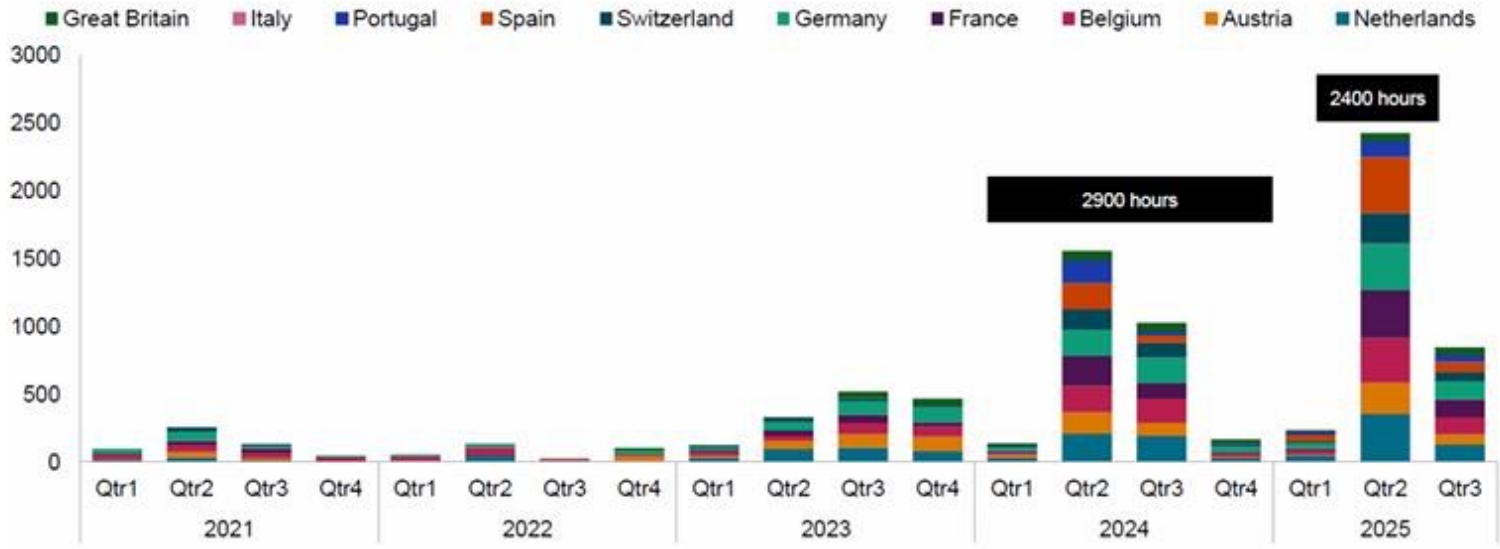


Figure 1. Negative prices in Europe & Great Britain, 2021-2025 (Source: S&P Global Community Insights Solarplaza Solar Asset Management Europe conference)

PV KPIs and curtailment

IEC61724-3 Photovoltaic system performance – Part 3: Energy evaluation method

The measured energy (6.7) and expected energy (6.6) are compared:

$$\text{Energy performance index} = \text{Measured} / \text{Expected} \quad (1)$$

$$\text{Energy performance index with units of \%} = (\text{Measured} / \text{Expected}) \times 100\ \% \quad (2)$$

6.5.11 Curtailment because of external requirement

In the case of curtailment because of external requirement limiting the uptake of grid that was accounted for by the original model, then the model should correct for this accurately. The expected energy should be calculated in the same way. If curtailment is inconsistently implemented or the algorithm is modified in any way during the test, this shall be documented in the test report.

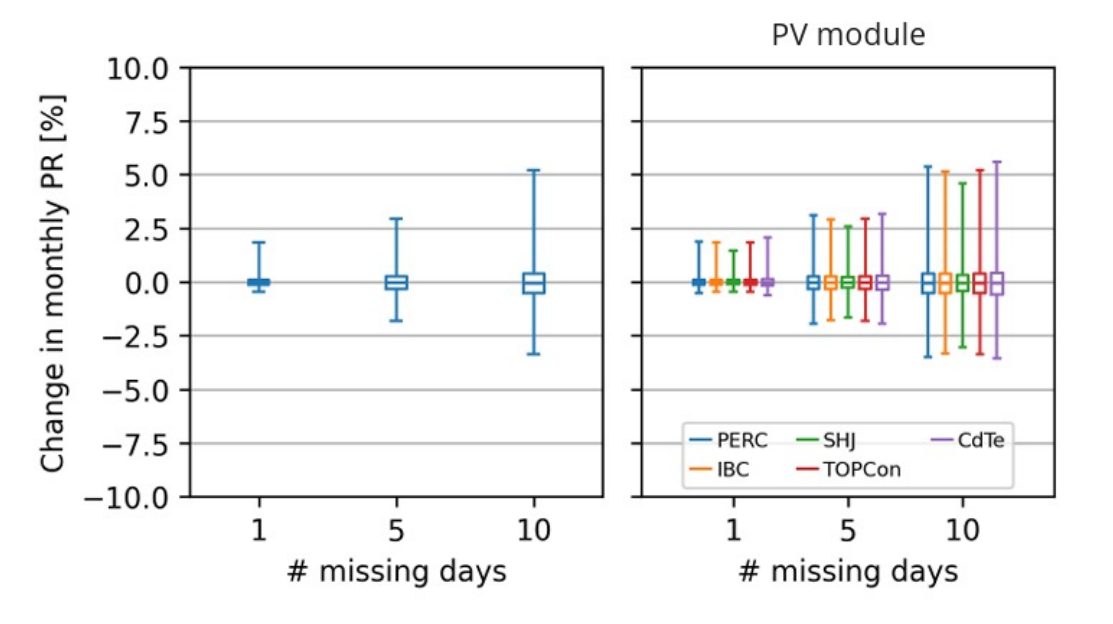
If the external requirement for limiting the uptake of the grid differs from the original model (either requiring no connection to the grid or an input to the grid that is less than what was originally modeled), the difference between the two external requirements shall be documented as a time of unavailability if the new external requirement is reduced.

In general, unavailability caused by unplanned curtailment is considered to be an external cause of unavailability.

The external-cause-excluded energy availability is calculated excluding the expected energy during times of unavailability that were caused by circumstances outside of the control of the plant.

Is excluding the best option?

We know KPIs are affected by missing days – is the same true for missing hours?



Source: Kevin Anderson, O&M KPIs: Uncertainty Due to Data Loss and Operational Issues, PVPMC workshop 2025

Why is this important?

An unstable KPI is not actionable!

Test plant: hybrid solar-wind with limited grid capacity

Wind is king, solar gets curtailed

Anna Maria Polder

Solar: 27MWp – 20,4MVA

Wind: 14MVA

Grid: 19,4MVA

Kabeljauwbeek

Solar: 24MWp – 19MVA

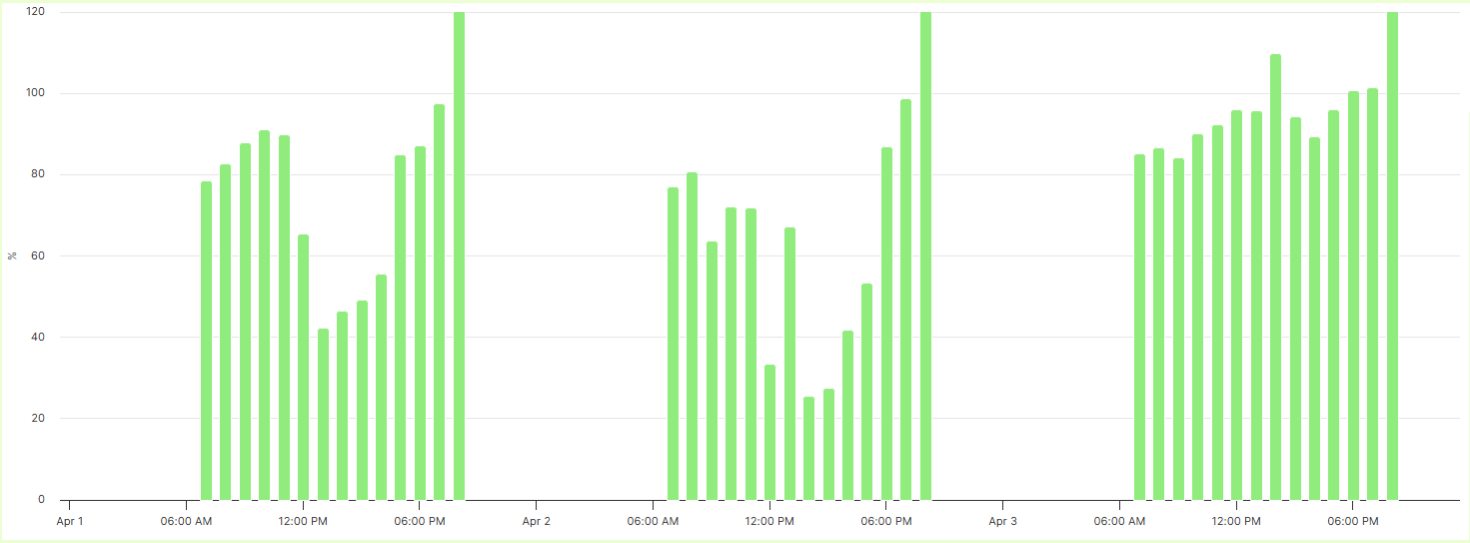
Wind: 18MVA

Grid: 16,8MVA

Eneco

Keeping EPI as is

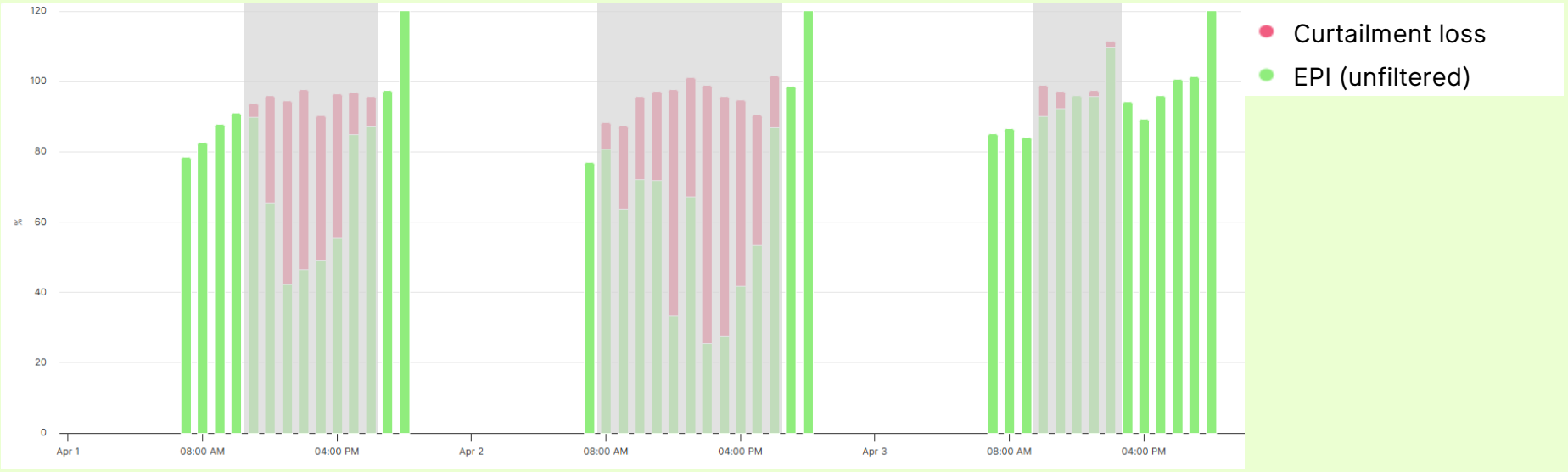
Not taking into account for curtailment



Is excluding the best option?

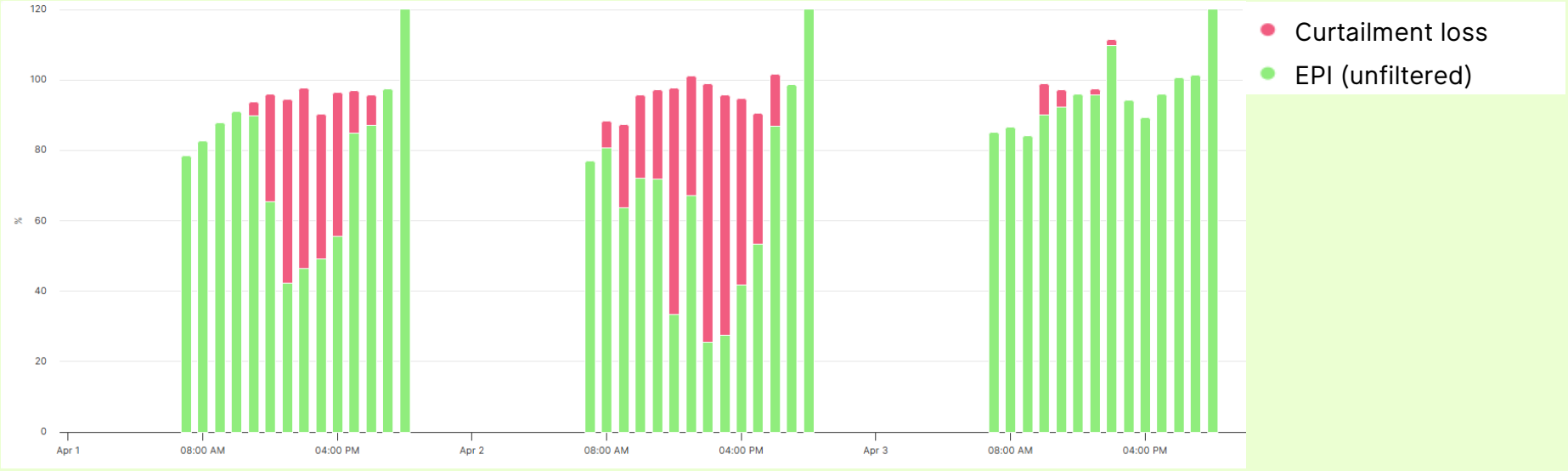
Qualitative assessment: filtering curtailed hours will likely lead to lower EPI

Curtailment often occurs during noon. EPI is not stable during the day, for instance due to shading, so filtering out noon affects EPI.



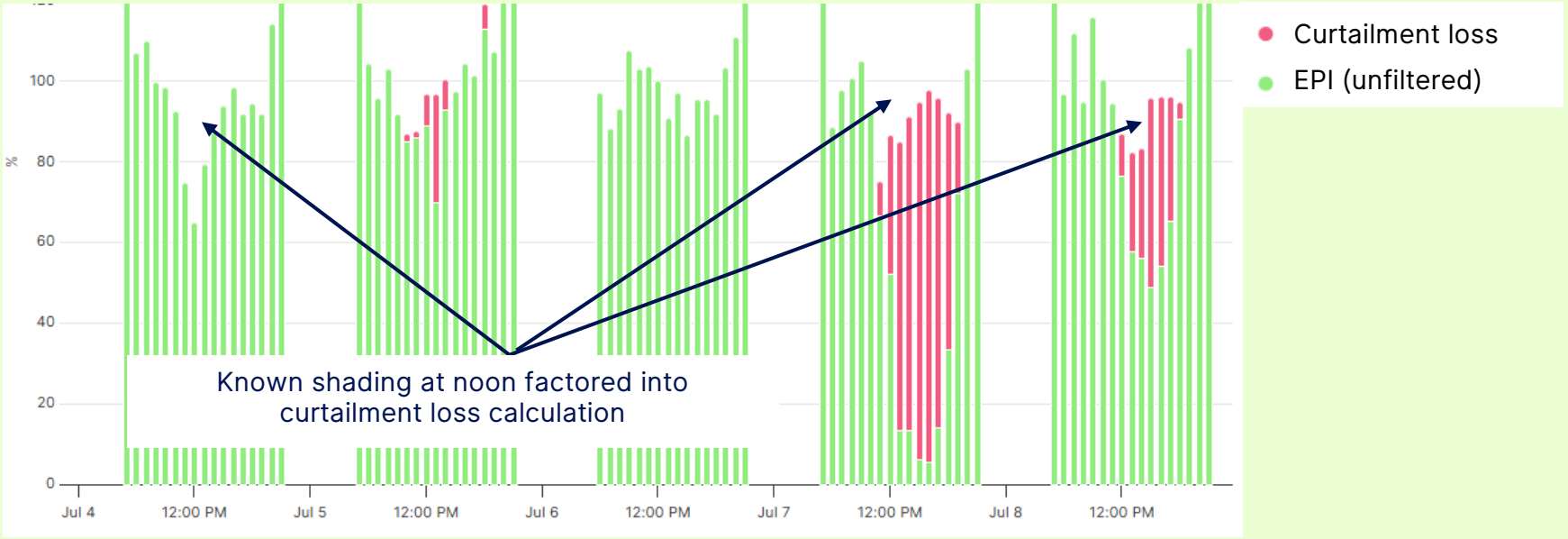
What's the alternative?

Introducing EPI Uncurtailed: EPI + Curtailment loss



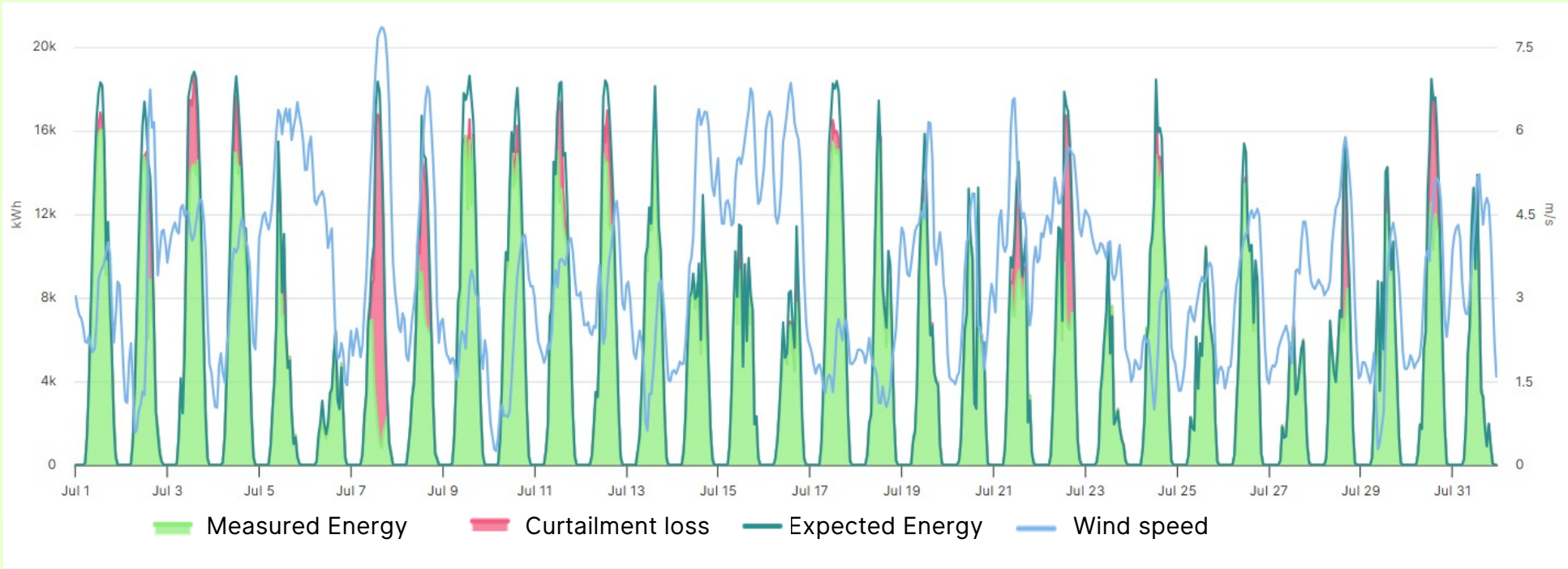
Example inverter

Heavily shaded inverter shows how known loss is taken into account



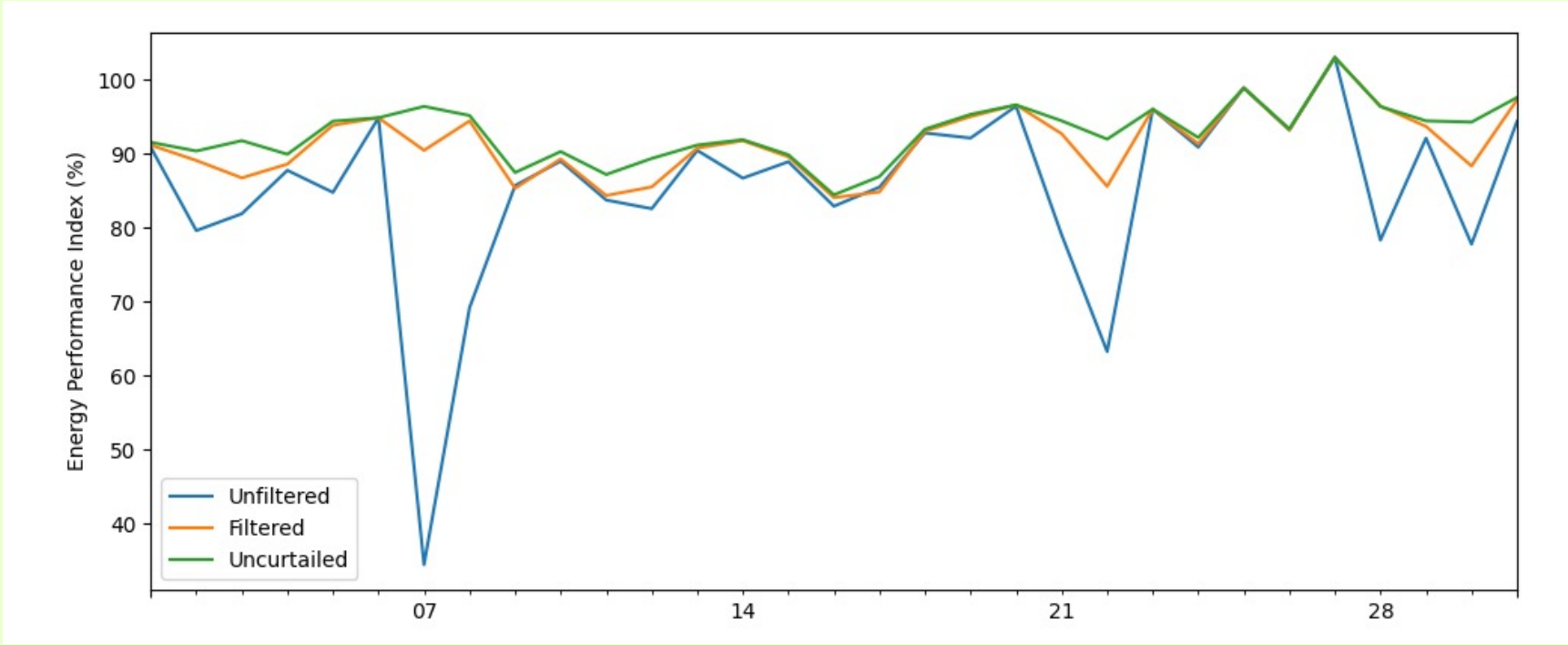
Example month

July 2025 saw curtailment almost every day



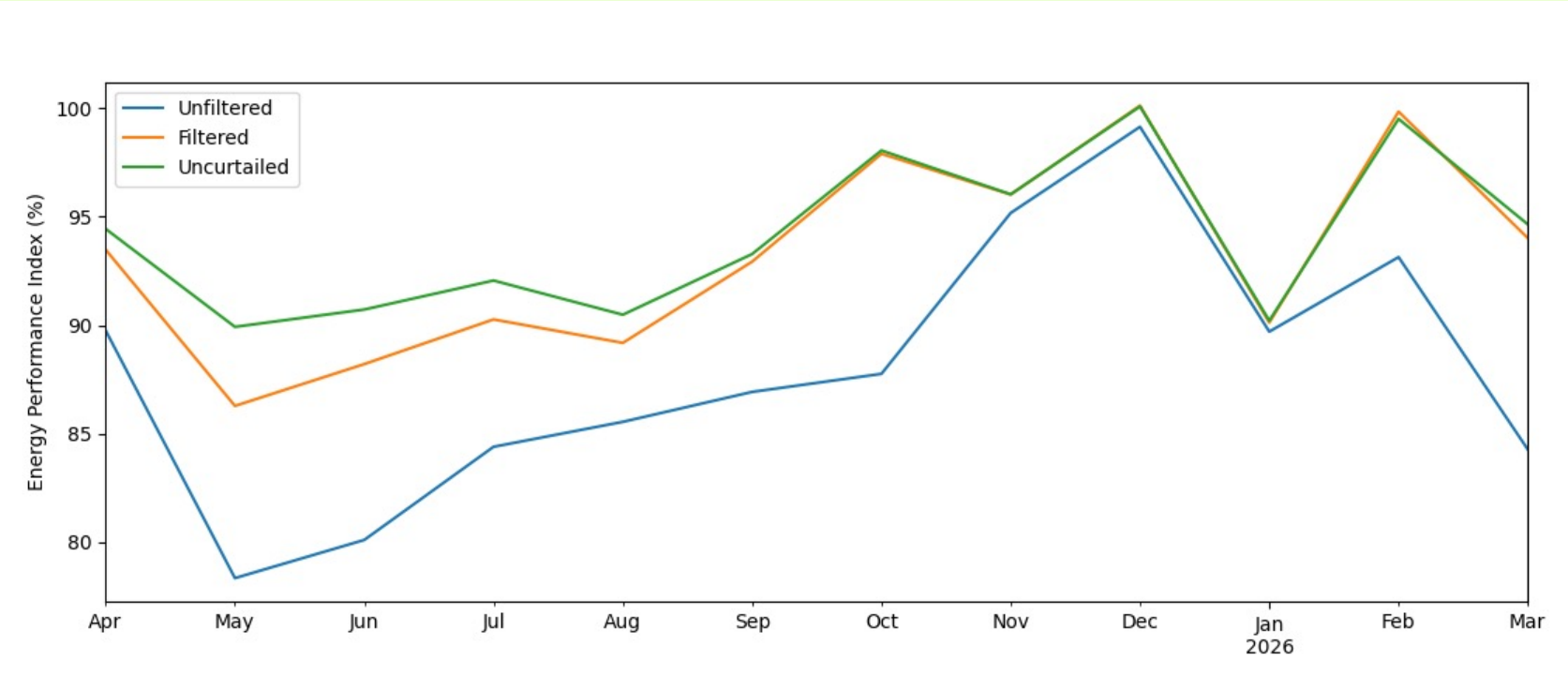
Results

July 2025 day to day: corrected KPIs are more stable



Results

Monthly EPI: difference of up to 5% between filtered and uncurtailed



Quantitative comparison

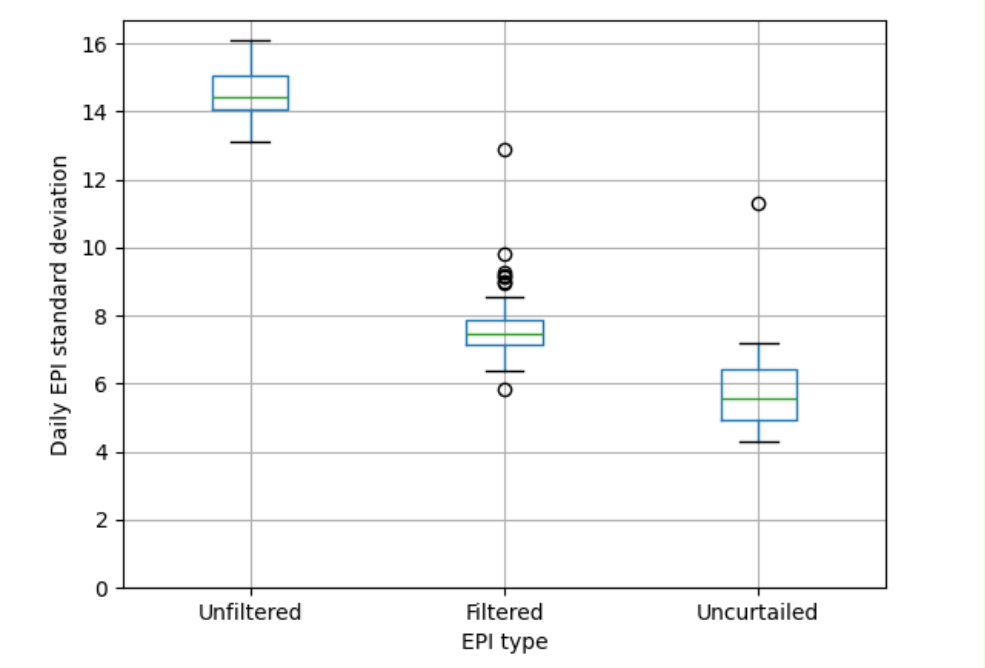
How to quantify the improvement of EPI Uncurtailed vs EPI Filtered?

The following metrics were calculated per inverter for period 2025-04-01 to 2026-03-31:

- Standard deviation per EPI type (28 day rolling window) – lower is better
  - Pro: gives a general view of the stability of the KPI
  - Con: stable is not always more correct. E.g. shading has effect only when the sun shines
- Correlation coefficient between EPI and relative curtailment loss – should be 0
  - Pro: addresses the downside of previous method: the EPI can have some variability, as long as it's not correlated to curtailment
  - Con: weak test - a random signal or a constant would also yield a correlation of 0

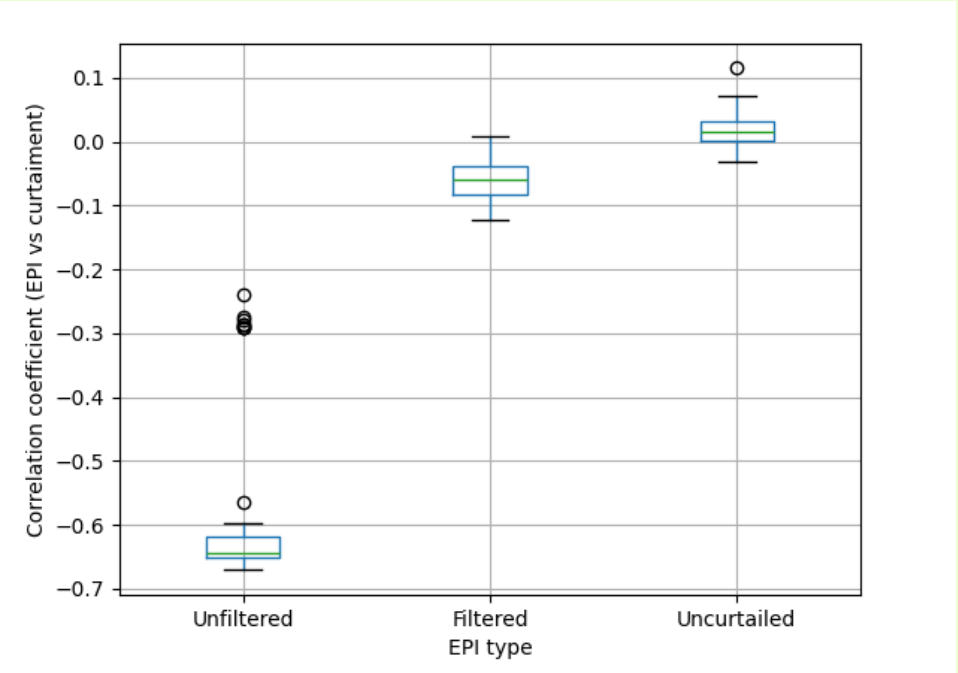
Results

Daily EPI standard deviation (28 days rolling window) across inverters



Results

Correlation coefficients between daily relative curtailment loss and EPI across inverters



Conclusions

- **Excluding** curtailed intervals can have a **significant impact** on the performance indicators
- **Correcting** the EPI for curtailed time intervals leads to **more stable** and thus **more actionable** KPIs
- The **EPI Uncurtailed** method introduces a **smaller bias**, but is **more complex** and requires an accurate estimate of persistent losses

Note: the data imputation method used for EPI Uncurtailed can be generalized to unavailability and data gaps

Thank you

Contact person

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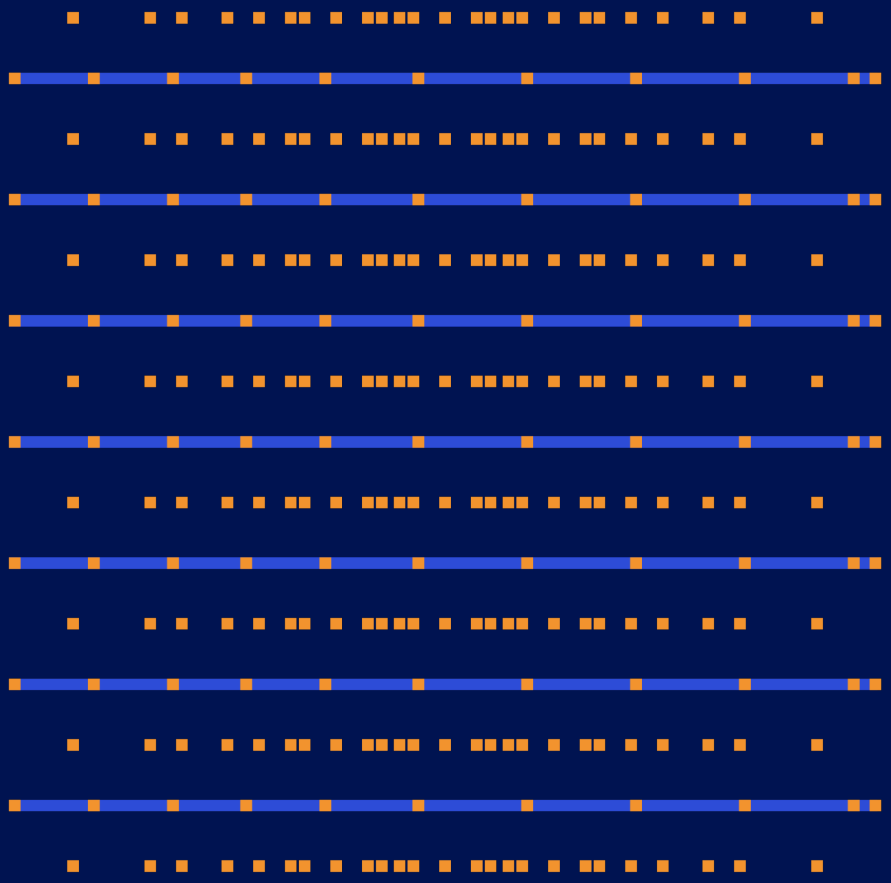
Phone number

+32 2 217 58 68



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