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Investigation of Persistent Sub-synchronous Oscillations in the Netherlands

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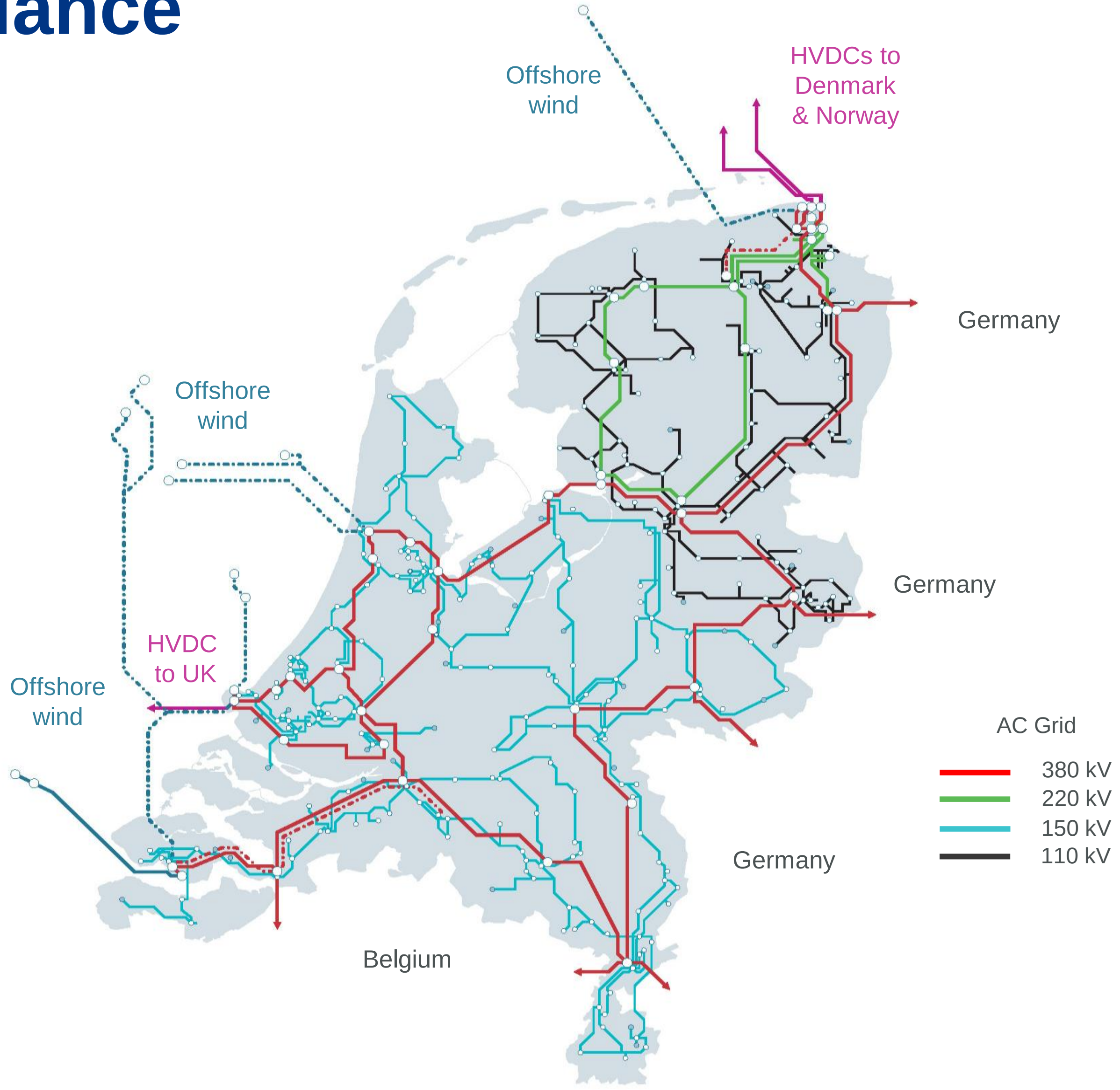
Agenda

1. Introduction to TenneT
2. Oscillations: What do we observe
3. Oscillations: Investigation
4. Current State & Open Questions

TenneT Netherlands at a glance

- Facts & figures*
  - Employees
    3,500+
  - Total grid length
    11,000+ km
  - Transformer substations
    350+
  - Number of end-users
    ~18 million
  - Grid availability:
    99.99988%
  - Peak load:
    ~21GW

Note: TenneT also owns and operates a part of the German HV grid, but today we focus on the Dutch transmission grid



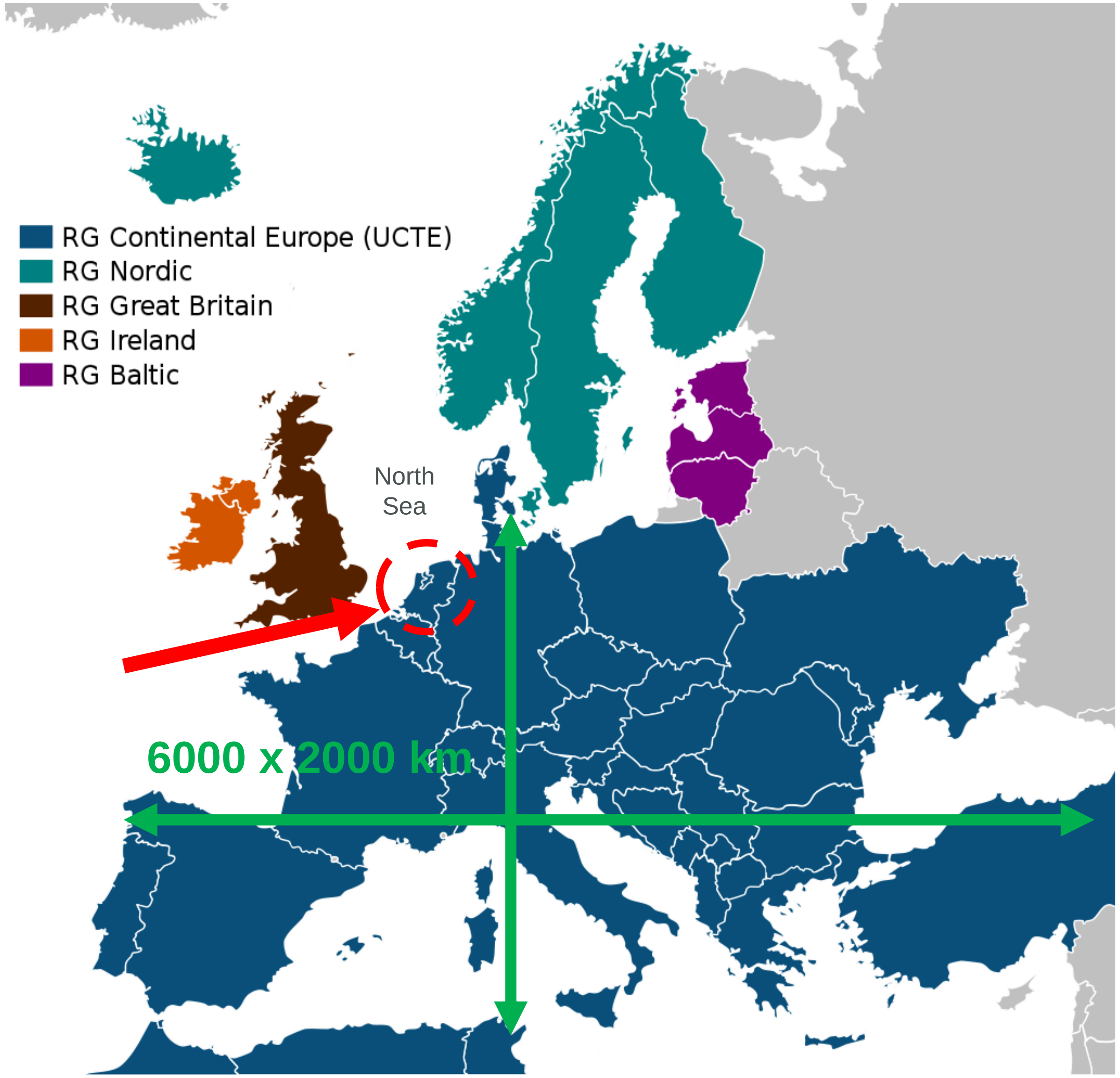
*Not all figures are fully up-to-date

The larger picture

- We are a part of a much larger Continental Europe Synchronous Area (CESA) grid
- CESA is expanding further - Ukraine and Baltics recently synchronized
- Many HVDC links to other areas, and more to be built in the future
- North sea will become a massive offshore power hub (Wind, H_2), with a large role for NL

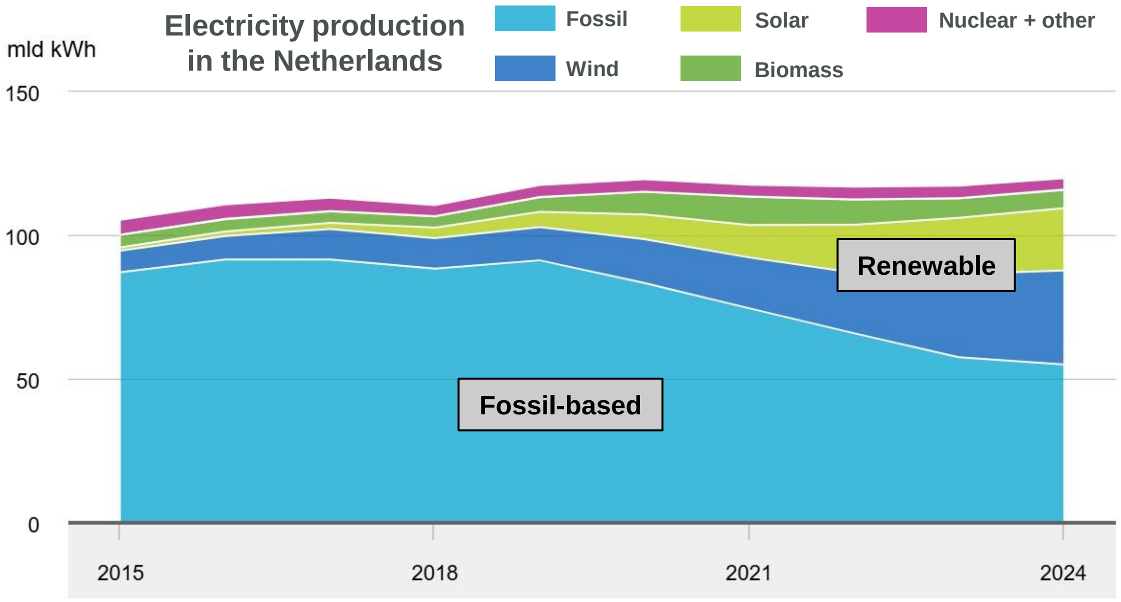
North Sea Wind Power Hub Programme

https://northseawindpowerhub.eu/



Energy Transition in the Netherlands

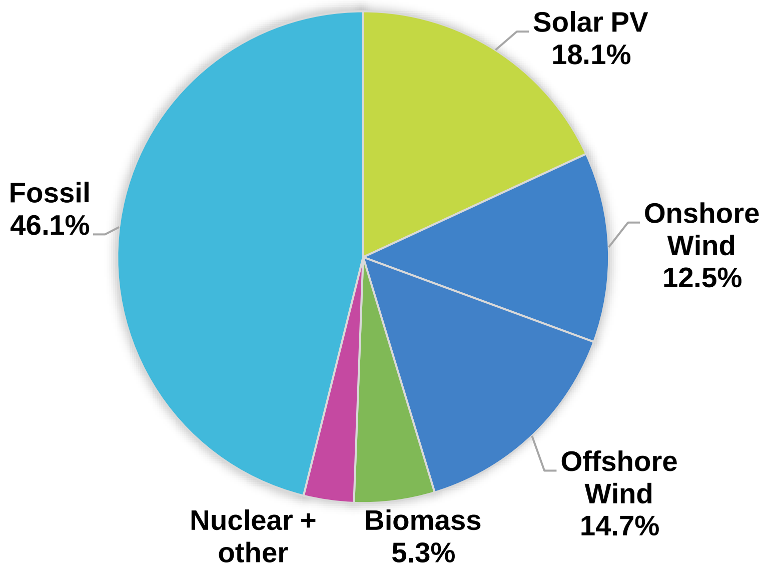
- 54% of electricity in the Netherlands (2024) was fossil-free. Aim: 70% renewable by 2030 (Klimaatakkoord)
- Many hours of grid operation are already >> 50% renewable (we see close to 100% more often!)
- The remaining 45% will be *much harder* to achieve, mainly due to *grid* bottlenecks (congestions, inertia & system strength, stability limits, P & Q reserves…)



Installed capacity	2025		2035
	24.4 GW	+100%	*>52 GW*
	6.7 GW	+20%	*> 8 GW*
	4.7 GW	+400%	*>25 GW*

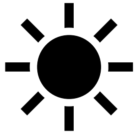
****conservative scenario***

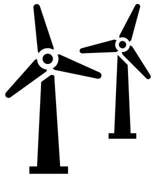
ELECTRICITY MIX 2024



Implications: Lower Inertia & System Strength

Huge infeed of renewables (IBRs),
pushing SyncGens out of the market

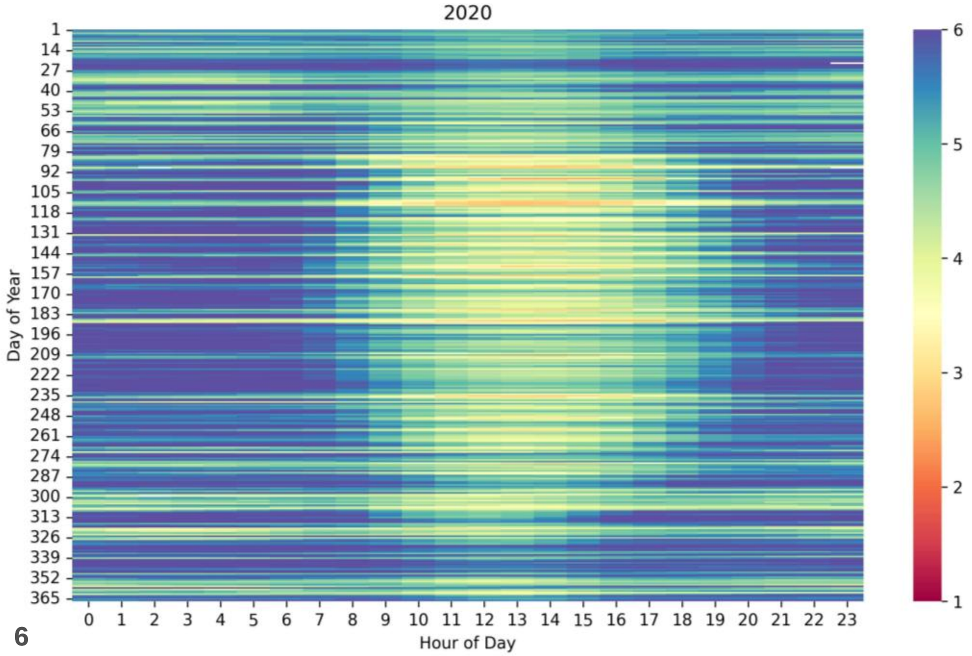




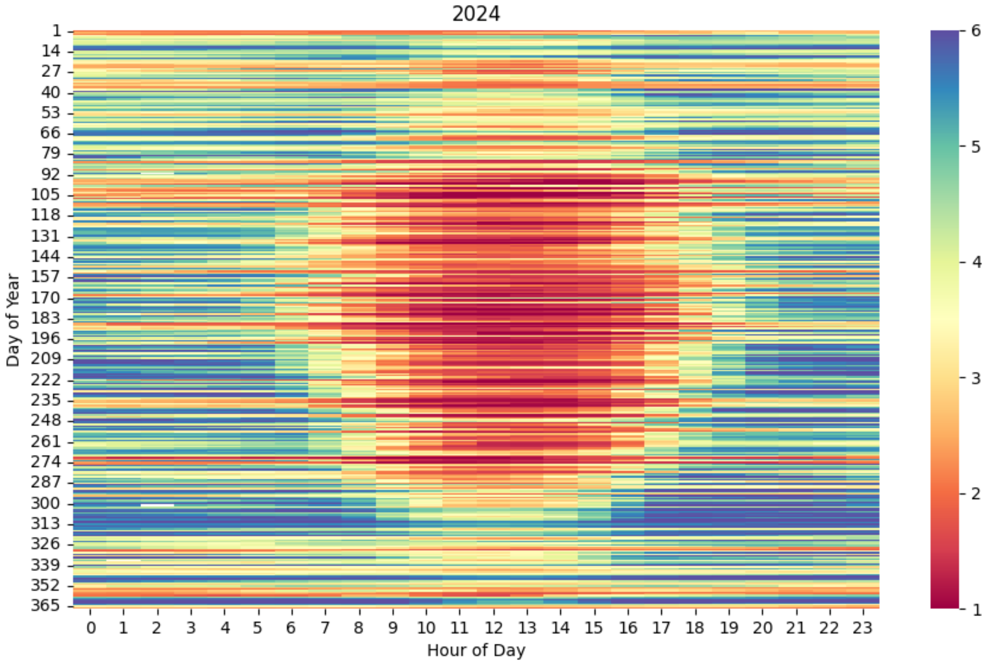
- Very low inertia
- Very low system strength

Grid stability challenges!

Example: System inertia constant (H [s]) 2020 vs 2024



Very large change
in only a few years!

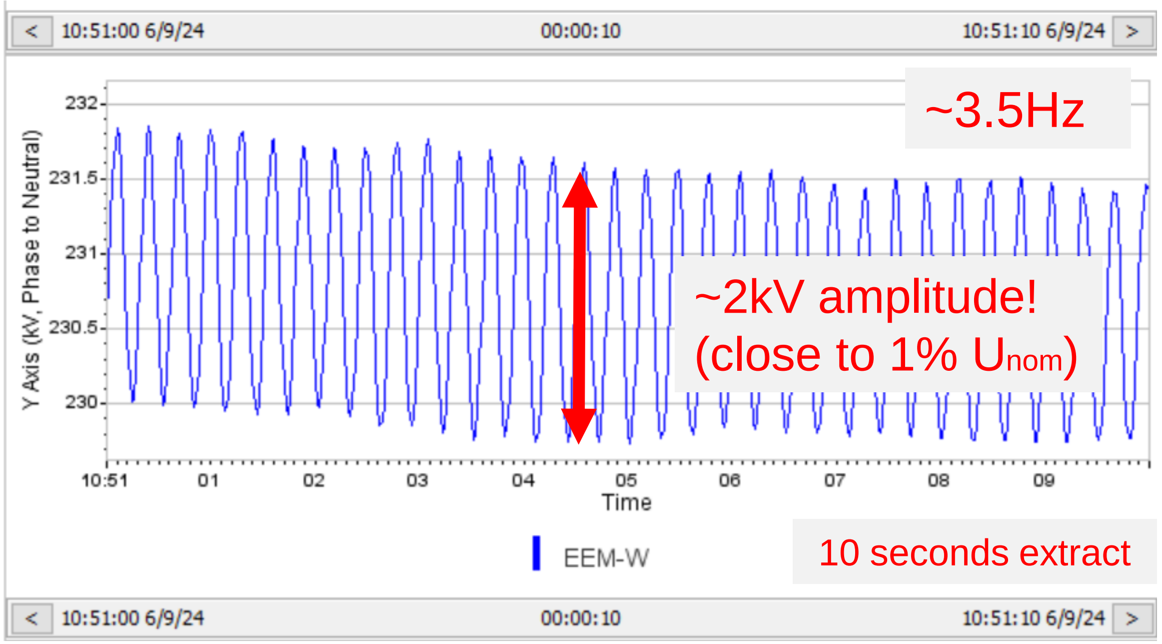


Oscillations: What do we see (data collection)

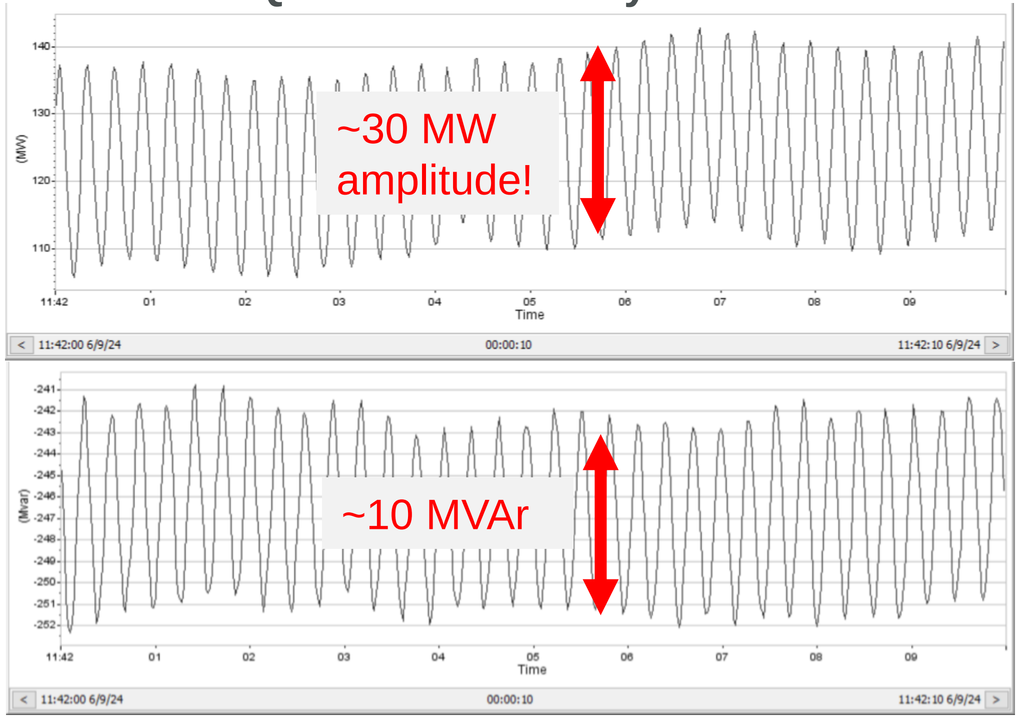
Sub-synchronous Oscillations in 2024

- We have been observing ~3.5Hz oscillations for a few months, strongest on sunny weekends
- They became more frequent and much stronger in the spring and summer of ‘24

Example (WAMS P-N voltage at 400KV)

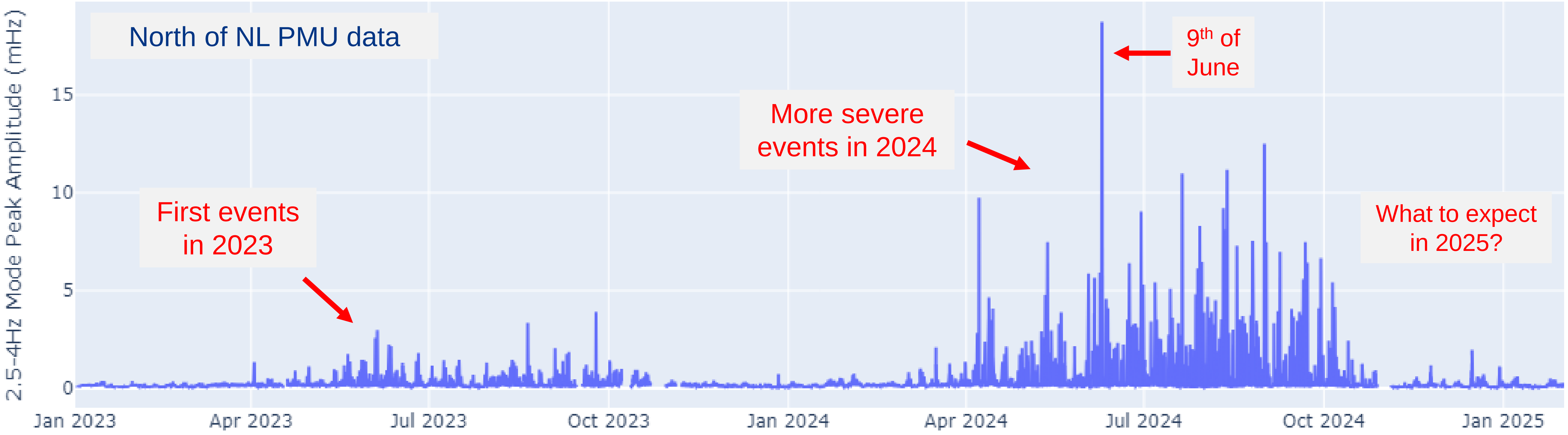


P & Q flows of a nearby corridor



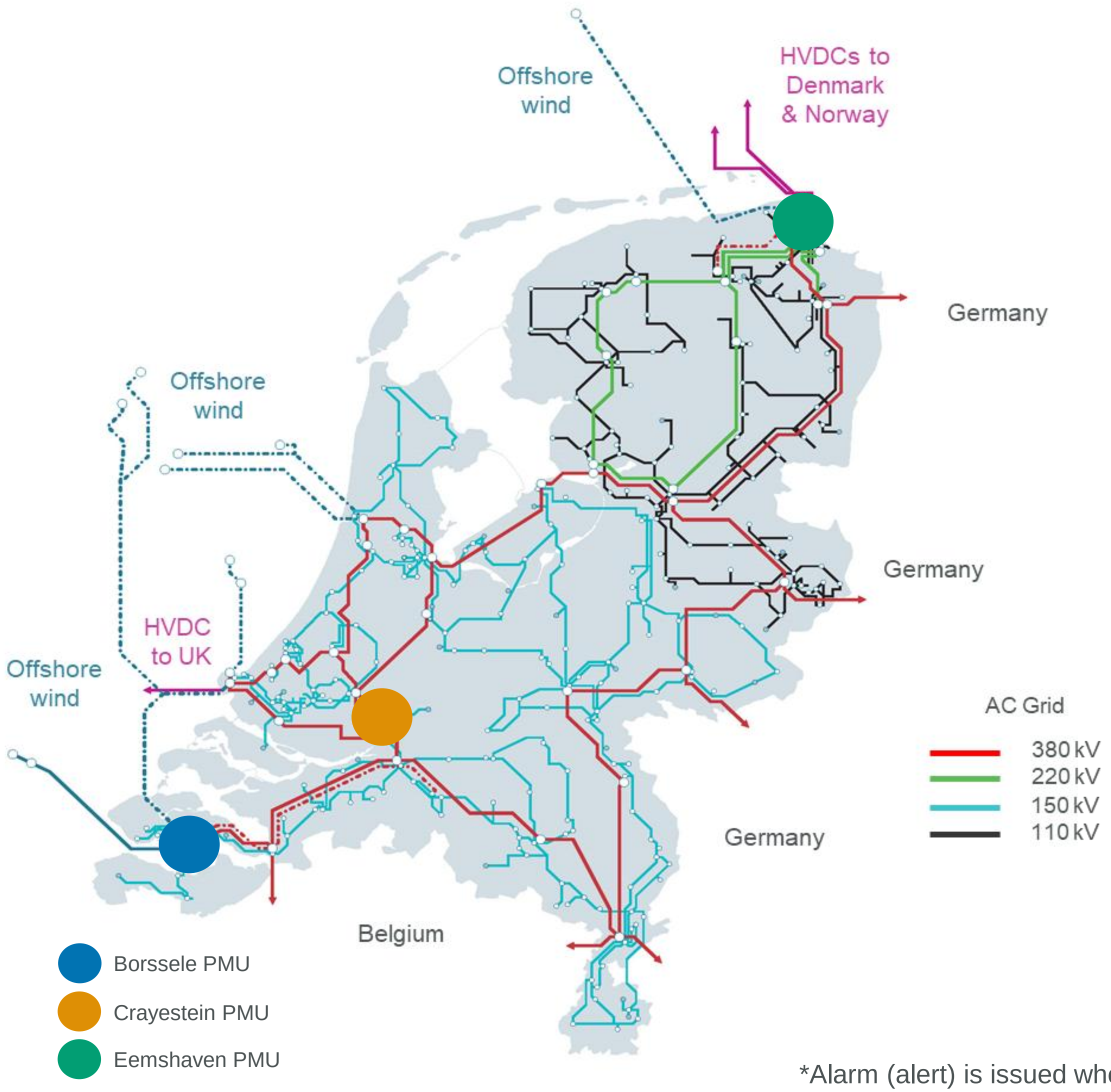
Sub-synchronous (~3.5Hz) oscillations in NL

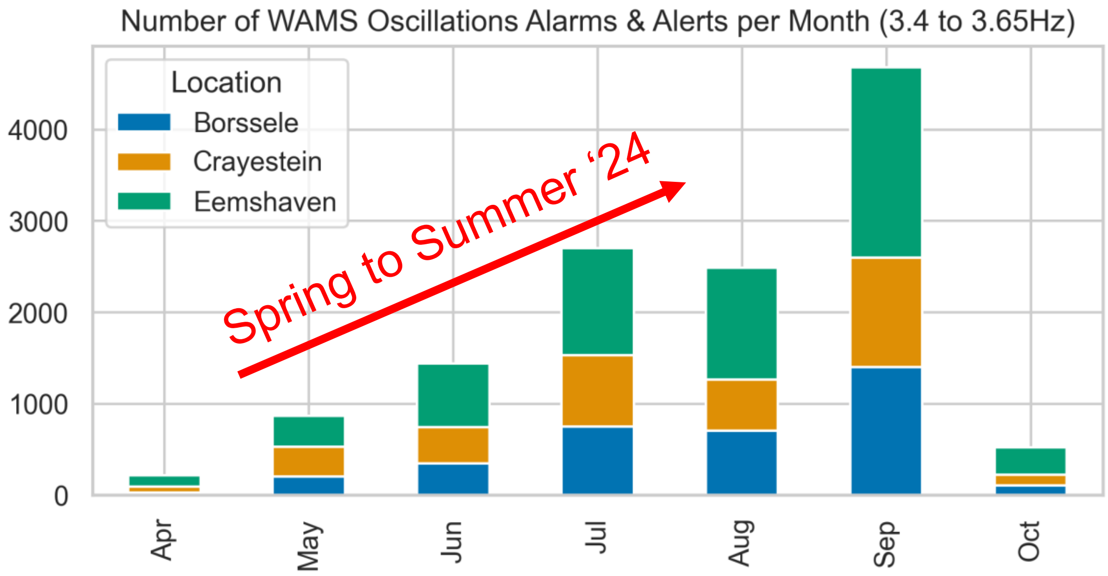
- First minor events detected in spring of 2023 already
- Events became more frequent and much stronger in the spring and summer of ’24
  - Sunny weekends were typically the most severe

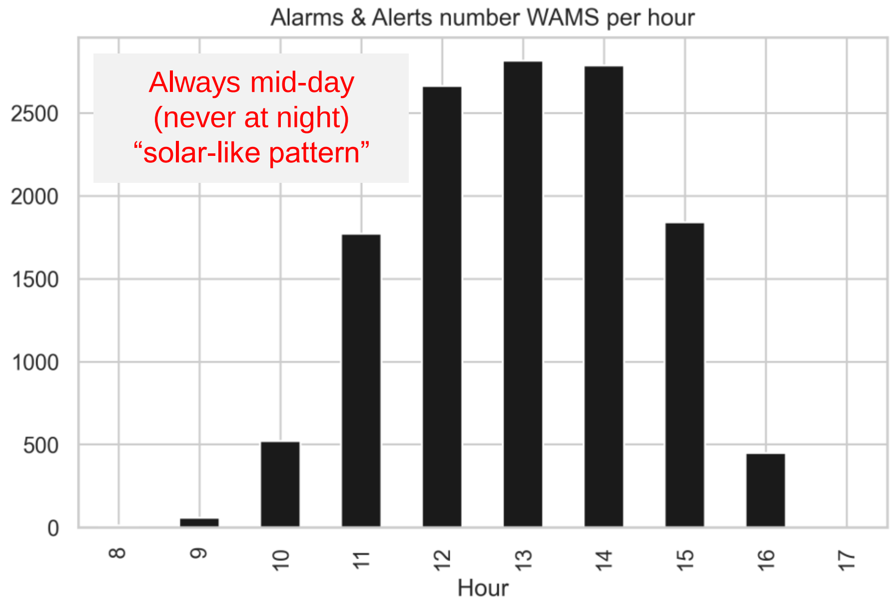


3.5Hz WAMS alarms/alerts

- Most frequent in the summer and mid-day



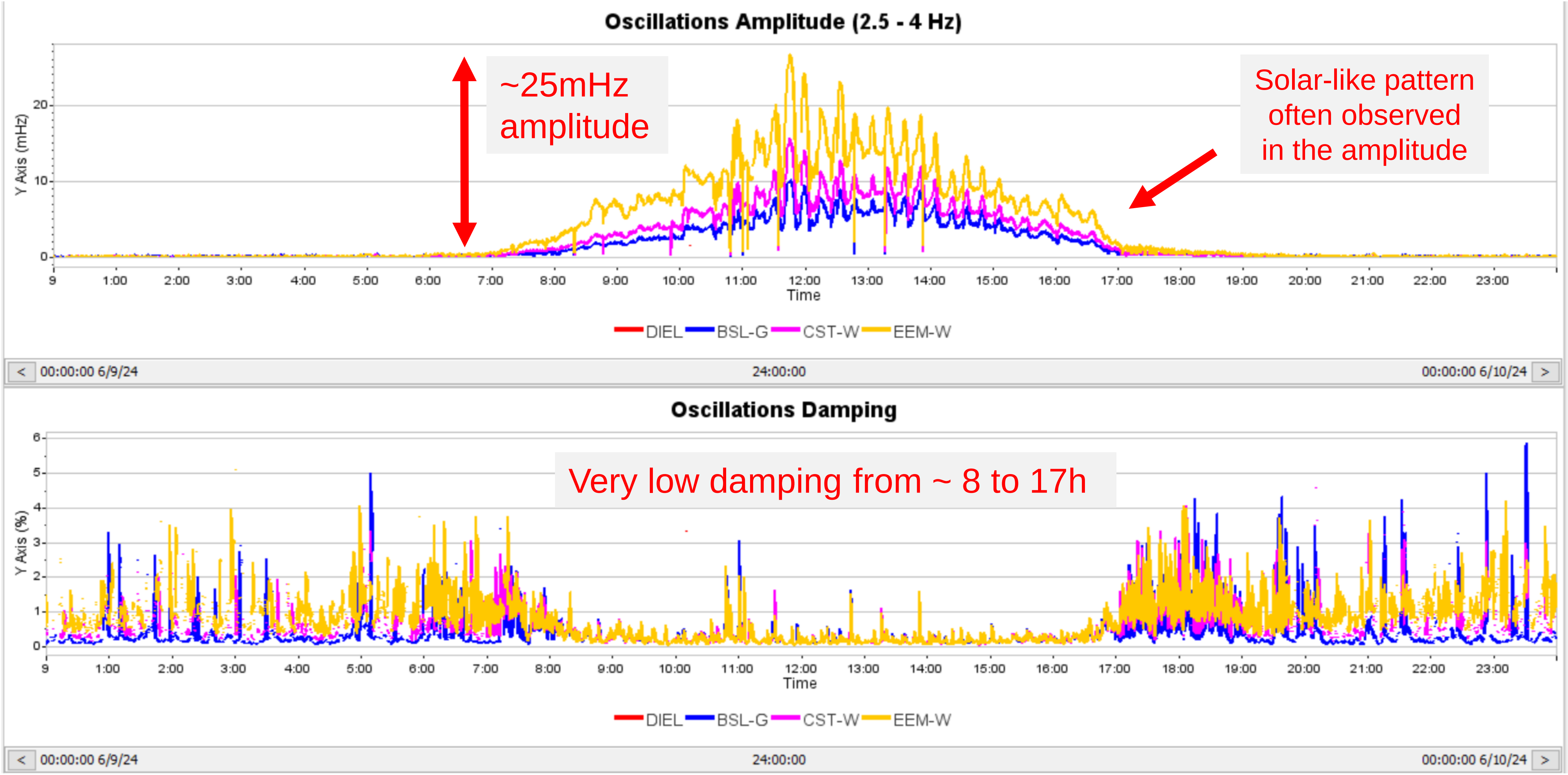




*Alarm (alert) is issued when oscillations breach the specified thresholds in amplitude and damping.

Example June 9

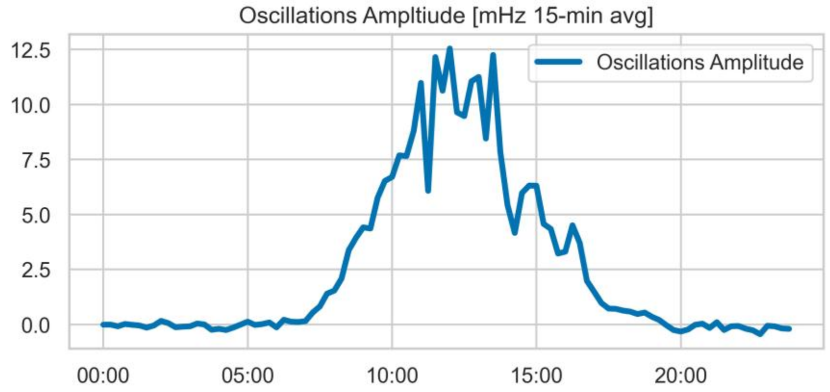
Frequency oscillations (~3.5Hz) captured by WAMS

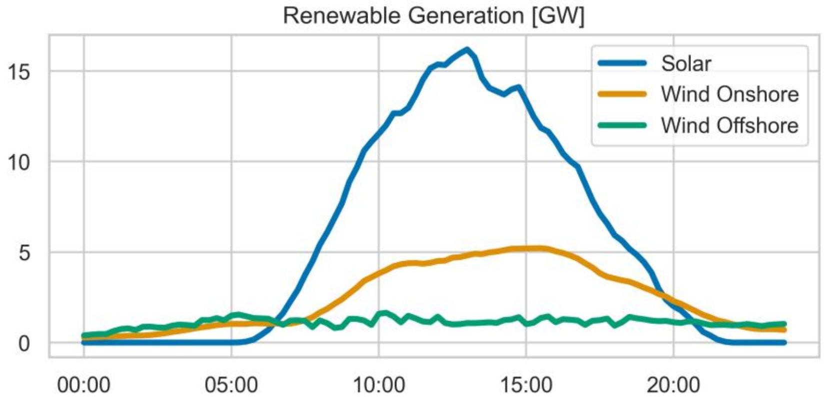


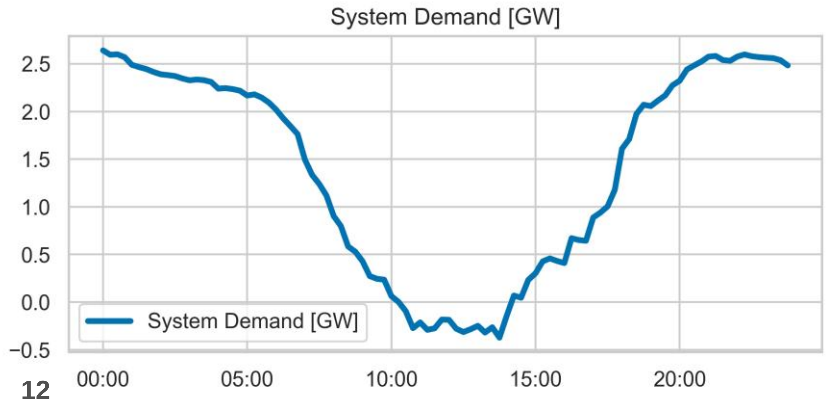
System conditions June 9 (Sunday)

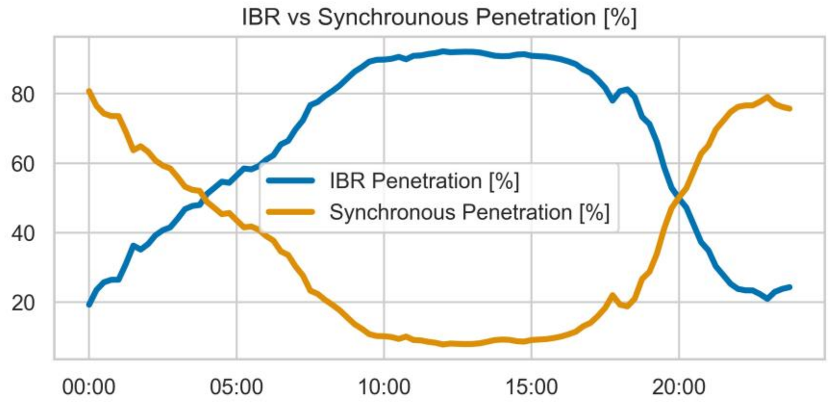
- Oscillations strongest mid-day, >20 GW of RES (conventional very low)
- IBR penetration (NL) **90%+** (high solar + on/off-shore wind)
- Negative net demand. Prices low/negative, high exports from NL

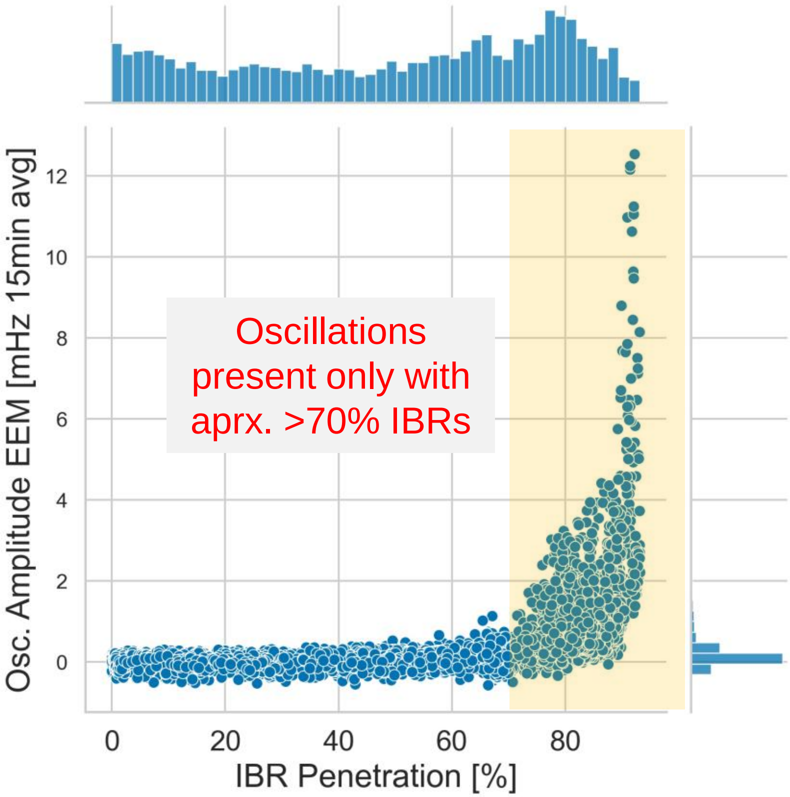
Large data analysis:
April to August ’24



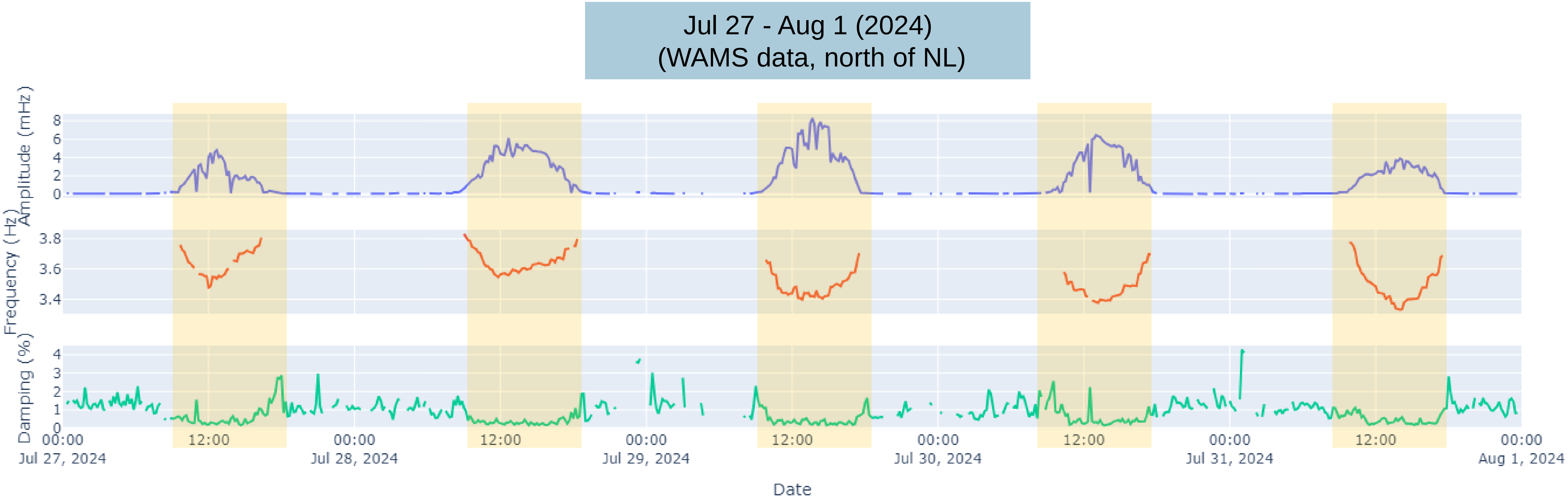








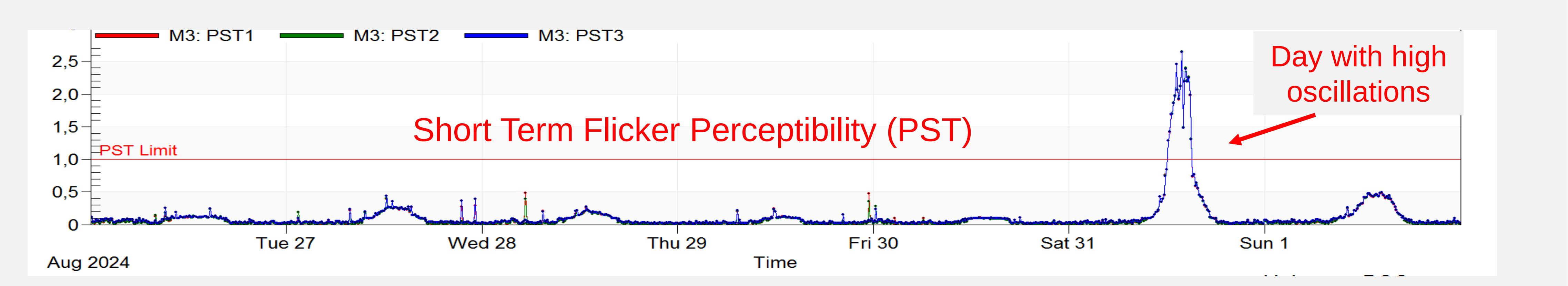
Oscillations magnitude, damping, and frequency behavior



- We observe changes in magnitude/damping and frequency of oscillations throughout the day
- Inverse relationship between magnitude and frequency → the reason is unclear so far

Oscillations impact on power quality

- Higher flickers are observed during oscillations (PQ meters data extract below)
  - ➢ Nuisance, but also risk of PQ/flickers regulations non-compliance



- Visible flickers due to 3.5Hz oscillations (for hours!)

(incandescent light bulb recording during oscillations)

Oscillations: Deeper investigation

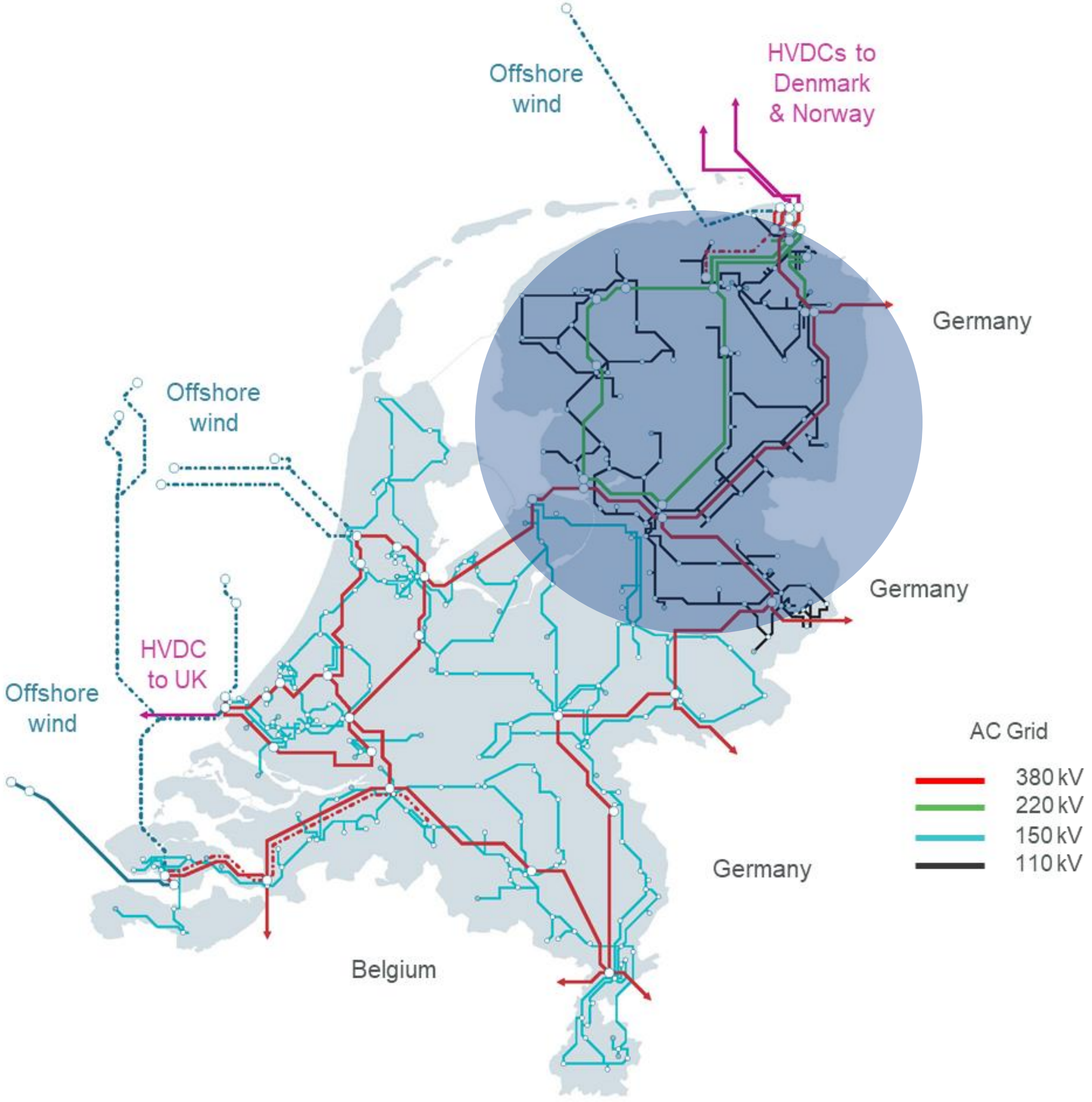
What does the available data tell us?

- **Where**: oscillations strongest in the north of NL (blue area)
  - Also observed in Germany, but with lower amplitude
    - ➢ Source likely in the Netherlands (North?)

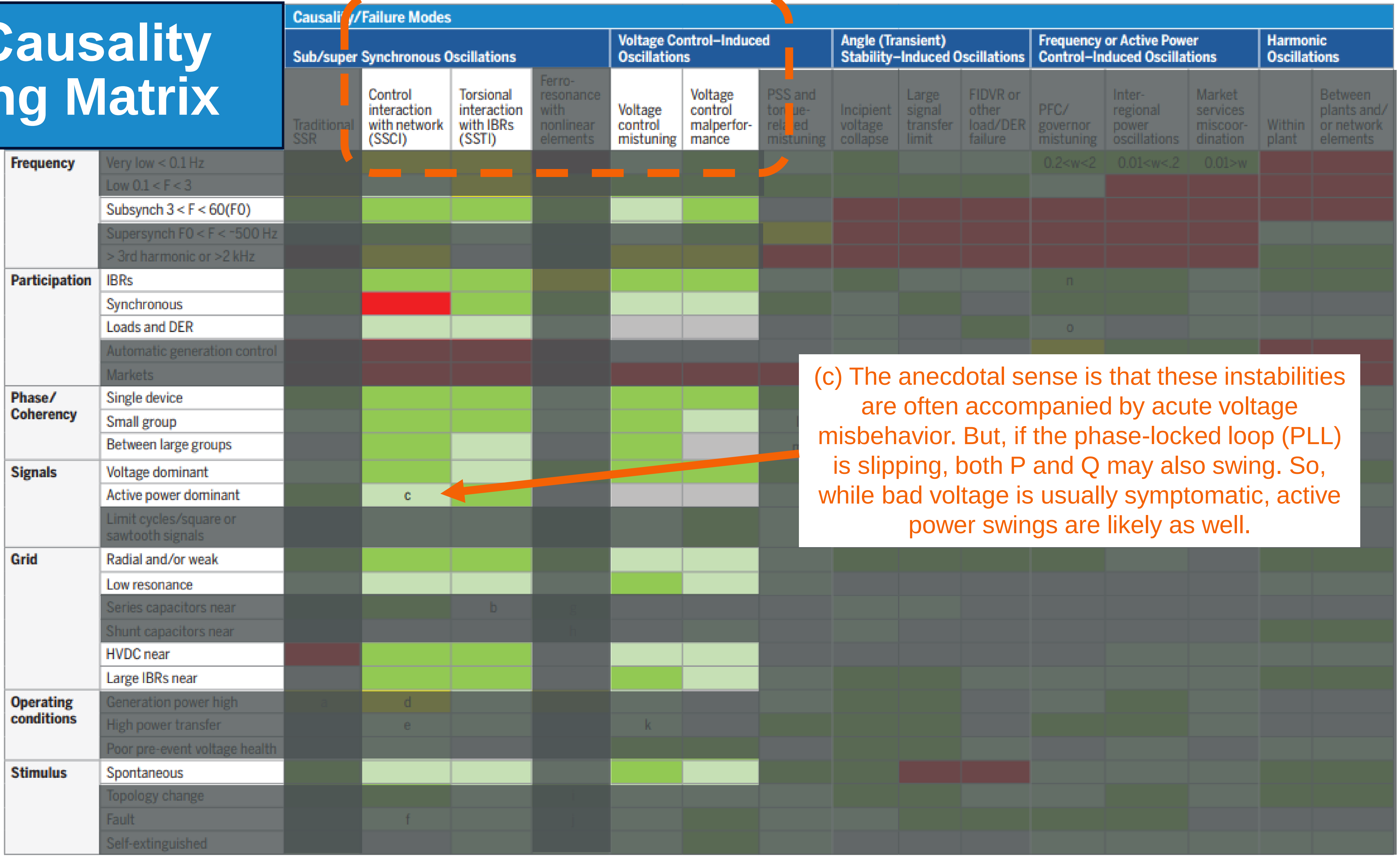
- **When**: oscillations occur only during sunny hours
  - Strongest on the weekends, with few SyncGens online
    - ➢ Relation to high PV infeed and weak grid situation

  - Oscillations are persistent across various op. scenarios
  - No specific trigger or unit P/Q patterns of interest found
    - ➢ Forced oscillations, interactions?

❖ **Focus of the investigation so far:**
  - IBRs in the north → Two large HVDCs (VSC + LCC)
  - Solar PV parks in the North → Many parks in operation



ESIG’s Causality Screening Matrix

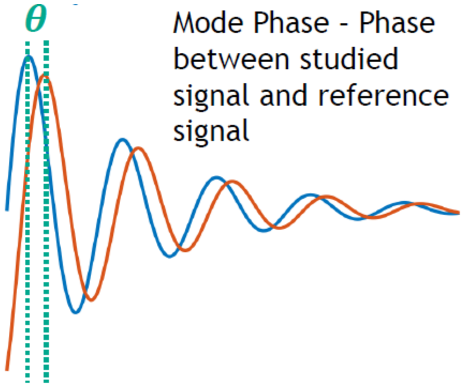


(c) The anecdotal sense is that these instabilities are often accompanied by acute voltage misbehavior. But, if the phase-locked loop (PLL) is slipping, both P and Q may also swing. So, while bad voltage is usually symptomatic, active power swings are likely as well.

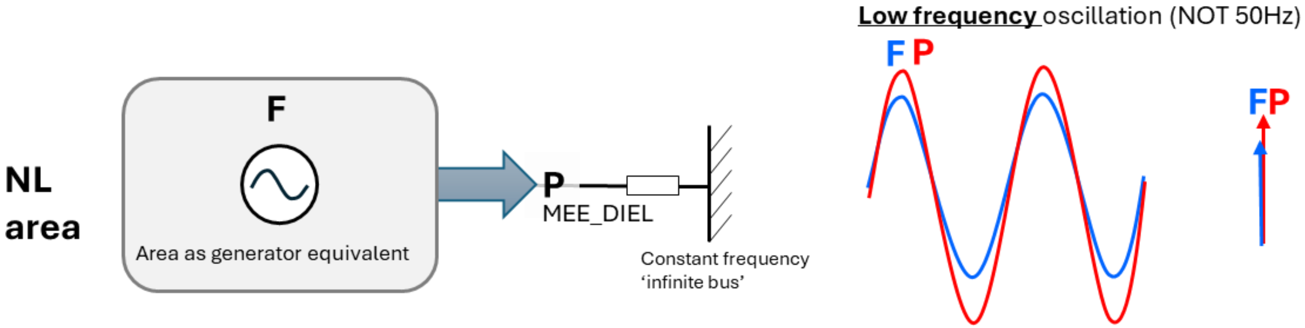
Strong positive indicator | Weak positive indicator | Neutral indicator | Weak contraindicator | Contraindicator (See page 40 for extended key and footnotes.)

ESIG-Oscillations-Guide-2024.pdf

Source investigation with available WAMS data



- Mode phase analysis used to try to find the source (as much as the PMU coverage allows)
  - P & f in-phase: Energy added into the oscillations magnitude (source)
  - P leading f 90°: Negative damping behavior (amplification)

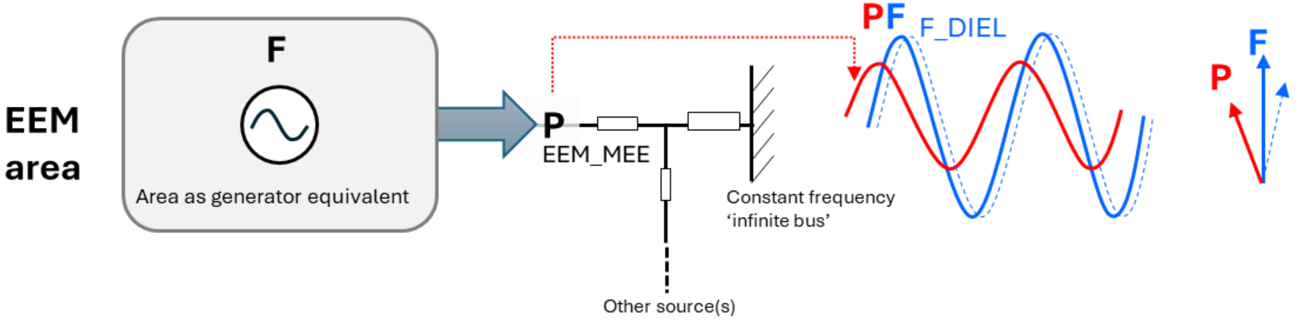


NL area is a SOURCE

Assume that there is a similar pattern in total border transfers as in MEE_DIEL, i.e. sum of interconnector P is similar in phase to NL frequency oscillation.

NL is feeding oscillation energy into the rest of interconnection during high frequency half-cycle and removing energy at low frequency half-cycle.

There is very little positive or negative damping contribution (i.e. no P at 90° to F)

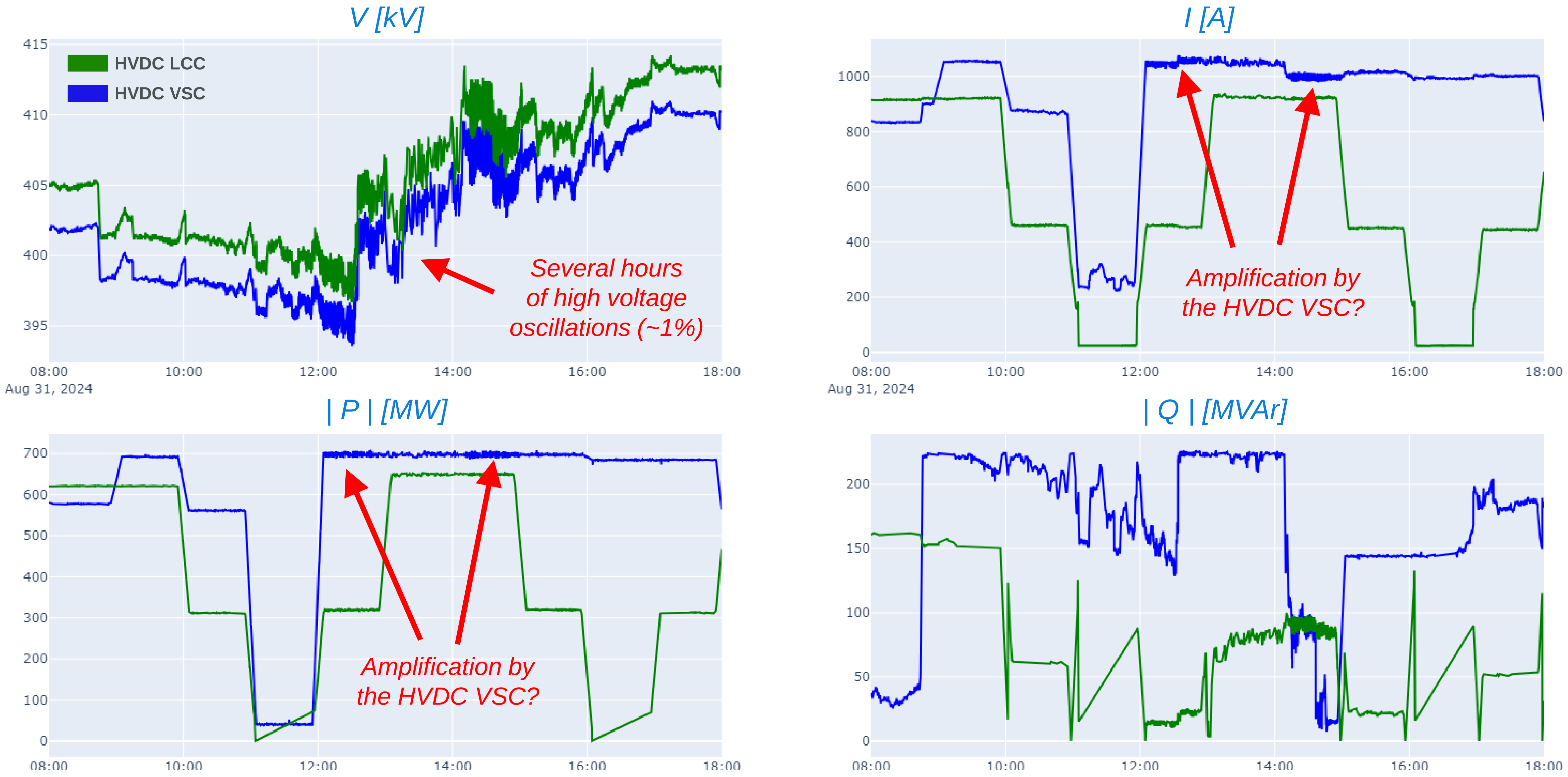


EEM area is a SOURCE

EEM is contributing negative damping into the system because of the leading phase of power oscillations. It is also contributing a component in phase with frequency.

However, comparing the amplitude of oscillations in EEM_MEE and MEE_DIEL, there must be another component adding into the oscillation at MEE, which is not measured.

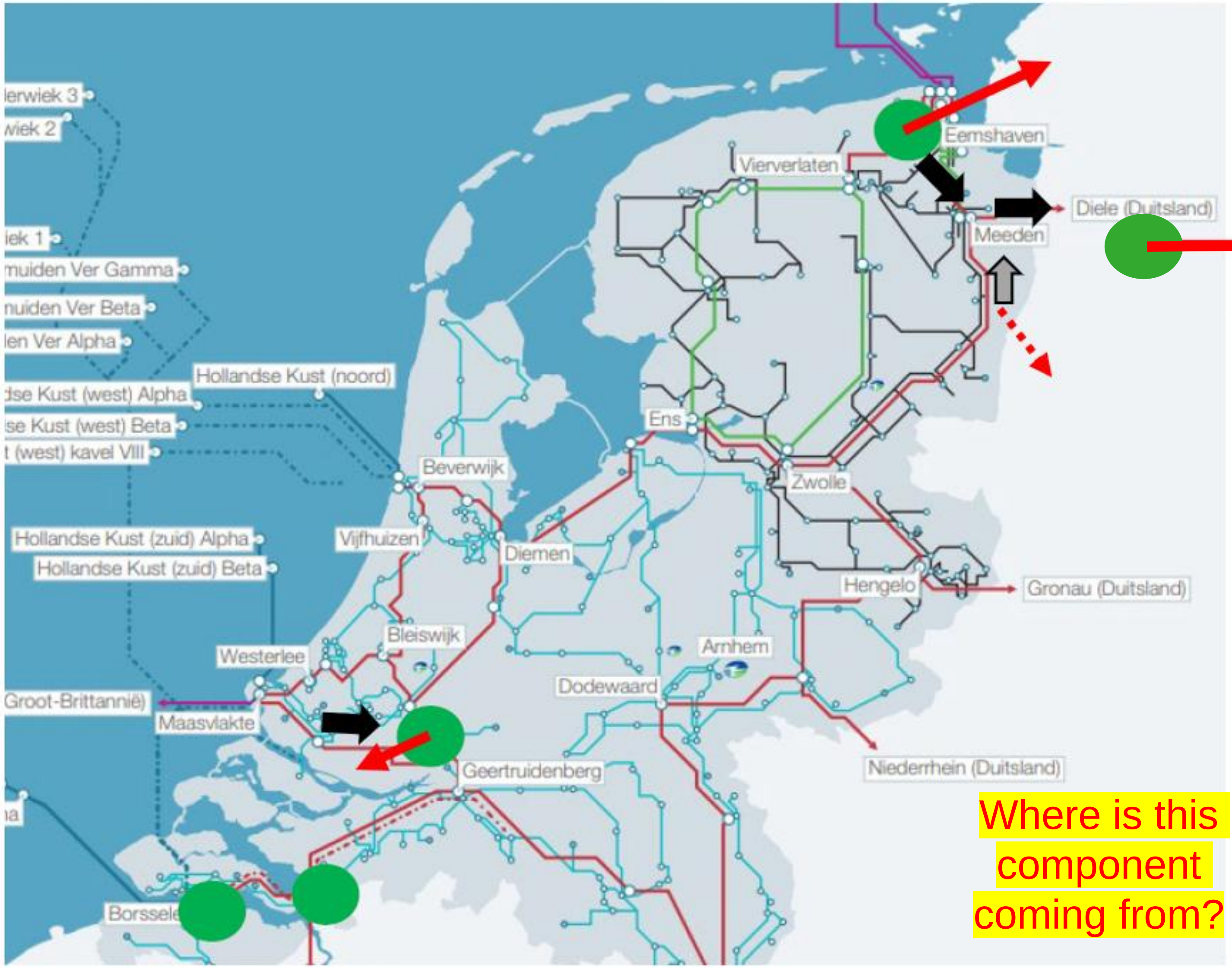
HVDCs in the North: No PMUs (yet), but EMS data shows “something”



P [MW] and I [A] oscillations from VSC mid-day (?) → EMT tests ongoing (no wide-area EMT model yet though)

- ➢ First results confirm osc. amplification when system strength is low & V-control is ON (negative damping <4Hz)

Multiple sources? (Sub-sync. control interactions?)



Power oscillations
magnitude & phase

MVL_CST lagging 155°
EEM_MEE leading 25°
MEE_DIEL reference 0°

MEE_DIEL P and DIEL F are close to 0° phase shift.

Assumed component adding to EEM_MEE to comprise MEE_DIEL

Legend: P_{osc} [mag, phase] Flow direction PMU

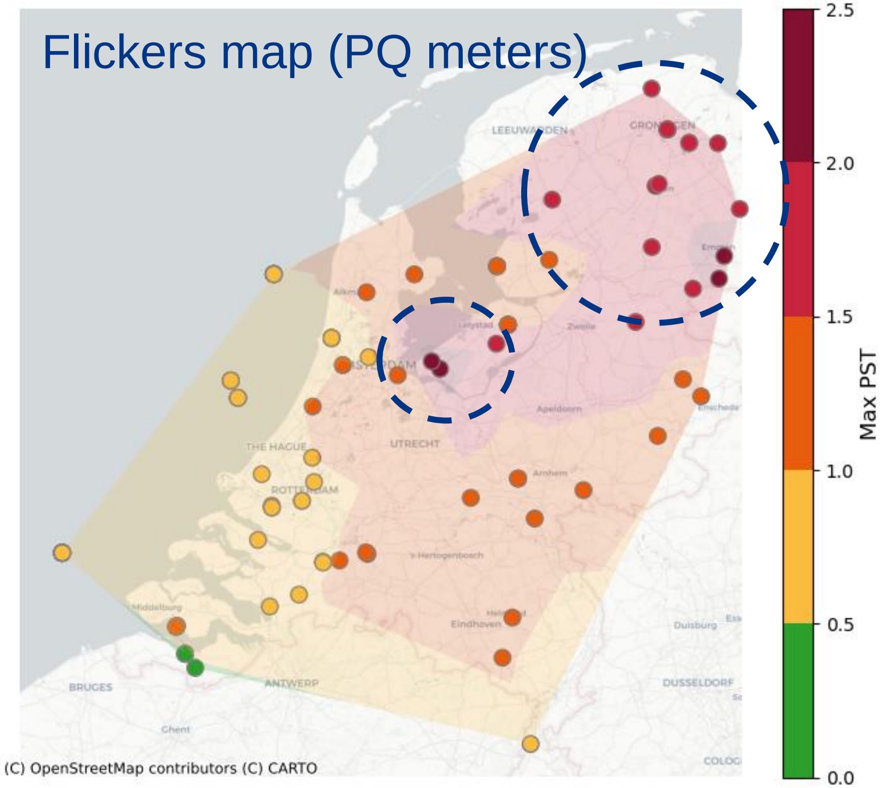
Solar PV parks

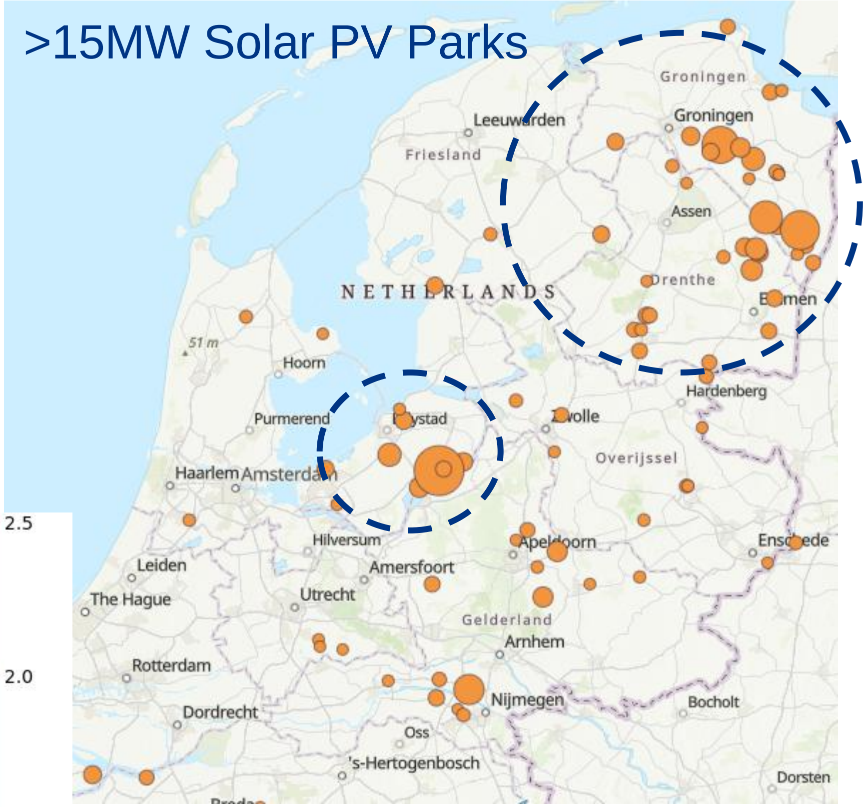
- Many large Solar PV parks in the North (orange circles)
  - These locations also coincide with highest observed flickers (PST)

- Challenge: Most parks are connected to the DSO grids
  - ➢ This significantly limits the data & models' availability

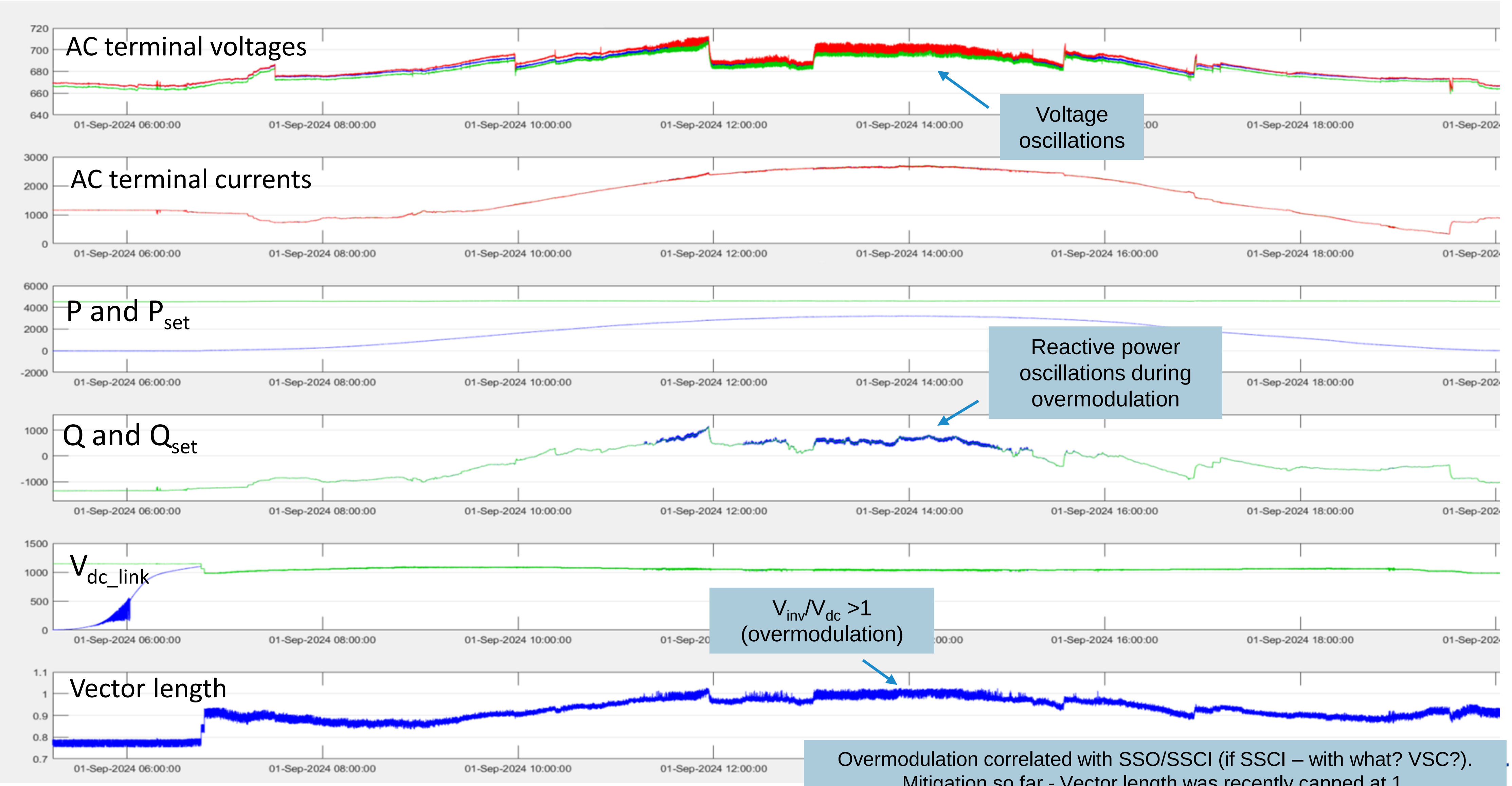
❖ Focus of the investigation:
  - TSO-connected parks
  - Collaboration with DSOs

➢ After discussing with several OEMs/connectees, one possible source (PV park) was found so far





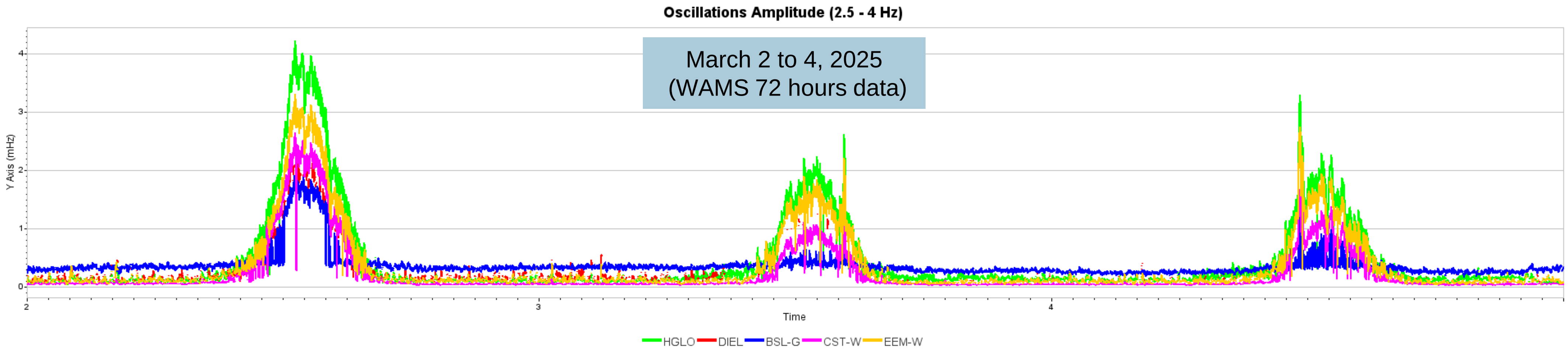
Large Solar PV park – one of the contributors?



Overmodulation correlated with SSO/SSCI (if SSCI – with what? VSC?).
Mitigation so far - Vector length was recently capped at 1.
Unfortunately, SSO was also observed afterwards – ongoing investigation.

Current State (March 2025)

- Unfortunately, recent WAMS data indicates that the problem was <u>not</u> (fully) resolved



- We *may* have found/fixed one source, but there seems to be more (??) → Many open questions remain.
  - We expect oscillations to worsen in sunny spring/summer (with fewer SyncGens online)

- Some of the ongoing activities on our side:
  - **Observability**: Accelerated PMU installations (incl. at HVDCs); temporary placement of portable measurement devices…
  - **Source location**: Lots of work ongoing in trying to locate/mitigate the source/issue
  - **System Operations**:
    1) Bring real-time oscillations monitoring to the control room / train the operators to use it
    2) Explore short-term mitigation actions (e.g., must-runs of SyncGens to increase damping, VSC control mode…)

Conclusions and Open Questions

- What kind of phenomena are we dealing with?
  - SSCI between PV parks and HVDC (?) Something else? What is the role of system strength here?

- 3.5Hz indicates slower controllers involvement (V-control?) However, P_{osc} >> Q_{osc} is observed
  - Perhaps the oscillations are initiated by e.g. V-control of PV park(s), and P_{osc} amplified by HVDC (?)

- If oscillations are forced, why does frequency change with rising PV infeed and osc. amplitude? (~3.8 to 3.4Hz)

- How to locate the source(s) despite the limited number of PMUs online? (accelerated installations ongoing…)

- How dangerous is this for grid security? What amplitudes can be temporarily “tolerated”?
  - We’ve seen >1% voltage swings, persistent for a few hours. No further stability consequences (yet)

- What can we do in system operations / real-time?
  - Must-runs of SyncGens to strengthen the grid: limit the amplitude & improve damping
  - Test HVDC VSC P/Q setpoints and V-/Q-control modes’ impact on oscillations…

- Future: +20GW offshore HVDC wind in 2035. How to prepare for oscillations? (incl. freq’s above PMU capability)
  - Example: In 2024, TenneT DE had ~500Hz resonance that tripped/damaged multiple offshore HVDCs
    - If (when?) similar happens in the future, it could result in a trip of several GW!

TenneT is a leading European grid operator. We are committed to providing a secure and reliable supply of electricity 24 hours a day, 365 days a year, while helping to drive the energy transition in our pursuit of a brighter energy future – more sustainable, reliable and affordable than ever before. In our role as the first cross-border Transmission System Operator (TSO) we design, build, maintain and operate 25,000 kilometres of high-voltage electricity grid in the Netherlands and large parts of Germany, and facilitate the European energy market through our 17 interconnectors to neighbouring countries. We are one of the largest investors in national and international onshore and offshore electricity grids, with a turnover of EUR 9.2 billion and a total asset value of EUR 45 billion. Every day our 8,300 employees take ownership, show courage and make and maintain connections to ensure that the supply and demand of electricity is balanced for over 43 million people.

Lighting the way ahead together