Adverse Weather and RES Event Detection from the meteorological perspective: A MultiScale PhysicsInformed Approach

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The rapid integration of renewable energy systems (RES) across Europe has heightened the sensitivity of power grids to adverse weather or weather affecting the RES, exposing critical infrastructure to risks from shortterm wind ramping to persistent compound events such as “Dunkelflaute” or "Hellsturm". Despite established meteorological frameworks for extreme event detection, applicationspecific definitions and impact metrics for energy systems remain inconsistent, posing challenges for operational resilience and grid management.

Here, we present a comprehensive, multiscale methodology developed at GeoSphere Austria to systematically define, detect, and assess adverse meteorological events relevant for renewable energy production and grid stability. Our approach couples physical meteorological diagnostics with energysector requirements, spanning timescales from subhourly nowcasting to subseasonal and climate projections.

We introduce a hierarchical classification framework distinguishing simple, compound, consecutive, and cascading weather events, calibrated to energy sector impact thresholds. For example, wind ramping events are stratified by severity (3–5 m/s up to ≥10 m/s over three hours), while Dunkelflaute is identified via combined criteria for wind (<3 m/s), solar (<150 W/m^2), and demand over >48 hours. Physicsinformed detection algorithms leverage multiparameter ensembles, pressure tendencies (>1.5 hPa/h), wind variability (>1.2 m/s), and system propagation speed (>12 m/s) to enhance spatialtemporal consistency and address the double penalty problem in highresolution verification.

Crucially, meteorological thresholds are mapped to infrastructure design standards (IEC 614001 for wind, IEC 61215 for PV), enabling direct assessment of operational risk—including turbine cutout (>25 m/s), structural risk (>60 m/s), and PV performance losses under extremes. Compound event analysis incorporates atmospheric teleconnections (NAO, Scandinavian Blocking), quantifying regimespecific risks for simultaneous wind/solar shortfalls and energy security.
Application to Central European datasets demonstrates operational value: realtime wind ramping detection yields +500 MW forecasted fluctuations with threehour lead time; weather regime classification enables probabilistic Dunkelflaute prediction at weekly scale; and subseasonal forecasts of wind droughts utilize teleconnection indices. Crossvalidation with Austrian and German grid data demonstrates improved skill in anticipating critical transitions between renewable surplus and deficit, informing reserve planning and system balancing.

Our framework underpins ongoing collaboration within IEA Tasks, supporting international standardization of event definitions and impact metrics, and facilitates integration of ensemble and machine learning approaches for enhanced predictive capacity. The results provide both the meteorological and energy communities with actionable tools for extreme event forecasting, grid planning, and climate adaptation.
Keywords: extreme weather, renewable energy, compound events, wind ramping, grid stability, event detection, standardization, energy meteorology

Motivation

- Rapid and continous integration of renewable energy systems (RES) across Europe
- Increased sensitivity of power grid to adverse/extreme weather affecting the RES including infrastructure
- Risks in both generation and grid impact as well as infrastructure
- Inconsistent definitions and impact metrics (which does have advantages, too)

Tackling

- A set of defined adverse/extreme events for both power production and infrastructure risks including meteorological reasoning
- A multiscale (applyable) Machine Learning and threshold based detection algorithms for adverse weather
- Probabilistic Risk Assessment (next step) „current and future hot spots“
- Here, we present a comprehensive, multiscale methodology developed

Definition – what do we as meteorologists consider an event, what does the industry consider

& „Hellsturm“ + „nice“ weekend + runoff (snowmelt) + not a lot of consumption
& combined air quality (+health) + Dunkelflaute + increased demand (heating)
& ….

Want to help us? A survey:

Adverse Weather Type	Causal Weather Patterns	Related Parameters	Notes on Compound/Consecutive Events	Detection/Forecasting Methods
Winter Peak Demand ("Dunkelflauten")	High pressure system over Germany/Central Europe (European Blocking), Scandinavian Blocking, Greenland Blocking	Low temperatures, Low wind speeds, Low solar irradiance	Can persist for multiple days (median duration 3.2 days, max 8 days)	Weather regime forecasts, especially for longerlived regimes
Wind Power Ramping	Low pressure systems moving across UK	Rapid changes in wind speed	Most frequent in autumn/winter	Highresolution NWP models (e.g. Met Office UKV1.5) for shortterm forecasts
Summer Wind Drought	High pressure system o… …ope	Very low wind speeds, High temperatures	Can last up to 32 days, may coincide with heatwaves	Weather regime forecasts, especially European Blocking
Extreme Solar Variability	Mixed sky cond…	Rapid changes in solar irradiance	Can occur frequently on short timescales (seconds to minutes)	Shortterm solar irradiance forecasts, satellite imagery
Flooding	Positi… …e systems	Heavy rainfall	More frequent in summer during NAO+ phases	Weather regime forecasts, hydrological models
Windstorms	…tems, typically in	High wind speeds	Frequency linked to NAO phase, can occur in clusters	Weather regime forecasts, storm track predictions
Cold Spells	…igh pressure, Negative NAO …se, Greenland Blocking	Very low temperatures	Can persist for extended periods, may coincide with low wind speeds	Weather regime forecasts, especially for Greenland Blocking
Heatwaves	Blocking high pressure in summer	Extreme high temperatures	Can last multiple days/weeks, often coincides with low wind speeds	Weather regime forecasts, especially for European Blocking
Thunderstorms	Unstable atmosphere, typically in summer	Lightning, heavy rainfall, strong winds, gustiness, squal lines, hail	Can occur in clusters or organized systems or single cells	Shortterm convectionpermitting models
Snow/Ice Events	Cold air masses, winter precipitation	Snow accumulation, icy conditions, snow fall, temperature and season (e.g. late April snow), wind, very low extreme temperatures, “wetness of snow”	Can persist for days, may coincide with low temperatures and wind speeds	Weather regime forecasts, precipitation type forecasts
Saharan dust and/or pollen events, air pollution				
Hellsturm				
Fast running low	At the southwest edge of a strong low pressure system a small, but fastrunning new system develops. It develops close to a cold front or occlusion.	High wind speeds	The fast running low develops much faster as the main low pressure system. Thus, it shows up very late in the forecast.	Some ensemble members show the development. High resolution NWP and rapid update rate
Dunkelflauten (Dark Doldrums)	European Blocking (22%), Scandinavian Blocking (15%), Greenland Blocking (14%)	Low wind speeds, low solar irradiance, often cold temperatures	Median duration 3.2 days, max 8 days. Occur mainly in autumn/winter.	Combined capacity factor threshold of 0.06 averaged over 48 hours
Compound High Energy Shortfall	NAO negative, Scandinavian Blocking	Low wind speeds, low solar irradiance, low temperatures	Doubled risk during NAO, 50% increased risk during Scand. Blocking	Weather regime forecasts, especially for longerlived regimes
WindDroughtPeakDemand	High pressure systems over UK/Europe	Low wind speeds, extreme temperatures (low in winter, high in summer)	Can persist for multiple days. More common in winter.	WindDroughtPeakDemand Index (WDI) exceeding 90th percentile, 7day accumulation
Surplus Generation	High pressure systems in summer	High wind speeds, high solar irradiance, moderate temperatures	Most common in summer. Can stress grid management.	SurplusGeneration Index (SGI) exceeding 90th percentile, 7day accumulation
"Hellsturm" (Sunny/Windy Overproduction)	High pressure systems with strong wind patterns	High wind speeds, high solar irradiance, low demand (often weekends)	Most frequent MaySeptember, especially on Sundays. Can lead to significant curtailment.	Identify days with renewable generation above 90th percentile and demand below 10th percentile. Analyze wind/solar ratio and time patterns.
Fastrunning Low Pressure Systems	Develops at southwest edge of strong low pressure system, near cold front or occlusion	High wind speeds	Develops much faster than main low pressure system. Can cause rapid fluctuations in wind power output.	Highresolution NWP models with rapid update rates. Monitor ensemble forecasts for potential development.

Power production

Definition – what do we as meteorologists consider an event, what does the industry consider

Adverse Weather Type	Effects on Infrastructure	Examples of Impacted Components	Threshold/Design Value	Standard/Reference
Extreme Wind/Gust	Turbines are designed to withstand winds up to this limit; above this, failure is tolerated.	Wind Turbines	≈ 60 m/s (Survival Wind Speed)	IEC 614001, ÖNORM EN 61400
Icing Conditions	Ensures aerodynamic performance; antiicing systems are recommended.	Wind Turbines	Temperatu… defin…	IEC 614003, ÖNORM EN 61400
Excessive Wind Loads/Gusts	Can damage structures and affect system stability.	P… …d …re	…p to ≈ …dent)	EN 50160, IEC 61850, Local Grid Codes
Temperature Range	Ensures module perf… and durability under e… ambient temperatures.	Photovol…	…perational: –40°C to +85°C	IEC 61215, ÖNORM EN 61215
Humidity/Damp Heat	Tests simulate longterm exposure to humid condi…	…tems	85% RH at 85°C for 1000 hours (damp heat test conditions)	IEC 61215, IEC 61730, ÖNORM EN 61730
Flooding/High Precipitation	Thresholds fo… which are… electrical in…	…dro Infrastructure	Defined thresholds for precipitation which may lead to Flooding for critical infrastructures.	EN 12975, EN 12976, Local Hydraulic Guidelines
Lightning	Adequate lightn… protection minimizes equipment damage.	Grid / PV Systems	Design based on risk assessment (e.g., systems rated for >10 kA peak current)	IEC 62305, Local Lightning Protection Guidelines

Power infrastructure

To be added:
- „vibration/oscillation“ indices (e.g. galloping, flutter, etc.)
- Wet and/or late snow

Part 1 of what we implemented

Event Type	Key Parameters	Severity Levels	Infrastructure Impacts	Impacts on Power Production and Grid Stability	Comments
Wind Speed Ramping	Change in wind speed over three time steps (m/s)	Minor: 3–5 m/s Moderate: 5–7 m/s Severe: 7–10 m/s Extreme: ≥10 m/s	Turbine cutin/cutout at 3–20 m/s Risk of turbine damage above 25 m/s, structural failure possible at 60 m/s	• Rapid fluctuations destabilize grid balance • Requires quick ramping of backup generation or curtailment • May reduce wind farm efficiency during extreme changes	Secondary effects of reduced power supply experienced offsite. Exposure analysis relates to where power generation is potentially affected by meteorological events. Different thresholds for different type of turbines?
High Wind & gust events	Sustained wind speeds > 20 m/s, gusts > 25 m/s	Turbines shut down for protection above 25 m/s Risk of blade, tower, or substructure damage at > 40 m/s	Mechanical failures, maintenance delays during storms	• Power output ce… …ut down • Extreme hi… …g during power ramp… • R… …load	• Could be combined with a forestry inventory .. • IEC 61400-1 defines turbine classes (I, II, III) based on 50-year return wind speeds. Class I: 50 m/s, Class II: 42.5 m/s, Class III: 37.5 m/s. Structural design must account for extreme coherent gusts (ECG) and extreme direction changes (EDC) per IEC standards.
Heatwaves	Temperatures > 35°C	Persistent events lasting >3 days	Overheating of compon… syst…	…s but efficiency drops above 30°C …icity demand for cooling …ansmission systems due to high demand	Combine with e.g. persistent ones
Cold Spells	Temperatures < 10°C	Persistent low temperatures, often coinciding with low wind speed…		…icant reliance on backup generation Increased heating demand amplifies grid stress Reduced wind energy efficiency due to icing	Combine with persistent inversions, low air quality etc.
Snow/Ice Events	Snowfall, ice accumulation, wet snow accreation	Wet snow weight > 2… damage PV mod… turbine bla…	…reduced PV …to shading	• Solar generation curtailed due to snow cover • Icing of transmission lines increases failure risks • Wind farm production halts due to icing • impact on powerlines due to weight of snow on trees	Proxy snow & T integration:
Thunderstorms	Lightning, hail, wind gust	…ages PV …hail > 5 cm	Hail cracks PV modules, rapid power fluctuations	• Power surges can damage grid components • Curtailment required during gusty conditions • Localized blackouts possible	• Thunderstorm severity index Integration of gusts? Possibly relevant for potentially severe thunderstorms • Integration with lightning detection networks Hail trajectory forecasting with dual-pol radar Reference to IEC 61400-24 (lightning protection) and IEC 61215 (PV hail resistance)
Flooding (precipitation)	River discharge > 98th percentile (duration >30 min)	Tailwater rise reduces hydropower generation capacity	Sediment load increases turbine wear	• Reduced hydropower output due to high tailwater • Infrastructure failures disrupt regional power supply • Risk of electrical faults in flood zones	Steps: 1) define catchments based on location of hydro power plants (hydrosheds.org) 2) quantify P totals for catchments 3) define thresholds based on precentiles of rainfall within catchments 4) begin with Kamptal as good example of extreme events (2002, 2024)

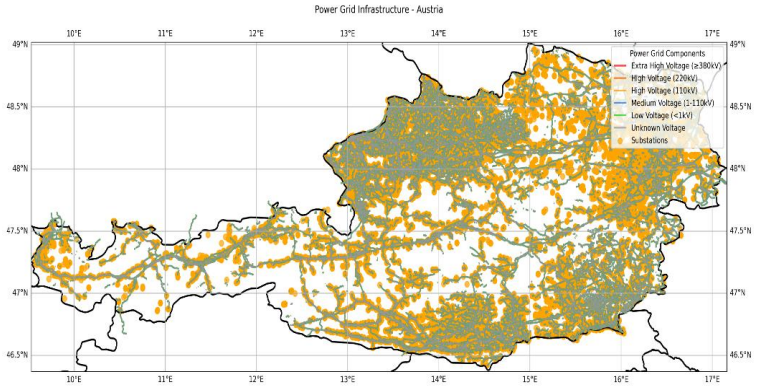
Dunkelflaute
Drought (wind, hydro, solar) single parameter
Low visibility due to fog/dust

Definition – data sets we use/used and their scales

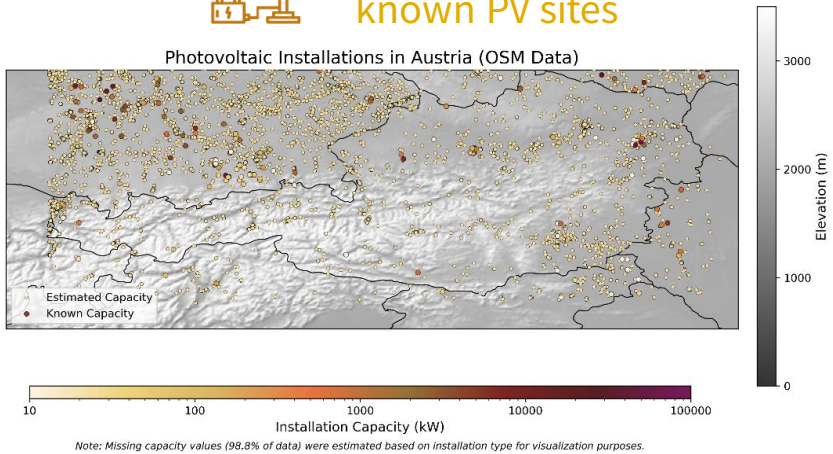
Datenquelle	Extremtyp-Beispiel
INCA (Analyse + Nowcasting)	Windrampen, Nowcasting
SPARTACUS (Historie)	Hitze-/Kältetage
ERA5 (Reanalyse)	Starkregenstatistik
CERRA (Reanalyse)	Blockings über Alpenraum
ARA (Reanalyse)	Gebirgsnahe Kaltluftseen
IFS (Prognose)	Sturmvorhersage
AROME (Prognose)	Windfelder über Gebirge
ECMWF S2S (Subsaisonal, Saisonal)	Persistente Kälte
EURO-CORDEX (Historie/Szenarien)	Langfristige Dunkelflauten
ÖKS15 (lokale Klimamodelldaten)	Klimasignale für Hitze/Flut
NEWA (Analyse)	Windpotenzial + Rampen
DestinE On-Demand (Prognose)	Feuerwetter, Mikroskalen
DestinE Global DT (Prognose)	Synoptische Sturmprognose
DestinE Climate DT (Historie/Szenarien)	Klimaprojektionen mit Tagesauflösung

Metadata – location, location, location … and a bit of additional stuff

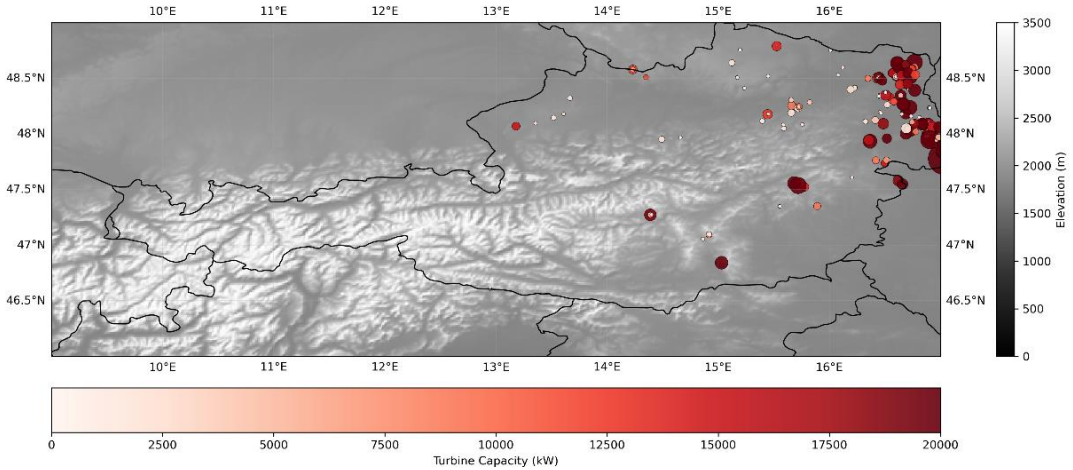
power lines, substats…

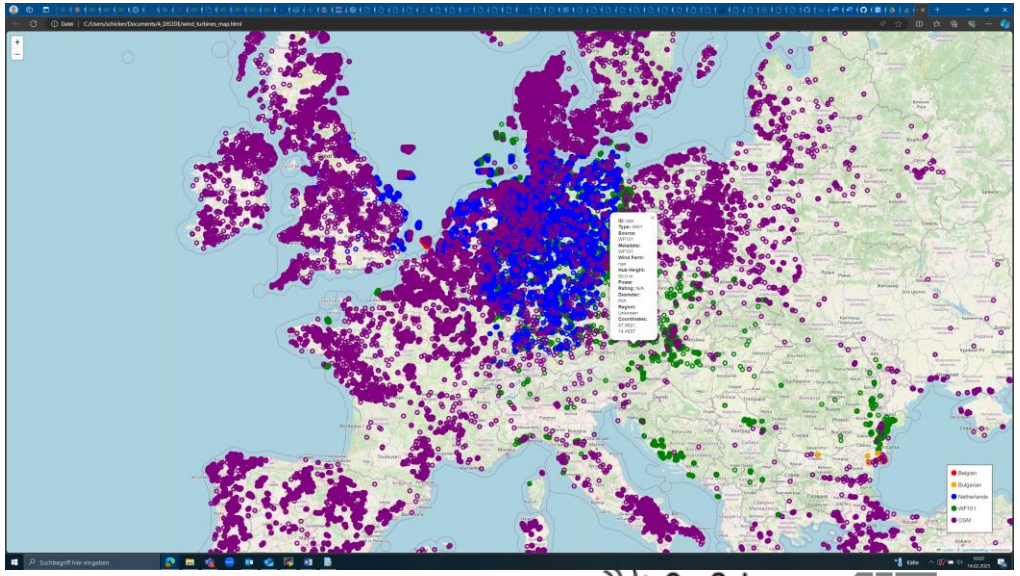


known PV sites



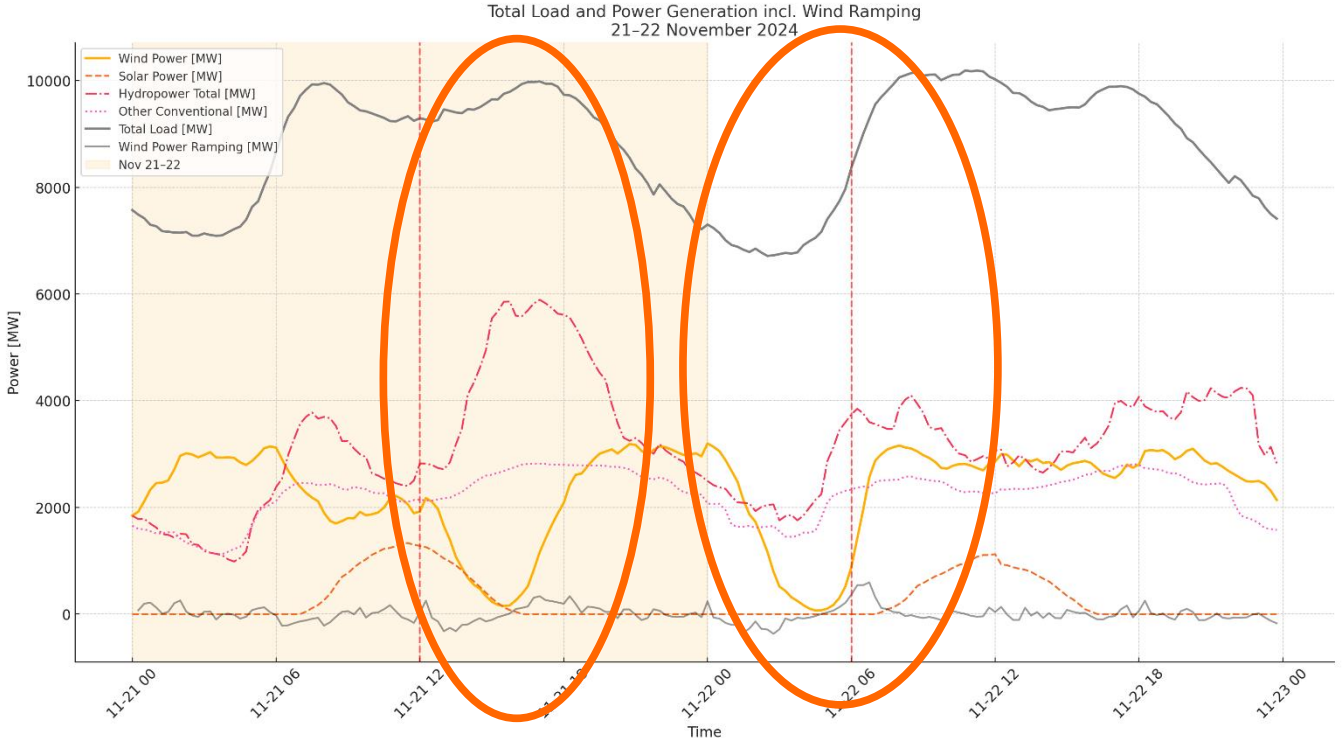
wind turbines



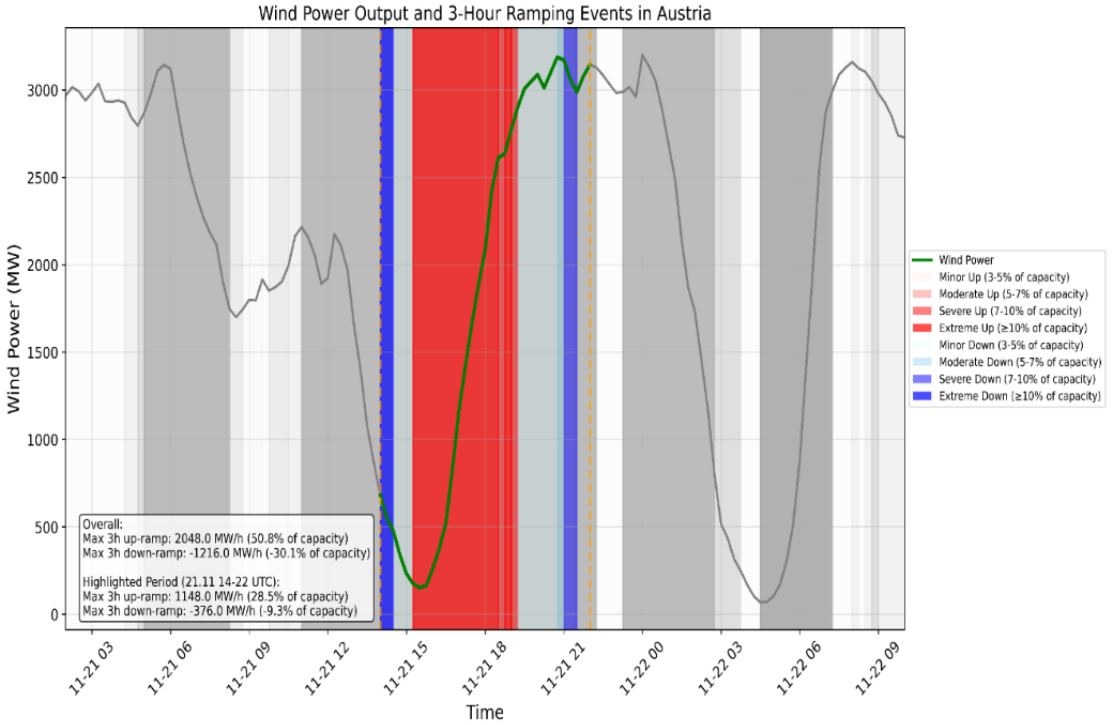


Detecting Adverse Weather – an example

Meteorological "adverse" (but season with in general reduced solar and hydro)



- **21 November, ~12:00/18:00:** A significant decrease/increase in wind power occurs (+500 MW in a short time). These ramping events cause a sudden shift in the generation profile.
- **22 November, ~ 01:00/06:00:** A sharp drop in wind production leads to a gap in total load coverage with increase again.



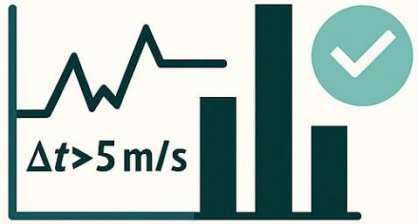
Detection and physics-informedness – implemented tools and results

Wetterlagen-klassifikation

SOM PINNs

Muster-/Cluster-detektion

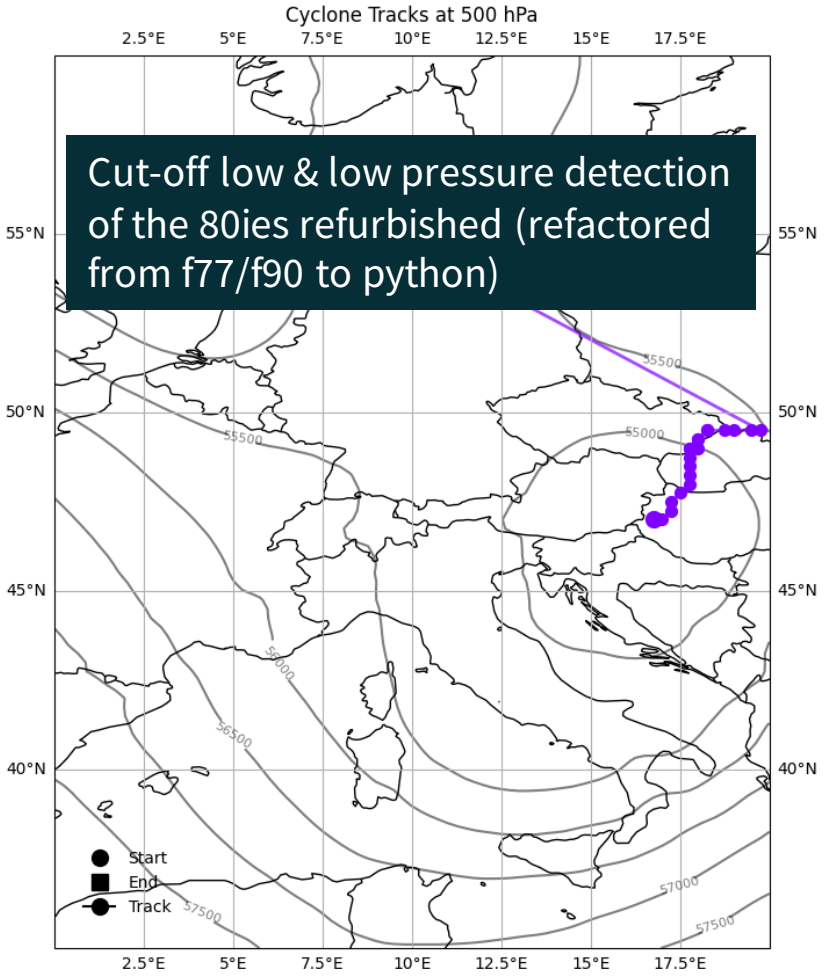
SGI WDI u.a.



Extremindizes

Verknüpfung mit Klimaszenarien & Reanalyse

Schwellenwert-basierte Detektion

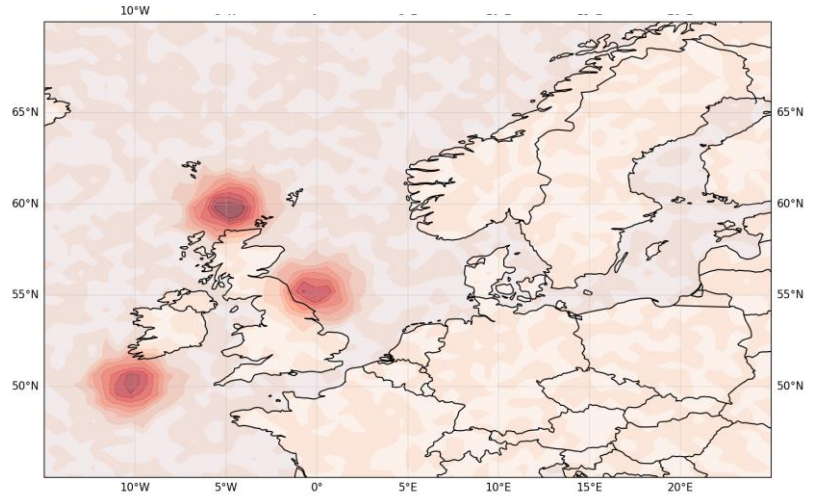


Physics-informed storm tracking and uncertainty

Method

- Multi-criteria ensemble approach for fast-system detection
- Spatial-temporal neighborhoods to reduce verification double penalty
- Energy-sector specific validation against wind farm observations
- Combine with historical entso-e data to build base for … later slides

Criterion	Meteorological Variable	Threshold	Physical Meaning	Data Level
Pressure Tendency	∂p/∂t (pressure change rate)	> 1.5-2.0 hPa/h	Rapid pressure drops indicate system passage	Surface (MSL)
Wind Variability	σ(wind speed) temporal std	> 1.2-1.5 m/s	High wind fluctuations during system passage	10m level
System Speed	Propagation velocity	> 12-15 m/s	Fast-moving systems of interest	Derived from pressure field
Wind Shear	$\lvert u_{850} - u_{10} \rvert$	> 10 m/s	Vertical wind structure indicates system strength	850 hPa - Surface
Geostrophic Wind	$\sqrt{(u^2 + v^2)}$ at 500 hPa	> 20 m/s	Upper-level flow pattern strength	500 hPa level
Thermal Wind	$\lvert u_{850} - u_{10} \rvert$ magnitude	> 15 m/s	Temperature gradient indicator	850 hPa - Surface



Storm Tracking & Detection:

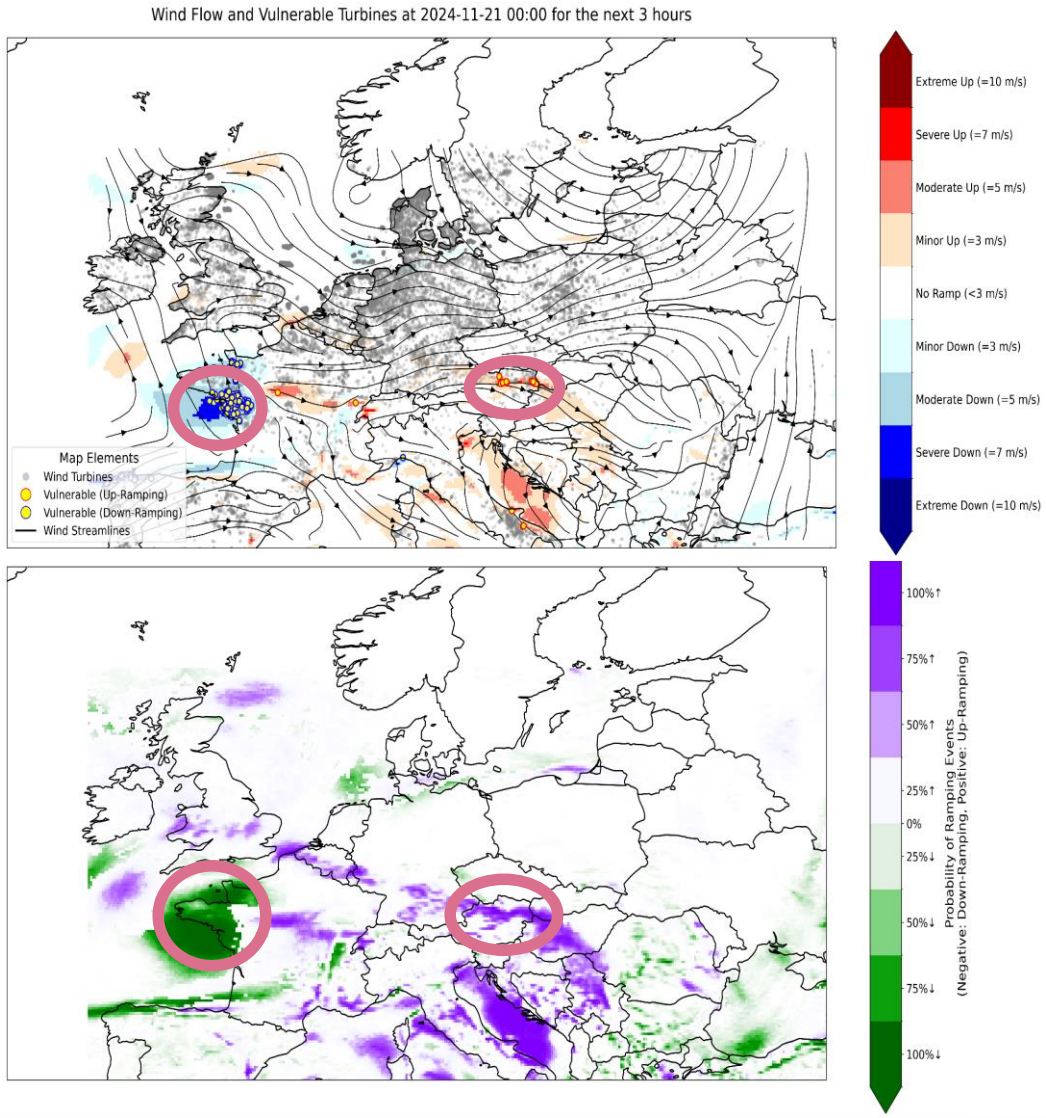
- **Hodges (1994)**: *"A general method for tracking analysis"* - Established fundamental tracking algorithms
- **Neu et al. (2013)**: *IMILAST intercomparison* - Standardized detection criteria and validation metrics

Renewable Energy Meteorology:

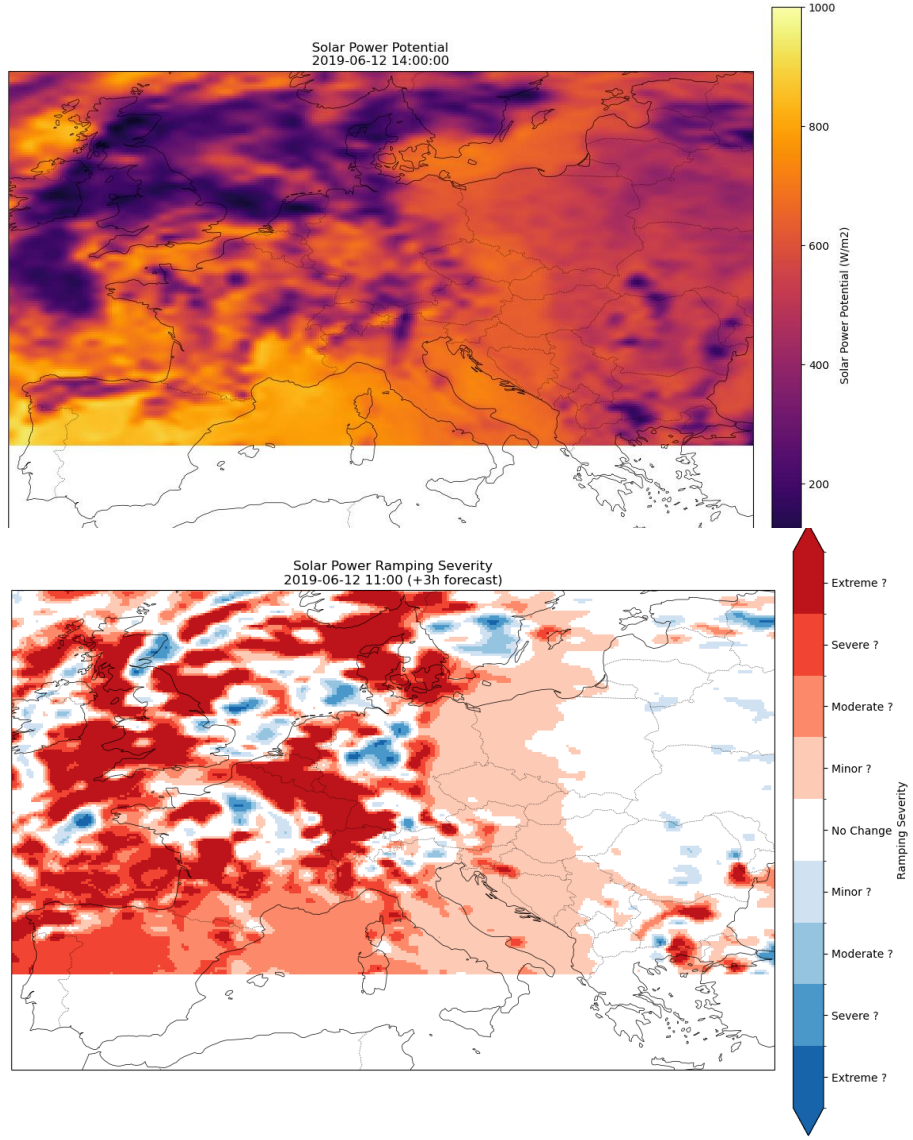
- **Brayshaw et al. (2011)**: *"Impact of large scale atmospheric circulation patterns on wind power"* - Linked synoptic patterns to energy generation
- **Cannon et al. (2015)**: *"Using reanalysis data to quantify extreme wind power statistics"* - Statistical approaches for energy applications

Ramping detection

Windspeed ramping (power is in the making)

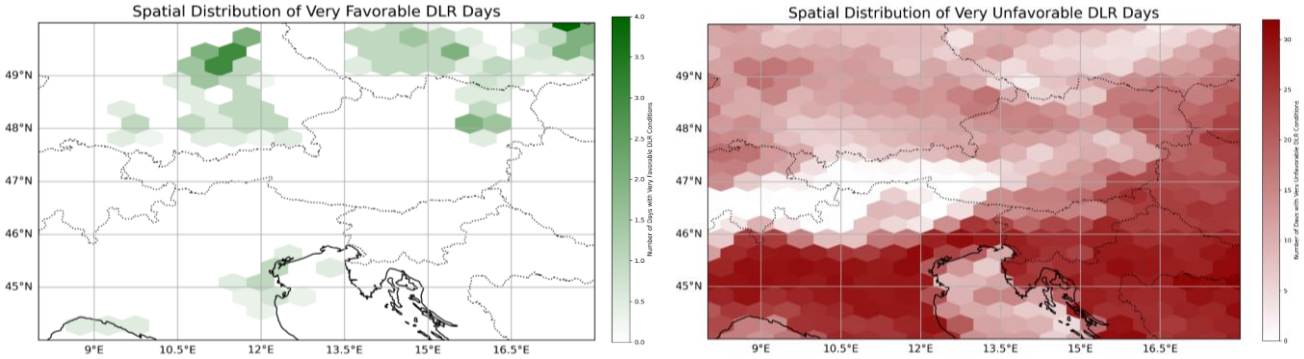


Solar potential ramping (PV is in the making)



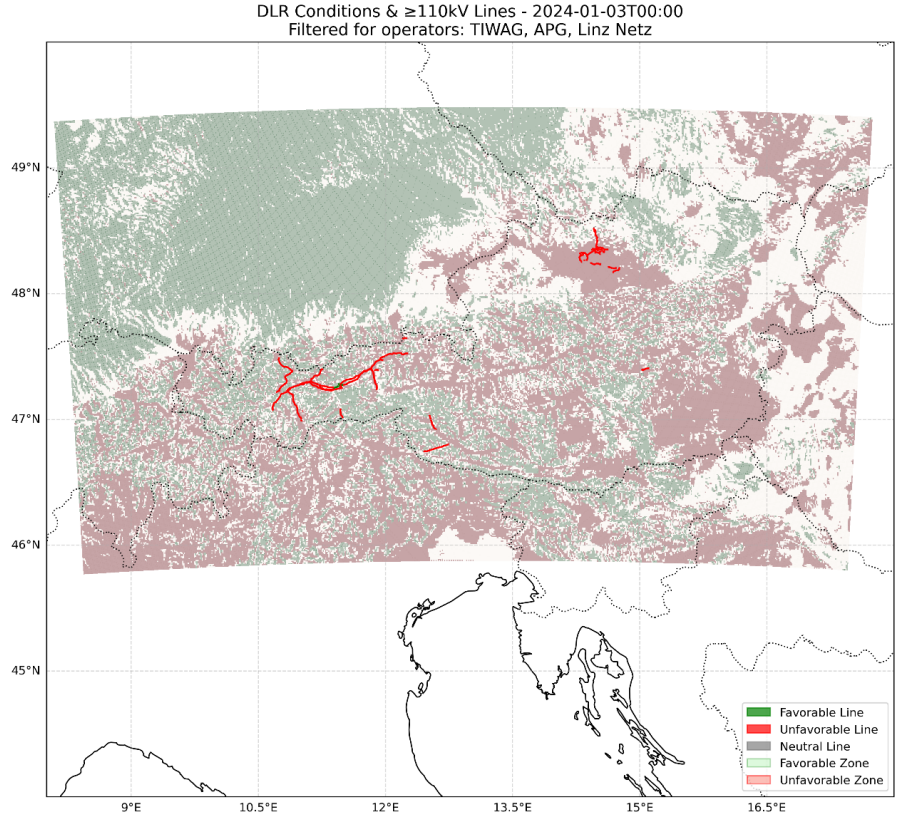
Dynamic line rating conditions

Detection on historical cases (ERA5/CERRA/ARA) for Dynamic Line Rating applications



Parameter	Favorable Conditions	Unfavorable Conditions
Wind Speed	> 5 m/s	< 2 m/s
~~Wind Direction~~	~~Perpendicular to line (±30°)~~	~~Parallel to line (±30°)~~
Temperature	< 25°C	> 30°C
Solar Radiation	< 400 W/m²	> 600 W/m²

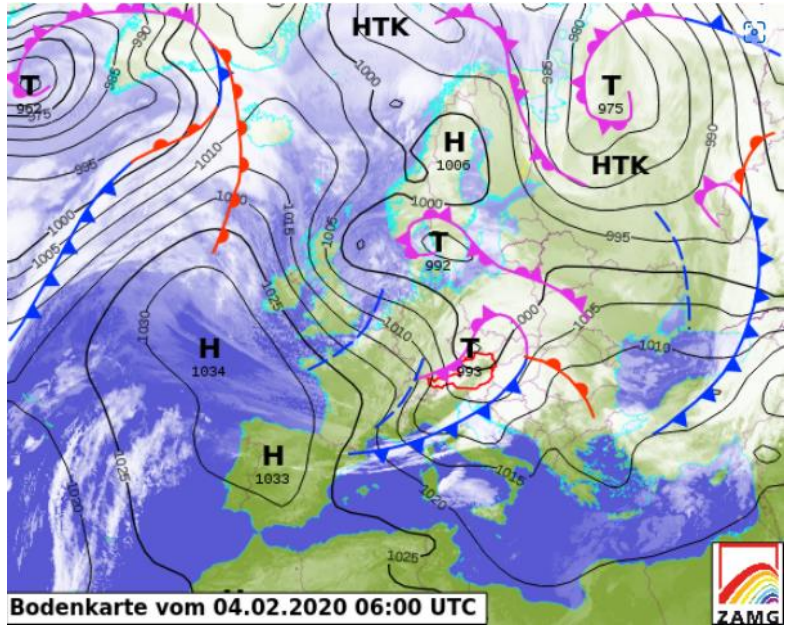
Applying to forecast data

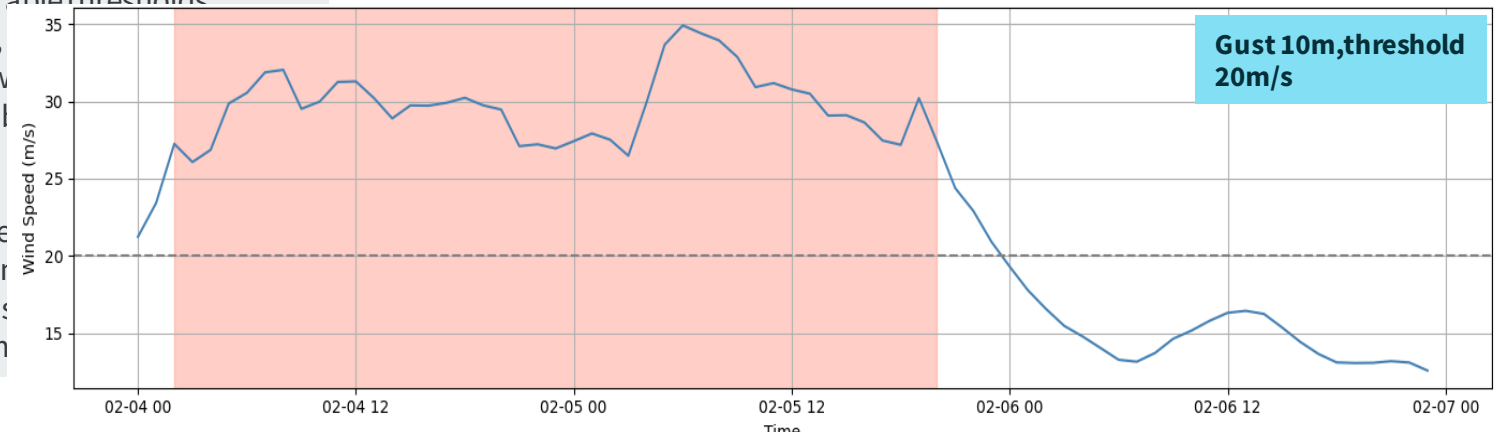


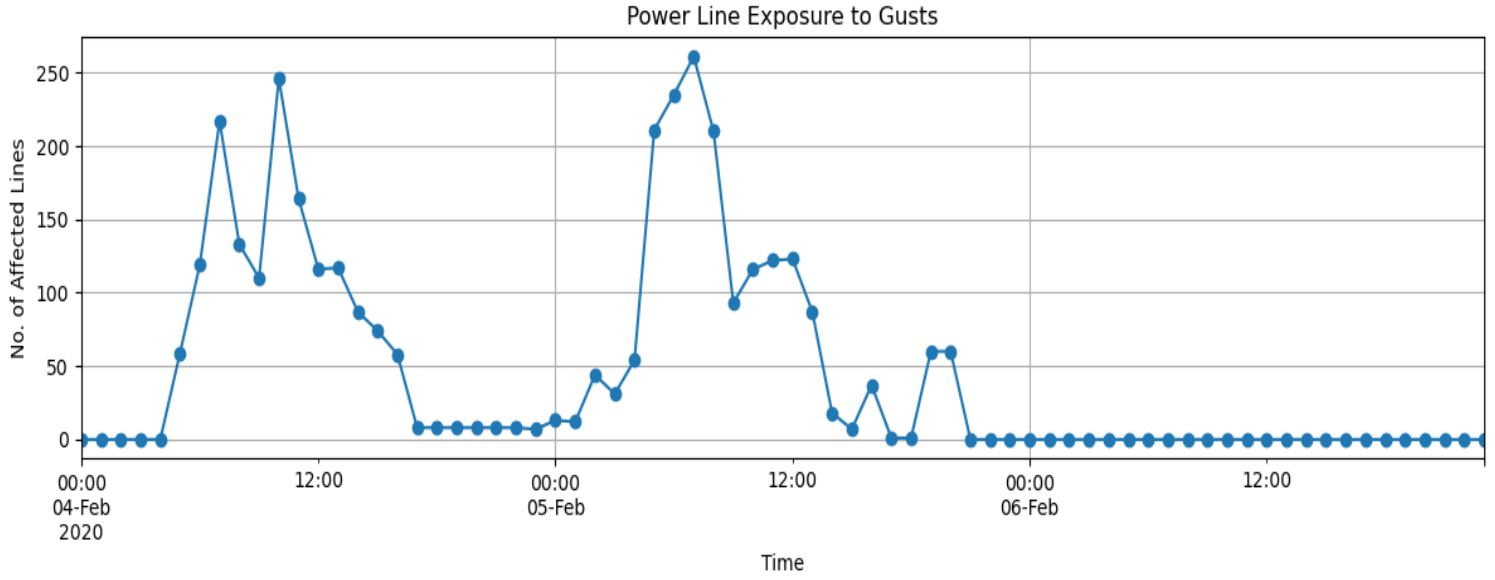
Methods & Results – storm & gustiness use case storm Petra (4 – 6 February 2020)

Threshold based (included/core of new “stormdetect” library) → will be combined with other methods into adverse weather python library

- **Storm Detection**: Identify severe wind/gust events using configurable thresholds
- **Storm Characterization**: Calculate propagation speed, direction,
- **Infrastructure Impact Assessment**: Evaluate vulnerability of pow
- **Vulnerability Mapping**: Identify geographical hotspots of vulneral
- **Multiple Operation Modes**:
  - **(re)Analysis Mode**: Detailed analysis of historical events
  - **Forecast Mode (testing)**: Early warning of potential severe
  - **Climate Mode (testing)**: Longterm vulnerability assessmer
- **Interactive Visualizations (testing)**: Comprehensive maps, time s
- **Reporting (testing)**: Detailed reports for operators and decisionm





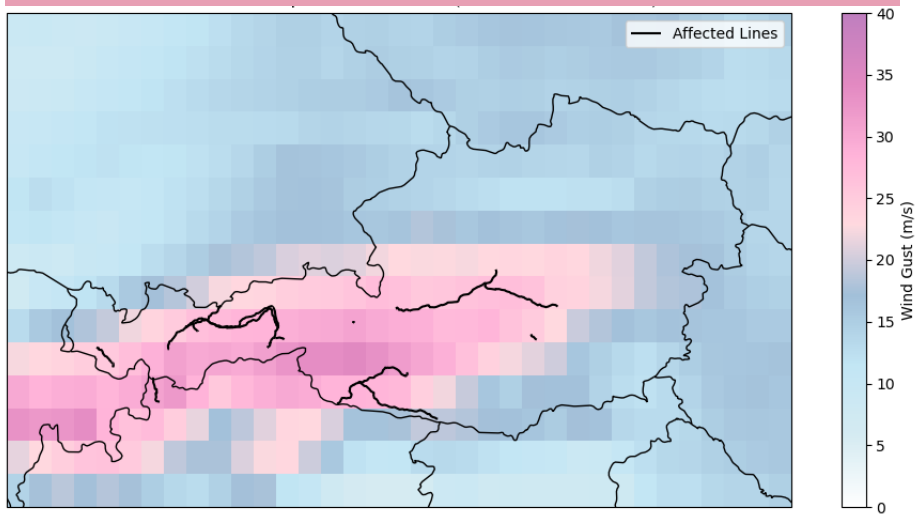


Was tut sich im Bereich Extremereignisse, Wetter, Klima

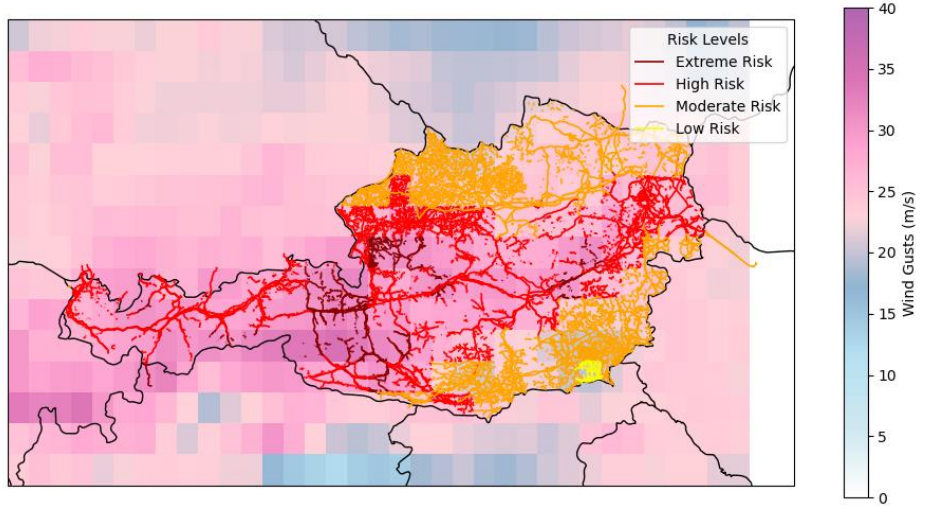
Beispiele Detektion - Windböen & Stromleitungen

Sturm Petra (4-6 Feb 2020)

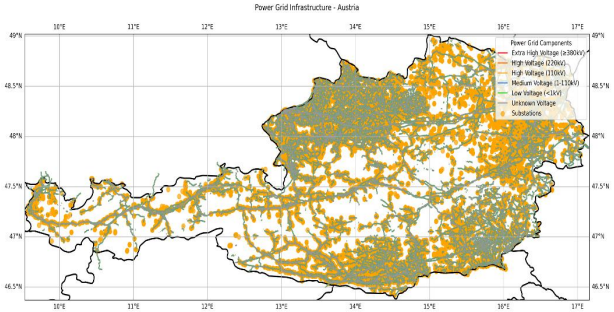
Power lines (220kV) affected during peak gust (2020-01-05 07:00:00)

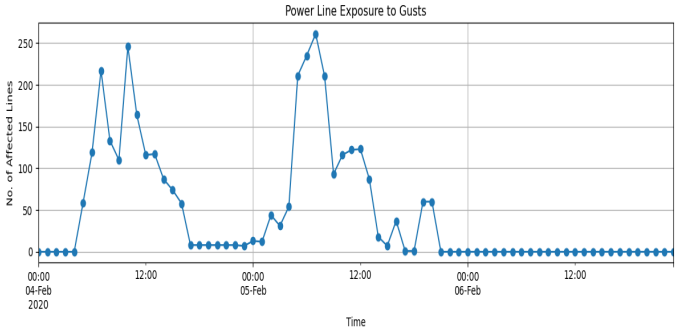


Power lines (all types) risk levels **during event**

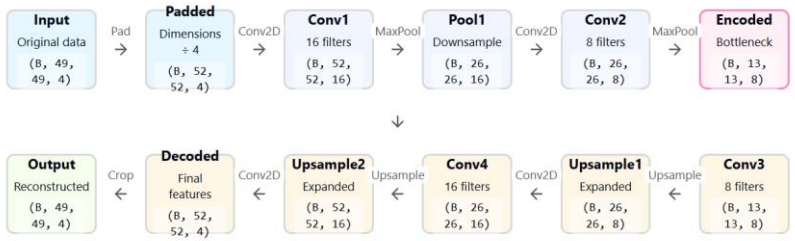


Power lines and substations in Austria and how many of the power lines were affected





Next model iteration – adding causalities



Anomaly Detection Process:

- The autoencoder learns the "normal" patterns in meteorological data during training
- For new data, reconstruction error = MSE between input and output
- Higher errors indicate anomalous weather patterns that may precede storms
- These patterns can be detected before traditional threshold criteria are met

MLStormDetector

+BaseStormDetector base_detector
+AnomalyDetector anomaly_detector
+CausalDiscovery causal_discovery
+PatternMiner pattern_miner
+bool is_trained
Main class integrating traditional
threshold-based detection with
ML-enhanced approaches

+train_models(historical_data)
+detect_storms(data)
+combine_risk_assessments(results)
+visualize_enhanced_results(results)

Contains

BaseStormDetector

+float wind_speed_thresh
+float gust_thresh
+float pressure_drop_thresh
+int min_duration_hours
+string output_dir
Traditional threshold-based
storm detection system with
infrastructure risk assessment

+load_data(era5_path, powerlines_path)
+detect_storms()
+calculate_storm_propagation()
+score_risk_by_gusts()
+compute_impact_timeseries()

Contains

AnomalyDetector

+model
+float threshold
+list features
+bool is_trained
Self-supervised anomaly detection
using autoencoders to identify
unusual weather patterns

+train(historical_data)
+detect(data)

Contains

CausalDiscovery

+dict causal_graph
+dict importance_scores
+bool is_trained
Identifies causal relationships
between meteorological variables
leading to extreme events

+discover(data, target_var)
+analyze(data)

Contains

PatternMiner

+dict patterns
+bool is_trained
Extracts and recognizes recurring
spatiotemporal patterns that
precede extreme events

+extract_patterns(data)
+detect_patterns(data)

Still training……

Produces

EnhancedResults

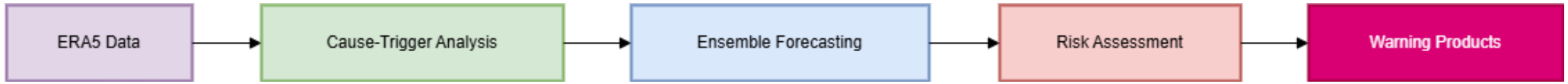
+dict threshold_detection
+dict anomaly_detection
+dict causal_analysis
+dict pattern_detection
+dict enhanced_risk
Comprehensive results combining
threshold-based and ML-enhanced
detection with unified risk assessment

Summarizing

- Stormdetect library for historical, forecasts, and climate applications, will be extended to probabilistic and tested on pointshapefiles/locations.
- All event detection methods, both deterministic and probabilistic, are combined to an adverse weather for RES detection library (applicable to different time scales and scopes
- Historic period currently being calculated for ERA5, NEWA, and Austrian ensemble reanalysis (ARA) → issues with ARA slowed this part down
- Pattern recognition algorithms (SOM, HDBSCAN) currently running

Upcoming:

- Adaptation and integration of the "CauseTrigger" idea and algorithm (HlavackovaSchindler et al.,2025) for our purpose and for probabilistic datasets



HlavackovaSchindler, Katerina & Wöß, Rainer & Pecorino, Vera. (2025). Cause or Trigger? From Philosophy to Causal Modeling. 10.48550/arXiv.2504.01398.

Questions?
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