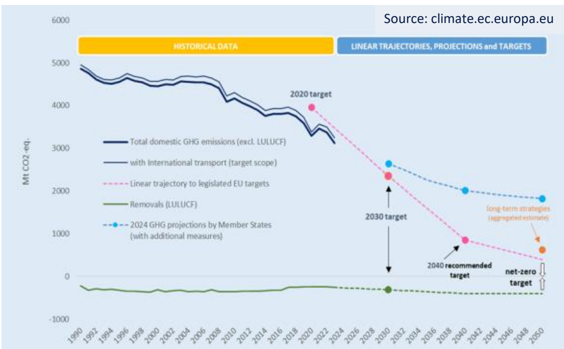
Thank you for attending this seminar. Sorry that I couldn't share it on zoom. I'll keep my notes here so that you can have an idea of what was said in the presentation.

Today, I will present work that is part of a larger ongoing methodological development for the use of CORDEX data in renewable-energy applications. Specifically, I will show results on projected changes in sub-daily wind and solar variability.

1 INTRODUCTION

Energy transition and the growing role of renewables



Decarbonization goals

- “Reducing GHG emissions by at least 55% by 2030, compared to 1990 levels.”
- “Achieving climate neutrality by 2050, meaning net-zero greenhouse gas (GHG) emissions.”

Increasing the share of renewables in the electricity mix

Future power systems will rely increasingly on weather-dependent resources.

Renewable energy -> variable renewable energy (VRE): e.g., solar and wind

2

I want to start with some context. The electricity sector is undergoing a major transformation, driven by the decarbonization goals.

In Europe, these goals include strong emission reductions by 2030 (which is right there) and climate neutrality by 2050.

These transformations rely heavily on increasing the share of renewables in the electricity mix.

In particular, the decreasing costs of solar PV and wind power over the last decade have made them the fastest-growing renewable energy sources.
But they are also a kind of renewables that we call variable renewable energy, or simply VRE, because their generation depends strongly on weather conditions.

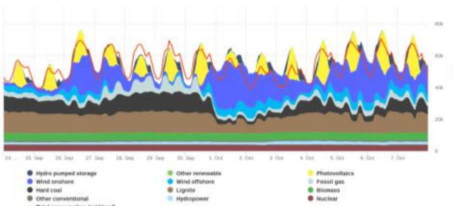
1 INTRODUCTION

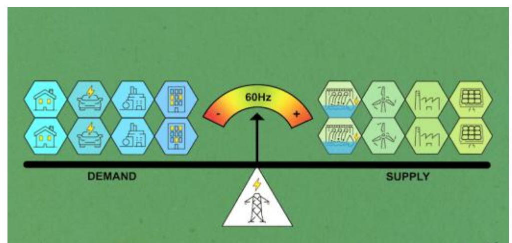
VRE and power-system challenges


Source: pnnl.gov/

Wind and solar variability creates integration challenges, especially at short time scales.

Balance: need for flexibility, storage and reserves.





Source: pnnl.gov/

3

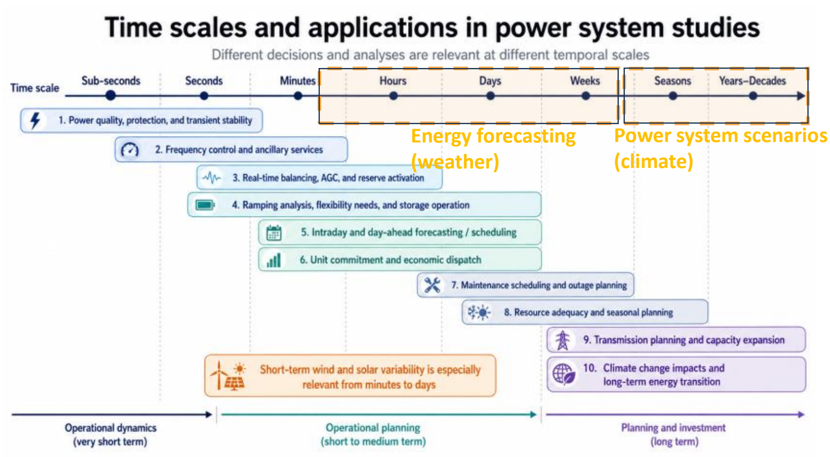
VRE also means intermittent and not controllable, because their output follows atmospheric conditions. The sun is not always shining, and the wind is not always blowing… So they cannot be started at any time, such as dispatchable or more constant sources, as you can see in this example of a generation mix for nuclear, or hydro, or coal, in opposition to solar pv and wind and those cycles of ups and downs as it can be seen in the figure at the bottom left.

In a simplistic way, we can think of a system with batteries to store the excess and be used when necessary, but in reality, the intermittency creates challenges for power systems integration. At short time scales (from hour to sub minute), the system must balance the demand and the supply, deal with forecast errors, respond to rapid ramps, and ensure enough flexibility from different sources, storage, and reserves.

The animation in the bottom right illustrates how this sensitive balance works. If for some reason one of the variables sources goes down, the supply is surpassed by the demand, leading to instabilities or it can even trigger a more serious thing such as a blackout. When it happens, the system operator needs to activate some mechanism to restore the balance, like starting or increasing one of the dispatchable sources, as hydro and coal in this example.

2 MOTIVATION

Why study VRE variability?



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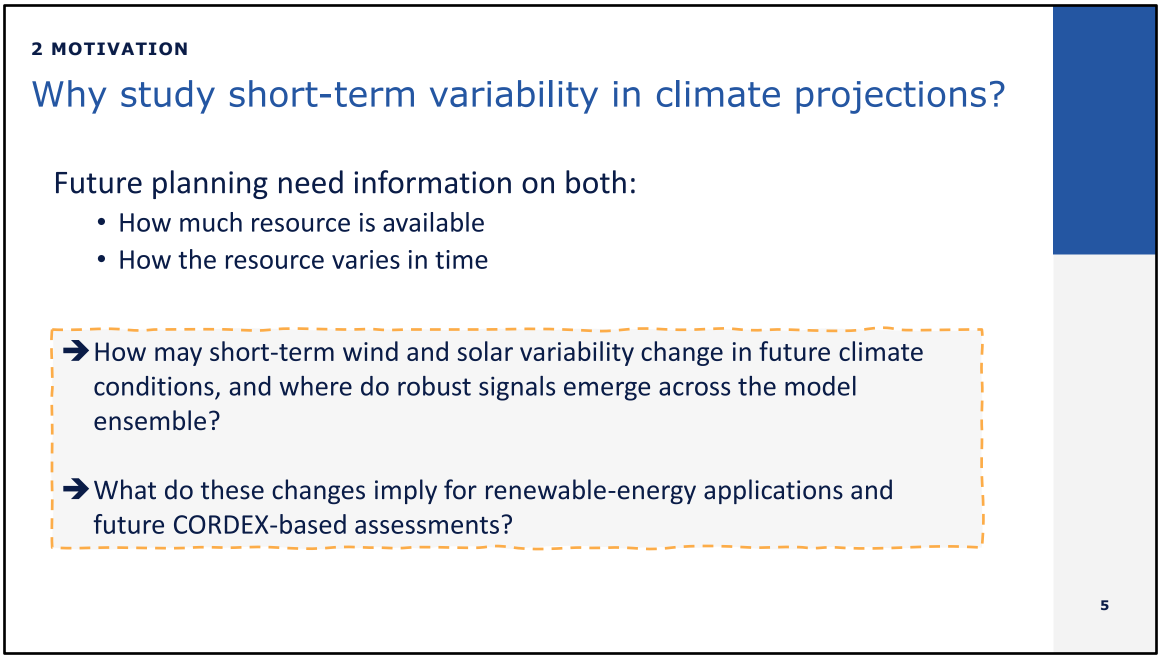
This figure helps to understand the role of time scales in power systems. Different decisions are relevant at different temporal scales.

Very short time scales are related to protection and frequency control.
Hours to days are important for forecasting, balancing, ramping, storage operation, and unit commitment.
Longer time scales, from seasons to decades, are more connected to planning, adequacy, transmission expansion, and climate-change assessments.

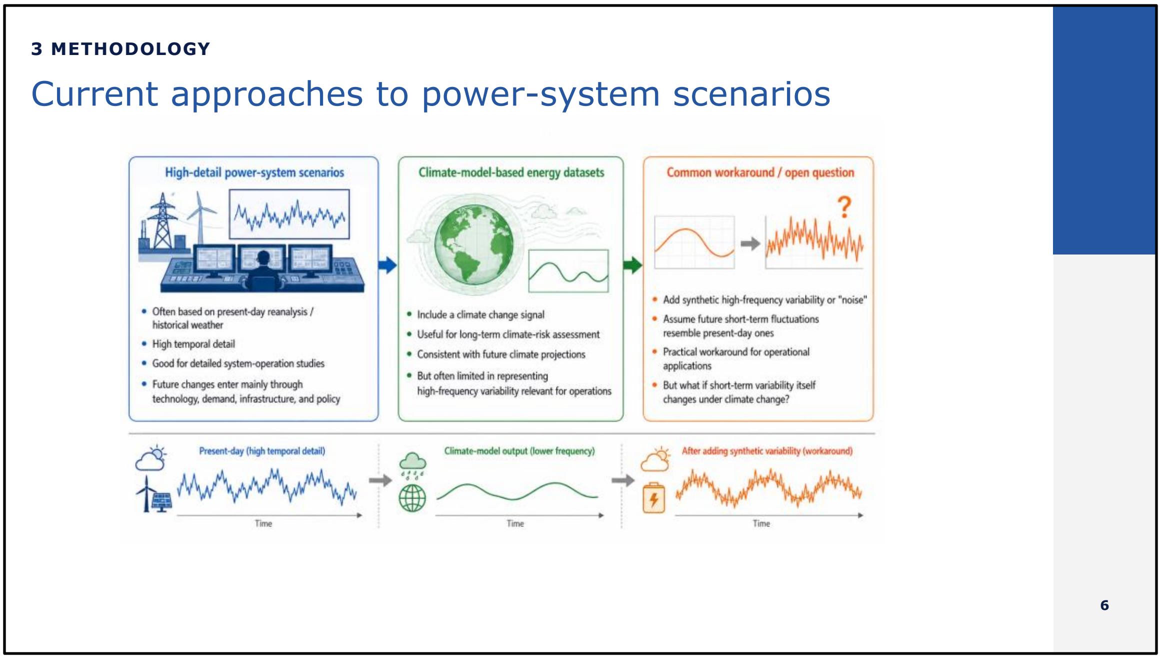
My motivation is at the intersection between these two perspectives. Short-term variability is usually treated as an operational issue, while climate projections are usually used for long-term planning. But if future systems depend strongly on wind and solar, then long-term planning may also need information about how short-term variability could change.



This leads to the central motivation of the work. Future planning needs information on both how much renewable resource is available and how that resource varies in time.

The main research question is: how may short-term wind and solar variability change in future climate conditions, and where do robust signals emerge across the models?

A secondary question is what these changes could imply for renewable-energy applications and for future CORDEX-based assessments.



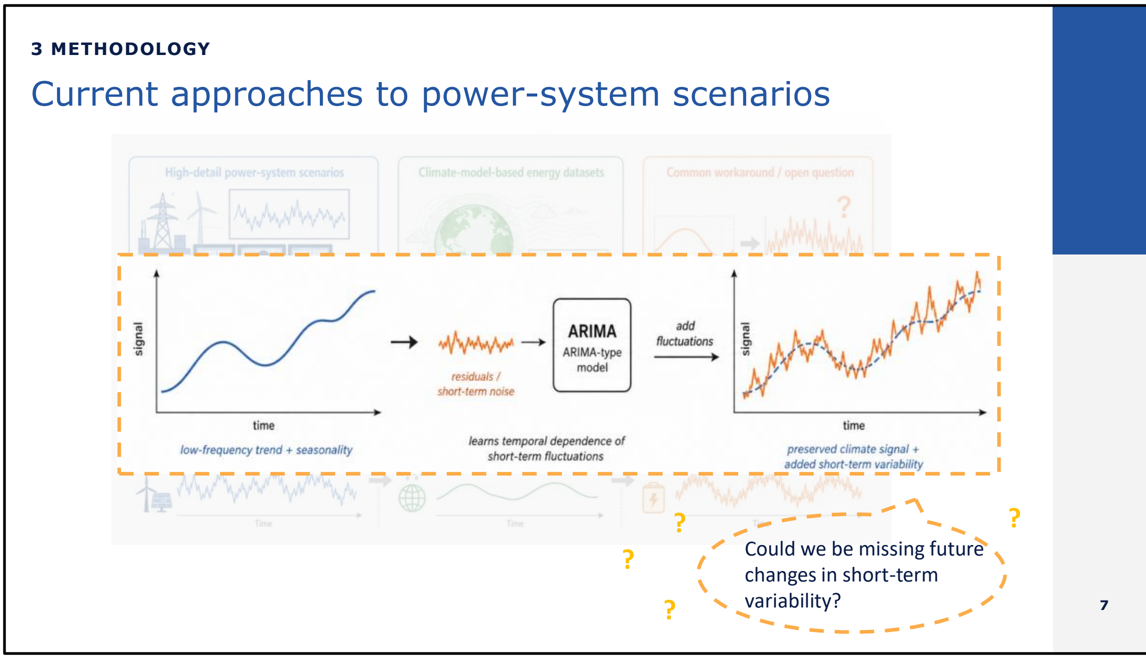
Here I wanted to briefly place the study in relation to current approaches to power-system scenarios, because this is an open problem in the intersection of energy and climate modeling.

Detailed power-system scenarios are often built using present-day weather data, such as reanalysis, and they are combined with assumptions about future changes in technology, demand, infrastructure, and policy. This provides high temporal detail and is very useful for system operation studies. But they do not include effects of climate change on it.

On the other hand, dataset from climate-models do include a climate-change signal, but they are not always used in a way that preserves or evaluates short-term variability relevant for operations. Sometimes high-frequency variability is added synthetically to future time series.

For instance, similarly we do with energy forecast, a statistical model such as ARIMA can be used to generate artificial noisy and be added to make a smooth time series more realistically. The same can be done with the future time series, as to preserve climate signal and add short term variability.

In fact, I have seen some works that compute the delta change from climate simulations and then add this to the reconstructed time series. But this raises a question: by doing this, could we be missing future changes in short-term variability itself? This is something that might help answering the second question of the study.



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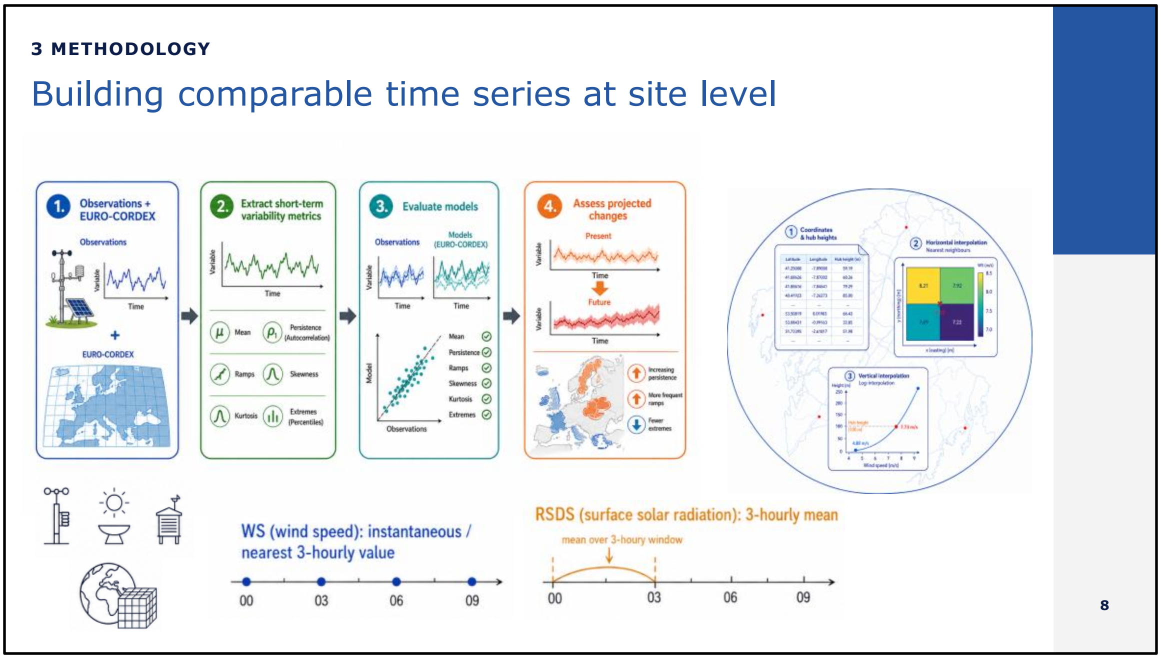
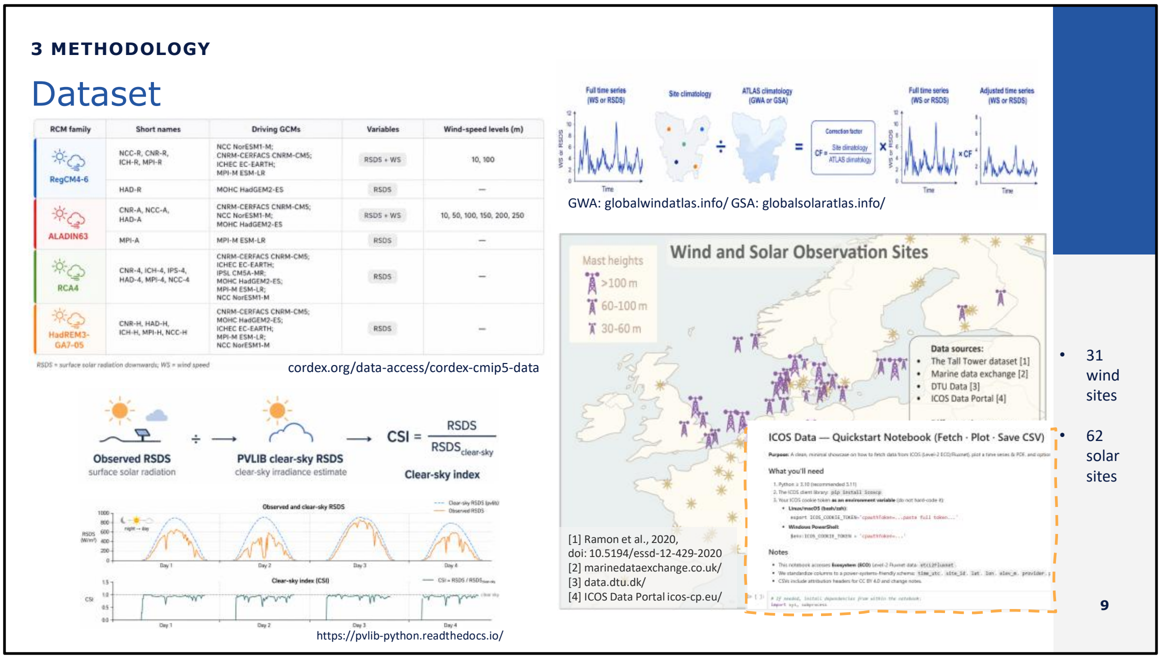


The analysis is done for Europe but at site-level because wind and solar applications are strongly location-dependent, and because observations allow us to evaluate the models more directly.
Additionally, power system models use local time series of solar and wind to simulate VRE generation, and so we can evaluate this potential use for the dataset as a bonus.

For each site, I extracted the corresponding EURO CORDEX time series and extract also the ERA5 time series to be used as a known reference as it is widely used in those power system studies I mentioned before.
I then compute the variability metrics and perform the evaluation. Finally, I compute the present and future model projections for the multiple metrics and assess the projected changes and where the signal is more strong.

The figure shows details on how the horizontal and vertical interpolation are applied, using the k-nearest neighbor and log interpolation using two existing levels.
Below, it's the temporal aggregation, where observed time series extracted from different sources in their native time frequency, were aggregated to 3 hourly frequency (instantaneous for wind and 3-hourly mean for solar) to match the frequency of the cordex data.



As I said, the observations came from different sources, among them, The Tall Tower dataset, Marine Exchange for UK, both of them for wind… Then ICOS dataset (mostly for solar and some wind sites), and others.

It's important to notice that the spatial distribution is not perfectly homogeneous, but there is a considerable number of observed sites and the wind sample cover different heights in various locations. The criteria was to choose data that could be aggregated in 3-h frequency, they are a minimum 5 years long and with more than 80% of completeness. My python notebook with a demonstration on how to extract time series from ICOS is available at ICOS website.

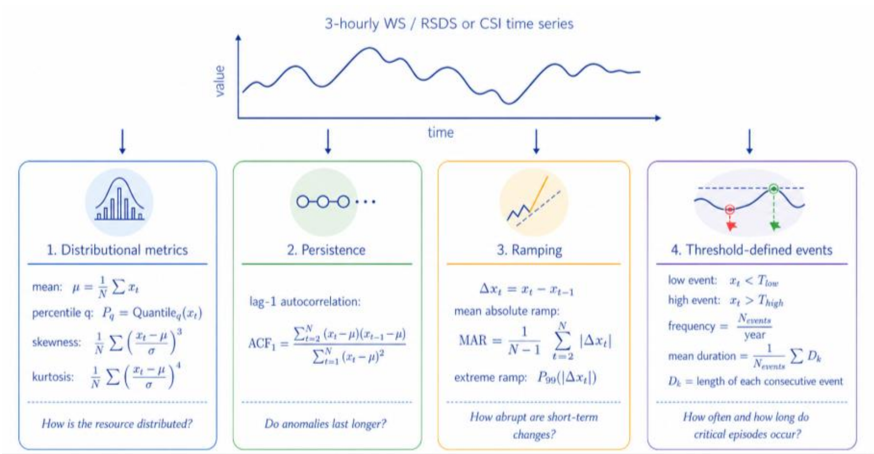
The climate simulations were obtained from EURO CORDEX 12 km. They provide present and future time series (from RCP8.5), which are then processed with the same metric framework used for the observations.

For some solar analysis, I use surface solar radiation directly (RSDS), for others when removing the diurnal cycle was relevant, I used it together with clear-sky information from pvlib to derive clear-sky-index diagnostics.

Lastly, all modeled time series were adjusted using a correction factor to the mean value computed from high resolution atlases (wind and solar). This simple method only shifts the time series up or down, and it's widely used in renewable energy studies. It does not affect the variability metrics.

3 METHODOLOGY

Metrics



These metrics are computed consistently for observations, present-climate simulations, and future simulations.

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As for the metrics, the core of the method is to summarize each time series using families of short-term variability metrics. The first family are basic statistics and describes the distribution of the resource, including mean conditions, percentiles, skewness, and kurtosis, etc.

The second describes persistence, mainly through lag-1 autocorrelation, being lag1 = 3h.
The third describes ramping, using step-to-step changes and extreme ramps.
The fourth describes threshold-defined events, including how often low or high resource episodes occur and how long they last.

The metrics are computed consistently for observations, present-climate simulations, and future simulations. This consistency is what allows the same framework to be used for validation and for projected changes part.

3 METHODOLOGY

Short-term hazards

Short-term hazards and related variability metrics

Hazard / challenge	Why it matters	Related metrics
Persistent low-resource periods	Lower generation for hours–days; more backup, storage, or imports needed.	Event frequency below threshold; mean duration below threshold; P10; lag-1 ACF
Rapid ramps	Sudden power changes increase balancing and flexibility needs.	Mean absolute ramp; ramp P99
Persistent anomalies	Low or high generation regimes may last longer than usual.	Lag-1 ACF; event duration
Extreme high-resource episodes	May cause curtailment, congestion, or operational constraints.	P99; frequency above threshold; mean duration above threshold
More variable distributions	Resource spends more time away from typical conditions.	Std; skewness; kurtosis; P10; P99
Frequent transitions	Repeated low-to-high changes complicate scheduling and flexibility.	Mean absolute ramp; ramp P99
Long cloudy / low-irradiance periods	Relevant for solar adequacy, storage sizing, and backup needs.	Low-CSI event frequency; low-CSI mean duration; lag-1 ACF of CSI
Extended low-wind episodes	Important for wind-energy droughts and system adequacy.	Low-wind event frequency; low-wind mean duration; P10; lag-1 ACF

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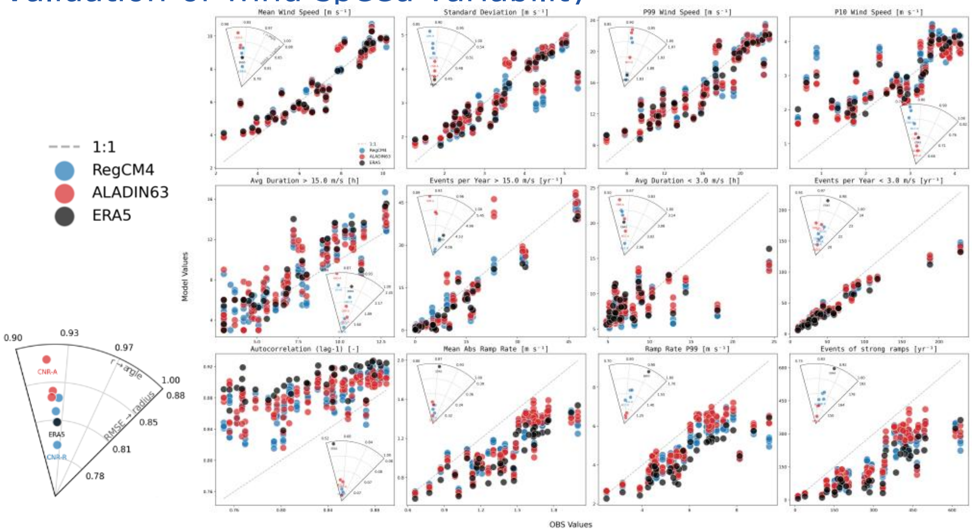
Here are some short term hazards and the related metrics. Note that they are mostly “operational hazards”, meaning that they are disruptions or issues related to operational aspects (not necessarily extremes that might cause damages to structures, which are also important!)

4 RESULTS

Validation of wind speed variability



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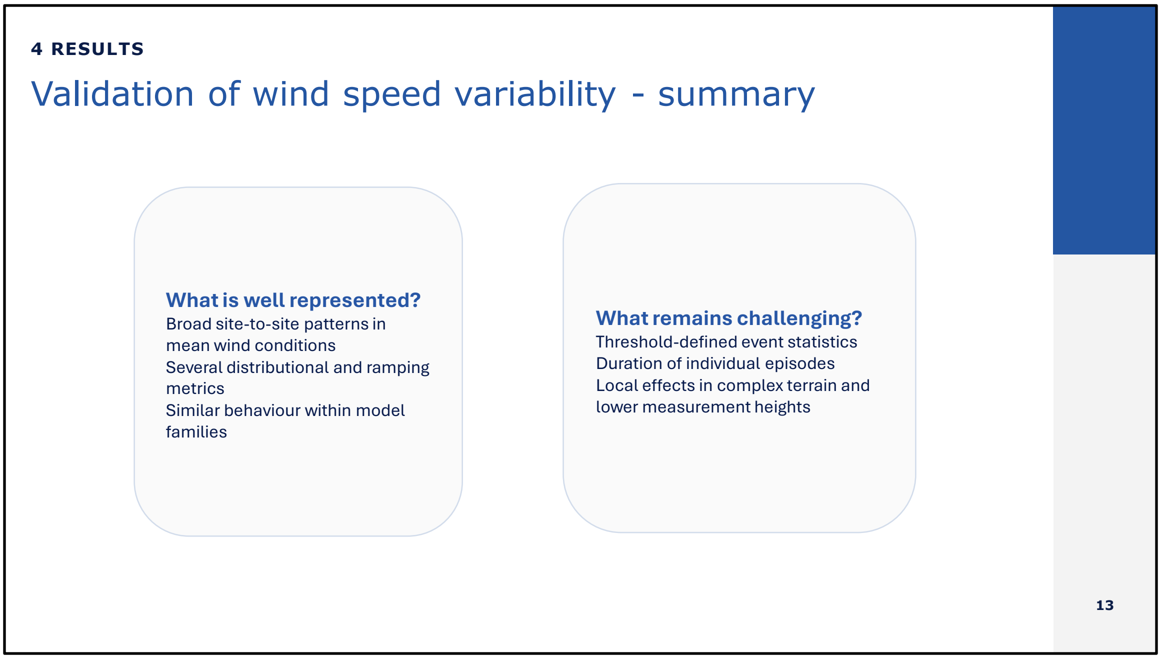
I first apply this framework to wind-speed validation. The figure compares observed metrics with the corresponding values from ERA5 and the EURO-CORDEX simulations at the same sites. The purpose is to ask whether the models reproduce the observed site-to-site variability.

Overall, the models capture several broad patterns, especially for distributional and ramping-related metrics. The event-based metrics are more challenging, particularly when they depend on consecutive threshold exceedances. This is important because these are precisely the metrics that are most closely linked to persistent operational episodes.

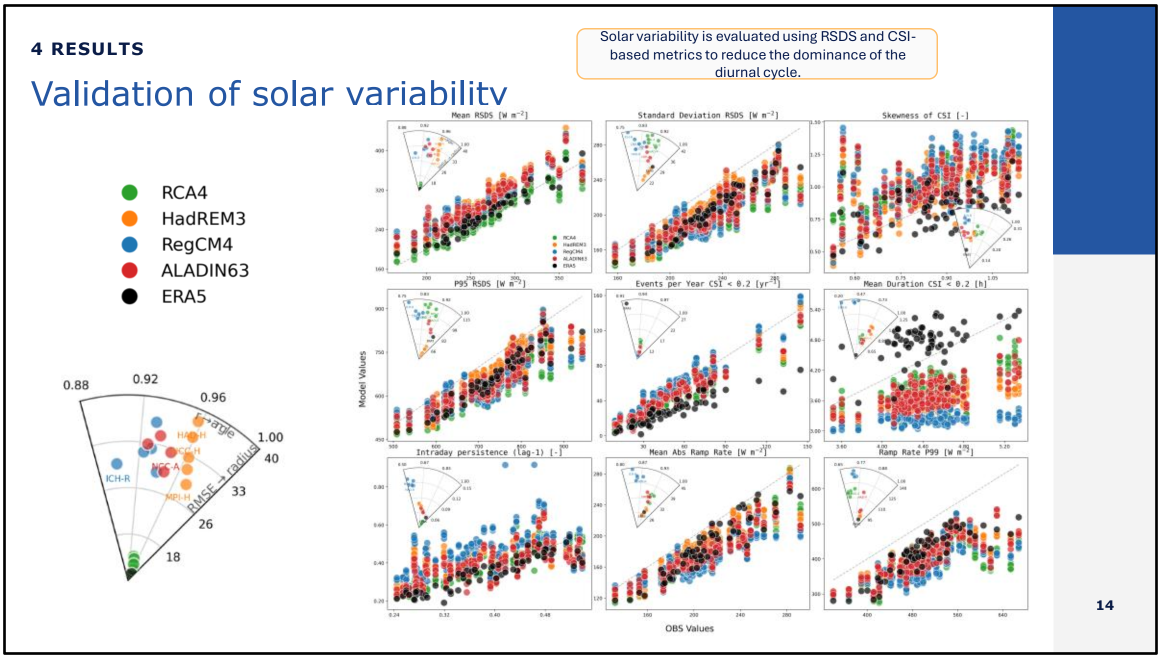


Some aspects are relatively well represented, such as broad site-to-site differences in mean wind conditions and several distributional or ramping metrics.

Differences within model families are often smaller than the differences between simulations and observations or ERA5.

The more challenging aspects are threshold-defined events and the duration of individual episodes, especially at sites where local effects, complex terrain, or measurement height matter.

---->This does not mean the projections cannot be used, but it means that the interpretation should focus on robust, spatially coherent signals rather than isolated site-level changes.



For solar, the validation has an additional complication because surface solar radiation has a very strong diurnal and seasonal cycle. To focus more on short-term variability, part of the analysis uses the clear-sky index, which compares observed or simulated radiation with an estimate of clear-sky conditions.
The validation therefore considers both radiation-based metrics and CSI-based metrics. As for wind, the goal is to evaluate whether the models capture distributional behaviour, persistence, ramping, and low-resource events.

The results suggest that some broad patterns are reproduced, but the spread among sites and the duration of low-resource episodes are more difficult to capture.

4 RESULTS

Validation of solar variability - summary

What is well represented?

- Broad distributional behaviour across sites
- Occurrence of low-CSI events more than their duration
- Some site-to-site contrasts in solar variability

What remains challenging?

- Intraday persistence and event duration
- Compressed spread among sites for some metrics
- Sensitivity to clear-sky normalization and temporal aggregation

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The solar validation summary is similar in spirit to the wind case, but with some solar-specific caveats.

The models reproduce parts of the broad distributional behaviour and some occurrence-based diagnostics, but persistence and event duration are more sensitive to how the clear-sky normalization and temporal aggregation are handled.

This means that CSI-based metrics are useful as variability indicators, but they need careful interpretation!
For the projection analysis, the validation step helps identify which metrics can be interpreted with more confidence, and which ones should be treated mainly as exploratory diagnostics.

4 RESULTS

Projected changes in near surface wind speed

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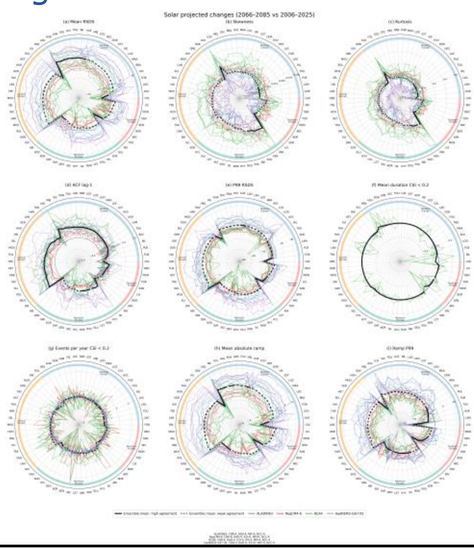
Here the same metrics are computed for a present period and a future period, and the change is calculated for each site, model, and metric.

The radial plots are used to show the spatial sequence of sites and the spread across the ensemble.

The main point to look for is not only whether the mean wind resource changes, but whether the short-term structure changes as well. In particular, I focus on persistence, ramping, and threshold-defined events, and on where the projected changes are more coherent across models.

4 RESULTS

Projected changes in surface solar radiation



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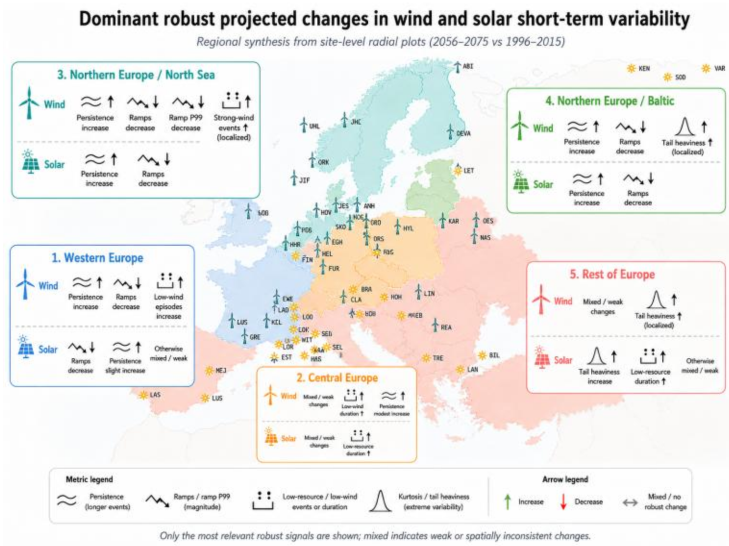
The important message is that the framework is parallel for wind and solar, but the interpretation is resource-specific.

For solar, changes in variability may reflect changes in cloudiness, radiation regimes, and the persistence of low-resource conditions, rather than only changes in total radiation.

5 CONCLUSIONS



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6 NEXT STEPS

- Extend the analysis from separate wind and solar metrics to **combined wind-solar short-term hazards**, including compound low-resource events such as **wind-solar droughts**.
- Evaluate whether the key variability metrics are also represented consistently in the newer **CMIP6-CORDEX simulations**, to assess their suitability for renewable-energy applications.
- Develop methods to adjust short-term variability biases in climate-model output while preserving the projected climate-change signal in variability metrics.
- Finally, expand the framework beyond Europe to other CORDEX domains, allowing comparison of short-term VRE hazards across different climatic and energy-system contexts.

Summary

- Short-term wind and solar variability provides information that is not captured by mean resource changes alone.
- The evaluation shows that EURO-CORDEX simulations reproduce several broad variability patterns, but persistence and event-duration metrics require careful interpretation.
- Projected changes can be assessed through a common metric framework, highlighting where persistence, ramping, and threshold-defined events may change more coherently across the ensemble.
- This provides a methodological basis for using current and forthcoming CORDEX datasets in climate-aware renewable-energy assessments.

To summarize, this work focuses on short-term variability as a complementary perspective to conventional climate-change assessments of renewable resources. Mean conditions remain important, but they do not fully describe the features that matter for balancing, forecasting, ramping, storage, and reliability.

The validation shows that EURO-CORDEX simulations can reproduce several broad variability patterns, although persistence and event-duration metrics remain more challenging.

The projected-change analysis then uses the same metric framework to identify where changes in persistence, ramping, and threshold-defined events may emerge more coherently across the ensemble.

More broadly, the work provides a methodological basis for using current and forthcoming CORDEX datasets to assess climate-related risks for variable renewable energy systems beyond mean-state indicators.


Thank you!
gluzia@ictp.it

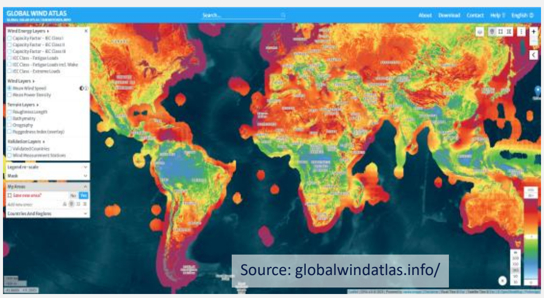
2 RCM FOR RENEWABLES

Wind atlases

Support **energy planning, site selection, and integration studies**

Regional climate simulations used to produce **high-resolution wind atlases**. Provide maps of **long-term averages**, **seasonal patterns**, and **variability**.

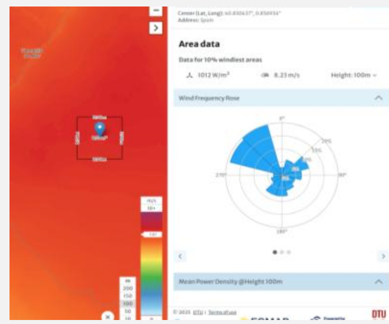
Global Wind Atlas (DTU/World Bank)
Corrected with **mesoscale–microscale coupling** using **CFD**



Regional wind atlases:

- South African wind atlas [1]
- Wind energy resource atlas of Southeast Asia [2]
- New European Wind Atlas [3]

[1] https://sawea.org.za/
[2] http://documents.worldbank.org/curated/en/252541468770659342
[3] https://map.neweuropeanwindatlas.eu/



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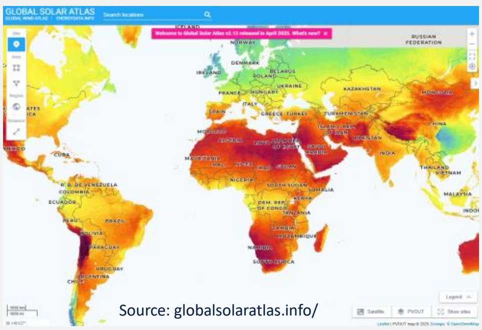
RCMs have also been used to create renewable energy atlases. These combine long-term climate simulations with observational datasets to provide maps of wind speeds and solar radiation across regions. The Global Wind Atlas and Global Solar Atlas are widely used tools for site selection and planning

2 RCM FOR RENEWABLES

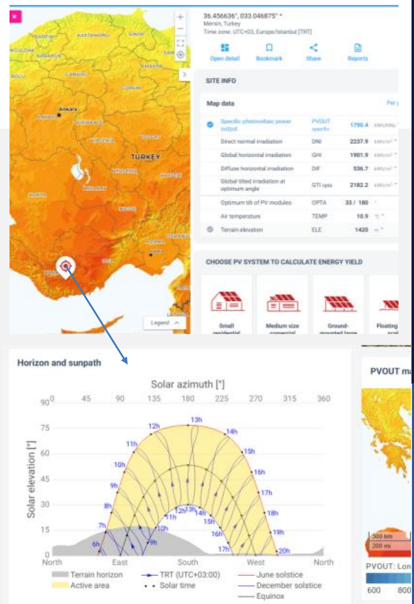
Solar atlases

Usually **satellite + reanalysis based**, or **radiative transfer models**, not RCM-forced. Corrected with ground station measurements.

Global Solar Atlas (World Bank/Solargis)
Regional solar (e.g.): Brazilian Solar Atlas
https://labren.ccst.inpe.br/atlas_2017-en.html



Source: globalsolaratlas.info/



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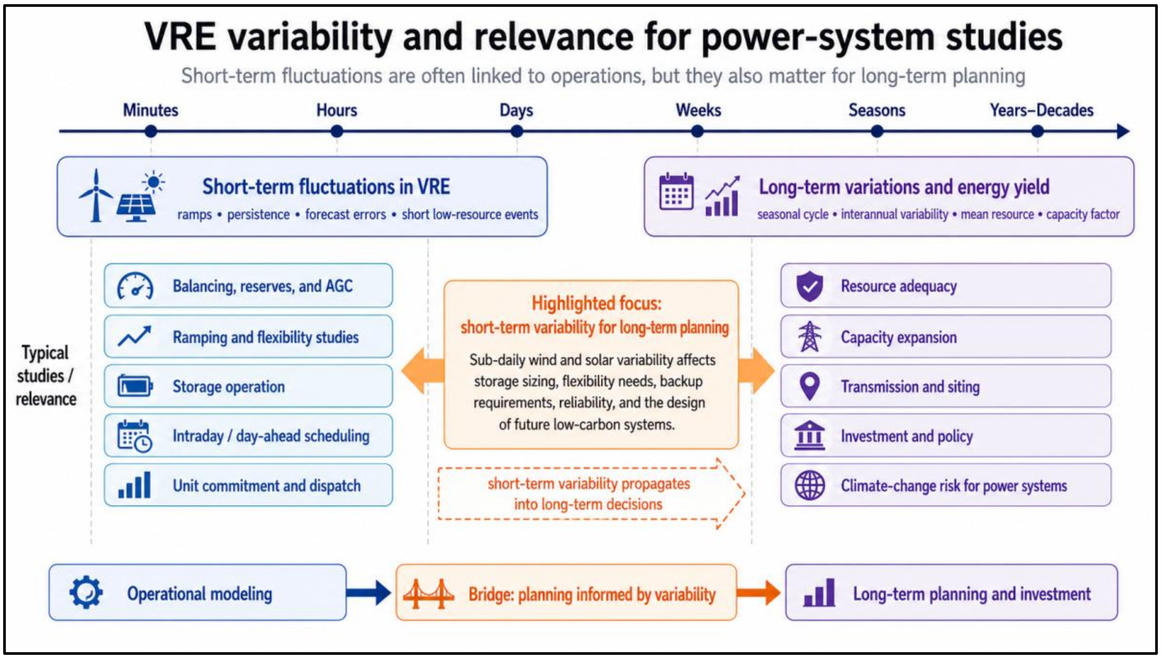

Just a more focused diagram to frame the research in between time scales