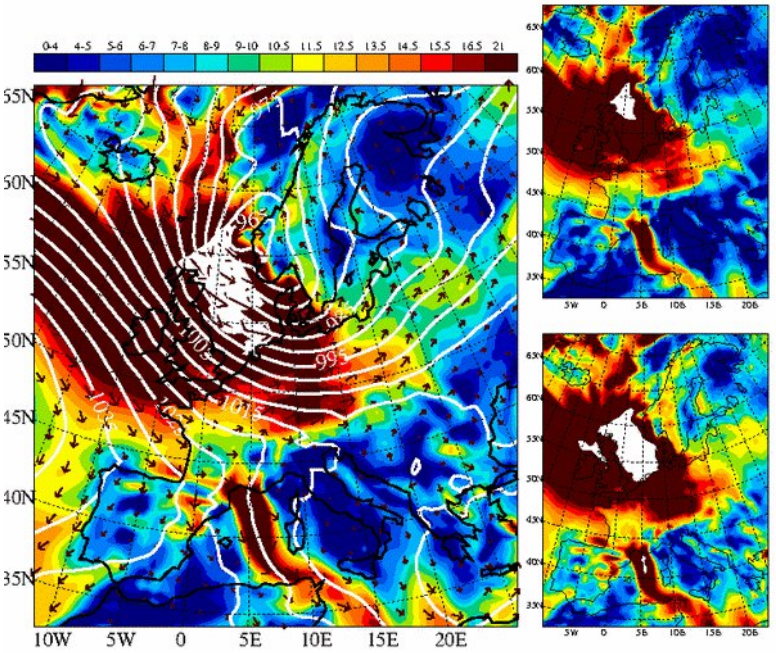
Introduction to weather and power forecasting for the weather-driven Energy System
– WEN II lecture -



Dr. Corinna Möhrlen, WEPROG
University of Stuttgart – 17. January 2024

Corinna Möhrlen - My Background

I am co-founder and director of WEPROG, a European pioneer in wind and solar forecasting, *research-start-up* and the first commercial established wind power forecast vendor in Germany in 2003!

WEPROG's name is an abbreviation of **W**eather & **E**nergy **PROG**noses. We provide **real-time ensemble weather forecasts and energy forecast derivatives** on a global basis for a sustainable energy system in a **continuous (24/7/365) forecast production cycle since 2005.**

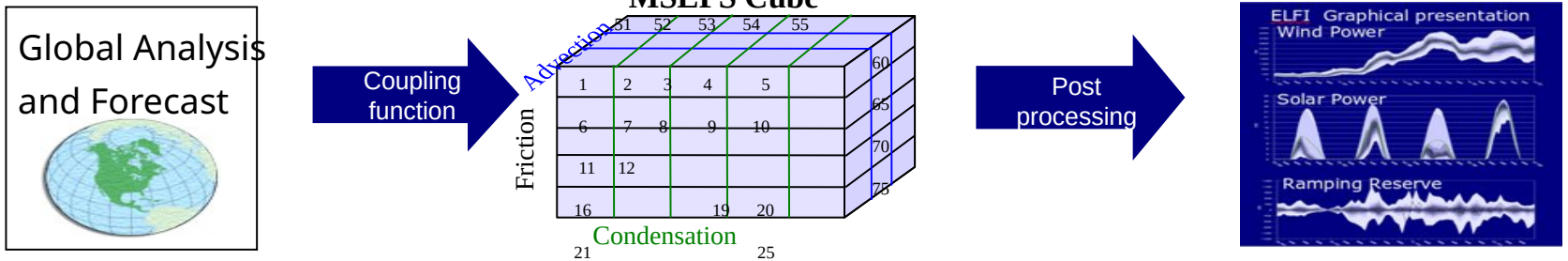
My engagement in forecasting started in 2000 with a PhD in Ireland at University College Cork. Today, I am also member of the management board of the **IEA Wind Task 51** "Forecasting for the weather-driven Energy System" and **lead author and editor of the IEA Wind Recommended Practice industry guideline.**

The **lecture** is an introduction into renewables forecasting for grid integration and trading with an exercise developed in the IEA Wind Task 51 framework in collaboration with Dr. Nadine Fleischhut from Max-Planck institute of Human Resources

WEPROG

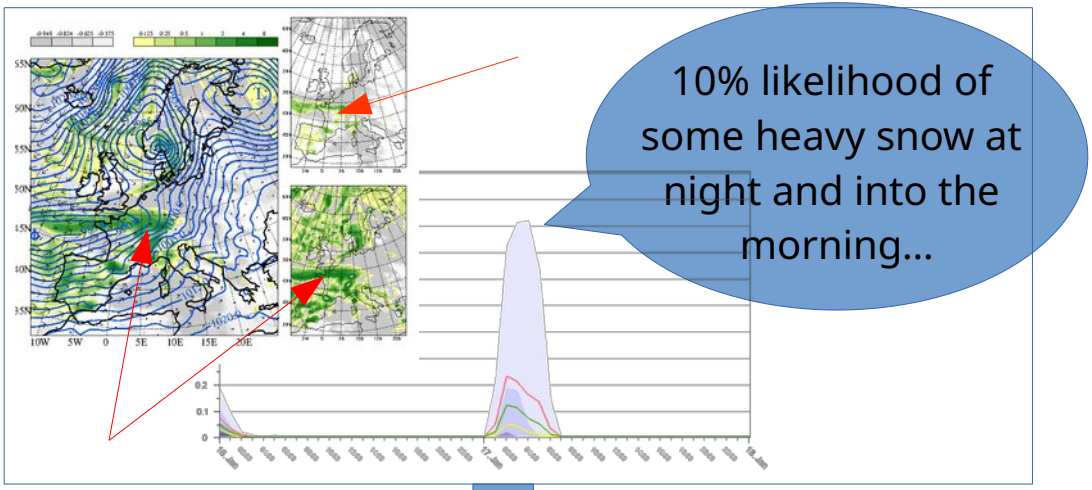
75 independent limited area numerical weather prodiction (NWP) forecasts

Probabilistic weather, wind & solar power forecast services



What is the purpose of (uncertainty) forecasts ?

Cloudy with splits of freezing rain, temperatures mostly above zero and some sun...



Do you take your umbrella with you or wear your winter boots and hat in the morning ?

Just a rainy day ?

Traffic chaos ?

Getting it right is not always only a matter of a “correct” or bad forecast, but also dependent on the ability to understand and interpret the raw forecast well enough !

How and why forecasts create value

Global analysis/ state estimate (Met center)

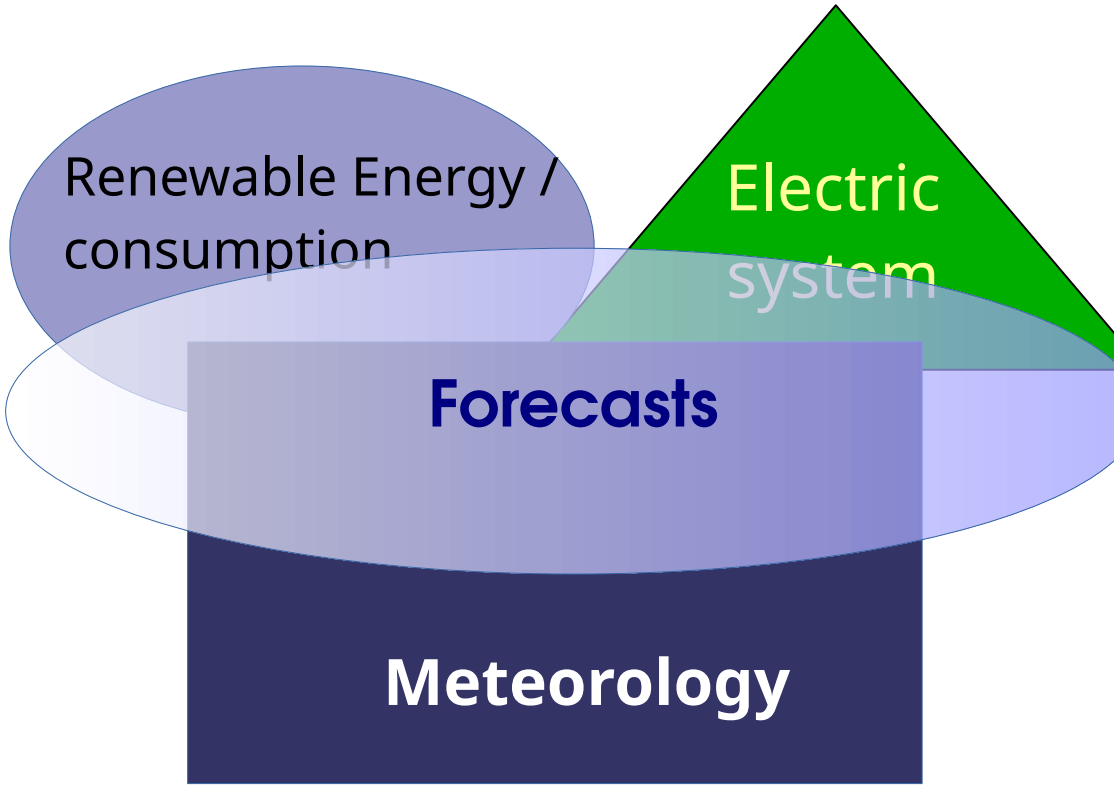
Ensemble Forecasts (WEPROG)

Power Forecasts (WEPROG)

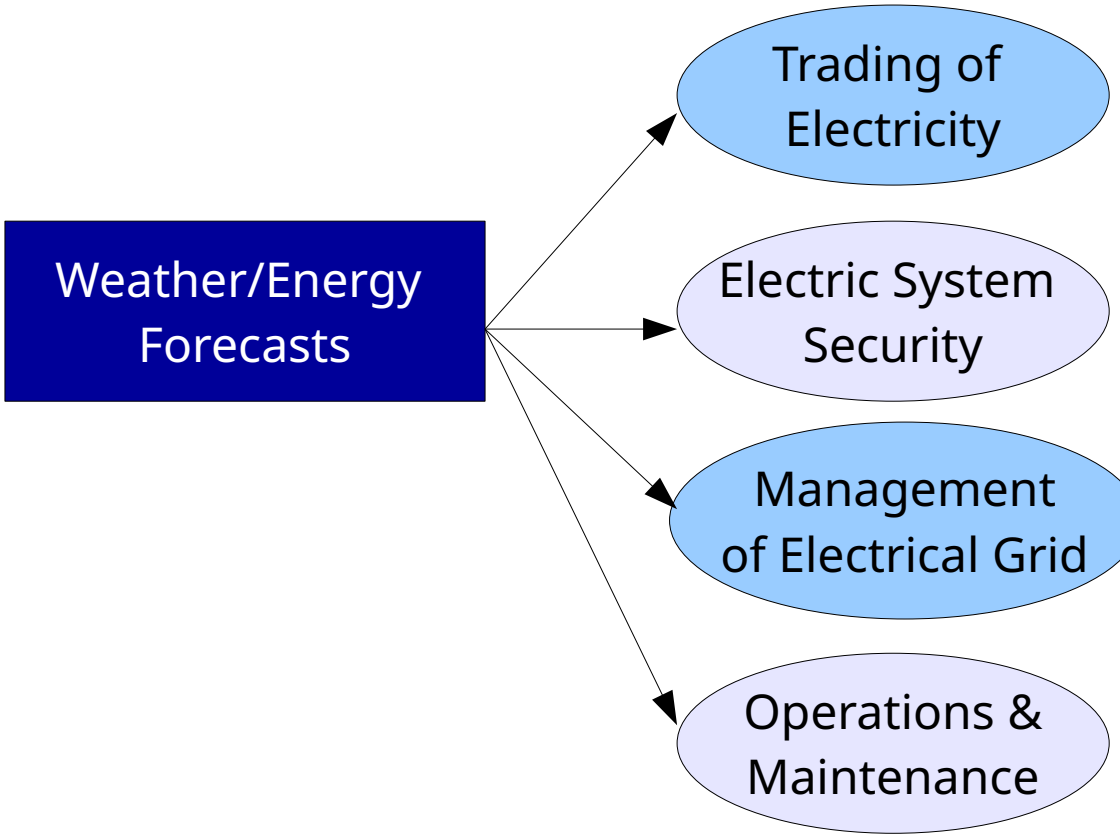
Balance responsible party (Trader)

Power Market (EPEX, NordPool,)

System operator (in Germany: Trannsnet, Ampron, 50Hertz, TenneT)



Applications of Weather & Energy Forecasts in Energy Industry



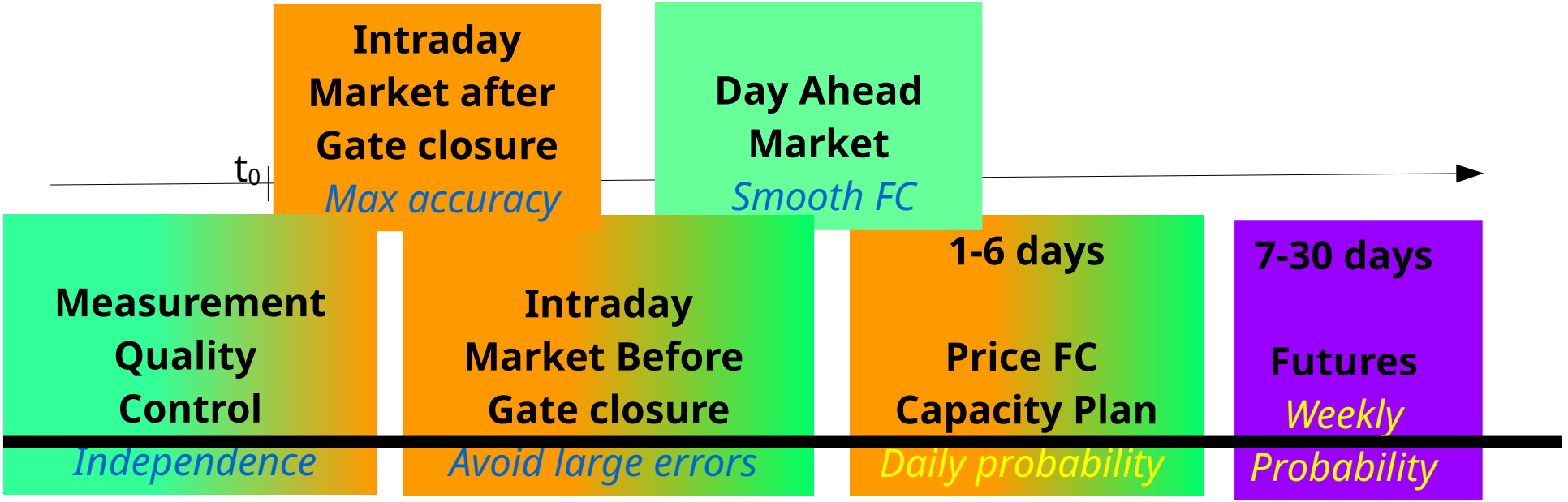
- Wind/Solar power Forecasts
- Temperature Forecasts
- Load forecasting

- Weather forecasts
- Wind/Solar Power forecasts

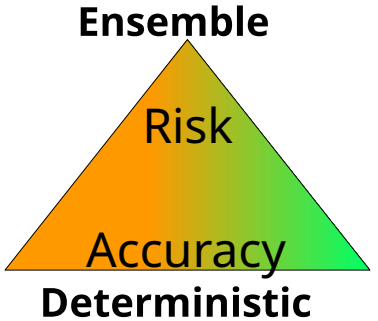
- Temperature forecasts
- Wind/Wind chill forecasts
- icing forecasts
- Wind/Solar forecasts

- Weather conditions forecasts
- Wind/Solar Power Forecasts

Time-scales of Forecast Applications in Energy markets



Can one Ensemble approach work for all applications ?



It is a prerequisite !!!

How Weather & Power Forecasts are used

Forecast use in industry TODAY:

- **Long Term Forecast**
  delivered 6 hourly | 5 day time horizon | 15 minute resolution
- **Short Term Forecast**
  delivered every 15 minutes | 36 hour time horizon | 15 minute resolution
- **Regional Forecasts**
  delivered 6 hourly | 5 day time horizon | 15 minute resolution

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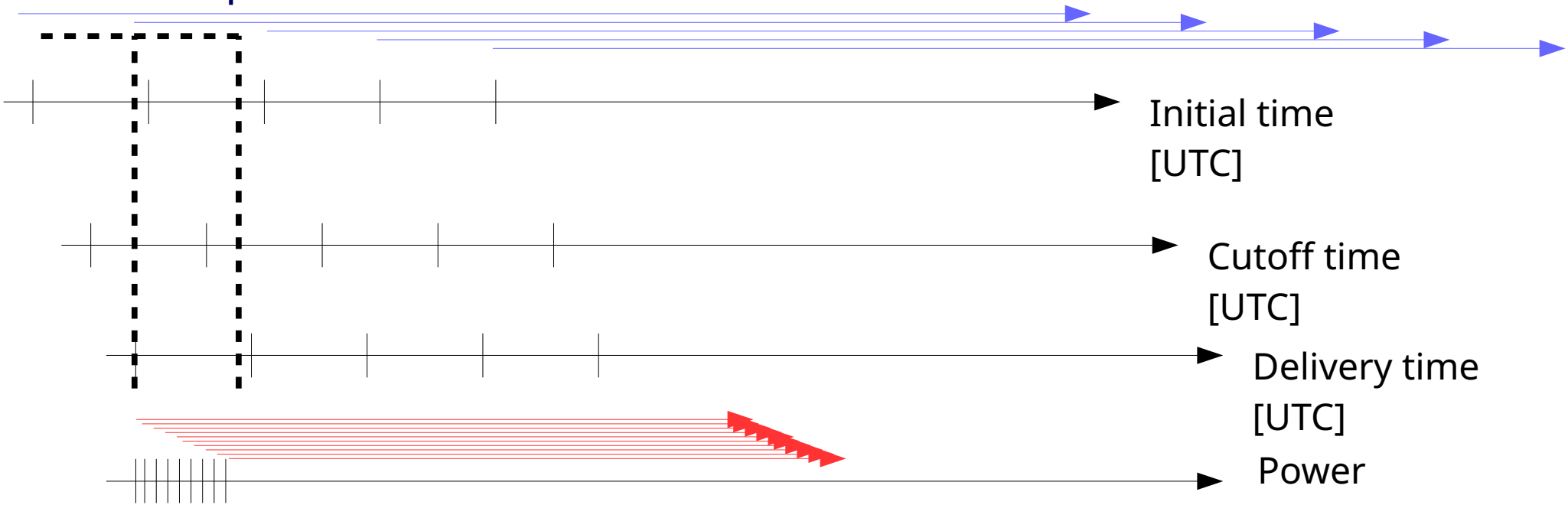
Forecast use in industry with high penetration > 30%

Ultra-short-term Forecasts
delivered every 1 minute | 1 hour time horizon | 1 minute resolution

High-Speed Shut-down Warning System
delivered on-demand | 6-7 day time horizon | 15min/1 hour resolution

Bridging two cultures: Meteorology and Power Industry
Expectations on “Lead time” and “Time resolution”



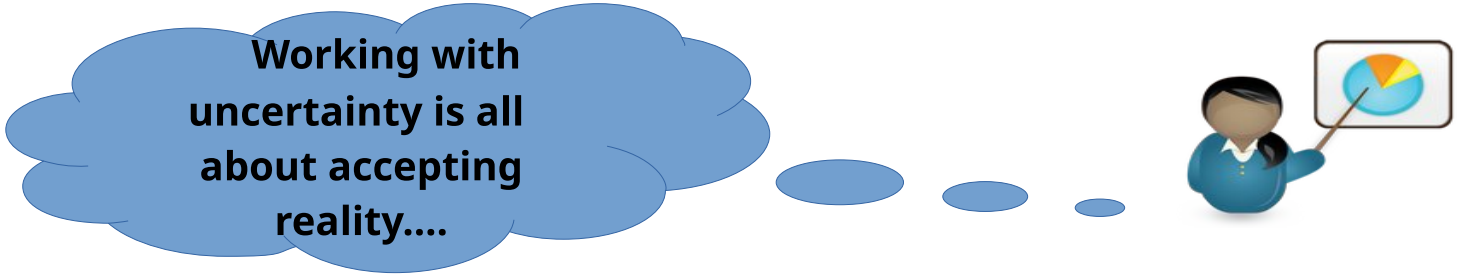
Note about native NWP data:

Minute scale variability → no correlation with reality → noise

All data spatially averaged → amplitude weaker than reality

Dynamical imbalance etc. → most accurate lead time at 6-7 hours

What is the purpose of uncertainty forecasts ?



.. if a forecaster issues a deterministic forecast the underlying uncertainty is still there, and **the forecaster has to make a best guess at the likely outcome**.

Unless the forecaster fully understands the decision that the user is going to make based on the forecast, and the impact of different outcomes,

Uncertainty forecasts make the unknown atmospheric development visible, so we can take a decision based on a more realistic picture of the future...

What is a Short-Range Weather Ensemble ?

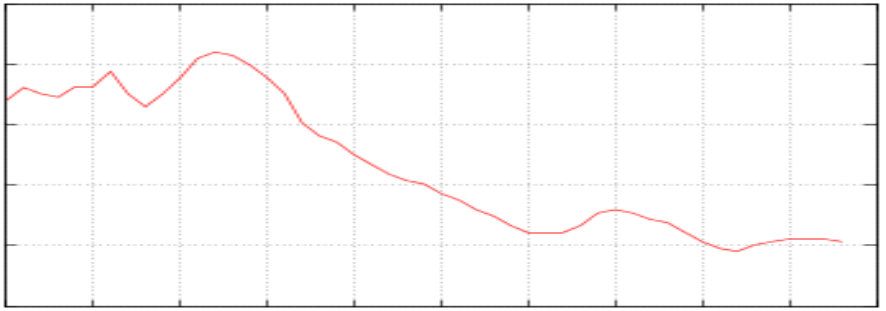
Ensemble Forecasts => Many weather forecasts

Short-Range => 0-48 hours ahead

Traditional method of weather forecasting:

Deterministic

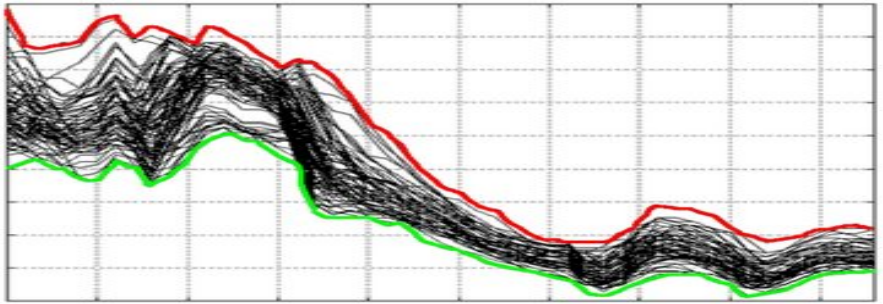
=> 1 forecasts that is considered
the best possible outcome from
the numerical model



Ensemble method:

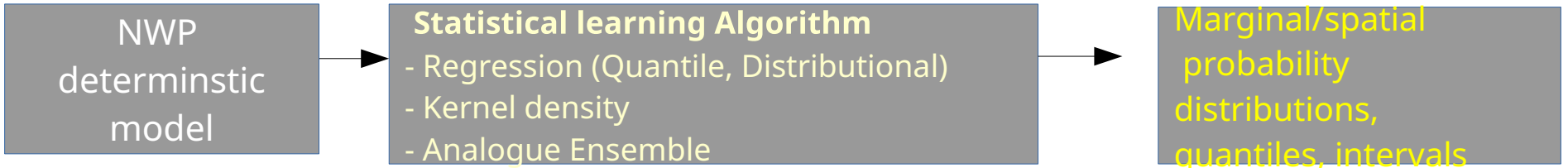
Probabilistic

=> statistical interpretation of
the most likely of many
physically possible outcomes

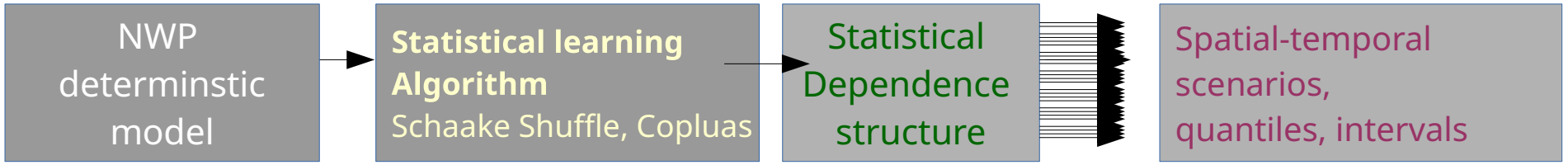


Methods for generating Uncertainty Forecasts

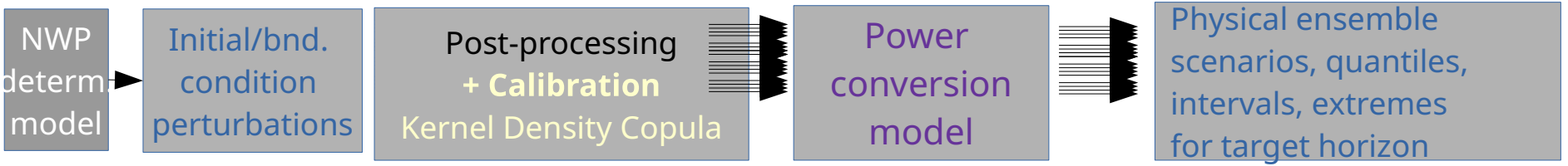
(1) Statistical Methods of Probabilistic Forecasts



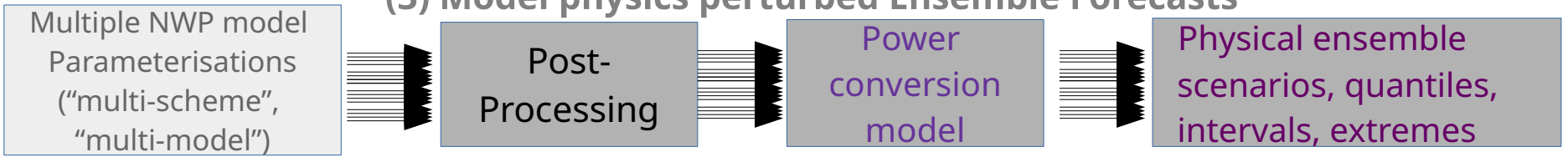
(2) Statistically-based Scenarios



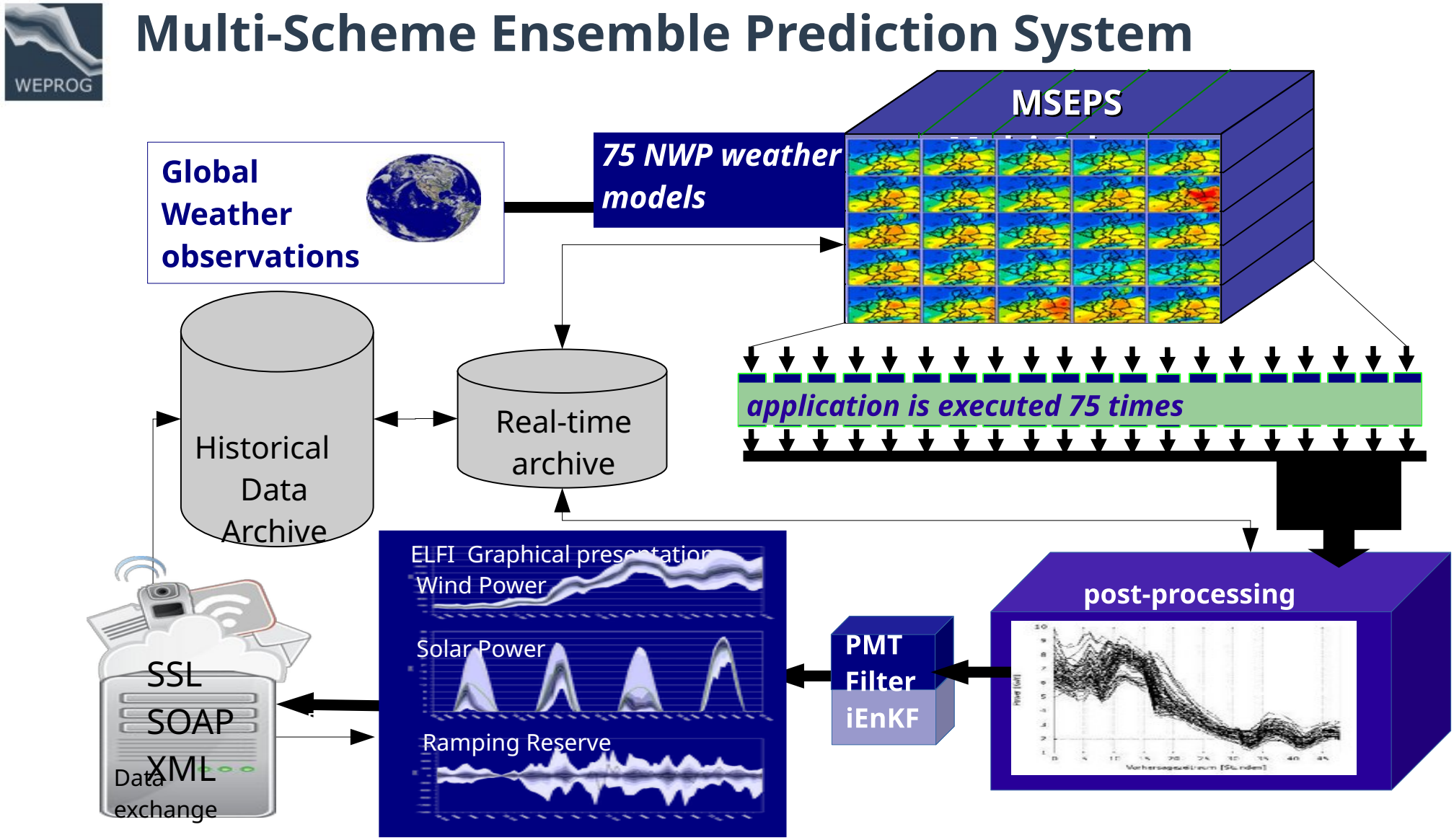
(4) Initial Conditions perturbed Ensemble Forecasts



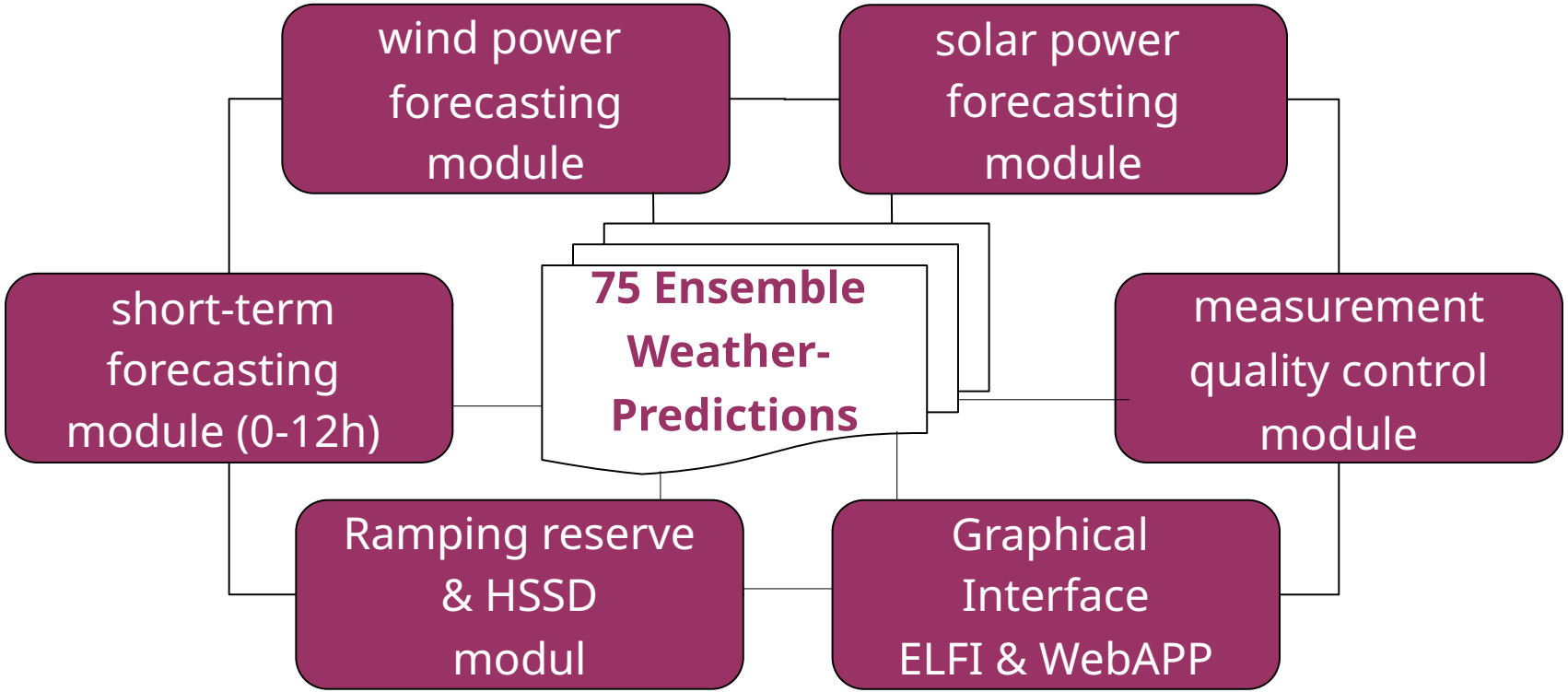
(3) Model physics perturbed Ensemble Forecasts



Multi-Scheme Ensemble Prediction System

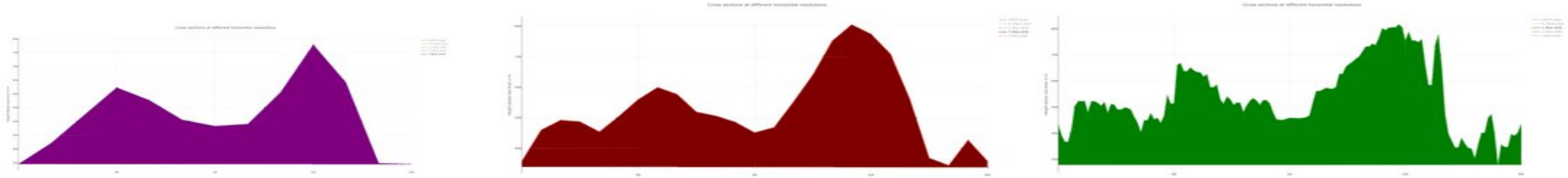


WEPROG's MSEPS modular Forecasting System

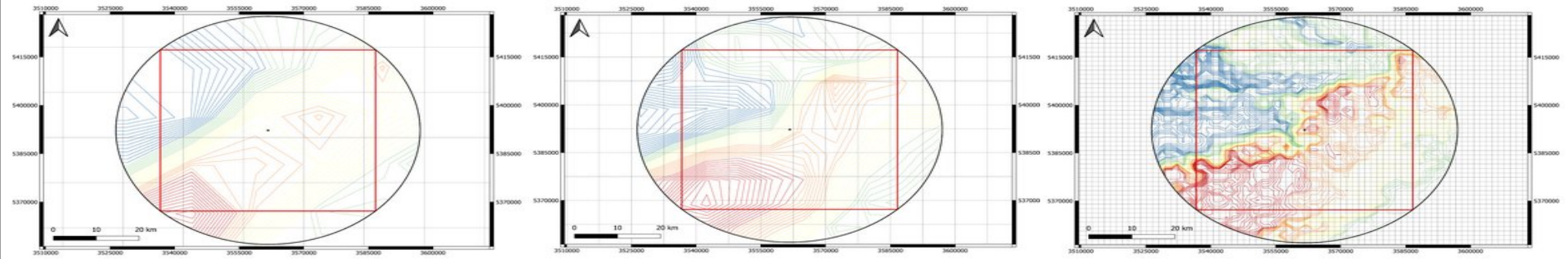


Visualisation of different resolutions in climate data for the meso-scale model

Profile of different model resolutions



Terrain profile of different model resolutions

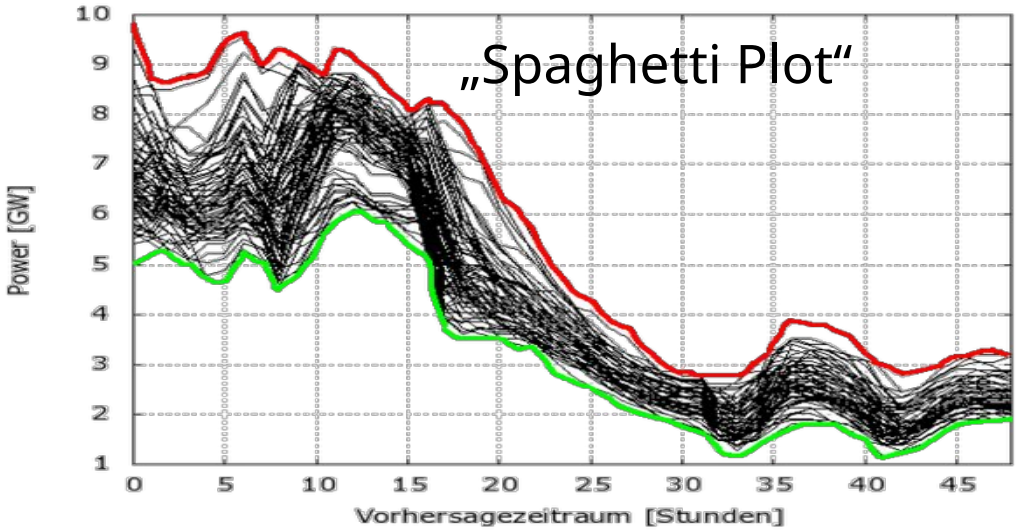


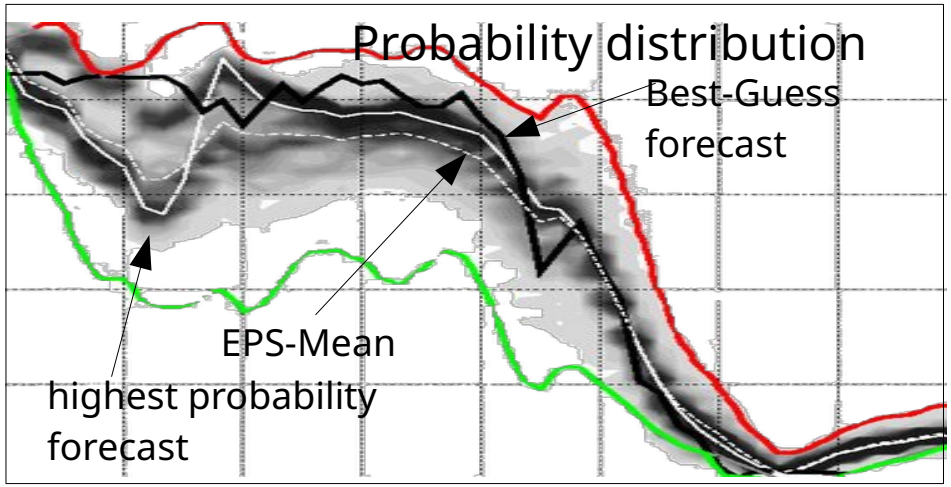
15km (operational)

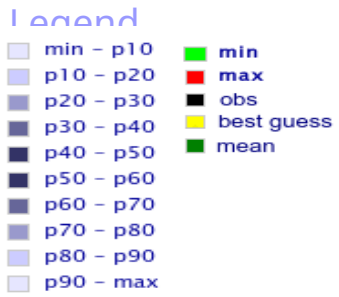
7.5km (partially operational)

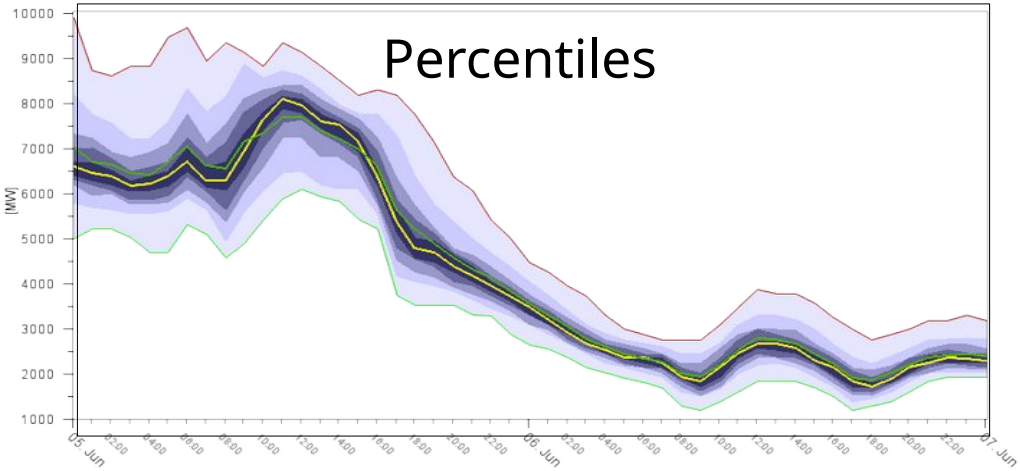
1.4km (research)

Different ways of visualising uncertainty forecasts







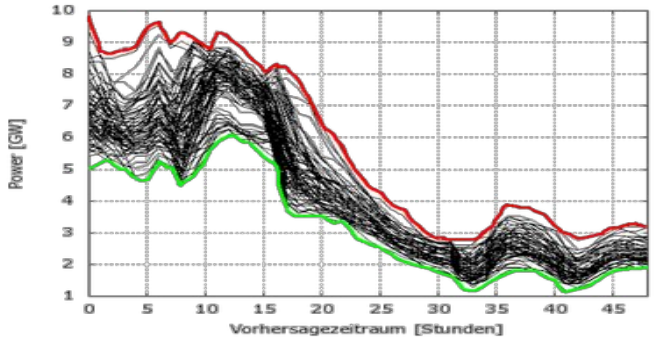


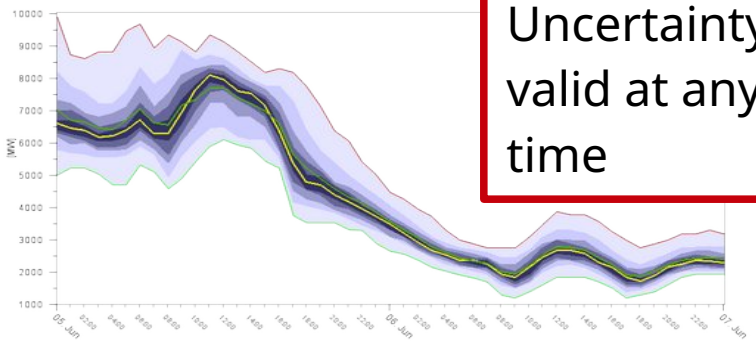
Meaning of “target lead time” in Ensemble Forecasting

Type 3

Multi-Scheme / Multi-model Ensemble Prediction Systems

- physically stirred uncertainty -



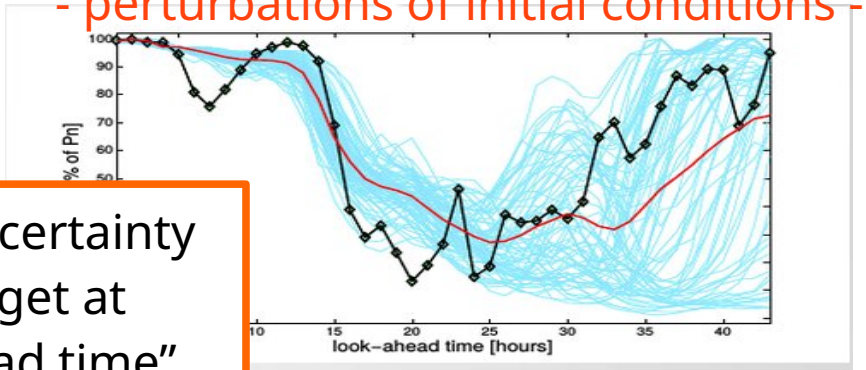


Uncertainty valid at any time

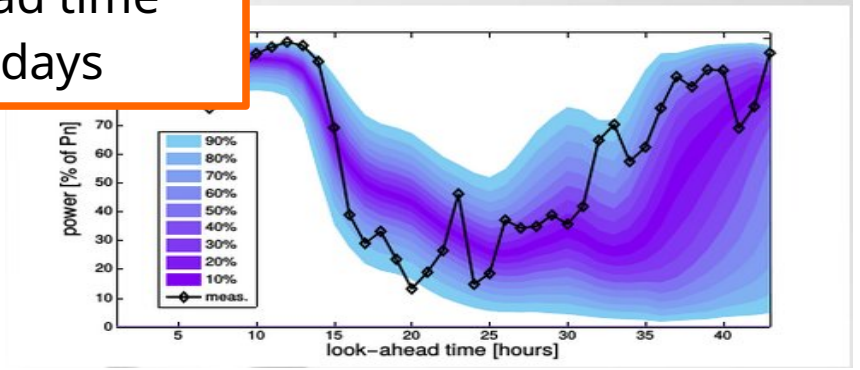
Type 4

Stochastic/SV/Breeding Ensemble Prediction Systems

- perturbations of initial conditions -

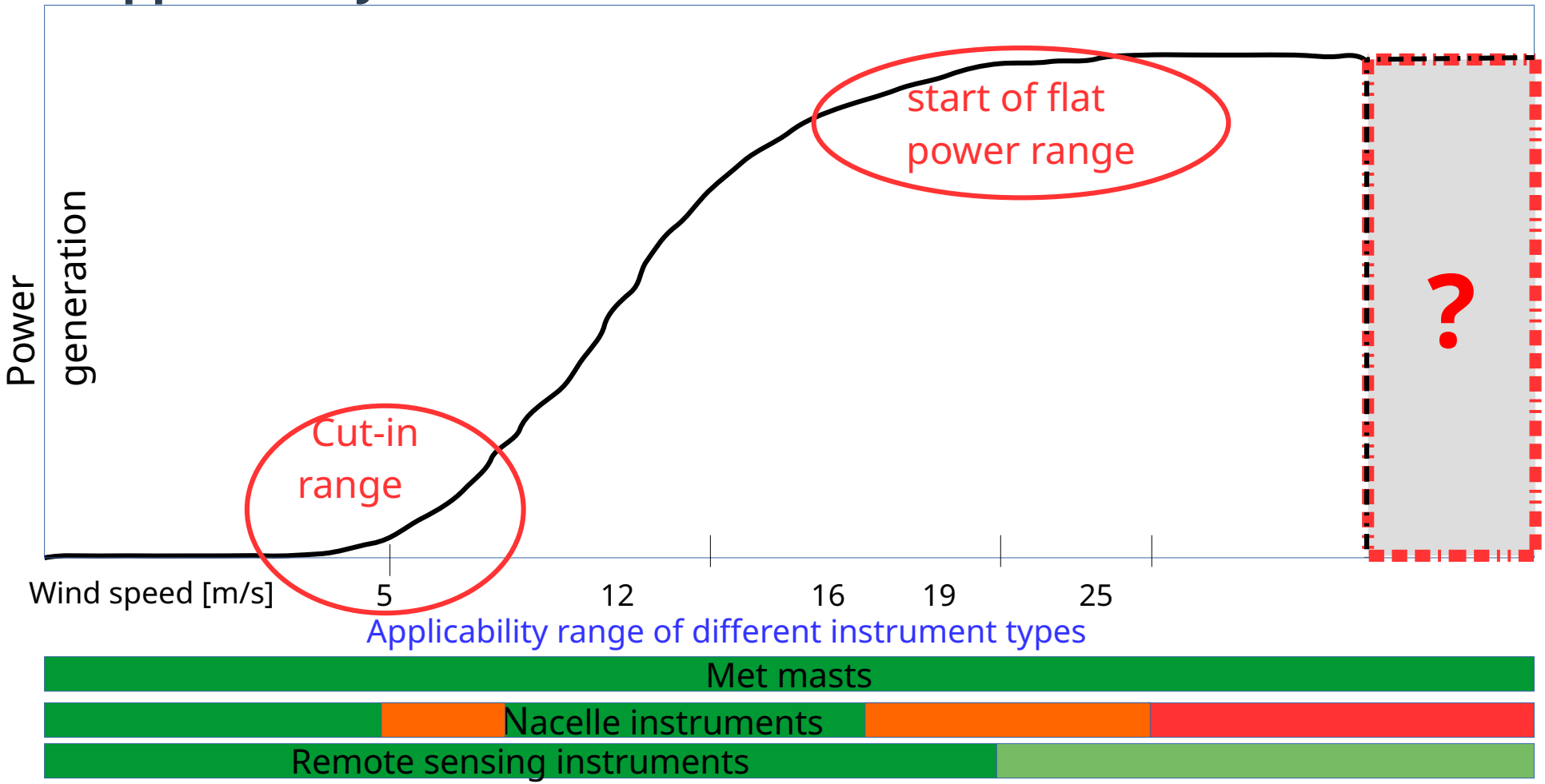


Uncertainty target at “lead time” > 2days



Source: http://www2.imm.dtu.dk/%7Epp/docs/pinsonmadsen09_ensemble_techreport.pdf

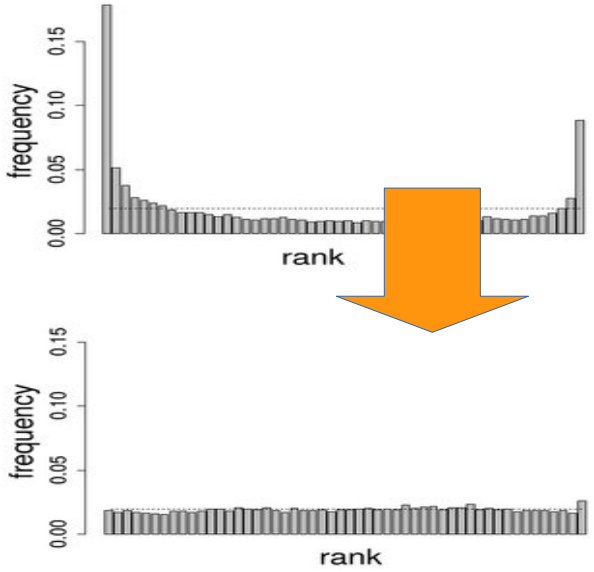
Importance of Meteorological Measurements and Applicability of various Instrumentation



Non-model-physics-perturbed (statistically generated) Methods often require calibration

Statistical calibration methods:

- Analogue Ensemble (AnEPS)
- Ensemble Model Output Statistics (EMOS)
- Logistic regression
- Non-homogenous Gaussian Regression
- Adaptive Calibration



Methods are required to generate statistical consistency at specific lead times

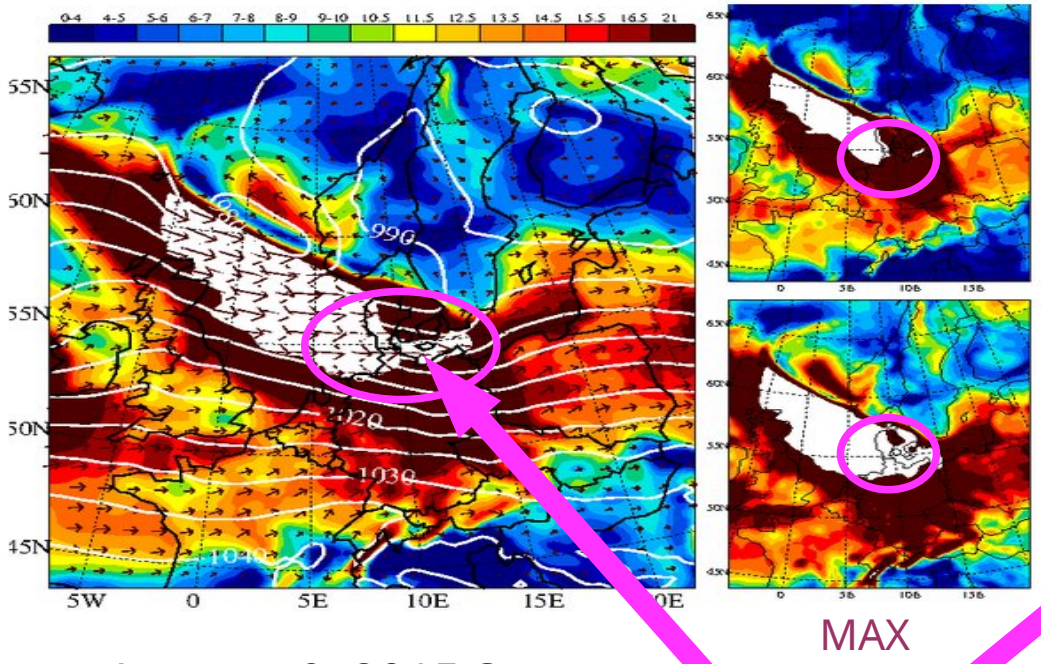
→ correct for dispersiveness (bell/u-shaped ranked histograms)
→ correct for missing spread

Example of weather Uncertainty at German Offshore Wind Farm

Mean, Maximum and Minimum Wind Speed from 75 forecasts

Mean of 75 forecasts

MIN



MAX

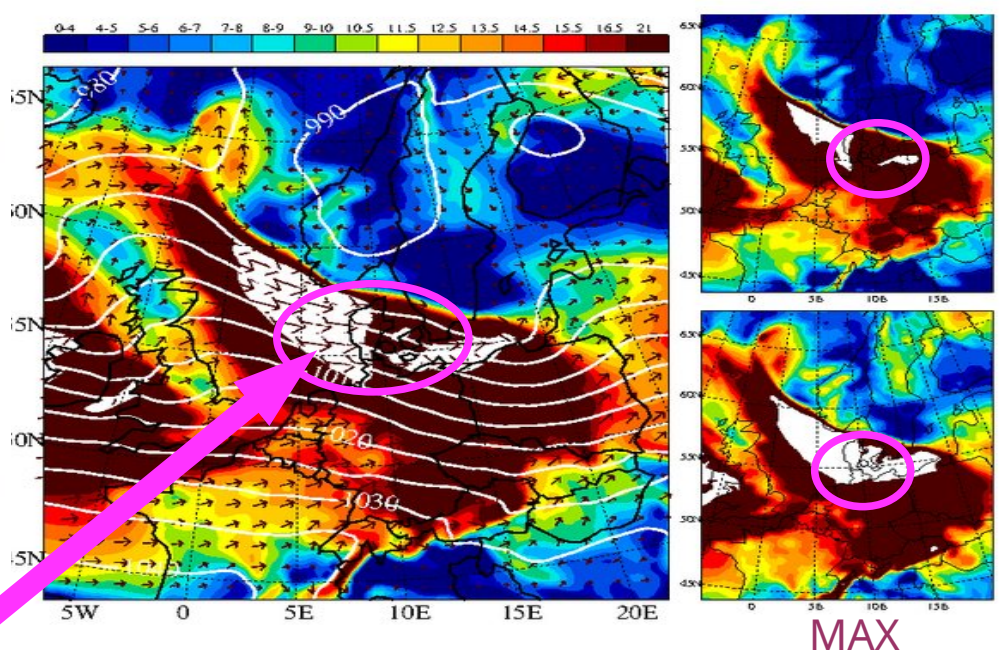
January 9, 2015 Storm

12 UTC

White areas:
Wind speeds out of scale (>25m/s)

Mean of 75 forecasts

MIN

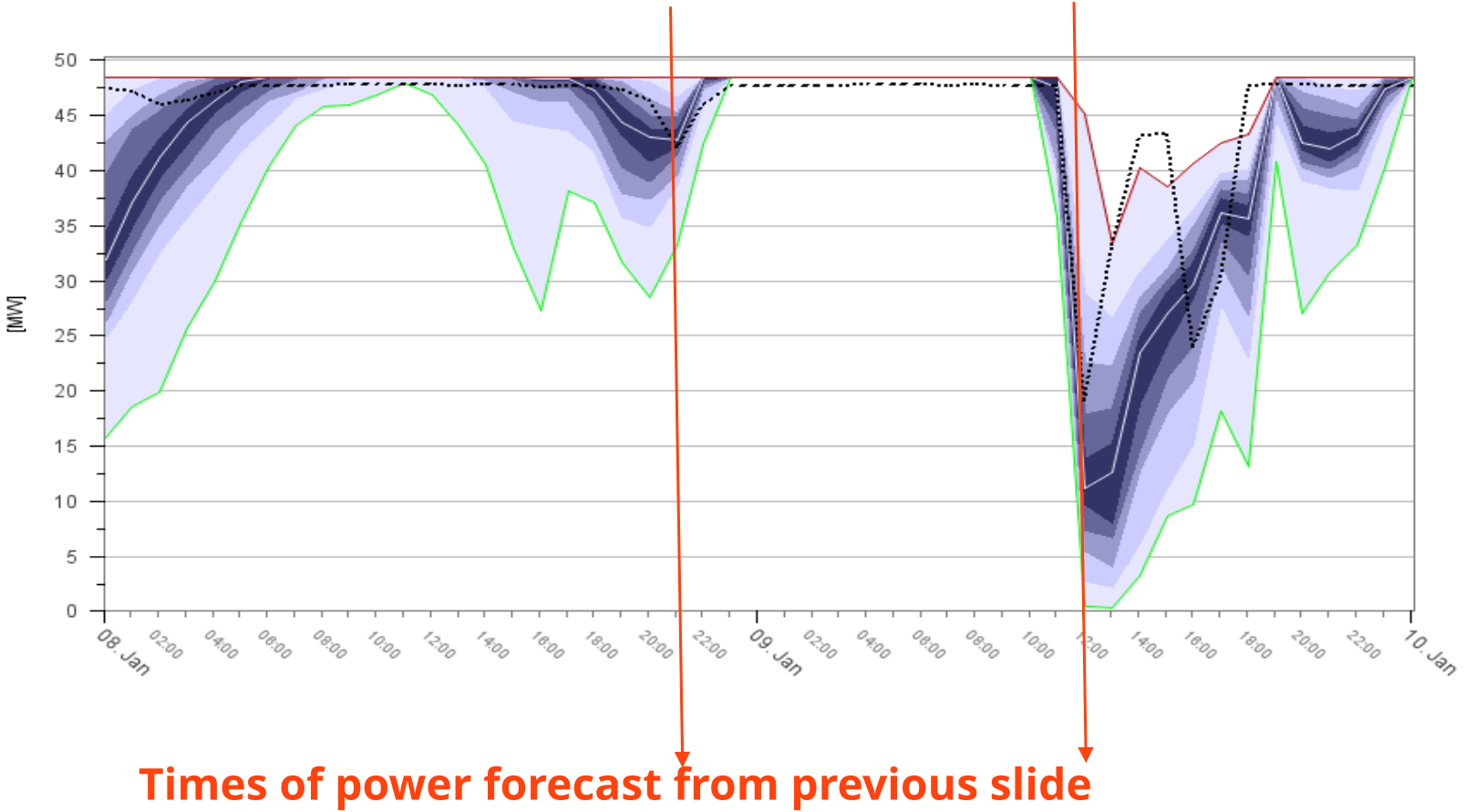


MAX

January 9, 2015 Storm

16 UTC

Example of weather Uncertainty at German Offshore Wind Farm



sometimes large uncertainty shows exactly what the issue is at hand..

Often it is extreme events:
- Cut-off
- Icing

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wexicom

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Max-Planck-Institut für Bildungsforschung
Max Planck Institute for Human Development

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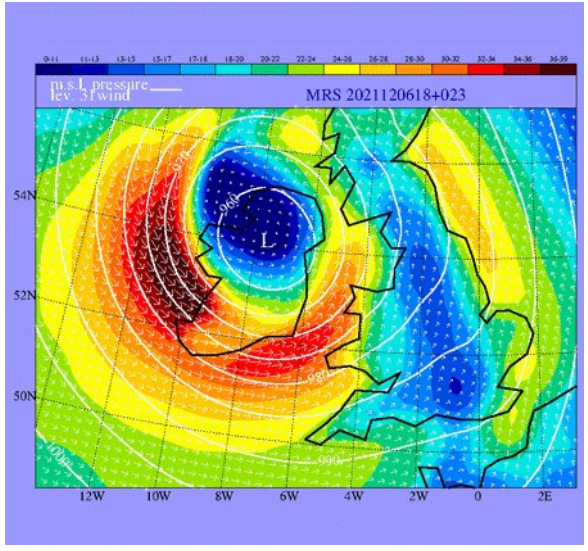
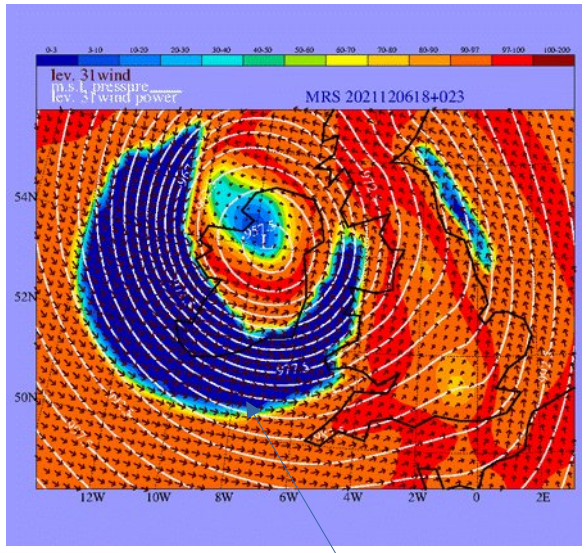
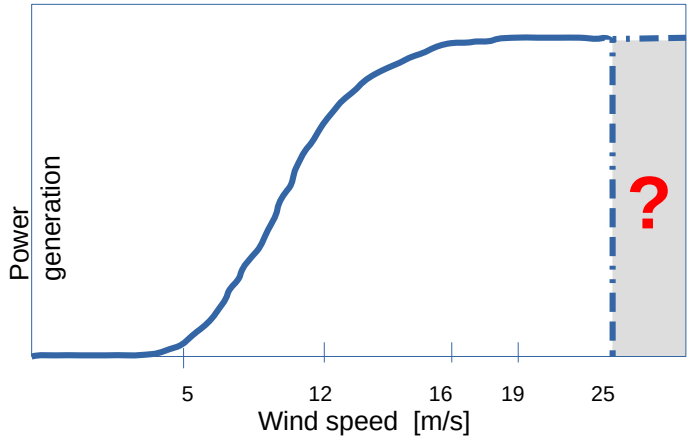
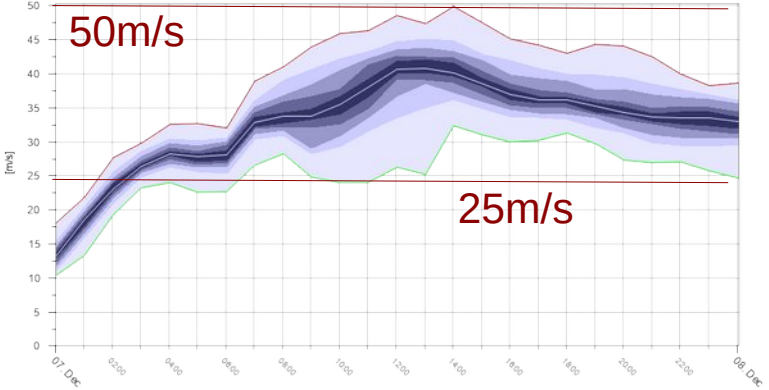
Dealing with Extremes....
...from forecast to impact...



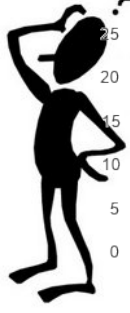


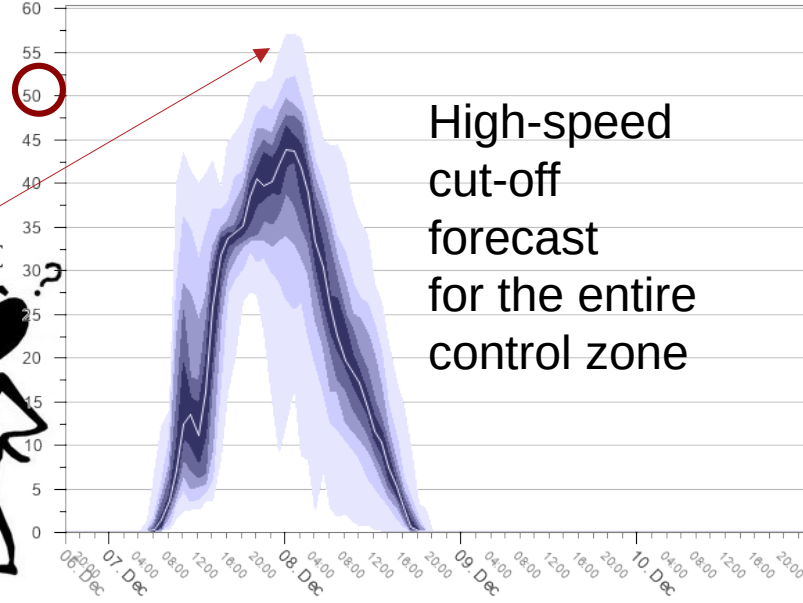




Cut-off area

...if over 50% of capacity can drip, how do I have to handle this.. ?



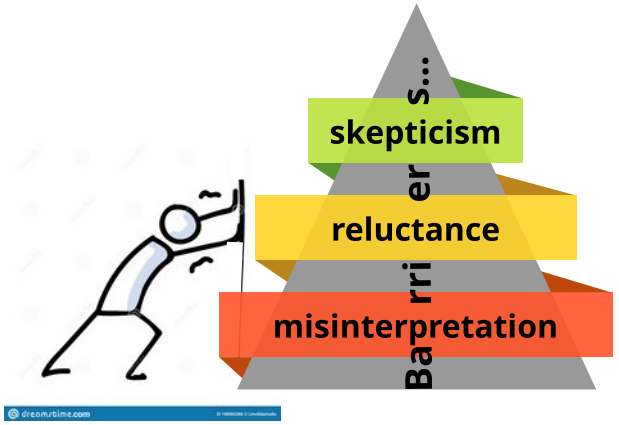


High-speed cut-off forecast for the entire control zone

Forecast Games and Experiments Initiative

Goals and Objectives of the Initiative

Our aim is:
break down barriers of making use of probabilistic forecasts



Our experiments are designed with the following principles:

i. from "~~**decision from description**~~" → "**decision from experience**"

ii. from "~~**theoretical learning**~~" → "**learning with feedback**"

iii. from "~~**classroom setup**~~" → "**Playing games of (complex) problems in a relaxed atmosphere**"

Forecast Games and Experiments Initiative

Research Questions

How are probabilistic forecasts used & when do they benefit decisions?

- Decision outcomes: Do users make better decisions and in which forecast situations?
- Risk preferences: Do they decide more risk averse or risk seeking?
- Decision strategies: What cues (“predictors”) do they use and how?
- Representation format: Which representations work best?

Do probabilistic forecasts allow better learning from feedback?

- How confident are users in their decisions?
- How well can they learn to calibrate their confidence? (Knowing when you don’t know)
- How do users react to failure?

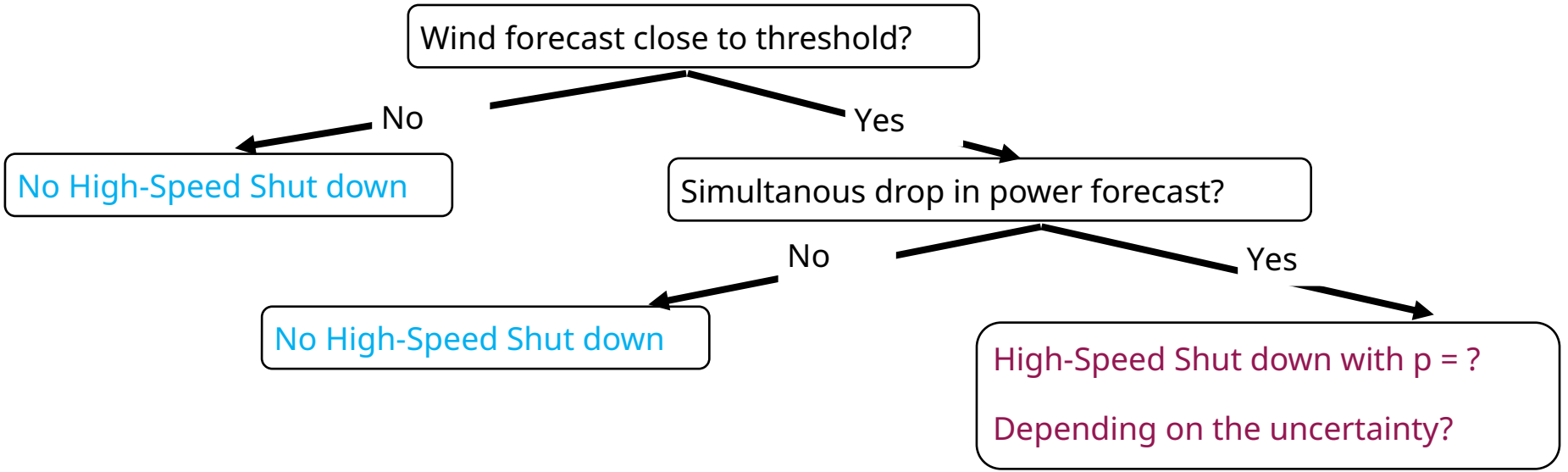
Do probabilistic forecast allow better adaptation to new environments?

- Train in one environment and test behavior in new environment

Heuristic Decision strategies

Which cues (“predictors”) do people use and why?

Simple heuristic decision tree?



Is it all about “dealing with extremes….” ?

iea wind task 36

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Max-Planck-Institut für Bildungsforschung
Max Planck Institute for Human Development
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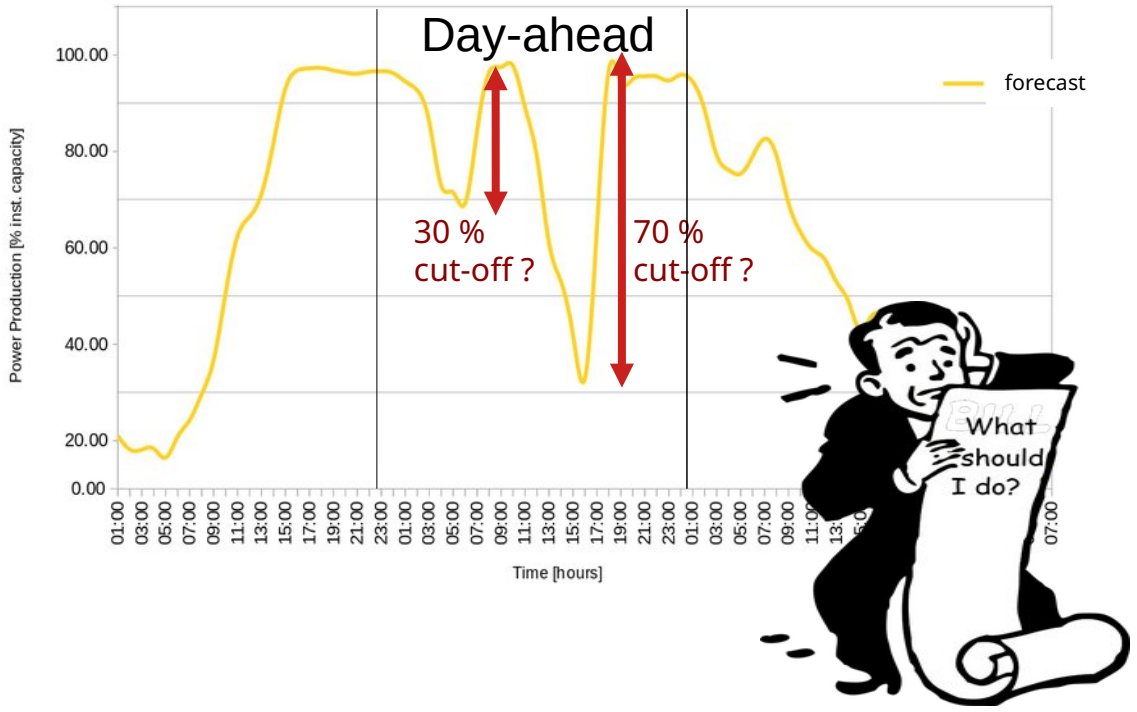
Scene: Decision to be made for Day-ahead:
Wind Power Forecast



Situation

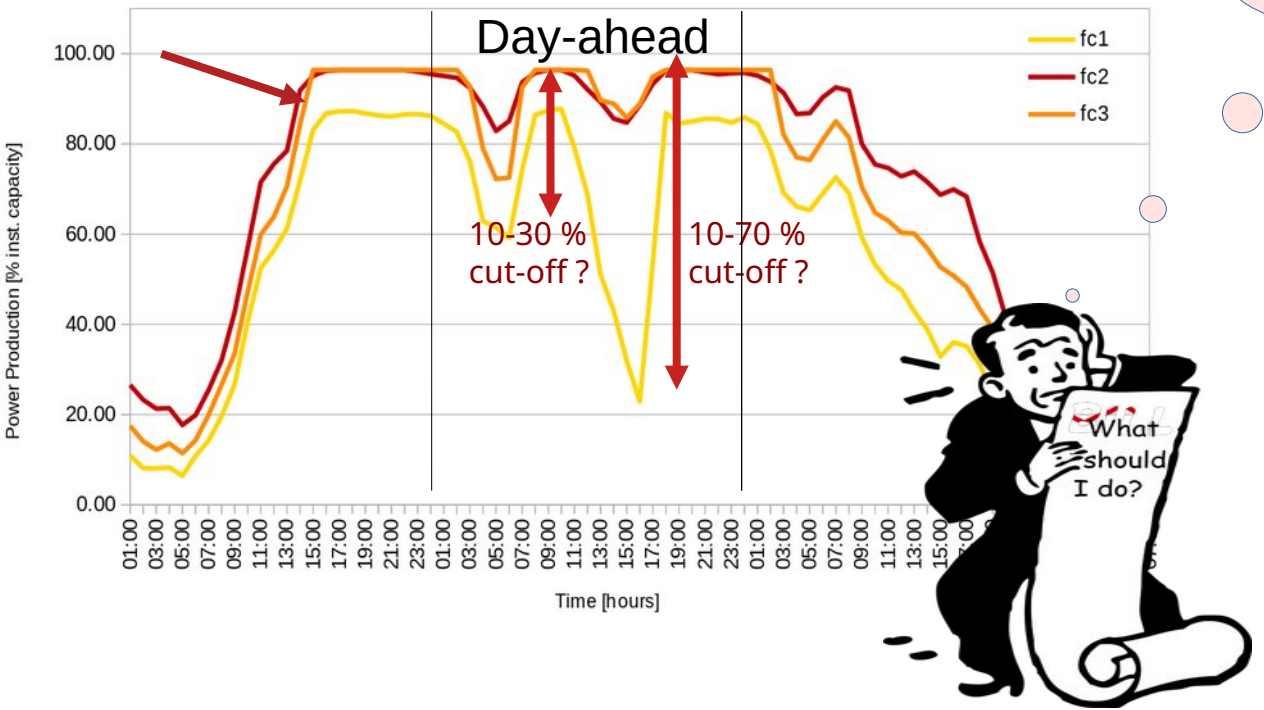
→ Deterministic methods **“hide”** inherent uncertainty of forecast

→ Climate change requires more focus on **extremes**

→ **Increasing penetration levels** change system security levels

Dealing with Extremes….

Scene: Decision to be made for Day-ahead:
Wind Power Forecast



…these extra forecasts do not help me at all…

Situation

Randomly selected deterministic forecasts do not provide a realistic uncertainty!

Deterministic forecasts can deviate a lot or provide confidence, where there is no reason for confidence…!

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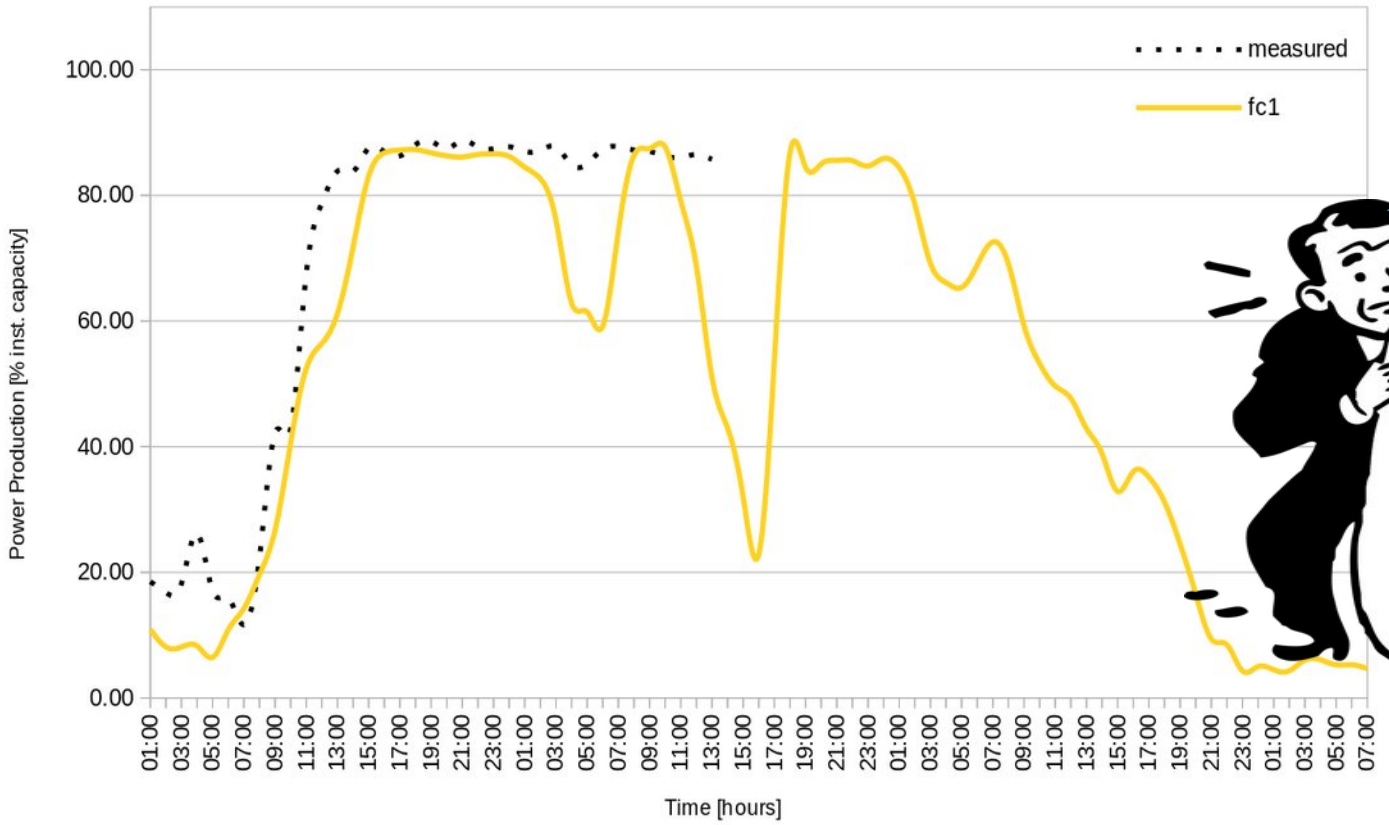
task 36

Dealing with Extremes….

Scene: Decision to be made for Intra-day:
Wind Power Forecast

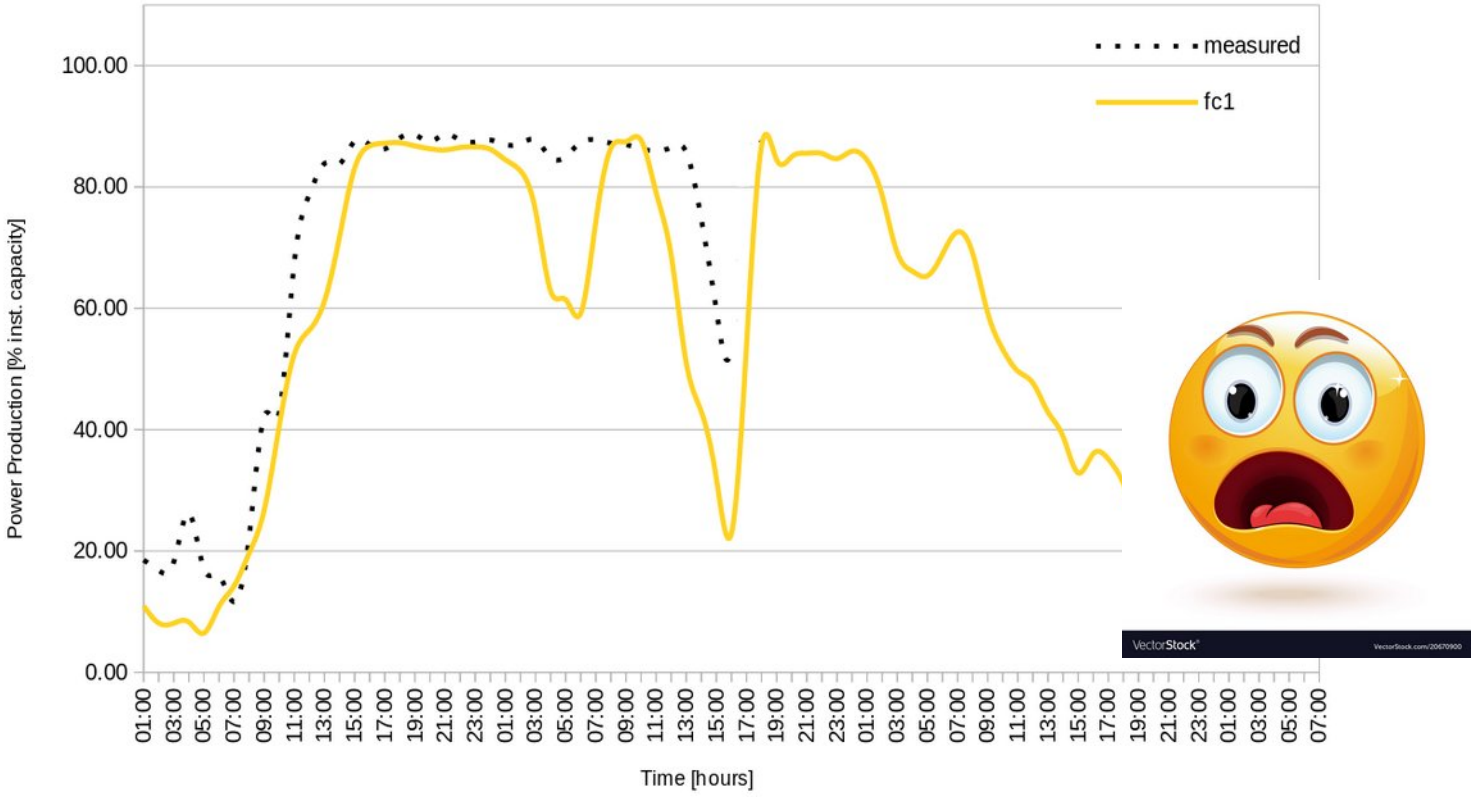


..if the power last night didn't cut off, it will probably also not do so now…

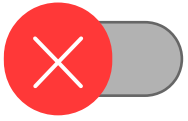
What worked yesterday does not automatically also work today…
when it comes to weather uncertainty
…

Dealing with Extremes….

Scene: Decision to be made for Intra-day:
Wind Power Forecast



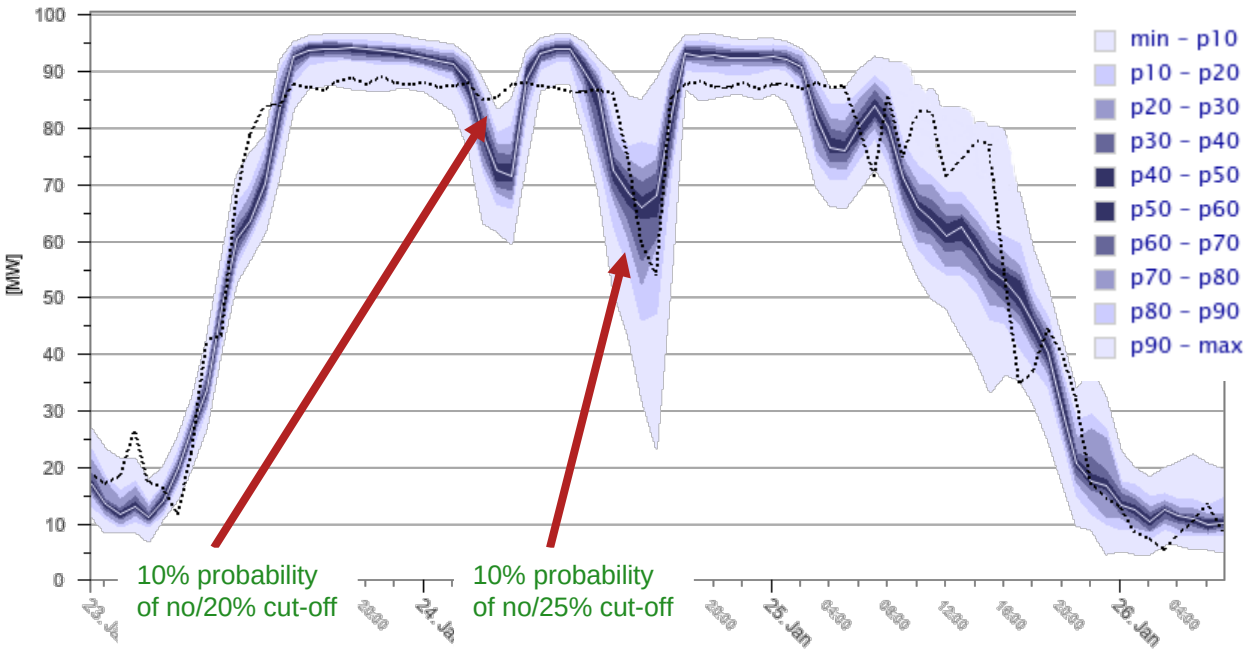
Decisions should not be made in extreme situations on the basis of a deterministic power forecast alone… !



Non-informed decision

Dealing with Extremes….

Scene: Decision to be made for Intra-day:
Wind Power Forecast **+ Uncertainty**



Situation:
In short-term balancing or grid operation:

Using uncertainty forecasts…

Does the uncertainty forecast alone give confidence and will I always make the correct decision.. ?

Dealing with Extremes....

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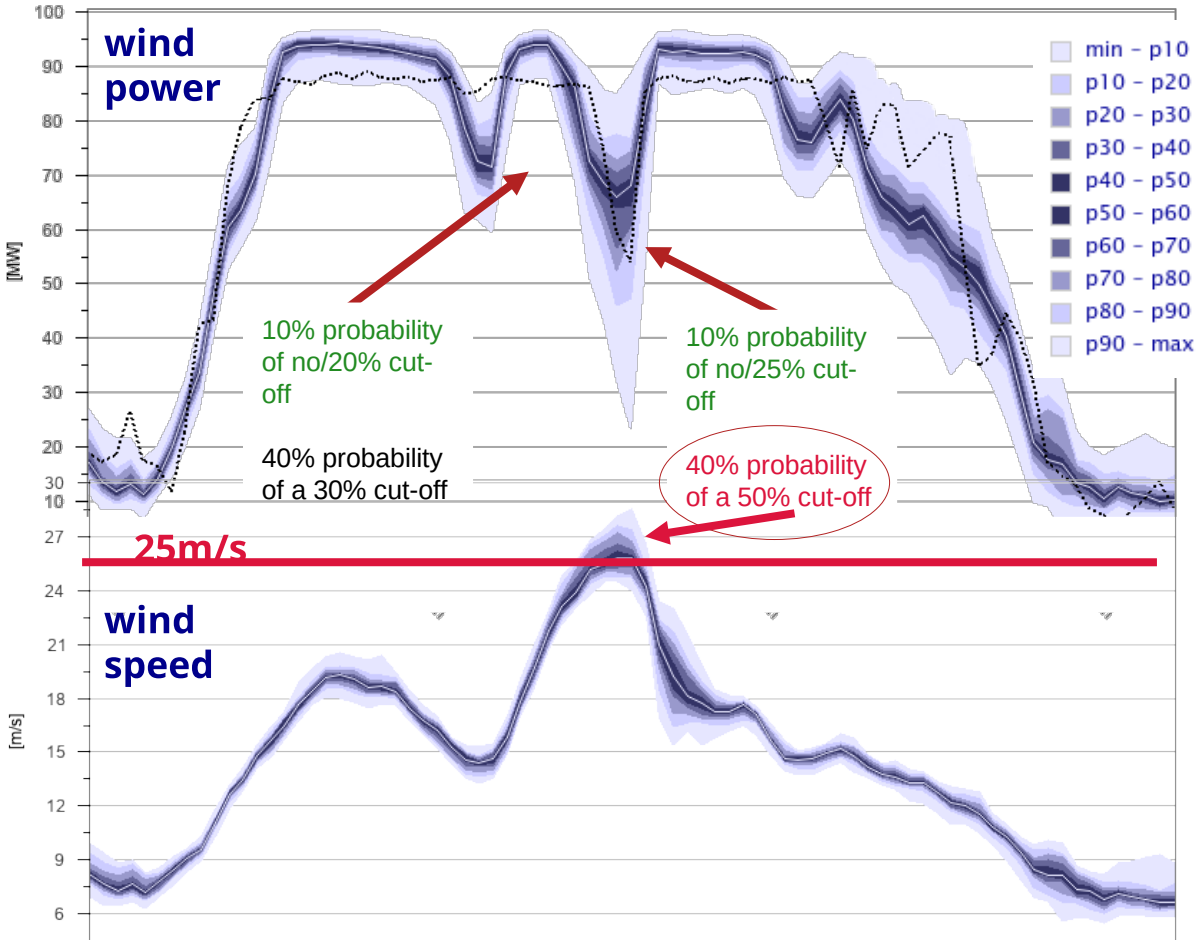
Scene: Decision to be made for Intra-day:
Wind Power + Wind Speed Forecast **+ Uncertainty**



Solution ?

Does the uncertainty forecast alone solve the problem...

Forecast Game Design: decision-making in extreme events

3 Postulates:

1) Success in the trading is highly dependent on the costs of the balancing power needed due to forecast errors
2) 5% of the cases, where there are large forecast errors are responsible for 95% of the costs in a month or a year.
3) Reducing these costs is more important than improving the general forecast by 1-2%.

Definition of a "high-speed shutdown" (HSSD) or "cut-off wind" event :

A high-speed shutdown event occurs typically in the **wind range above 20-27m/s**, mostly known as the *cut-off wind threshold of 25 m/s*.

Note: wind turbines use both wind gusts and the mean wind to determine, whether or not they turn into high-speed shutdown (HSSD).

Game experiments for decision making in extreme events*:

Experiment 1 (2020): Offshore wind park

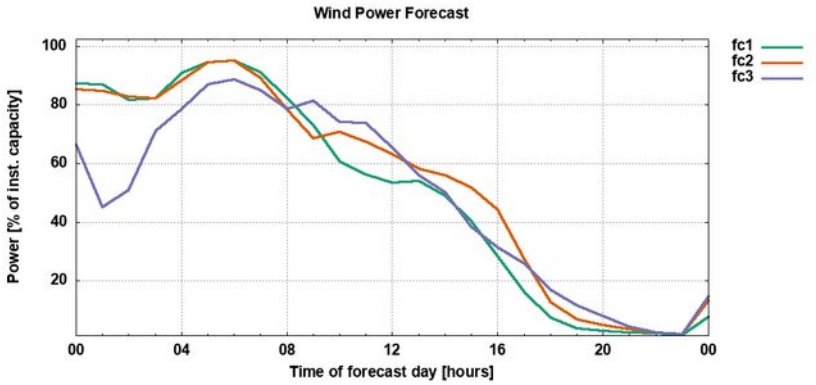
Experiment 2 (2021/2022): Wind park in complex terrain

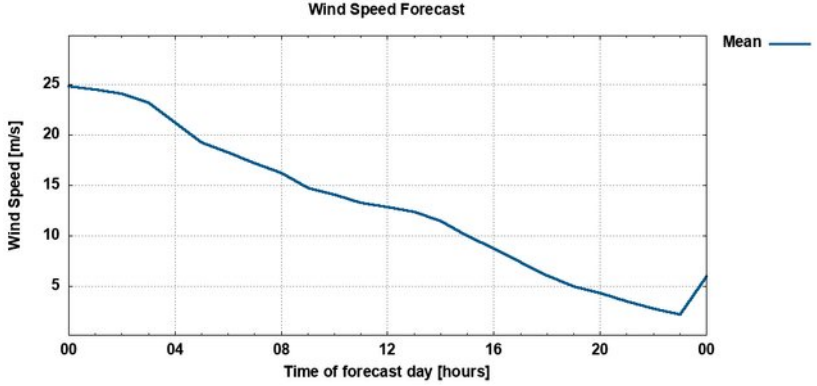
* https://iea-wind.org/task-36/work-packages/work-package-3-optimal-use-of-forecasting-solutions/probabilistic-forecast-games/

Forecast Game: decision-making in extreme events

Type of forecasts used in the game

In the games we use deterministic and probabilistic forecasts for the **day-ahead horizon**.
All forecasts are generated with input of NWP (numerical weather prediction) forecasts from the 00UTC cycle the day before.

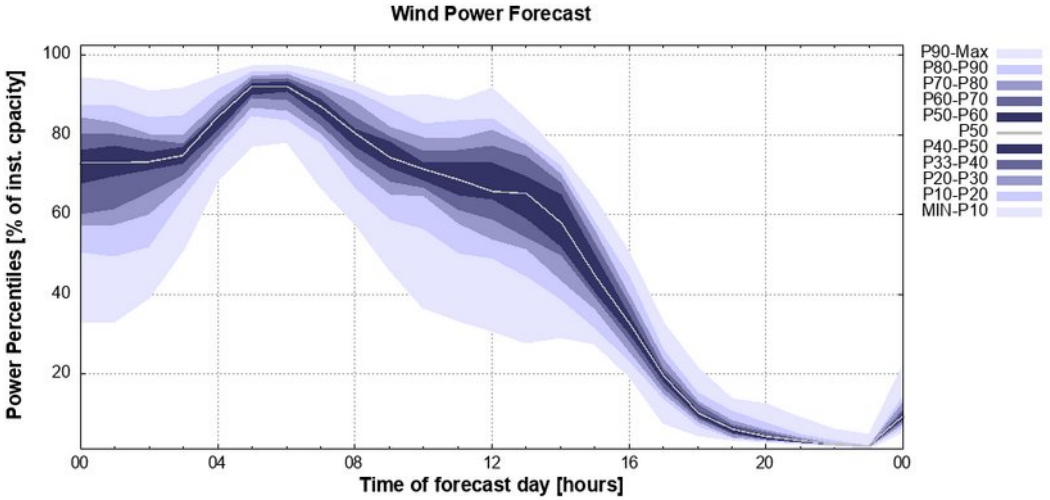


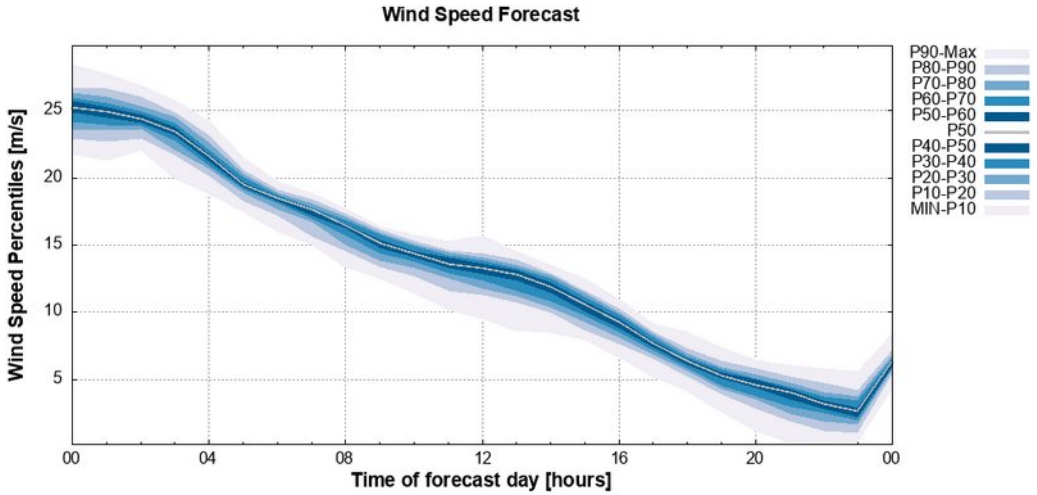


3 independent deterministic wind power forecasts in the unit [% of installed capacity] based on 3 different NWP (numerical weather prediction) models

1 wind speed forecast in the unit [m/s], which is a mean forecast from 75 ensemble members and smoother than a typical deterministic forecast.

Forecast Game: decision-making in extreme events





9 wind power percentiles (P10..P90) and a mean (white line) in the unit [% of installed capacity] generated from 75 NWP forecasts of a multi-scheme ensemble prediction system (MSEPS).

9 wind speed percentiles P10..P90 and a median (white line) in the unit [% of installed capacity] generated from 75 NWP forecasts of a multi-scheme ensemble prediction system (MSEPS).

Note: The percentiles here are physically based uncertainty bands and provide an overview of the uncertainty of the forecast.

Definition: A percentile indicates the value below which a given percentage of forecasts from the 75 available forecasts falls. E.g., the 20th percentile is the value below which 20% of forecasts are found.

Aspects on Cost Functions from 1st Experiment: "Offshore wind power trading in extreme events"

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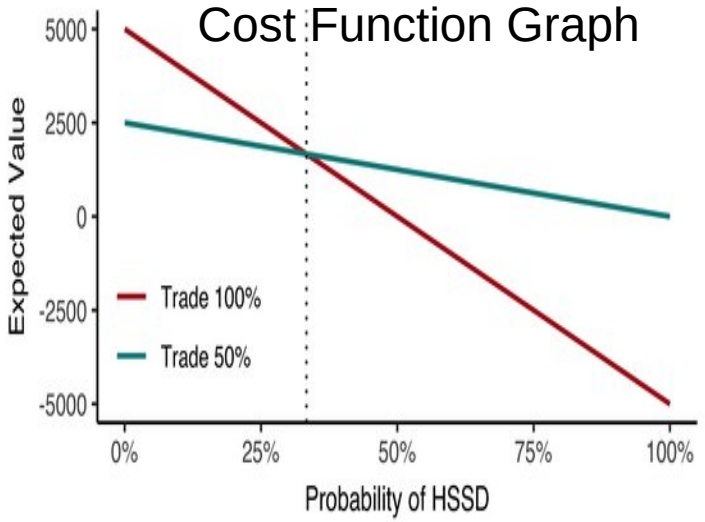
Cost Function Table

Trading	HSSD*	No HSSD*
100%	-5.000	5.000
50%	0	2.500

Cost Function Graph



Percentiles in Forecast graphs

- min – p10
- p10 – p20
- p20 – p30
- p30 – p40
- p40 – p50
- p50 – p60
- p60 – p70
- p70 – p80
- p80 – p90
- p90 – max

Some interesting aspects of the cost function:

- if the probability of a HSSD exceeds 33% trading 50% will give higher payoff

- if the probability of a HSSD < 33% trading 100% will give higher payoff

<u>Can/Could participants read this out ?</u>
Deterministic forecasts: no information

Probabilistic forecasts:
→ percentiles provided information about the probability in wind and power !

2nd Experiment Design

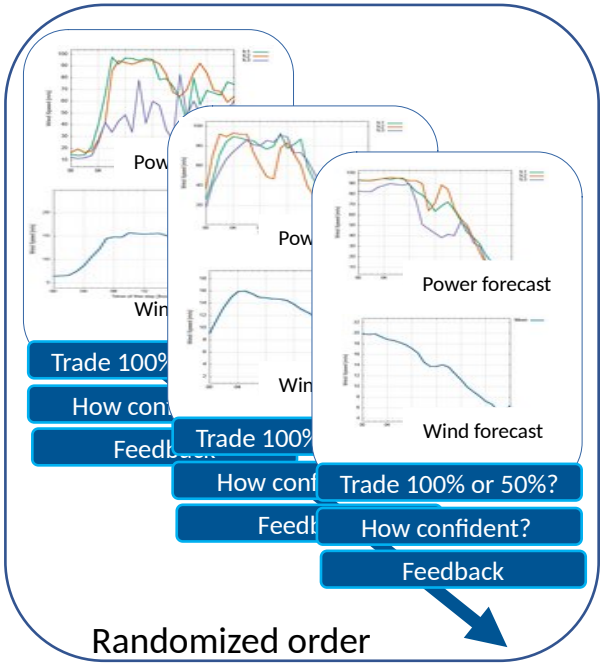
Value of probabilistic power forecasts

How do professionals decide based on probabilistic wind & power forecasts?

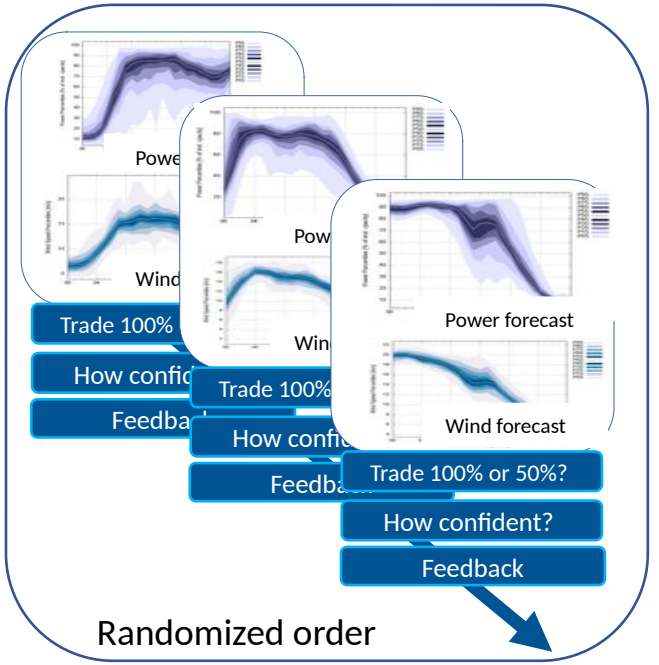
Design & Analysis: Dr. Nadine Fleischhut*, Dr. Corinna Möhrlen**
Host of Experiment: *Max-Planck Insititute for Human Development, Hans-Ertel Center for Weather Research, Germany
Ensemble Forecasts: **MSEPS 75 Member EPS of WEPROG

Trade 100% or only 50% wind energy – given the risk of high-speed shutdown?

Each participant



Blocks randomized

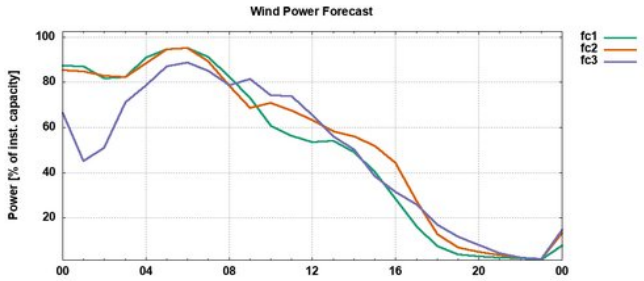


20 decision situations with deterministic forecasts

20 decision situations with probabilistic forecasts

How do professionals decide based on probabilistic wind/power forecasts?

Trade 100% or only 50% wind energy – given the risk of high-speed shutdown?



Power forecast

Wind forecast

Trade 100% | Trade 50%

How confident are you ?
50% | 60% | 70% | 80% | 90% | 100%

Confidence interpretation:

50% → I am guessing
...
100% → I am sure about my decision

Cost Function

	HSSD	No HSSD
Trading 100%	-5000	5000
Trading 50%	0	2500

High-speed shutdown occurred.

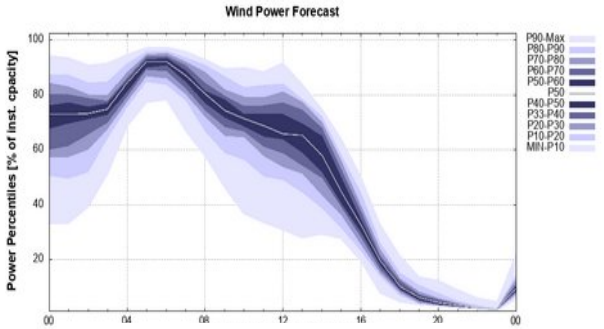
If you trade 100%, you loose 5000 EUR
If you trade 50%, you neither loose or gain anything.

You chose to trade 100%.
You current balance therefore is: -5000

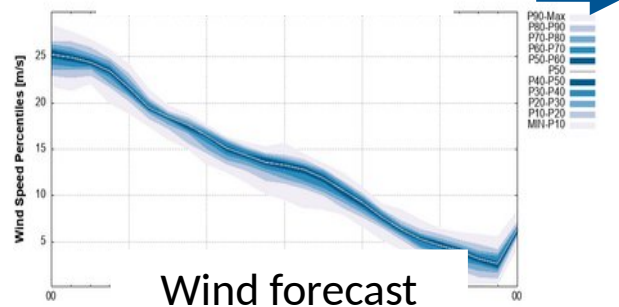
Feedback

How do professionals decide based on probabilistic wind & power forecasts?

Trade 100% or only 50% wind energy – given the risk of high-speed shutdown?



Power forecast



Wind forecast

Trade 100% | Trade 50%

How confident are you ?
50%|60%|70%|80%|90%|100%

Confidence interpretation:

50% → I am guessing

...

100% → I am sure about my decision

Cost Function

	HSSD	No HSSD
Trading 100%	-5000	5000
Trading 50%	0	2500

High-speed shutdown occurred.

If you traded 100%, you loose 5000 EUR
If you traded 50%, you neither loose or gain anything.

You chose to trade 50%.
You current balance therefore is: 0

Feedback

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Max Planck Institute for Human Development
WEPROG

Any questions ?
… if not …

https://wind-power-trading.exp.arc.mpib.org/

LINK to Game:
iea-wind.org/task51

RESULTS Page:
https://meteorology.mpib.dev/wind-power-decisions/workshop.html

2nd Experiment Design (2021)
Value of probabilistic power forecasts

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Link for the 2nd experiment

Open to Play!

https://arc-vlab.mpib-berlin.mpg.de/wind-power/experiment/

iea-wind.org
→ Task 36 → Workpackage 3
→ Forecast Games

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After playing the game...

Links to Game Results

Overall Results: https://meteorology.mpib.dev/wind-power-decisions/results.html

Results from Playing the Game in WEN-II

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Value of probabilistic power forecasts

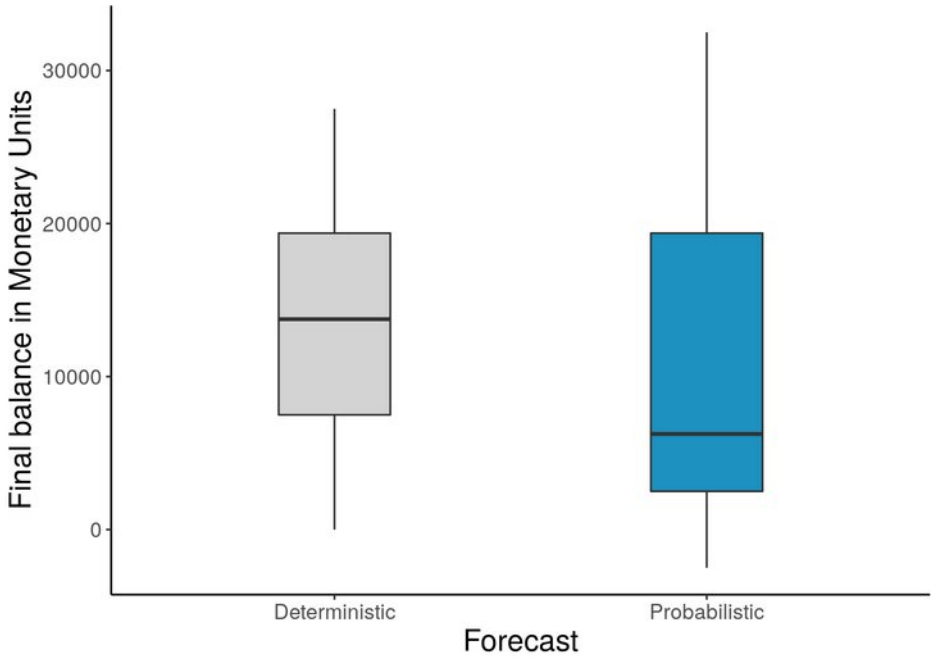
Nickname	Running number	Probabilistic score	Deterministic score
rosse	4075	32500	7500
Trader123	4078	30000	25000
~~tester3~~	~~4048~~	~~27500~~	~~27500~~
Chris_SWE	4063	25000	20000
ViolaW	[illegible]	[illegible]	20000
PANPAN	4061	17500	17500
Tarantoga	4076	15000	10000
FlyingQ	4064	15000	10000
enricoPalazzo	4055	7500	22500
Hurrikan	4066	5000	12500
Freeezar	4052	5000	7500
wiener	4067	5000	0
Trader123	4062	2500	17500
LidarObservation	4050	2500	15000
kl0024	4073	2500	5000
RalMau	4068	0	0
Randier	4049	-2500	15000
Dings5	4070	-2500	5000

Nickname	Running number	Probabilistic score	Deterministic score
~~tester3~~	~~4048~~	~~27500~~	~~27500~~
Trader123	4078	30000	25000
enricoPalazzo	4055	7500	22500
Chris_SWE	4063	25000	20000
ViolaW	4053	20000	20000
PANPAN	4061	17500	17500
Trader123	4062	2500	17500
LidarObservation	4050	2500	15000
Randier	4049	-2500	15000
Hurrikan	4066	5000	12500
Tarantoga	4076	15000	10000
FlyingQ	4064	15000	10000
Grosse	4075	32500	7500
Freeezar	4052	5000	7500
kl0024	4073	2500	5000
Dings5	4070	-2500	5000
wiener	4067	5000	0
RalMau	4068	0	0

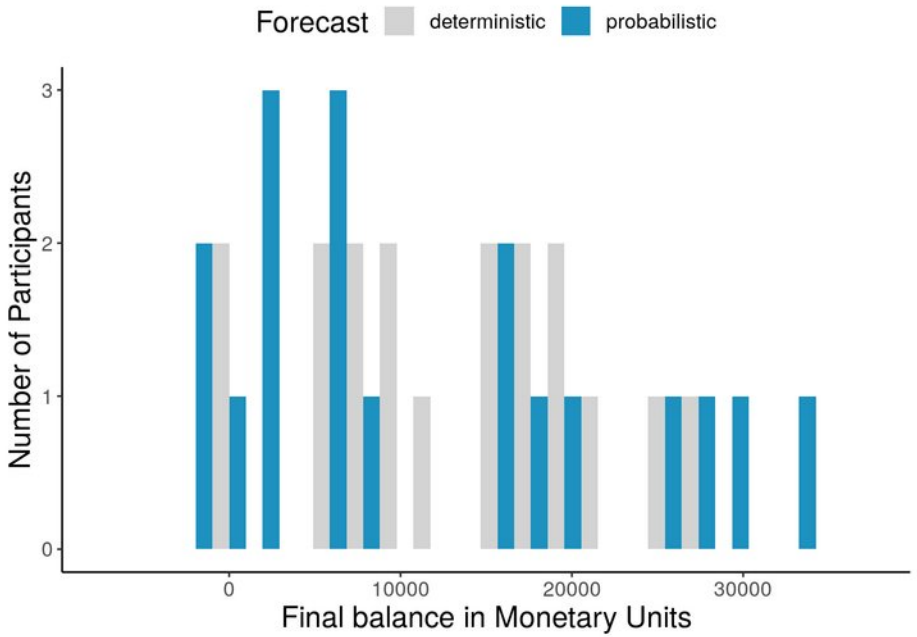
Results from Playing the Game in WEN-II

Value of probabilistic power forecasts

Participants' final balance based on deterministic and probabilistic forecasts



distribution of participants' final balance by forecast type



histogram of participants' final balance

Results from Playing the Game in WEN-II

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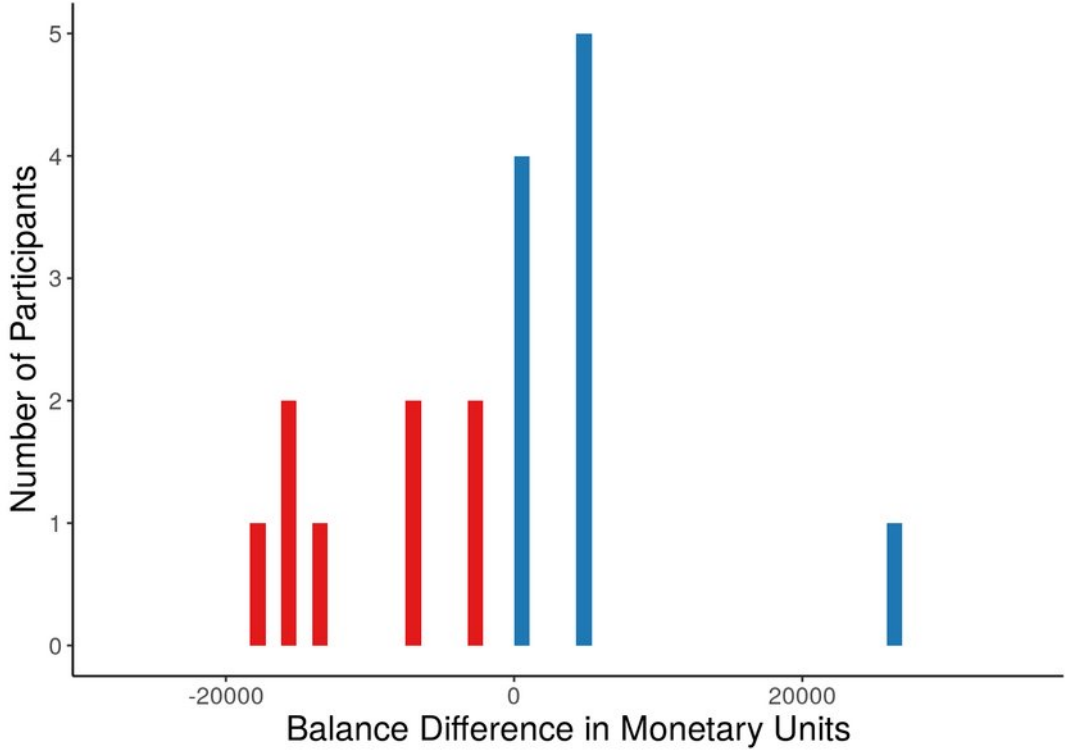
Value of probabilistic power forecasts

Difference between participants' final balance based on the probabilistic forecast and the deterministic forecast



Blue bars (values >= 0) indicate that participants performed better with probabilistic forecasts.
(10 out of 17)

Red bars (values < 0) indicate that participants performed better with deterministic forecasts.
(8 out of 17)

Results from Playing the Game in WEN-II

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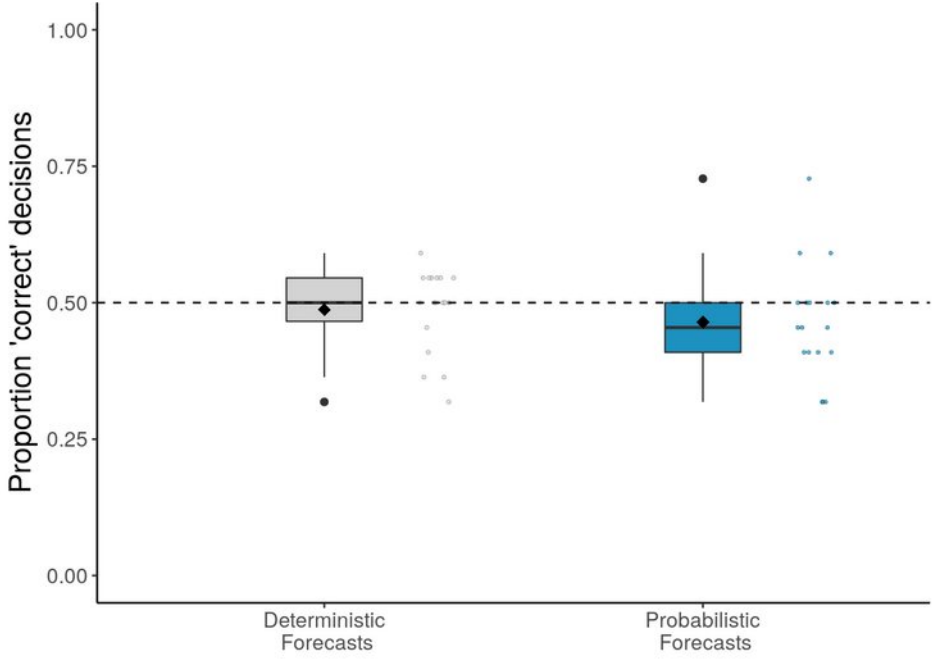
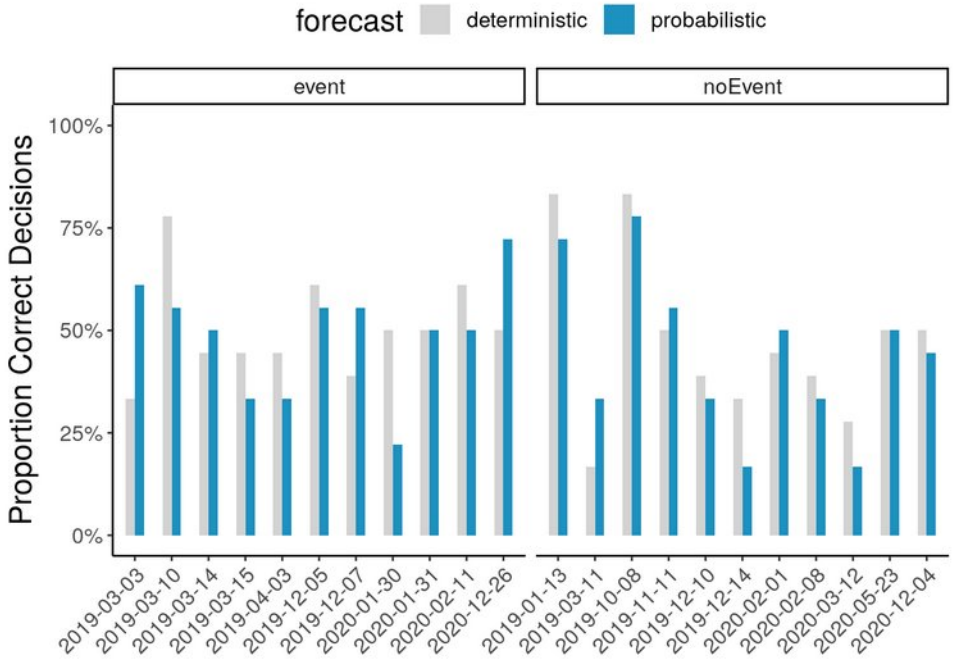
Value of probabilistic power forecasts

Proportion of correct decisions based on deterministic vs. probabilistic forecasts



distribution of participant's proportion of correct decisions by forecast type



Proportion of correct decisions by situation

Results from Playing the Game in WEN-II

Outcome after lecture mostly confirms overall results…

The skew cost function:

- leads to more than 50% of safe decisions - participants thus are aware of the asymmetric cost function
- participants get more risk averse in the course of the game

A portion of cases are difficult or not easy to interpret for participants:

- leads to scores that are little above a completely risk averse decision-making (score: 27500)
- confidence is challenged, if participants have no clear strategy
- learning is difficult, if the feedback is insufficient/not helping the understanding

Correct detection of events

- participants decision of no-events are more often correct with deterministic forecasts
- participants decision of events are also more often correct with deterministic forecasts

-> different to the overall result, where events are more correctly chosen with probabilistic forecasts

Observation after the workshop:

- Participants seems to only benefit from probabilistic ensemble forecasts, if they already have a strategy and understanding of the task for the decision-making
- The order in which forecast types are provided seems to have an impact on the scores (general learning?)

RELEVANT LITERATURE:

Corinna Möhrlen, John Zack, Gregor Giebel: **IEA Wind Recommended Practice for the Implementation of Renewable Energy Forecasting Solutions**. 370 pp. Elsevier Academic Press, November 11, 2022. ISBN: 9780443186813. DOI: 10.1016/C2021-0-03549-5 -- Link to OpenAccess Book (Download)

Möhrlen, C., Bessa, R. J., & Fleischhut, N. (2022). **A decision-making experiment under wind power forecast uncertainty**. Meteorological Applications, 29(3), e2077. https://doi.org/10.1002/met.2077

Corinna Möhrlen, Gregor Giebel, Ricardo J. Bessa and Nadine Fleischhut, **How do Humans decide under Wind Power Forecast Uncertainty — an IEA Wind Task 36 Probabilistic Forecast Games and Experiments initiative**, Journal of Physics: Conference Series (2022), Volume 2151, WindEurope Electric City 2021 23/11/2021 – 25/11/2021 Copenhagen, Denmark, DOI: 10.1088/1742-6596/2151/1/012014, Published under licence by IOP Publishing Ltd.

Jie Yan, Corinna Möhrlen, Tuhfe Göçmen, Mark Kelly, Arne Wessel, and Gregor Giebel, **Uncovering wind power forecasting uncertainty sources and their propagation through the whole modelling chain**. Renewable and Sustainable Energy Reviews, 165:112519,23, DOI: 10.1016/j.rser.2022.112519, 2022.

Bessa, R.J.; Möhrlen, C.; Fundel, V.; Siefert, M.; Browell, J.; Haglund El Gaidi, S.; Hodge, B.-M.; Cali, U.; Kariniotakis, G. **Towards Improved Understanding of the Applicability of Uncertainty Forecasts in the Electric Power Industry**. Energies 2017, 10, 1402, doi:10.3390/en10091402 - Open Access Online: http://www.mdpi.com/1996-1073/10/9/1402/

CONTACT:

Dr. Corinna Möhrlen – com@weprog.com