

Journées Scientifiques de l'Eolien  
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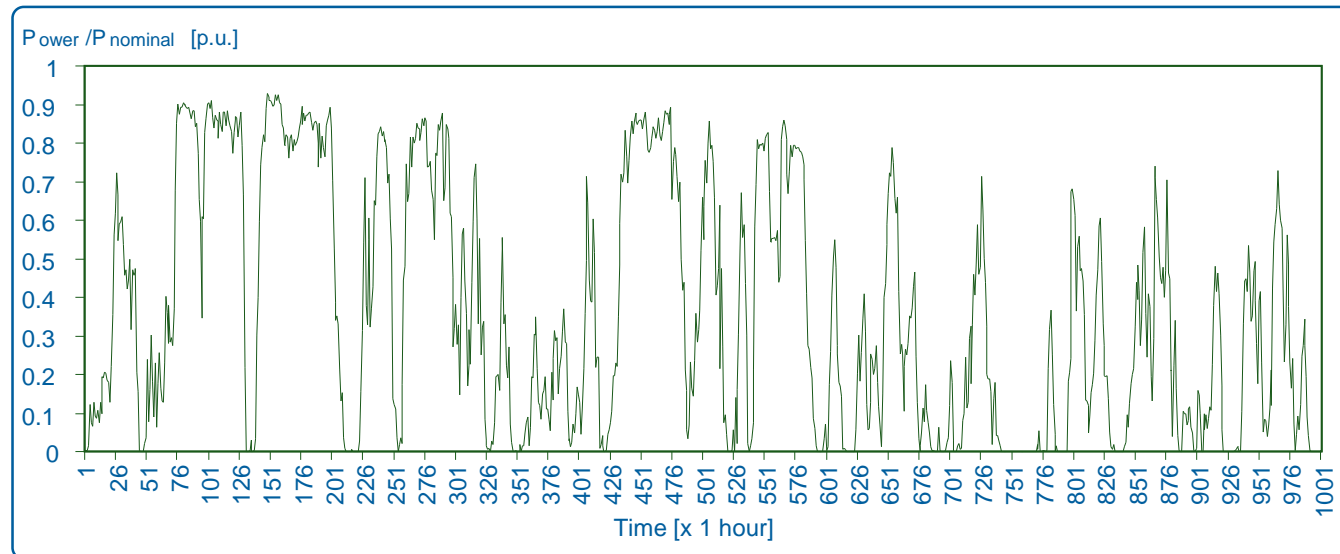
# Wind Power Forecasting - State of the art and new directions of research.

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Coordinator of Smart4RES  
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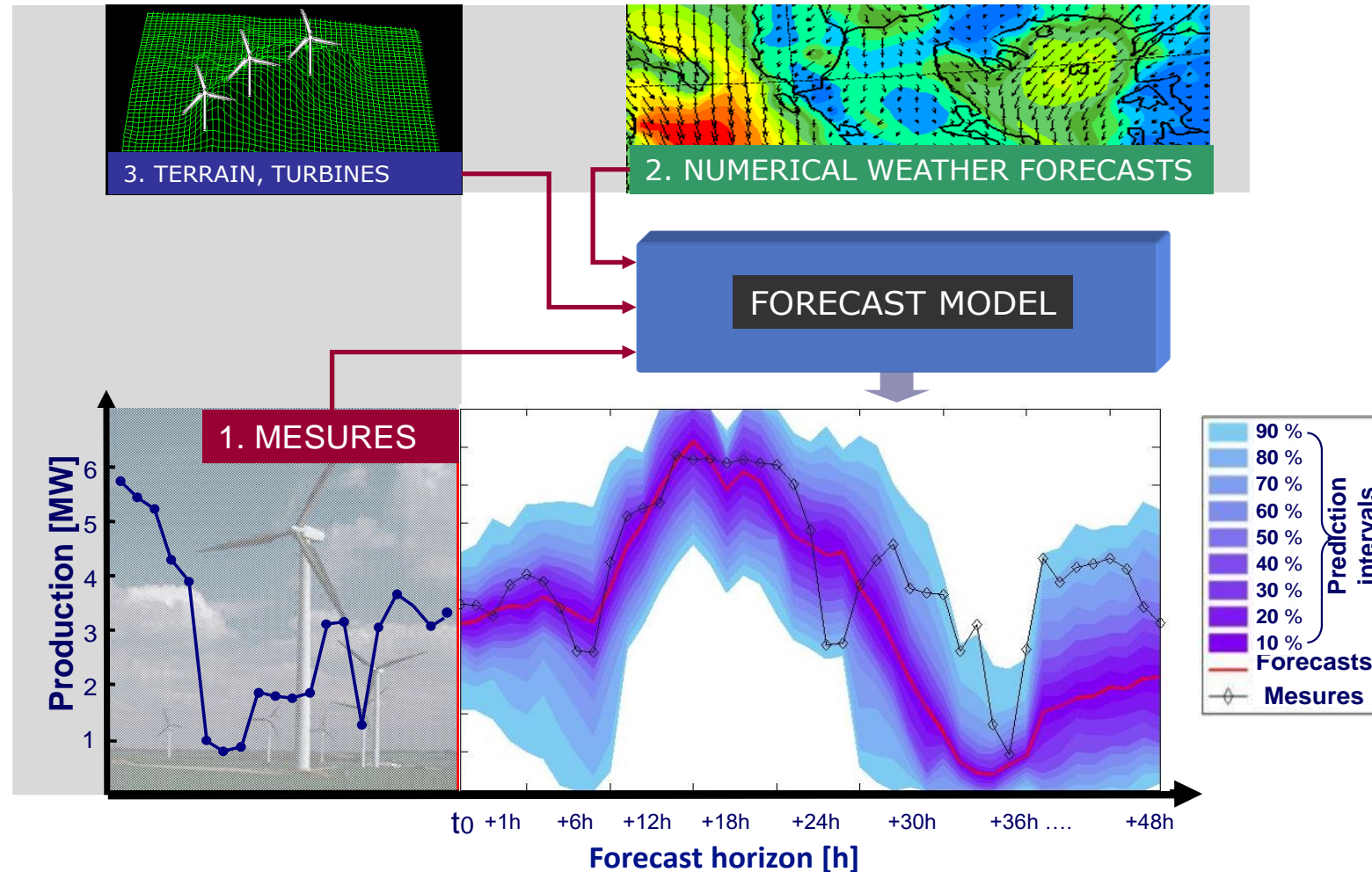


- Short-term forecasts of **weather-dependent** renewable generation (wind, solar) (RES) are necessary for the secure and economic operation of power systems.
- Today, the RES forecasting technology is quite mature: **deterministic (spot) & probabilistic** forecasts of wind and solar generation for the next 2-3 days are used **operationally**.

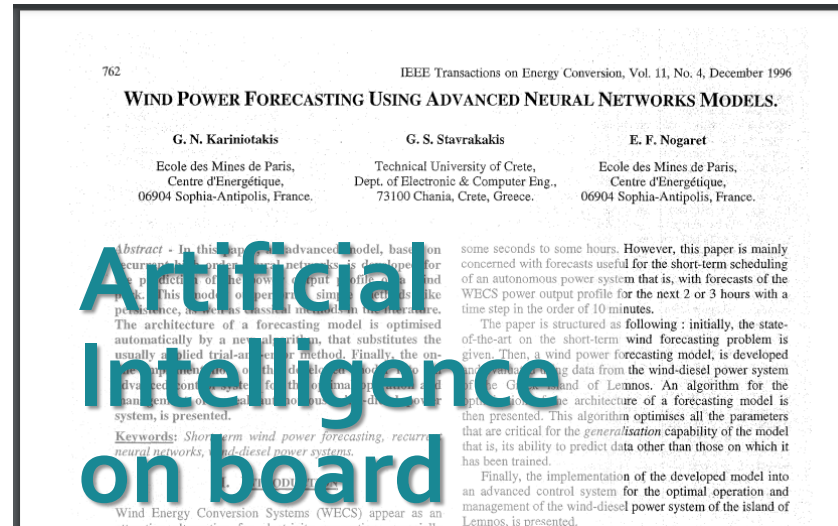
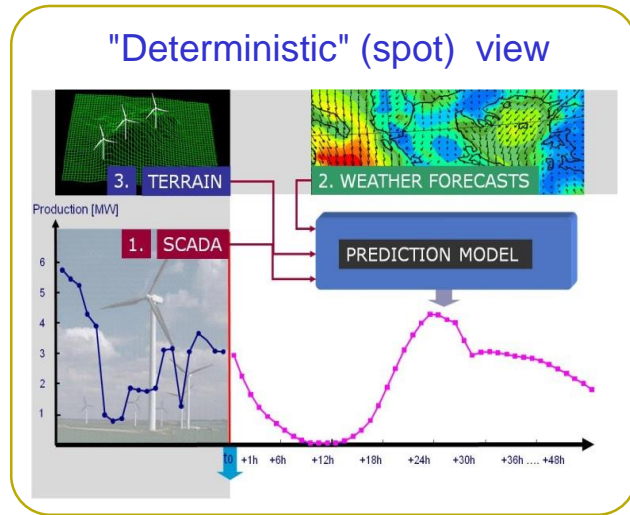


Example of hourly wind farm production over a month

# The general principle of wind power forecasting



# The history of wind power forecasting



❖ (1996) 1<sup>st</sup> journal paper ever with AI applied in RES



- First purely time series methods on WPF

- Statistical / time-series approaches
- Physical modelling
- First AI-based approaches
- NWP's considered as input
- Empiric/hybrid implementations into operational forecast tools

[2002-2006] ANEMOS (FP5), <http://www.anemos-project.eu/>

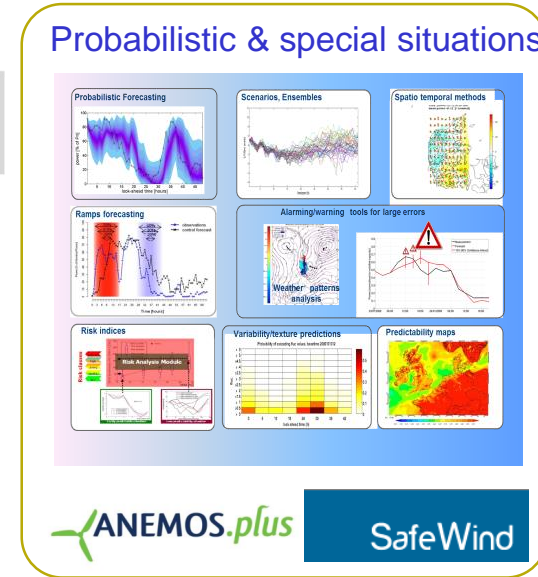
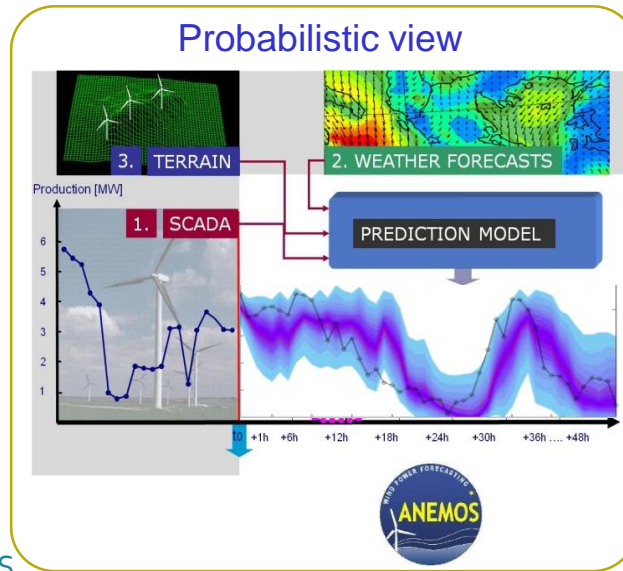
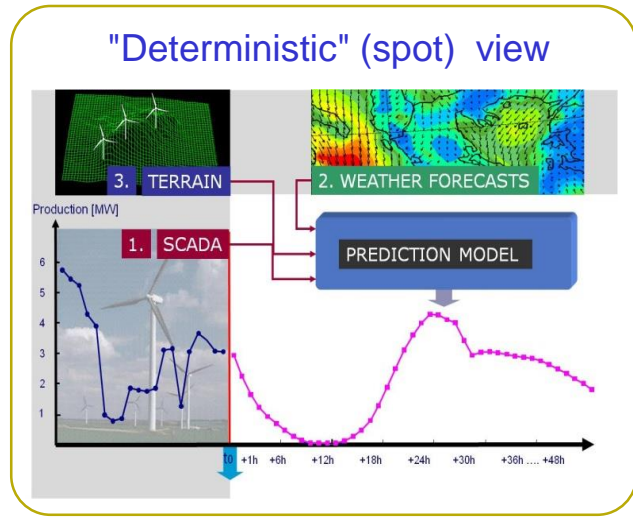
[2008-2011] ANEMOS.plus (FP6), <http://www.anemos-plus-project.eu/>

[2008-2012] SAFEWIND (FP7), <http://www.safewind.eu/>

[2019-2023] Smart4RES (H2020), <http://www.smart4res.eu/>



# The history of wind power forecasting



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- 1st benchmarking (Anemos competition)
- Physical modelling
- Statistical models, AI, Data mining,...
- Combination of models
- First probabilistic approaches/ensembles
- Upscaling
- Evaluation standardisation/protocol
- International collaboration

- Dedicated NWP's for RES
- Direct probabilistic predictions
- Ramps forecasting
- Scenarios, Ensembles,
- Risk indices
- Large errors warning/alarming
- Spatiotemporal forecasting
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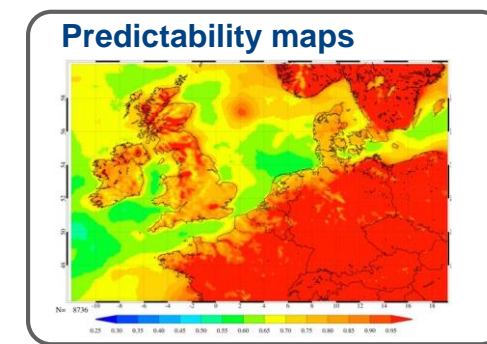
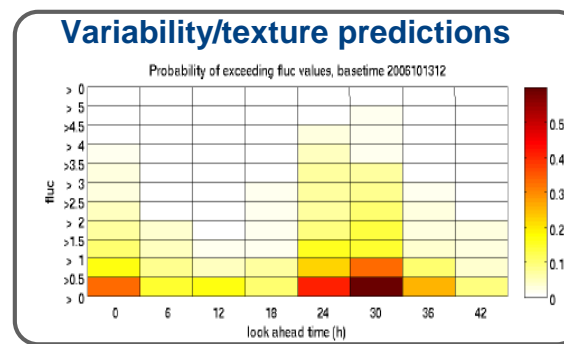
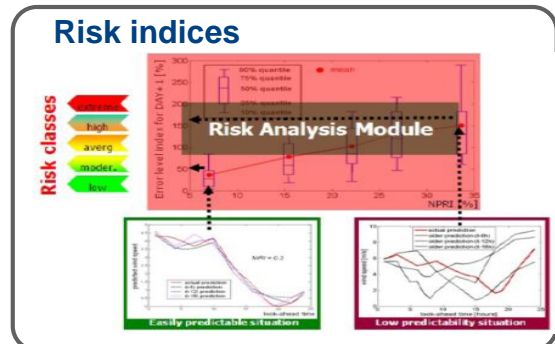
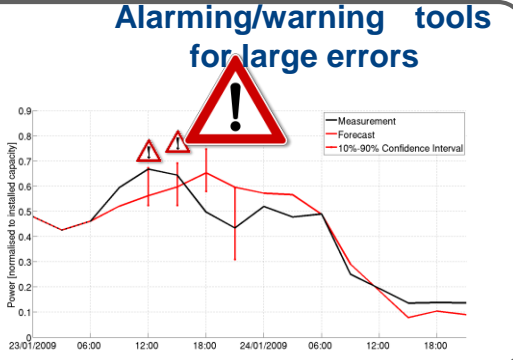
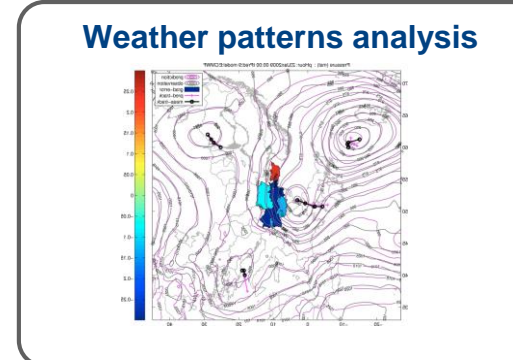
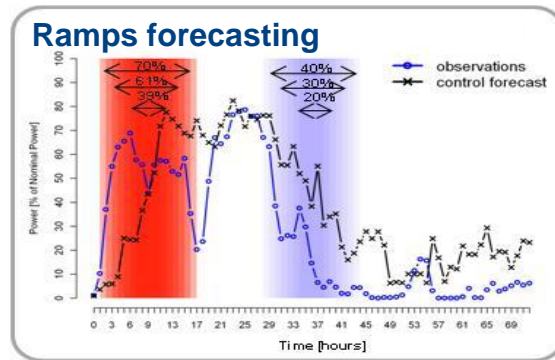
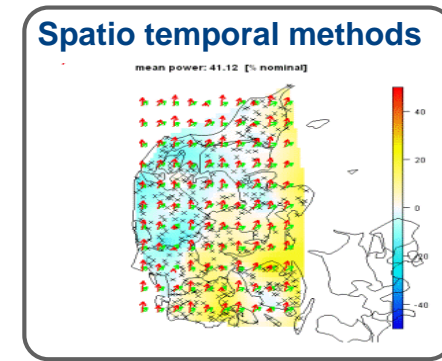
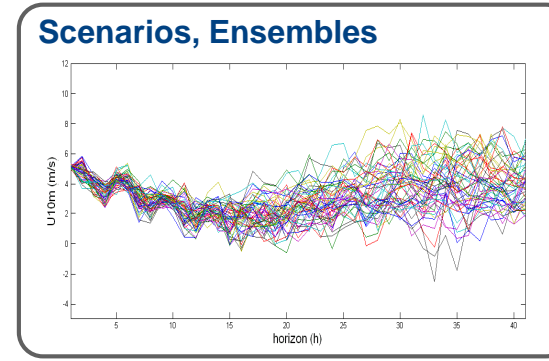
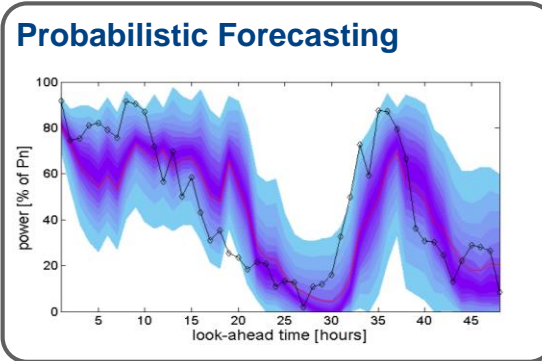
[2019-2023] Smart4RES (H2020), <http://www.smart4res.eu/>

# The history of wind power forecasting

A variety of new solutions developed in:

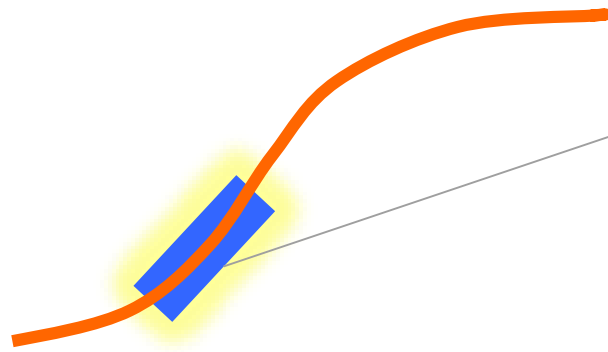


SafeWind

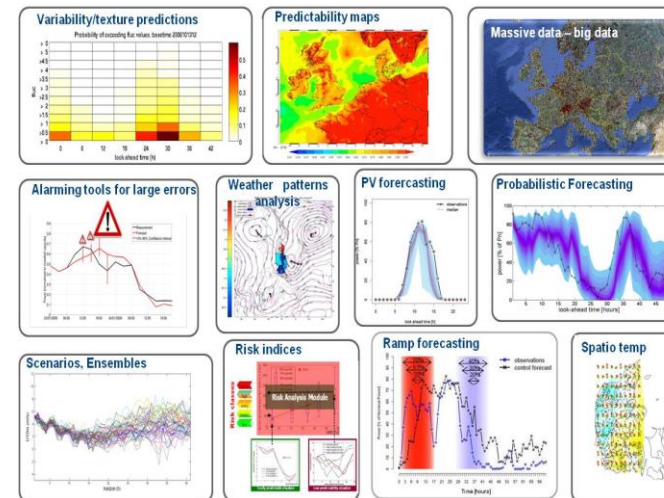


# The trends in the last years

- ❖ Already 10 years ago several actors (i.e. R&D funding agencies) were saying that everything was already done in wind forecasting in terms of research...
- ❖ By the end of SafeWind (2012) we supported a different vision:
  1. That we were still at the first part of the technology curve.



❖ Wind Power Forecasting Technology curve



Further R&D needed for improvement of wind predictability

ACCURACY++

# The R&D trends in the last years



## Weather forecasting:

- ❑ **RES plants as sensors** and integration in the weather model through data assimilation
- ❑ **Improvements in weather models with focus to RES sector** (marine boundary layer, combined wind/wave/ocean models, higher resolution/downscaling, ensemble predictions, different climates, ...)
- ❑ **Longer term** forecasts (week ahead for O&M of wind turbines and power system, seasonal for wind-solar-hydro matching / water value)

## Wind power forecasting:

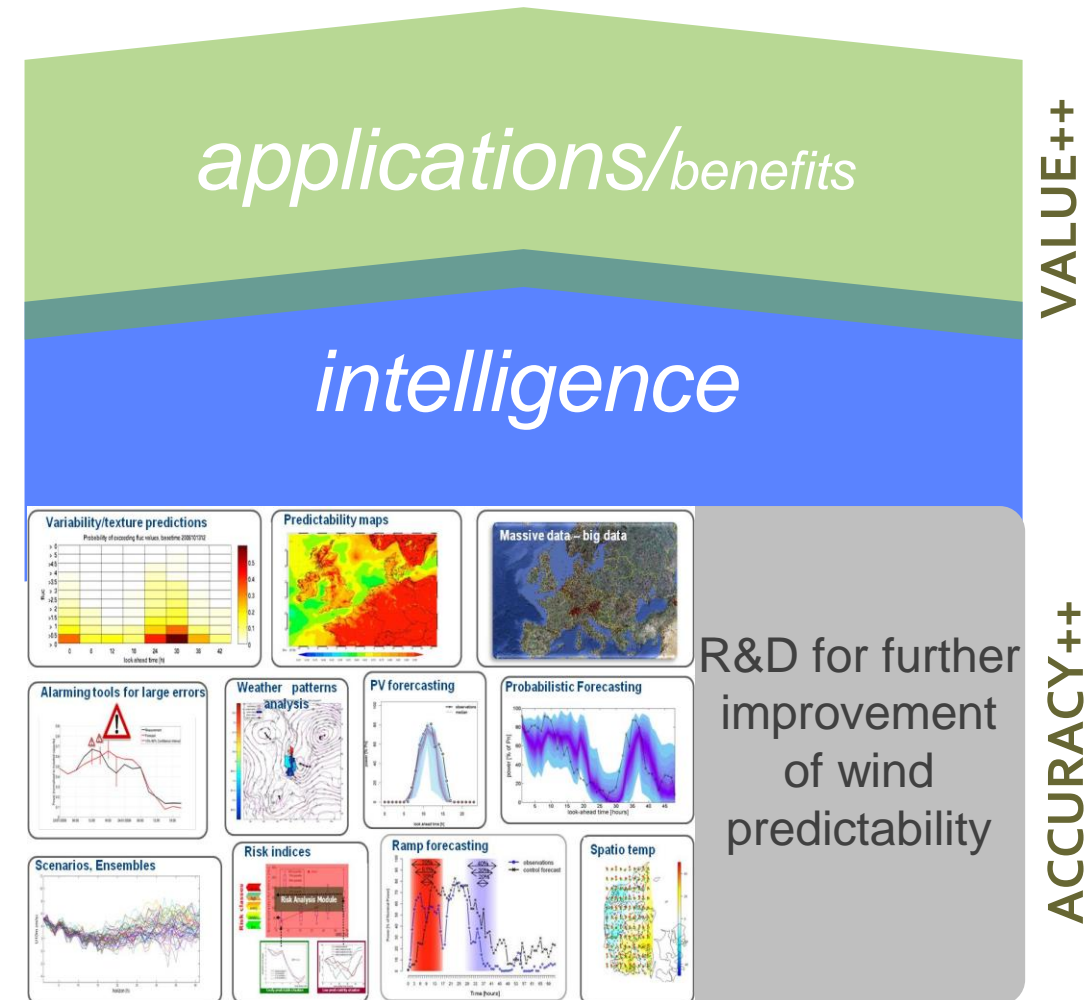
- ❑ **Remote sensing** (LiDARs, radars, satellites etc) for data assimilation or direct use in statistical tools)
- ❑ Upscaling/data selection and data assimilation in the context of **Big Data** (relevant for wind, even more relevant for PV)
- ❑ Improved forecasts for **extremes** (e.g. ramps / variability) and integration in business processes of end users
- ❑ **Forecasting of “everything”** (wind, pv, waves, load, DLR, and correlations between them)
- ❑ **Spatio-temporal forecasting** > European Vision for wind power forecasting (necessary due to larger TSO interaction, beneficial due to increased number of data, data exchange across nation borders)
- ❑ More integrated **use of the probabilistic forecasts** for end users (integration with business case)
- ❑ Use of different prediction products to **optimise decisions** (spot, uncertainty, ramps, cut-off, risk indices, scenario generation and reduction etc).



# The R&D trends in the last years

- ❖ Already 10 years ago several actors (i.e. R&D funding agencies) were saying that everything was already done in wind forecasting in terms of research...
- ❖ By the end of SafeWind (2012) we supported a different vision:
  1. That we were still at the first part of the technology curve.
  2. Necessity for an “intelligence layer” to optimise the value of forecast products in applications

❖ Wind Power Forecasting Technology curve



# The R&D trends in the last years

- ❖ Already 10 years ago several actors (i.e. R&D funding agencies) were saying that everything was already done in wind forecasting in terms of research...
- ❖ Academic literature explodes since....

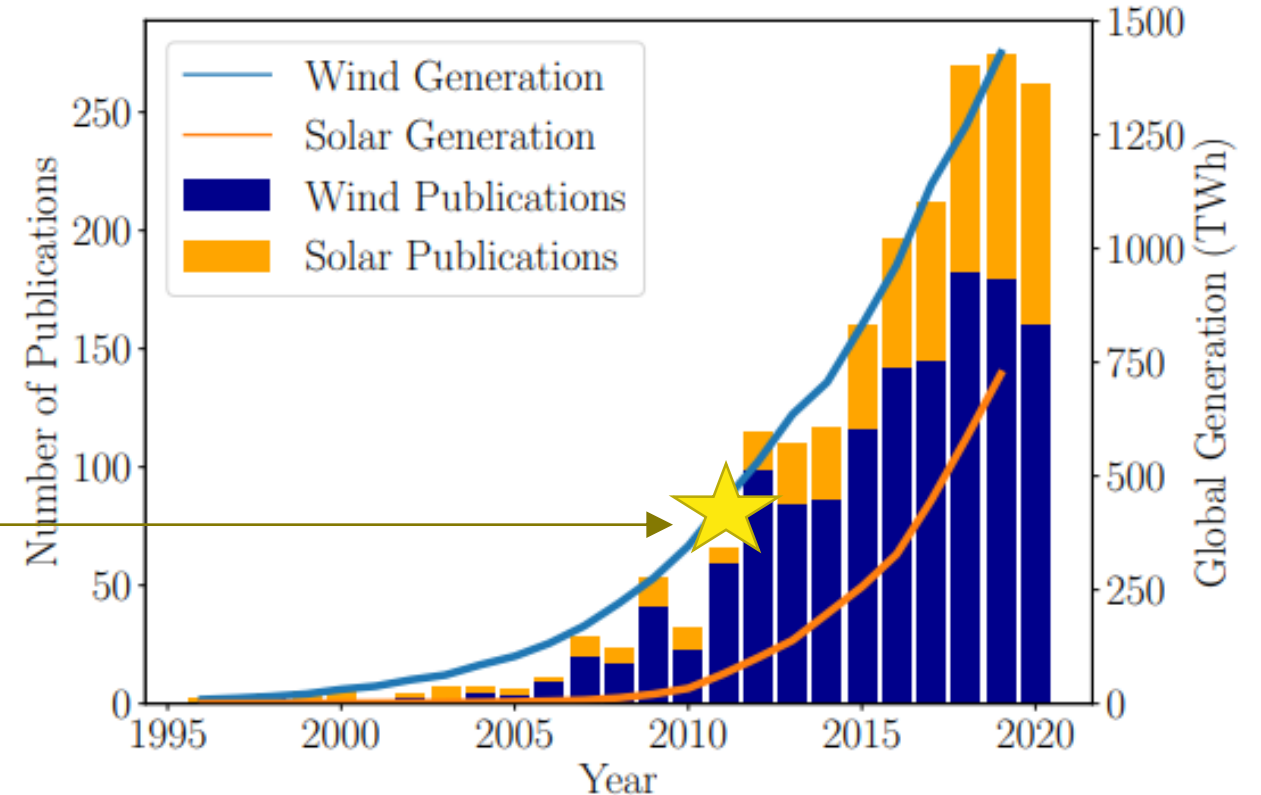


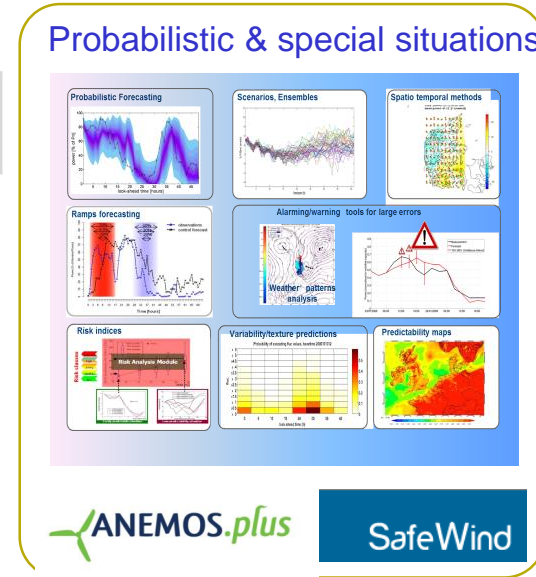
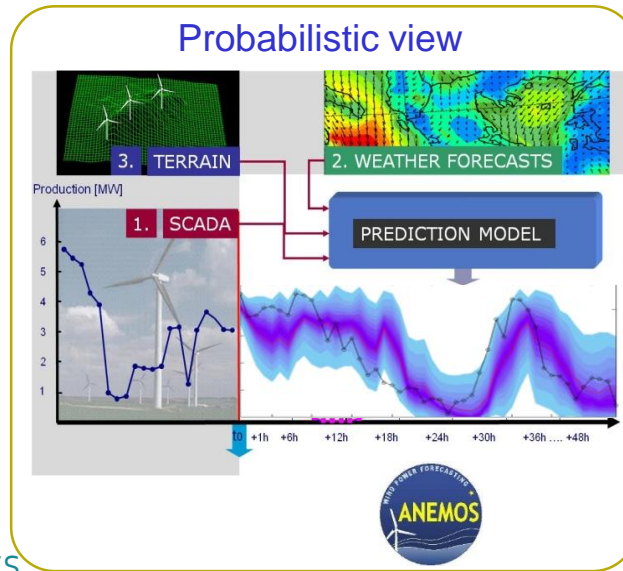
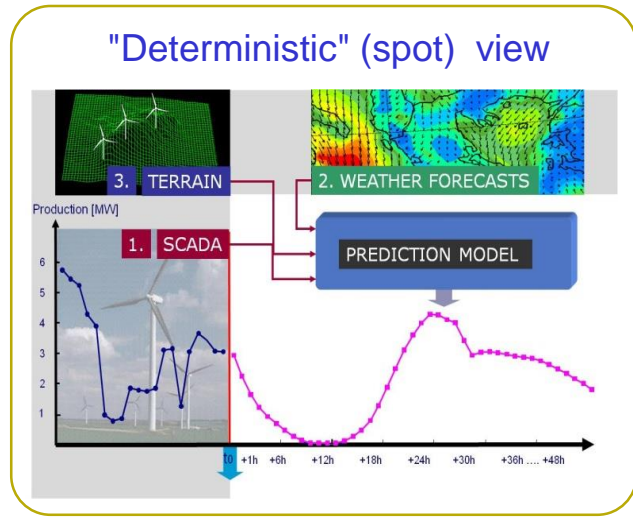
Figure 2.1: Forecasting publications broken down by wind and solar as a stacked bar chart, also plotted with global energy generation through time. Generation data provided under CC BY 4.0, Hannah Ritchie & Max Roser, [ourworldindata.org/renewable-energy](https://ourworldindata.org/renewable-energy).

SOURCE: PhD thesis Rosemary Tawn, Strathclyde University, 2022.



250 publications at conferences and journals

# The history of wind power forecasting



❖ (1996) 1<sup>st</sup> journal paper ever with AI applied in RES



1985

1990

2000

2010

2020

- First purely time series methods on WPF

- Statistical / time-series approaches
- Physical modelling
- First AI-based approaches
- NWP's considered as input
- Empiric/hybrid implementations into operational forecast tools

- Mapping of state of the art
- 1st benchmarking (Anemos competition)
- Physical modelling
- Statistical models, AI, Data mining,...
- Combination of models
- First probabilistic approaches/ensembles
- Upscaling
- Evaluation standardisation/protocol
- International collaboration

- Dedicated NWP's for RES
- Direct probabilistic predictions
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- Spatiotemporal forecasting
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- Seamless forecasting
- Ultra high resolution (LES)
- Advanced NWP's
- Prescriptive analytics
- Extremes
- Data sharing/Data markets
- New forecasting products
- Resilience in forecasting
- Optimal use in applications

[2002-2006] ANEMOS (FP5), <http://www.anemos-project.eu/>

[2008-2011] ANEMOS.plus (FP6), <http://www.anemos-plus-project.eu/>

[2008-2012] SAFEWIND (FP7), <http://www.safewind.eu/>

[2019-2023] Smart4RES (H2020), <http://www.smart4res.eu/>

# New directions of research “The Smart4RES approach”



# The Smart4RES project in a nutshell



- A multi-disciplinary consortium

**6 countries**  
**12 partners**

End-users  
Industry  
Research  
Universities  
Meteorologists

Funds: H2020 program  
Budget: 4 M€  
Duration: 3.5 years

**11/2019-4/2023**

Denmark 

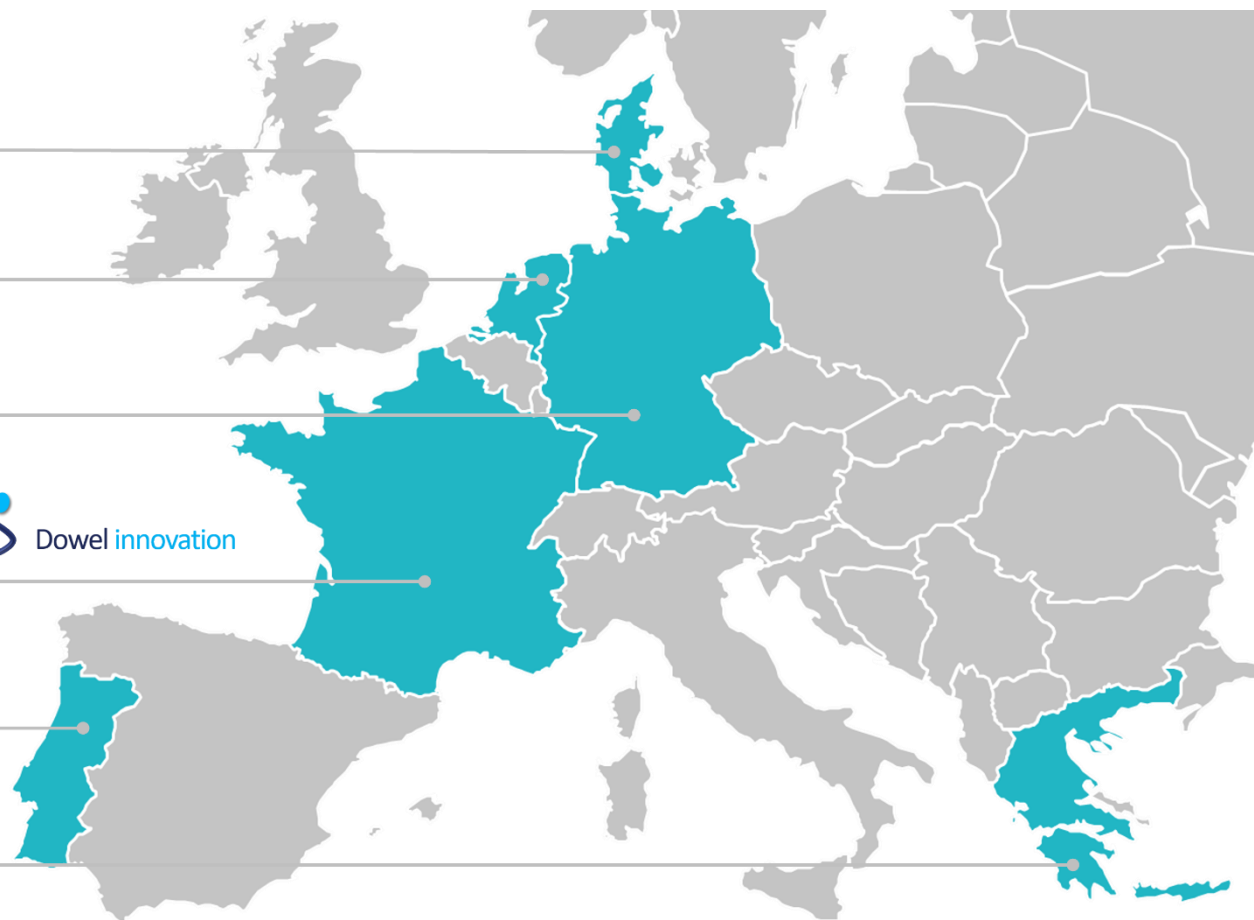
Netherlands  

Germany  

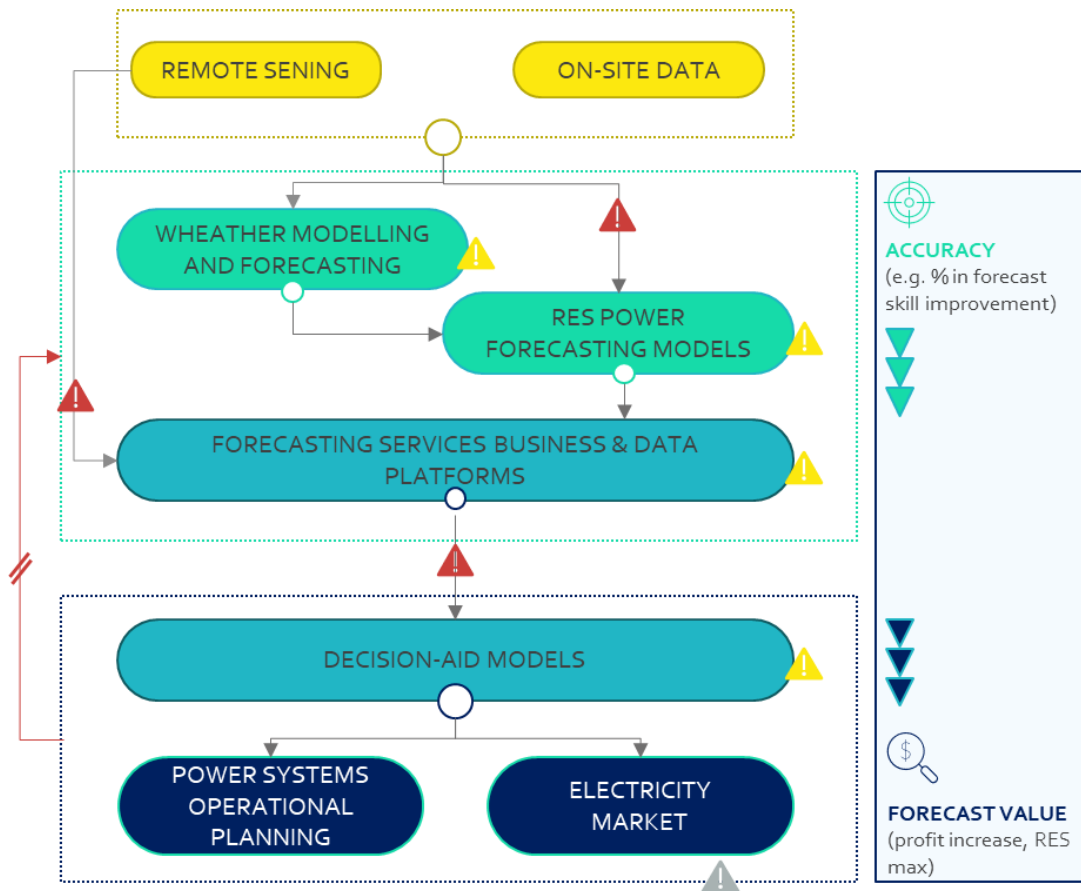
France      Dowel innovation

Portugal  

Greece  



# The Smart4RES project



The typical RES forecasting model/value chain

**Project vision:** Achieve outstanding improvement in RES predictability through a **holistic approach**, that covers the whole model and value chain related to RES forecasting

## Objectives:

- 1 **Requirements** for forecasting solutions to enable 100% RES penetration
- 2 RES-dedicated weather forecasting with 10-15% improvement using various sources of data and very high resolution approaches.
- 3 New generation of RES production forecasting tools enabling 15% improvement in performance.
- 4 Streamline the process of getting optimal value through new forecasting products, data market places, and novel business models
- 5 New data-driven optimisation and decision aid tools for power system management and market participation
- 6 Validation of new models in living labs and assessment of forecasting value vs remedies.

## REDUCED KNOWLEDGE OF THE PHYSICAL SYSTEM

- Weather forecasting is an essential input but not always tailored to energy applications.

## VULNERABILITY

- Not 100% reliable data (i.e. communication faults).
- Possible corruption of data and models from cyberattacks or other malicious factors.

## COMPLEXITY

- High dependability of RES prediction models on specific data sources.
- Due to multiple modelling steps, the resulting decisions lack interpretability especially in situations with high uncertainties/extremes
- Difficulty to integrate the human experience in the model chains (human-in-the-loop).

## UNCERTAINTIES

- High uncertainties not always understood by operators
- Optimisation tools remain deterministic in business practices

## SUBOPTIMALITY

- Potential value of the available data not fully extracted. Data not shared due to confidentiality or privacy constraints.
- Forecasting models are seen as stand alone without considering the application they are used and the value they bring.

# Smart4RES solutions and impacts



**REDUCED KNOWLEDGE OF THE PHYSICAL SYSTEM**

- Ultra/high resolution modeling of weather conditions
- Weather forecasts adapted to the energy sector
- Modelling based on multiple sources of data

**HIGHER MODELLING ACCURACY**

**VULNERABILITY**

- Solutions that permit operators to take optimal decisions under situations with lacking information

**RESILIENCE**

**COMPLEXITY**

- Convergence of the technology through seamless solutions
- Joint forecasting and optimisation prescriptive approach
- Reduce information for human operators

**SIMPLICITY**

**UNCERTAINTIES**

- Reduce uncertainties through better predictions
- Optimisation tools to manage uncertainties

**ROBUSTNESS**

**SUBOPTIMALITY**

- Value-oriented vs accuracy-oriented forecasting
- Privacy/confidentiality preserving data sharing & optimisation
- Prescriptive analytics

**VALUE MAXIMISATION**



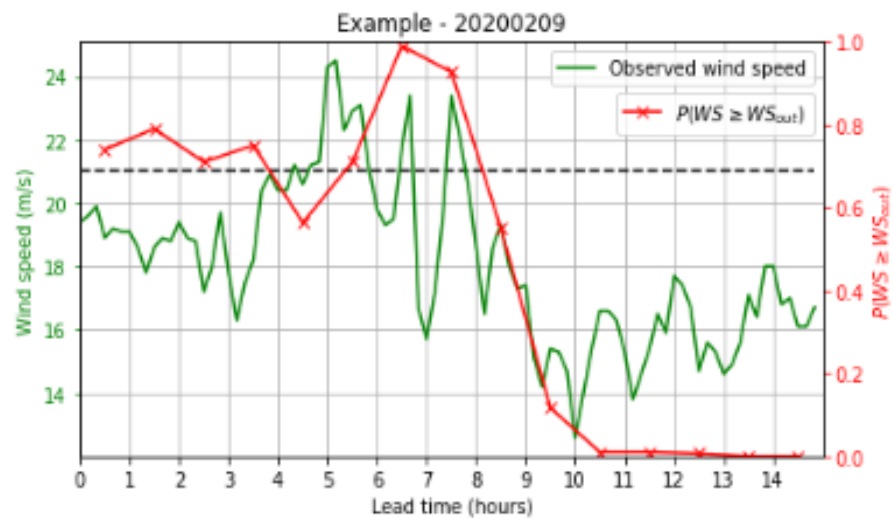
# Highlight results

# High-resolution weather forecasting

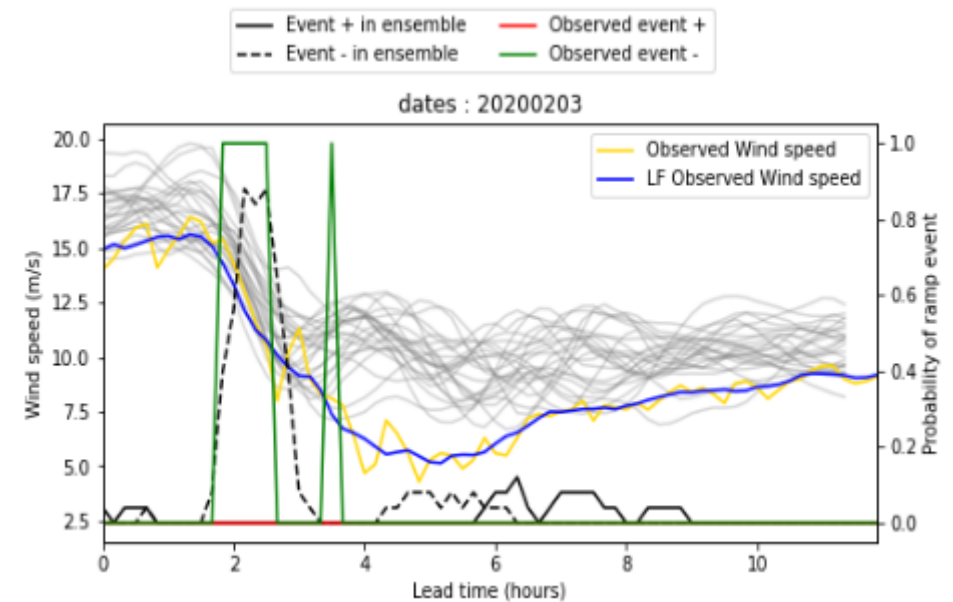
- Generation of high resolution ensembles (1km - 5min, MeteoFrance)

Derive different types of products, i.e.:

- Pseudo-deterministic Numerical Weather Predictions
- Forecasts for extreme situations (cut-out, ramps...).
- Applied to wind speed and direction at hub height (121 wind farms)



Cut-out probability



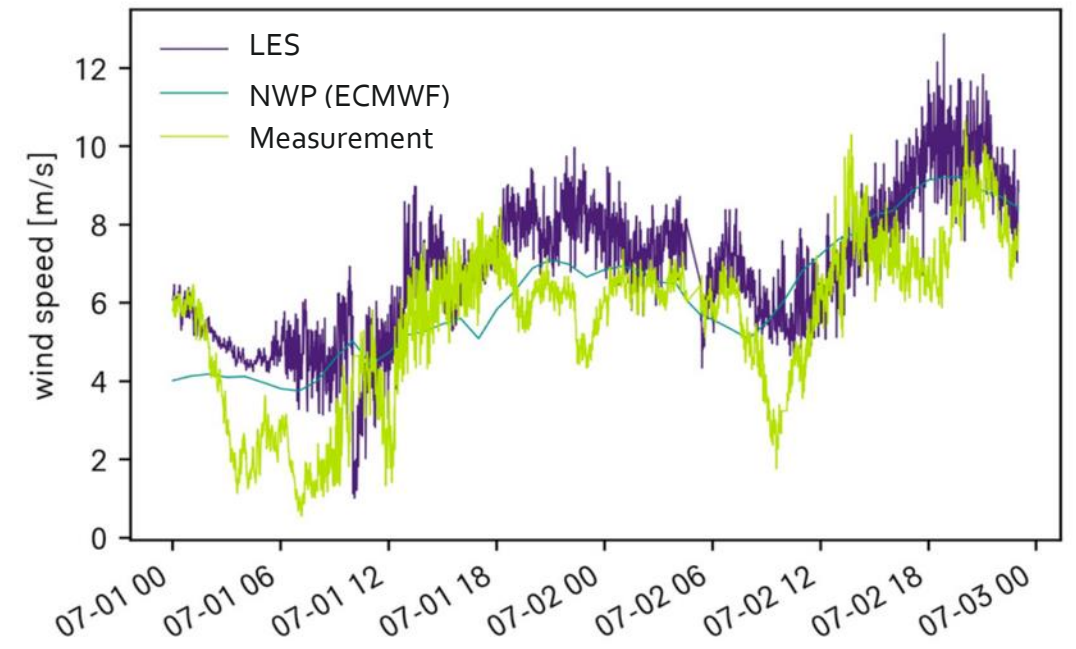
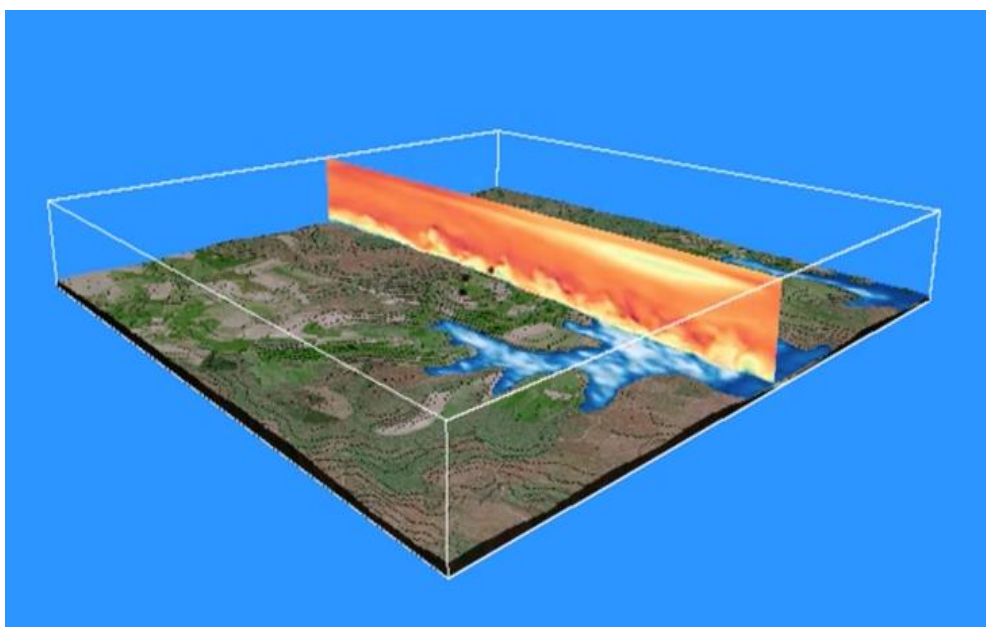
Ramp probability

- **15%** improvement of RMSE compared to standard NWP model
- Forecasting products for specific situations, eg extremes or ramps

# High-resolution weather forecasting

- Large Eddy Simulation provides local forecasts of wind speed and power (Whiffle)

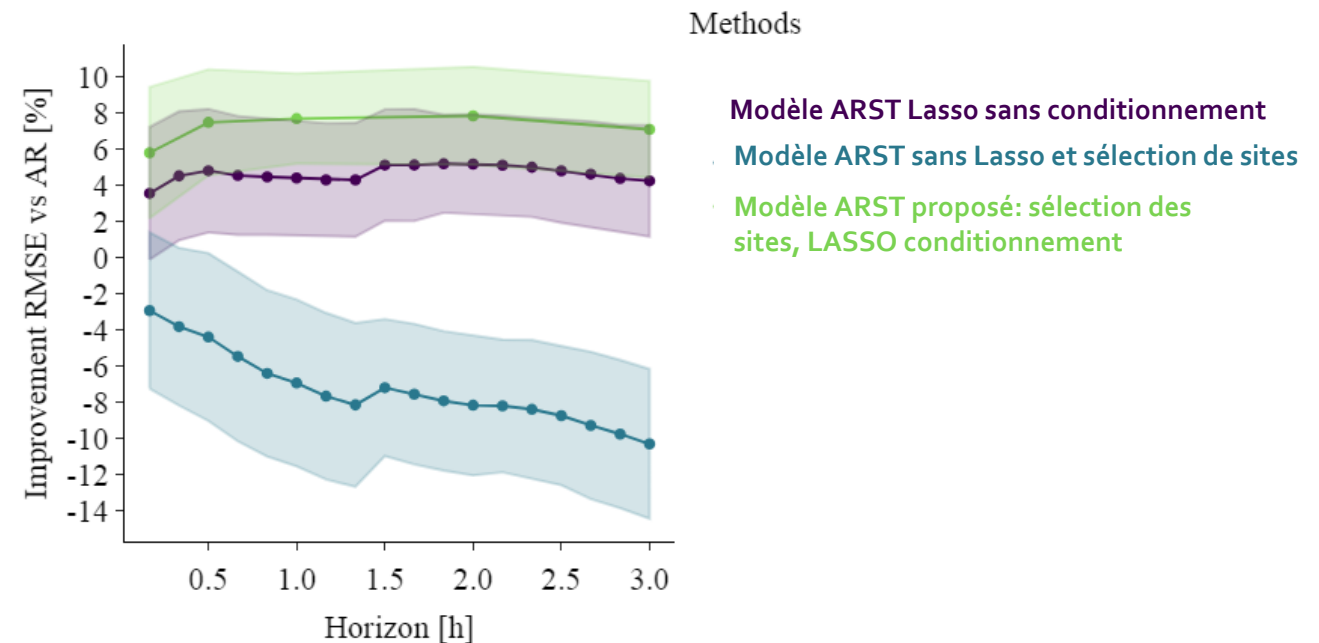
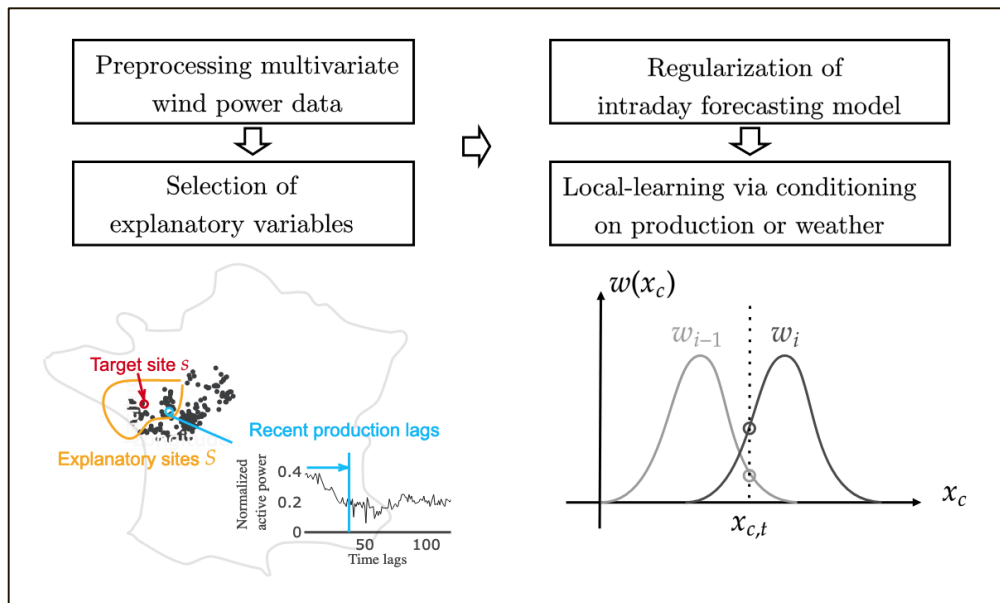
Resolves turbulence, clouds/fog and effect of surface on local weather conditions, by numerical simulation over a much finer grid than conventional NWP (50m - 30sec resolution)



- Accurate modelling of turbulent fluctuations at timescales below 15 min
- New forecasting product for grid management and flexibility provision

# Spatio-temporal intraday forecasting

- Exploitation of measurements from neighbor sites to predict wind production of a site (direct collab. MINES/RTE):
  - Interpretable model combining data from neighbour sites conditioned to local winds forecasts.
  - **Application** to 670 onshore sites in France monitored by RTE. Horizons from 10 min to 6 hours.
  - **Results: +8%** RMSE improvement compared to a model that considers only local data.



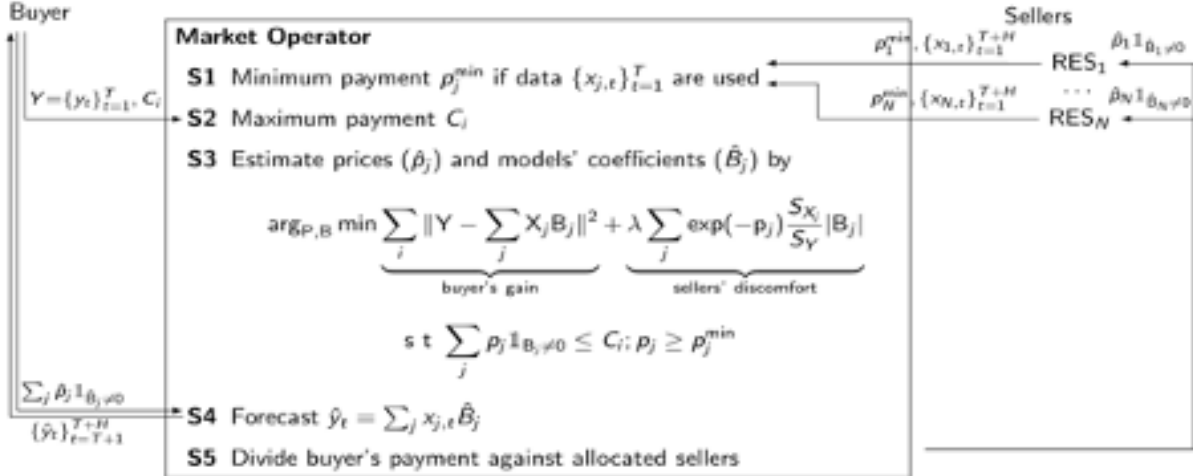
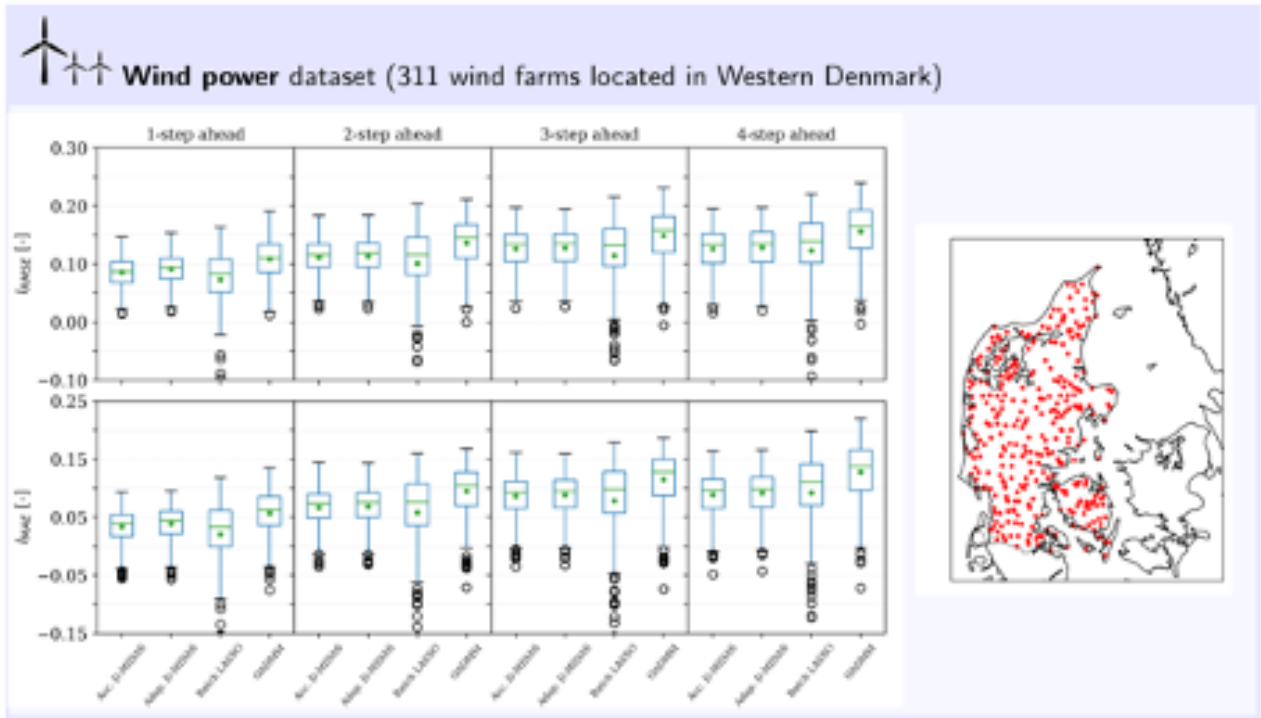


# Collaborative forecasting, data sharing and data markets



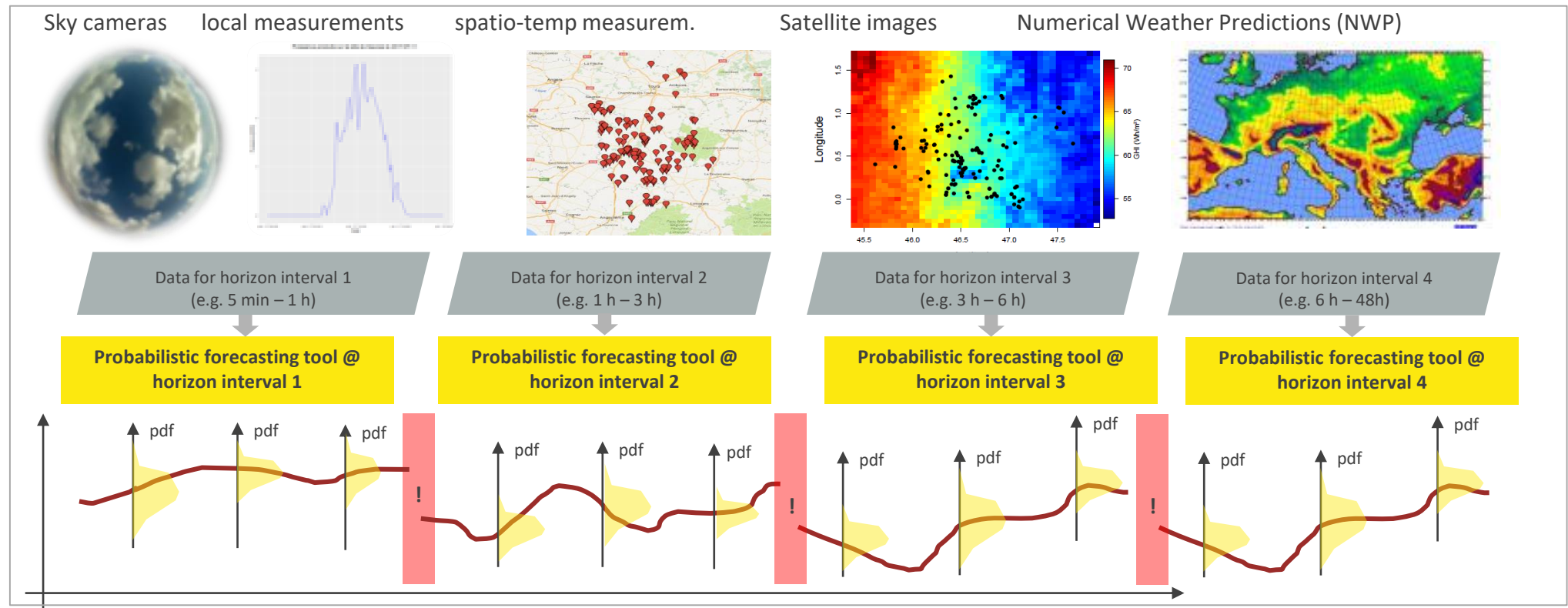
- Cutting-edge collaborative and distributed learning approaches that set a new standard within the field of renewable energy forecasting (INESC, DTU)
  - Data sharing while respecting confidentiality and privacy constraints.

- First-even proposal of a data market for energy applications, relying on several methodological and application-related developments (INESC, DTU)



# Seamless RES forecasting

- Objective:** develop a single probabilistic model able to cover all time frames, all available data input and applicable to all technologies (wind/solar/combinations...). Have at least same level of performance as existing dedicated models.

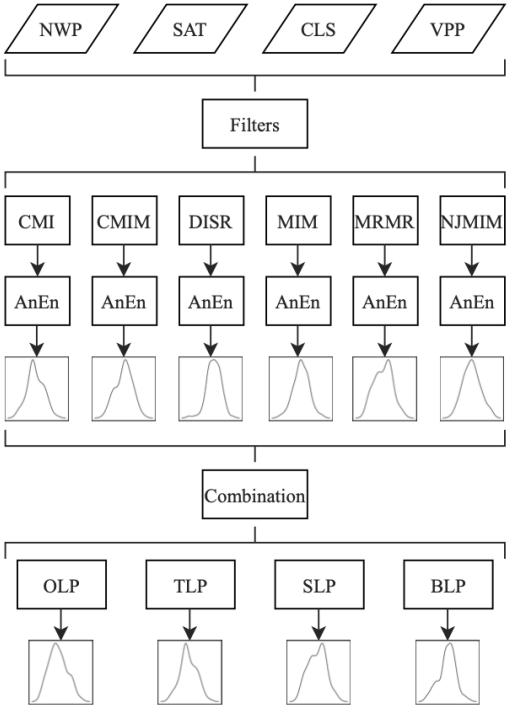


The usual RES forecasting consists in separate models for different time frames

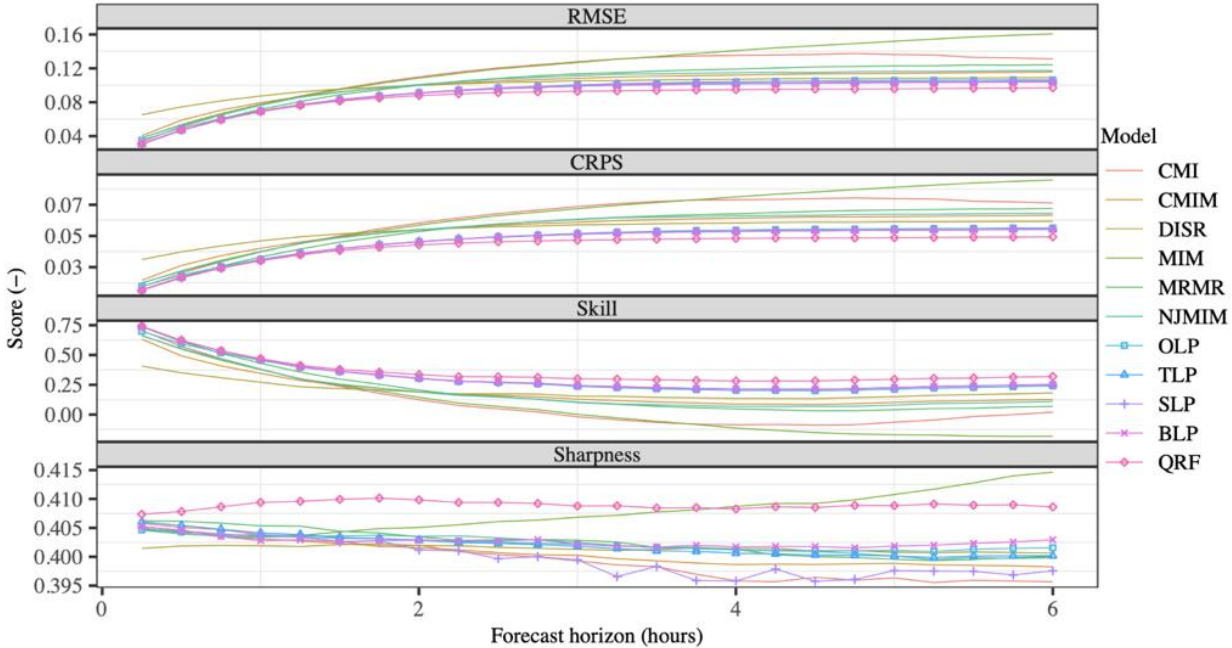
# Seamless RES forecasting

- **Objective:** develop a single probabilistic model able to cover all time frames, all available data input and applicable to all technologies (wind/solar/combinations...). Have at least same level of performance as existing dedicated models.
  - Method based on analog ensembles (MINES Paris)

## Model workflow



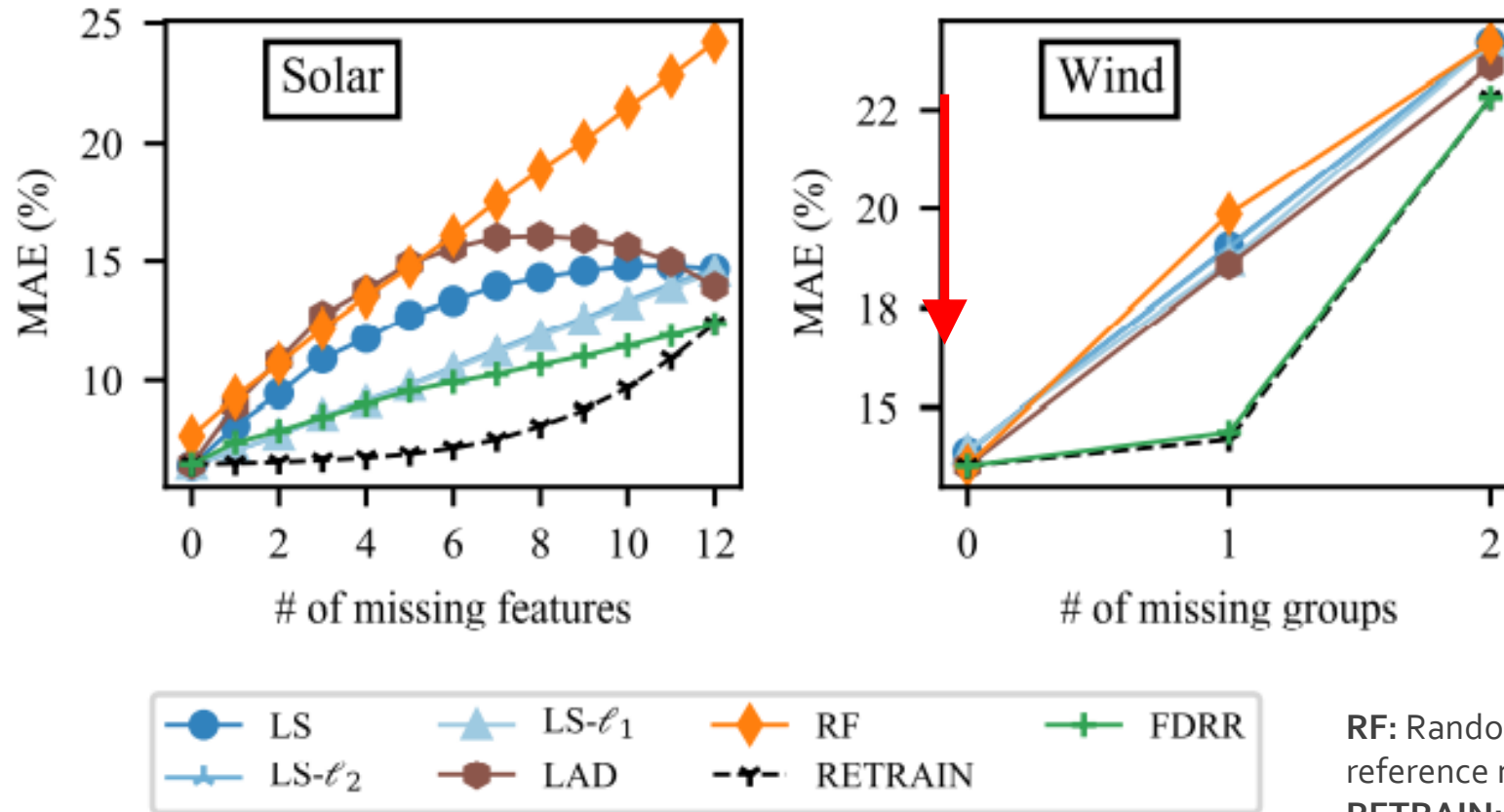
## Obtained results



Similar performance to computationally-intensive models (eg QRF)

# Resilient RES forecasting

- **Objective:** develop a forecasting approach that is robust against missing data at operational environment.
  - Feature-deletion robust regression (FDRR) minimizes the worst-case loss when  $\Gamma$  features are missing (MINES Paris).



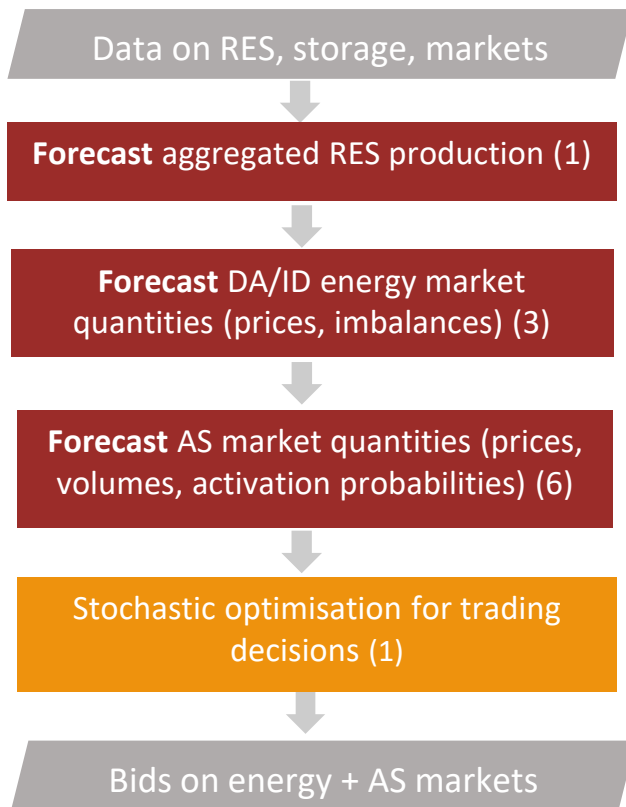
RF: Random Forest approach commonly used as advanced reference model.

RETRAIN: retrained models with missing features.

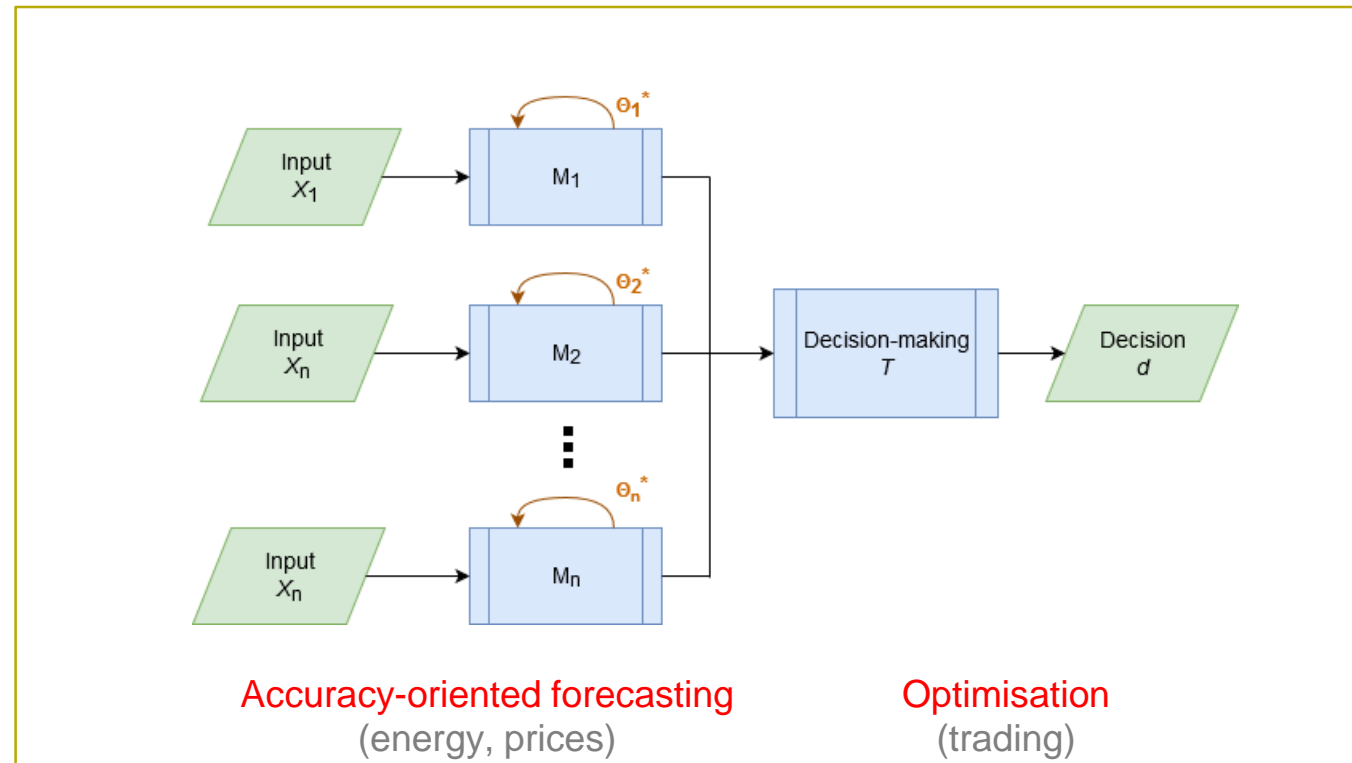


# Value-oriented forecasting

**Example Use-Case: Optimisation of VPP participation in day-ahead (DA) + Intraday (ID) + Ancillary Service (AS) markets:**  
(in parenthesis the number of models: 11 in total)

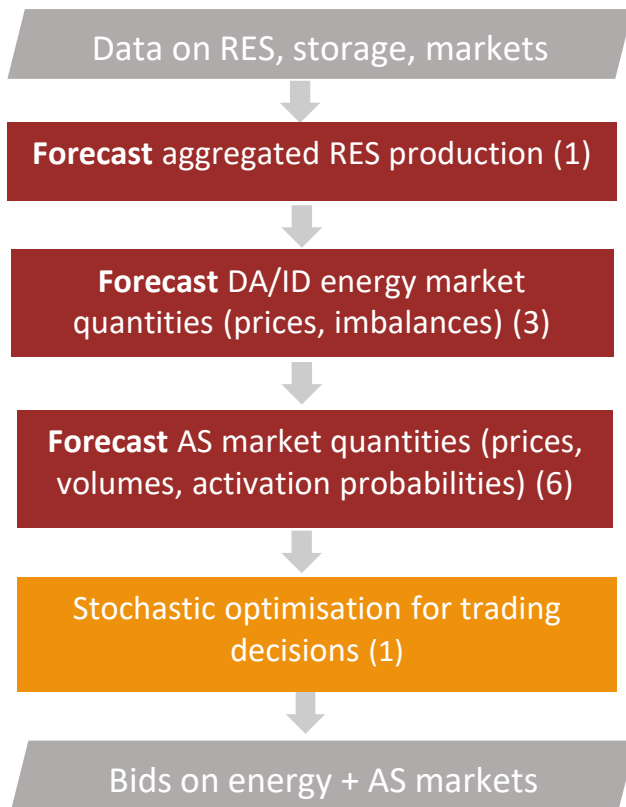


The classic approach:  
**FORECAST THEN OPTIMISE**

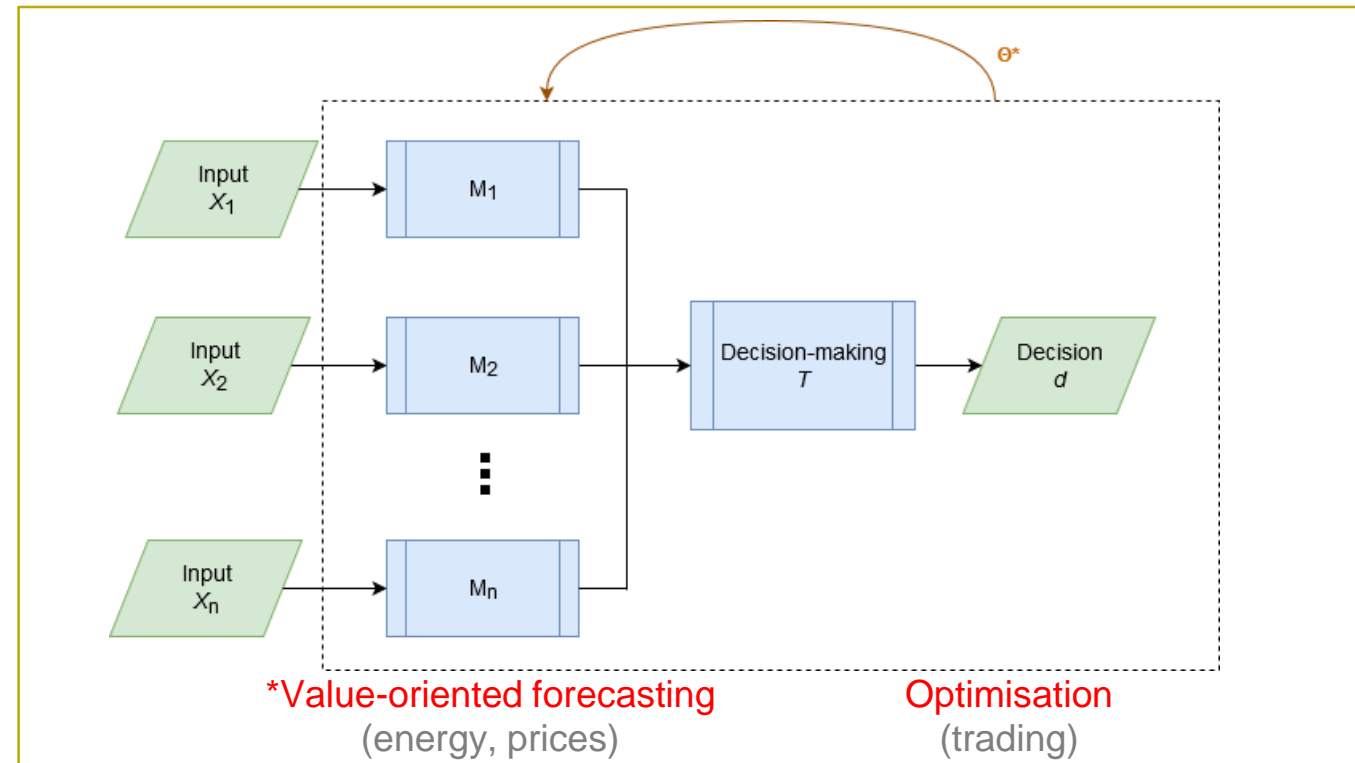


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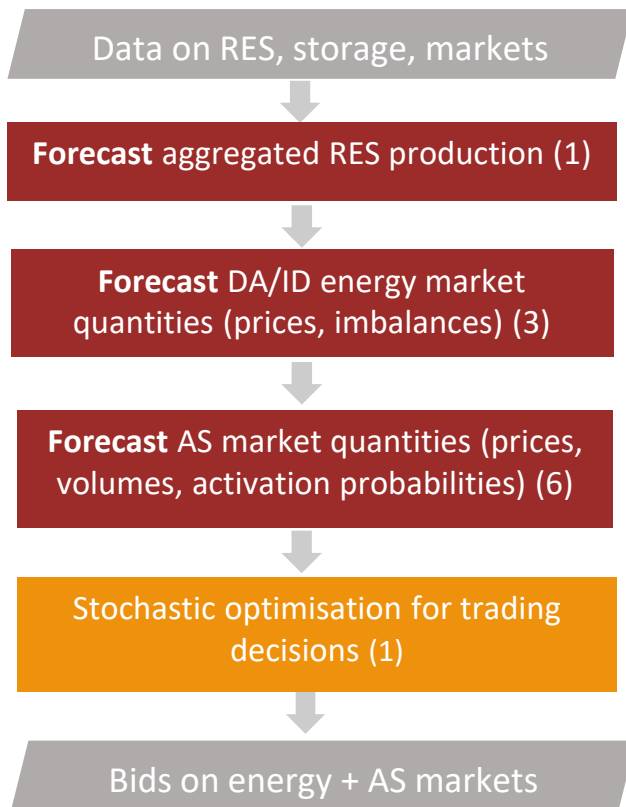


## FORECAST\* THEN OPTIMISE

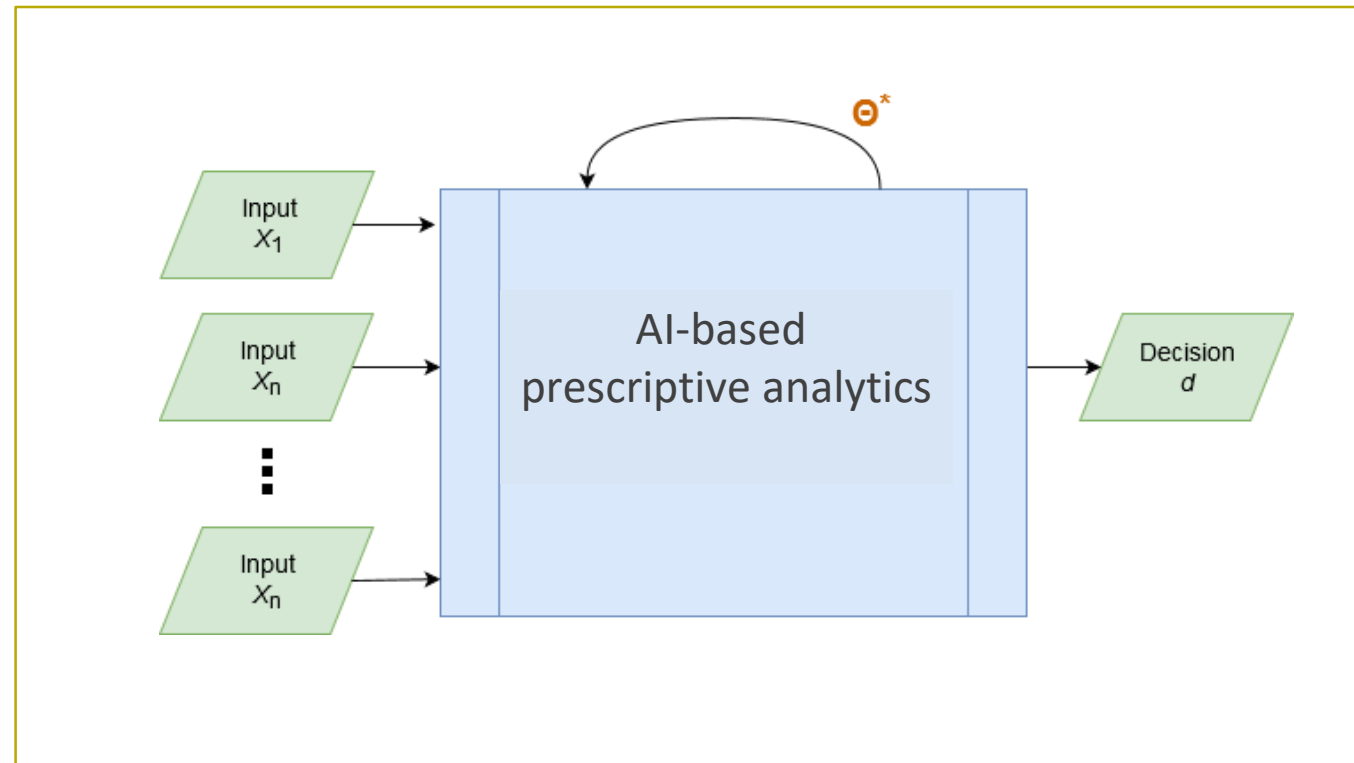


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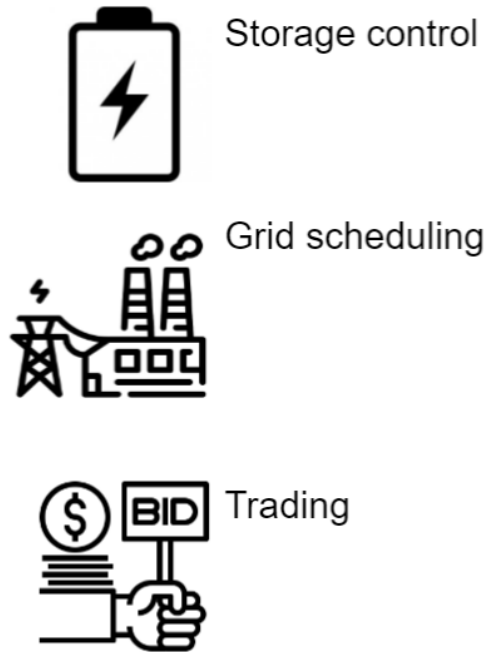


## JOINT FORECASTING & OPTIMISATION

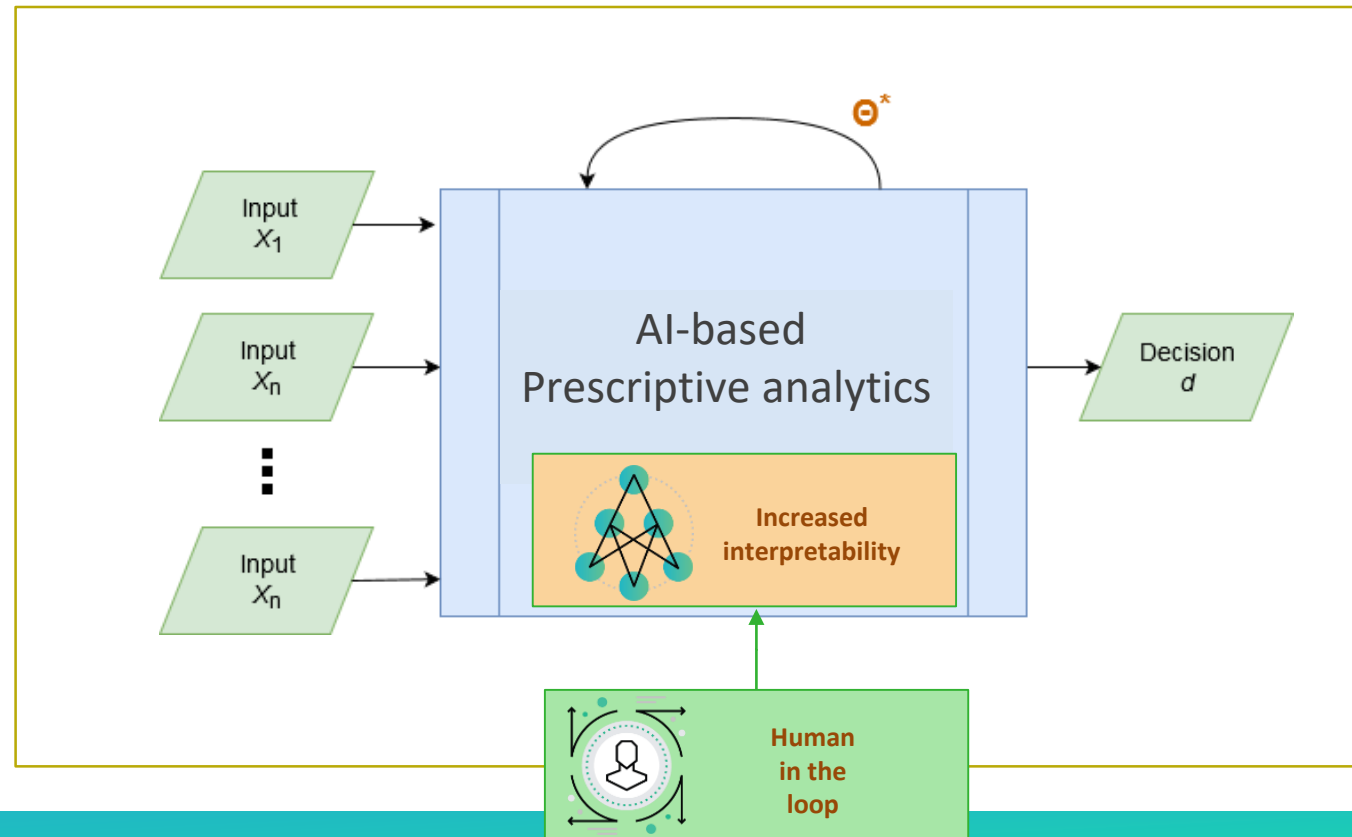


# Value-oriented forecasting

Example Use-Case: Optimisation of VPP participation in day-ahead (DA) + Intraday (ID) + Ancillary Service (AS) markets:  
(in parenthesis the number of models: 11 in total)



## JOINT FORECASTING & OPTIMISATION (Perspectives)



- Further evolutions of **weather forecasting** models needed (data assim., frequent updates...)
- **New forecasting products** will be requested by emerging applications.
- **Simplification & automatisisation of the model/value** chain will remain a challenge.
- Energy forecasting and related decision making tools should become **resilient** (missing data, cyberattacks...)
- Optimisation/decision-making tools will benefit by integrating **alternative forecasting products**
- The adoption of probabilistic optimisation/decision-making tools by industry should be facilitated. **Operator-centric innovation adoption policies** needed inside the companies.
- ...





THANK YOU !

Denmark 

Netherlands  

Germany  

France      Dowel innovation

Portugal  

Greece  



- Get in touch on our social media



<https://twitter.com/Smart4RES>



<https://www.linkedin.com/company/30726283>

<https://www.smart4res.eu/>



The Smart4RES project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864337



# APPENDIX

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## COPYRIGHT

Smart4RES project: “Next Generation Modelling and Forecasting of Variable Renewable Generation for Large-scale Integration in Energy Systems and Markets”

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## PROJECT COORDINATOR & CONTACTS

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*The Smart4RES project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864337*

