EARS4WindEnergy

Ensemble-based Approach utilizing a Refined SODAR for Wind Energy Applications

An *EU-Energy IF - Eurostars III - Call 3* Project

Demonstration Report

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Executive Summary

The EARS4Windenergy project developed and validated an integrated solution combining AQ Systems' AQ510 SODAR remote-sensing instrument with WEPROG's Multi-Scheme Ensemble Prediction System (MSEPS) to improve wind-resource assessment, operational forecasting, and wind-power integration. The project addresses the growing need for alternatives to traditional meteorological masts, which are costly, difficult to permit, and increasingly limited by the greater hub heights of modern wind turbines.

The solution is intended to provide accurate wind measurements at heights of up to approximately 300 metres while reducing installation time, cost, environmental impact, and dependence on fixed infrastructure. When combined with ensemble-based numerical weather prediction, the system can support wind-farm siting, data gap filling, short-term forecasting, power trading and balancing, grid management, and operational decision-making.

Demonstration activities were conducted across a broad range of environments in Sweden, Denmark, Germany, and Ireland. The test sites included relatively flat agricultural and coastal locations, established turbine test centres, semi-complex terrain, mountainous terrain, and an operational wind farm. Measurements were compared with meteorological masts, scanning LiDAR systems, wind turbines, and precipitation gauges. This range of conditions enabled the project partners to assess the SODAR's performance across different levels of wind shear, turbulence, surface roughness, topographic complexity, and weather exposure.

A real-time data exchange and analysis infrastructure was successfully established between AQ Systems and WEPROG. SODAR measurements and dedicated forecasts were exchanged through web services and made available through the AQ Online and PLUTO platforms. This demonstrated the technical feasibility of integrating remote-sensing measurements with ensemble forecasts in operational workflows. The project also advanced signal-processing methods, including improved wind-profile retrieval and initial processing of precipitation signals.

The most significant validation was conducted at an approximately 100 MW wind farm in County Donegal, Ireland. The site presents challenging conditions, including rugged terrain, strong Atlantic winds, mountain-induced flow channeling, turbulence, and spatial variation in wind conditions across the wind farm. These conditions provided a demanding test of the AQ510's ability to support the real-time meteorological data requirements applicable to Irish wind farms.

The Irish benchmark produced strong results:

The correlation between AQ510 wind measurements and the reference turbine's nacelle wind was 0.96. The correlation between the AQ510 signal and the forecast was 0.87. The correlation between the forecast and nacelle wind was 0.85. Across 10,502 ten-minute intervals, AQ510-based power estimation achieved a mean absolute error of 5.36, compared with 12.16 for the

reference forecast. The resulting power estimate represented an improvement of approximately 6.8% compared with the forecast. This exceeded the 3% improvement threshold applicable to larger wind farms and also met the 5% improvement target identified for average conditions.

These results demonstrate that the AQ510 can provide locally representative wind information and improve wind-power estimation relative to area-averaged numerical forecasts, particularly in complex and semi-complex terrain. The findings also indicate that measurements taken near a representative turbine or capacity centre could further improve accuracy. However, for large wind farms with substantial spatial variation, multiple measurement locations may be needed to represent conditions across the entire site.

The project identified some remaining technical considerations. Data losses occurred primarily during severe weather and turbine cut-out conditions. Additional measurements of precipitation, temperature, and near-surface wind could improve system availability, extreme-weather awareness, and minute-scale forecasting. Ensemble forecasts could also be used to assign quality flags to measurements and estimate missing or related meteorological variables.

Overall, the project achieved substantial progress toward its technical and commercial objectives. It established a validated proof of concept for combining SODAR measurements with ensemble weather forecasts, demonstrated real-time data integration, and showed that the AQ510 can improve wind-power forecasting performance in challenging terrain. The results support the commercialization of a turnkey remote-sensing and forecasting solution for wind-farm development and operation. Based on the Irish demonstration, the report concludes that the AQ510 is ready for consideration as an alternative instrument for meteorological data delivery under the relevant Irish grid-code requirements.

Introduction

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1. Introduction to the Project

1.1 Background Information

The aim of the project EARS4Windenergy – Ensemble-based Approach utilizing a Refined SODAR for Wind Energy Applications – was to (1) provide the wind industry with new products for the accurate quantification of pre-construction wind conditions and (2) enable major productivity improvements in existing wind farms regarding operation and maintenance, the integration of wind power into the electric grid, trading and balancing of wind power. The plan foresees through a new partnership between a manufacturer of ground-based remote sensing instruments and another SME which supplying ensemble-based meteorological simulations and the support of two universities, to be able to invent, innovate and validate these new developments for their purpose in real-world applications.

The necessity of dedicated research and development on this topic springs out of an urgent need to find a replacement for the expensive meteorological towers, which are traditionally used to determine the relevant wind conditions for both wind farm operations and wind turbine siting. Apart from the cost, the permit process for installing meteorological masts usually involve long waiting times and delays the time-to-market for new wind projects. The combination of a measurement height up to 300m, unit mobility, cost, durability and immunity to environmental conditions makes the product we want to develop ideal for the transition. Turbulence measurements and data availability, covered in this project, are the remaining barriers.

The new partnership of the project can lead to substantially extended business opportunities for both AQSystem and WEPROG in a market of strong growth. The proposed products have the potential to reduce both cost and time-to-market for new and existing wind farms, which is essential in order to move towards a carbon-free energy system. With the project partnership, the two SMEs plan to extend their business area to each other's main markets by adapting the new products to the need of the respective markets. AQSystem plans to offer WEPROG's services as a part of each sold instrument unit and contracted power forecasts by WEPROG may be strongly improved by use of AQSystem instruments.

1.1.1 Current state-of-the-art

The accurate siting of wind turbines is critical for optimizing performance and ensuring safety. Achieving less than 1% error in wind climatology is essential, influencing turbine selection and operational efficiency. Reliable data acquisition is therefore vital, traditionally gathered by using meteorological towers.

However, the increasing costs associated with larger wind turbines necessitate the exploration of remote-sensing alternatives to lower operational costs without compromising data quality.
At the outset of the project, AQSystems is focusing on siting and WEPROG on operational weather and energy forecasting. This joint initiative aims to leverage advancements in remote sensing and numerical weather prediction to improve the accuracy of wind measurements and their application in forecasting processes.

1.1.1.1 The Multi-scheme Ensemble Prediction System (MSEPS)

The Multi-Scheme Ensemble Prediction System (MSEPS) was developed in 2005 to provide a real-time ensemble forecasting tool for efficiently integrating renewables, especially wind and solar energy, into markets reliant on weather-driven resources (see e.g.[18, 20, 21]).
The MSEPS forecasts physically-based weather uncertainty, leveraging 75 ensemble forecasts generated with a multi-scheme approach that varies the NWP model's physical and dynamical processes within the numerical model kernel, focusing on crucial aspects in the lower boundary layer such as condensation and advection processes important for renewables forecasting.
Though ensemble forecasts are often claimed to be more accurate than deterministic forecasts, WEPROG challenges this, advocating that no single forecast can be relied upon. In wind power, operational balance and minimizing errors are critical. Therefore, using ensemble forecasts enhances the ability to schedule dispatch securely and cost-efficiently. Ensemble forecasts also foster competition by providing insights into weather uncertainties and supporting smarter balancing and trading strategies. The system's robustification filters uncertain forecasts to produce a conservative mean, acknowledging that reliance on single forecasts is unadvisable.
MSEPS quantifies security needs and offers probability distributions for key weather variables, accurately predicting uncertainty changes for critical infrastructure aspects and extreme events.
MSEPS is modular, allowing easy integration of various weather applications as third-party tools. In this project, we use the MSEPS to enhance data assimilation processes by use of remote sensing information and investigating model configurations for the purpose of gap-filling of data for resource assessments and extreme event forecasting.

1.1.2 New markets

The project envisaged AQ Systems to enter a new market section that is subject to growth over the next decades due to a gap in instrumentation for real-time wind energy applications that the AQ510 SODAR can fill. The instrument can become an important enabler for high levels of wind energy on the electric grids.
Enabling the SODAR to be a player on the real-time market, supplying reliable and trustworthy measurements of local weather conditions, will enable WEPROG to serve the electricity markets anywhere on the globe, even if there are sparse other meteorological measurements.
In that way, both AQ Systems and WEPROG can fill gaps and use niches in the markets that are not served by the big players and thereby contribute to the global sustainability goals on clean energy for everybody.
Being able to deliver a turn-key solution without dependencies on other suppliers (both on software and hardware), is paving the way to support underserved areas as well as areas, where weather conditions are difficult. AQ Systems independent power supply solution and WEPROG's independence on weather data enables the provision of services anywhere and limitless.
To conclude, the project has made substantial progress towards achieving its goals and anticipated outcomes. Both companies successfully tested and analysed the expected impacts (**??**) and requirements necessary to advance the solution to the next level of technology readiness for ultimately being able to bring it to market. Meanwhile, the universities played a key role in the software development for the SODAR's signal processing, as well as in verifying all developments. Their enhanced collaboration also facilitated a successful joint "proof of concept."

II Demonstration Sites

2. Description of the Demonstration Sites

In this project, we have been working with five site demonstrations, which have also been presented at various workshops (see e.g. [7, 9, 10, 11, 12, 5]). Figure 2.1 is showing the five locations and Table 2.1 summarises the characteristics of the demonstration sites and the respective duration, reference instruments, measuring heights and primary objective. The sites have been carefully selected to cover a broad range of different orography and climate types and their associated challenges for the SODAR.



Figure 2.1: Map of the demonstration experiments with the AQ510 SODAR marked as five red flags. The locations are distributed over four countries, one site in Southern Sweden, two in Denmark, one in South-West Germany and one in the North-West of Ireland.

WEPROG generated for all locations dedicated forecasts and provided them together with the measurements from the SODAR in an Online Data-management and -analysis tool.
Additionally, AQ Systems provided access to their data platform “AQ Online” (https://aqonline.se/) for the partners to access and download data.

Both AQ Systems and WEPROG exchanged online data with each other via WebServices in real-time throughout the project and especially while the experiments were running. In that way, the exchange of measurement and forecast data was already established and well tested throughout the project for those projects and customers that can provide access to the measurement data. In those cases, where access would not be possible through AQ Systems, the software for gap-filling (see chapter **??**) would have to be installed on the instruments CPU or the SCADA system of the end-user. Both services are technologically feasible and realtively straight forward implementable.

Within the project, the twofold solution of data and forecast access enabled all research partners to follow the performance of both the instrument and the improvement of the forecasts over time.

Area	Country	Start	End	Months	Reference	Height	Primary Objective
Mohol	SE	2023/03	2025/09	30	Met Mast	100m	Seasons/long-term
Hornamossen	SE	2022/05	2022/07	5	Met Mast+ ZX	180m	Upper heights
Østerild	DK	2023/07	2023/08	1	Met Mast	244m	Upper heights
Østerild	DK	2016/03	2016/08	3	Met Mast	244m	Upper heights
Risø	DK	2023/11	2024/03	4	Met Mast+ WS	200m	WS + Rain
Stötten	DE	2023/11	2024/02	4	Met Mast+ Halo	3 00m	Complex terrain
Donegal	IE	2024/11	2025/06	6	Mast+Turbine	100m	Certification

Table 2.1: Summary of the demonstration sites, the length of the demonstration, the reference measurements and the primary objective. The abbreviations “WS” stands for WindScanner, which is a scanning Doppler LiDAR from ZSW, Halo stands for DTU Risø Halophotonics wind scanner, a Doppler LiDAR system. Both LiDARs are specifically developed for measuring wind profiles.

2.0.1 Swedish Demonstration Site Moholm in Southern Sweden

The demonstration site Moholm, is located in Southern Sweden between the two large Swedish lakes named Vänern and Vättern (see Fig. 2.2). The test site consists of a met mast with a top measurement at 103m and is located to the North of a smaller airport field, where the terrain is flat to the Southwest and Northeast, limited by small forest areas around 400-800m to the met mast to the Northwest and to the Southeast.

The surrounding terrain is characterised by a flat inland landscape of mixed agricultural land, pasture and scattered woodland. The area exhibits moderate surface roughness from hedgerows, small forest patches and rural infrastructure, producing heterogeneous wind fetch and localized turbulence. The proximity to large lakes, Vänern to the North-West and Vättern to the South-East, can modify the local thermal regime and stability, occasionally causing lake-breeze circulations that interact with the topography. These combined land-cover and mesoscale influences can result in variable wind exposure and shear and generate site-specific flow characterisation.

The site serves as the reference site for the AQ510 SODAR, was used for IEC 61400-12-1:2017 resource assessment certification, and is currently used to calibrate new instruments.



Figure 2.2: Reference test site for certification of IEC 61400-12 for the AQ510 [Source: AQ Systems S.E.]

2.0.2 Danish Windturbine Test Center Østerild, North-West Denmark

The test Centre Østerild is located at the west coast of Northern Jutland in Denmark and has some of the best wind conditions in Denmark. With its 9 test stands, the centre allows manufacturers to test and to study full sized wind turbines before they enter the market. Researchers test instrumentation of all kinds to enhance control, management and efficiency of wind turbines.
The centre lies in a gently undulating coastal plain of sandy soils, dunes and beach ridges. The landscape is largely open and treeless with low vegetation, providing long aerodynamic fetch and low surface roughness. Prevailing westerly winds from the North Sea encounter minimal upstream obstacles, yielding relatively uniform incoming flow with only minor local turbulence from dune features and small structures. Fig. 2.3 shows a picture of four of the test stands and one of the adjacent met masts.



Figure 2.3: Test facilities for the 1-month experiment and calibration phase of the AQ510 at Østerild in the North-West of Jutland, Denmark [Source: DTU]

2.0.3 Danish Test Center at the DTU Risø Campus

The facilities at the DTU Risø Campus are used to test, certify and service LIDARs and other remote sensing instrumentation such as SODARs ad RADARS. The test facility was used in the project to compare the SODAR's new signal processing algorithm with DTU's wind scanner and an adjacent met mast. The precipitation signal processing was tested agains rain gauges. Fig 2.4 shows an arial figure of the test facility with the met mast in the background (left end of the red arrow), where also the rain gauges are installed.
The DTU Risø Campus is situated on a low-lying, gently rolling inland landscape characterized by mixed agricultural fields, pasture, and patches of woodland. The terrain is relatively flat with moderate surface roughness from hedgerows, small forests, and scattered buildings. Land use is semi-rural and fragmented, so wind fetch is shorter and flow is more heterogeneous than on typical coastal test sites. Local topographic features and vegetation cause increased turbulence and spatial variability in the approaching wind.



Figure 2.4: DTU Risø Campus test facilities for the windscanner experiment and verification of measured precipitation signals against rain gauges (left end of the red arrow) [Source: DTU]

2.0.4 German Test Site WINSENT on Stöttener Berg, South-West Germany

The WINSENT test site (https://winsent.de) is situated on a steep slope on Stöttener Berg in the Swabian Alb, approximately 70 km east of Stuttgart near the municipalities Geislingen an der Steige and Donzdorf in the county Baden-Württemberg in the South-West of Germany.
The site is a moderately complex inland test site characterized by undulating terrain of rolling hills and shallow valleys. The area comprises mixed agricultural land, pasture and patches of deciduous and coniferous woodland, yielding moderate surface roughness from vegetation, hedgerows and scattered built structures. Wind exposure is variable with shorter aerodynamic fetch in comparison to the coastal sites, producing increased shear, turbulence and spatial flow heterogeneity. The local topography induces flow acceleration over a forested escarpment of about 150m height (see Fig. 2.6) and sheltered zones in close-by valleys.
The site's topography—notably the prominent escarpment aligned with prevailing winds—and overall complex terrain led the Wind Energy Research Cluster – *WindForS* – (https://windfors.de/en) to select it. The test site is intended for studying wind turbines and conducting basic and applied meteorological research for wind energy in complex, mountainous terrain. Fig 2.1 depicts the location and Fig. 2.5 shows the topographic conditions at the site.



Figure 2.5: Aerial picture of the WINSENT test site. The red rectangle to the right of the met mast depicts the location of the AQ510 SODAR and the wind scanner of ZSW for the experiment. [Source: ZSW, David Arzt]

Key Features of the WINSENT Test Site are:

- Altitude: Approximately 670 meters above sea level.
- Location: Steep slope in Geislingen an der Steige and Donzdorf.
- Infrastructure:
  - Two wind turbines with a hub height of 72m and 50m rotor diameter.
  - Four meteorological measuring masts with a top instrument at ca. 100m, positioned before and after the turbines.
  - Additional measurement equipment consists of synchronized long-range scanning lidar systems, eddy-covariance systems, a ceilometer, a bird radar and bat detection microphones.
- Development: Concept created in 2013-2015 (KonTest project,

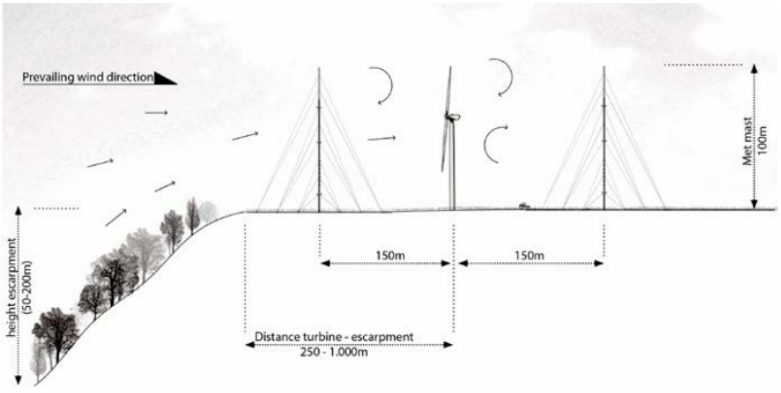


Figure 2.6: Schematic cross section of the WINSENT test site in the South-West of Germany. The SODAR and wind scanner were located right at the top of the slope. [source: TUM-LAREG]

2.0.5 Irish wind farm in Co. Donegal, North-West of Ireland

The Irish demonstration site is within an onshore wind farm, consisting of approximately 40 wind turbines with a total capacity of ca. 100 MW. Located in South Donegal, the area is surrounded by three mountain ridges that tunnel the wind towards the wind farm. Fig 2.7 shows the AQ510 SODAR at the site throughout the demonstration period.



Figure 2.7: Irish wind farm demonstration site in Co. Donegal with the AQ510 SODAR at the demonstration period November 2024 to May 2025 [source: AQ Systems]

The wind farm is built on a rugged, upland coastal plateau characterized by peat-covered moorland, rocky outcrops and rolling hills that descend toward nearby sea cliffs and estuarine inlets. The landscape is largely open with sparse, low vegetation and limited tree cover, producing relatively low surface roughness, but locally complex flow due to escarpments and abrupt elevation changes. Exposure to strong Atlantic winds gives high wind speeds and variable gustiness. The coastal proximity and orographic features generate flow acceleration, separation and enhanced turbulence in lee zones.
These topographic and exposure conditions, where wind turbines often do not experience the same wind makes the site complex, although the area is a semi-complex terrain type. Reliable wind conditions at the site therefore require carefully targeted measurement campaigns.

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3. Analysis of Experiments

3.1 Evaluation of Østerild Experiment

The first site test of the AQ510 took place at the Danish wind power test site at Østerild during July and August 2023 (see also Table 2.1).

The site test provided a one month benchmark of the AQ510 against the local mast. Our focus here is to evaluate the results of the 100m wind speed with respect to accuracy of the MSEPS production forecast and the AQ510.

There was a technical error on the AQ510 from 2023/07/30 12UTC to 2023/07/31 06UTC, where no results were delivered in any altitude. None of the results presented below have this period included. Other than that all 100m wind speed values were delivered.

The weather during the period was characterized by long periods of approximately 7-13m/s westerly wind with a nearly permanent 0.5-1.0m/s variability. There was one peak at 24m/s. The periods of non-westerly wind were short with strong wind shifts, where all wind directions occurred. The distribution of wind speed and directions were typical for a rather cold summer dominated by low pressure system activity from west.

3.1.1 Lessons Learned from the Østerild data collection

Time stamps

The original data from Risø and AQ-systems are timestamped differently. There were differences on timezone, daylight saving and forward/backward recording on the 10min level. The best match was found by shifting the AQ510 data 50 minutes backwards. Table 3.1 demonstrates the sensitivity to the use of time stamps.

We evaluated wind speed (ws) and power (pwr) for AQ510 and the ensemble mean forecast from the MSEPS production system. The times series in power are found by using a reference power curve to each wind speed time series. The assumption is equivalent to a perfect power curve for a single turbine with a hub-height of 100m without any direction dependent wake effect.

Assumptions

The assumptions required to produce power are on the one hand idealized compared to a larger wind farm, but the wind turbines do not experience exactly the same wind speed and therefore generate a smoother power time series than a single wind turbine. These two effects compensate each other and the result in power can be considered representative for single turbines as well as small and moderately sized wind farms and are used in data quality checks in the power system (see e.g. [15, 14, 19]).

Reference	Forecast	Type	BIAS [m/s]	MAE [m/s]
mast	MSEPS	ws	0.03	1.29
mast	AQ510	ws	0.19	0.60
AQ510	MSEPS	ws	-0.15	1.35

Reference	Forecast	Type	BIAS [MW]	MAE [MW]
mast	MSEPS	pwr	-0.32	10.97
mast	AQ510	pwr	1.36	5.04
AQ510	MSEPS	pwr	-1.68	11.60
data loss=0 delivered data=4200				

Table 3.1: Statistics of the Østerild experiment (see 2.0.2) for wind speed (ws) and reference wind power (pwr) computed from met mast wind speeds.

Error Analysis

The error of the MSEPS forecast is at the expected level in wind speed, and, given the reference is data from a met mast transformed into power. The result indicates that Østerild is a location with a high wind resource without local terrain complexity. The result is therefore representative for areas, where larger wind farms would naturally be installed.

The sensitivity to a 50 minute time-shift of the AQ510 relative to the mast, generate errors of nearly the same magnitude as the forecast. The reason is that the shorter time scales (10-20min) are out of phase and with 0.5-1.0 m/s amplitude, the MAE can hardly be under 0.5m/s. Both mast and AQ510 have an almost permanent variability on this time scale with a magnitude that changes randomly within the 0.5-1.0m/s range. For this reason a time shift of just 10 minutes increases the difference between the two time-series significantly.

The MSEPS forecasts in a horizontal resolution of 22km do not contain any comparable variability to what is observed by the measurements. Hence, it is not possible to time shift the forecast and thereby achieve better results. It is worth noting, that the result of the forecast would be significantly worse inclusive variability, because the magnitude and timing of such variability would be random and suffer from double-punishment.

The achieved MAE error of 0.6m/s is difficult to evaluate positive, because it is double the error of the reference site in Sweden (2.0.1). Also, the error is 50% of the NWP error. Clearly, the AQ510 is much better than the forecast. One could interpret the result that point variability is responsible for 50% of the NWP forecast error and that a perfect forecast would still contain about 0.6m/s MAE error due to the difference in variability between actual and forecast.

The wind speed MAE between forecast and AQ510 is 0.06m/s higher than the AQ510 against the met mast. This is a sign of that the mast is maybe more accurate than the AQ510, but the combination of met mast and AQ510 increases the accuracy of the validation further.

The MAE forecast is 0.03m/s better against the average of AQ510 and met mast than the met mast alone. Also, a small positive impact in power can be seen. All 3 signals are time averaged over 10 minutes. Therefore, our results suggest that two instruments provide a more useful measure seen from a forecast verification and assimilation perspective. The forecast is an average over an area, whereas both mast and AQ510 are point measurements. Combining these, becomes then equivalent to an area average. However, a longer distance between the met mast and AQ510 would increase the difference between the two and the forecast may perform even better against the average of the met mast and the AQ510. The distance sensitivity hence always needs to be considered.

Lessons Learned 3.1 — Combing MSEPS forecasts with measurement data. Our results suggest that a combination of met mast and SODAR provided the most promising measure seen from a forecast verification and assimilation perspective. The forecast is an average over an area and combining multiple measuring devices creates an equivalent to an area average.
The windy Østerild Test site, with well-maintained instruments has been very helpful in identifying core challenges of the SODAR signals and finding solutions for successful project progress.

3.1.2 Sensitivity Experiments

The robust result of the benchmark encouraged to use the same benchmark period to perform high spatial resolution sensitive studies of the MSEPS weather forecast model, because it is a highly relevant site for NWP forecast validation with a wind power scope.

The purpose of the sensitivity experiments were:

- To find the NWP configuration with the best score
- To clarify, if any of the MSEPS ensemble configurations forecast the observed variability
- To find explanations of the continued observed variability

The most obvious limitation in the MSEPS reference or production forecast in 22km resolution was the lack of detail of the coast line in the area arout Østerild. The fraction of sea and temperature of the sea surface differs fundamentally in upstream direction. This means that wind direction shifts often impact the effective surface temperature felt by an air parcels in the 10-20 minute period before arrival at the test site. Increased model resolution normally reduces the potential impact of wrong surface temperature, but with the constraint that the forecasted wind direction is correct. The uncertainty of the wind direction was relatively low during approximately 75% of the benchmark period.
For this reason, we conducted 13 sensitivity experiments at Østerild. Tab. 3.2 summarises the experiment setup with respect to model resolution and number of vertical model levels, as well as other changes and a brief explanation of the reasoning behind the choices. Common for all experiments is that they use the same lateral boundary conditions from a single ensemble member in 22km resolution. Each experiment consist of five semi-lagrangian ensemble members with different vertical diffusion schemes.
The series of experiments have been analysed as a comparison to a reference setup with different branches. We perform selected experiments on different branches to test if a given modification lead to a robust result. From the outset we knew that the 22km setup did not show variability and there was a tendency to a model bias. We tried to find potential weak points of the 22km setup with 32 levels.
All experiments have higher resolution in vertical and horizontal direction, because the 22km resolution with 32 levels does not provide the level of detail required for evaluation against 10 minute resolution point data.
The results of the sensitivity experiments can be seen in Tab. 3.3 and 3.4 and Fig. 3.1 and 3.2.
The overall result of the experiments point to that 20% of the error may be eliminated by using increased resolution in combination with an increase from 32 to 60 model levels. Increasing the number of model levels above 60 introduced a variability pattern of the forecast which was similar to the observed variability.
The results also indicated that both horizontal and vertical model resolution has impact on the solution of the vertical diffusion. Later during the project we found the same variability at each benchmark. Both time scales and amplitude were similar. Nevertheless, the surface characteristics are almost complementary among the test sites. Therefore we tend to conclude that the variability of the 72 level experiment could be an indication of that the variability originates from vertical exchange of heat/moisture and momentum.

Table 3.2: Summary of the Sensitivity Experiment setup of the 13 experiments.

Experiment	**Horizontal resolution**	**Model level**	**Other change**	**Description**
1	1.4km	72 level	—	layer distribution starting in 28m
2	1.4km	60 level	—	clarify impact of vertical layers
3	1.4km	60 level	analysis incr.	analysis incrementation added
4	1.4km	60 level	Time-stepping	physics each time step + analysis incrementation
5	1.4km	60 level	new schemes	experimental vertical diffusion schemes
6	5.0km	60 level	—	experiment 2 + new horizontal resolution
7	5.0km	60 level	analysis incr.	experiment 6 + analysis increments
8	5.0km	72 level	analysis incr.	experiment 1 + analysis incrementation
9	5.0km	60 level	climate file	experiment 6 with 15km resolution climate file
10	5.0km	60 level	climate file	experiment 9 with high resolution of fraction of land
11	5.0km	60 level	—	experiment 6 + use different condensation schemes
12	2.5km	60 level	climate file	experiment 11 with double horizontal resolution
13	2.5km	60 level	climate file	experiment 12 with interpolated high resolution climate

Table 3.3: Mean absolut error statistics (MAE) in [m/s] of the sensitivity experiments for five selected ensemble members. The "Best Guess" is the MSEPS ensemble member with the lowest RMSE, the Mean is the mean of the 5 selected MSEPS ensemble members.

Experiment	**Best Guess**	**Mean**	**Selected MEMBERS**				
	(m/s)	(m/s)	**1**	**2**	**3**	**4**	**5**
1	1.08	1.08	1.11	1.14	1.13	1.11	1.09
2	1.05	1.07	1.08	1.05	1.11	1.09	1.06
3	1.04	1.04	1.07	1.04	1.09	1.04	1.05
4	1.03	1.03	1.07	1.05	1.05	1.03	1.05
5	1.07	1.07	1.09	1.05	1.10	1.09	1.10
6	1.07	1.08	1.09	1.07	1.06	1.11	1.10
7	1.05	1.06	1.07	1.05	1.13	1.09	1.08
8	1.05	1.05	1.08	1.06	1.06	1.10	1.07
9	1.07	1.08	1.10	1.07	1.12	1.11	1.10
10	1.04	1.04	1.09	1.06	1.08	1.06	1.05
11	1.04	1.02	1.06	1.05	1.09	1.08	1.04
12	1.02	1.02	1.07	1.07	1.15	1.12	1.04
13	1.02	1.02	1.09	1.05	1.09	1.05	1.03

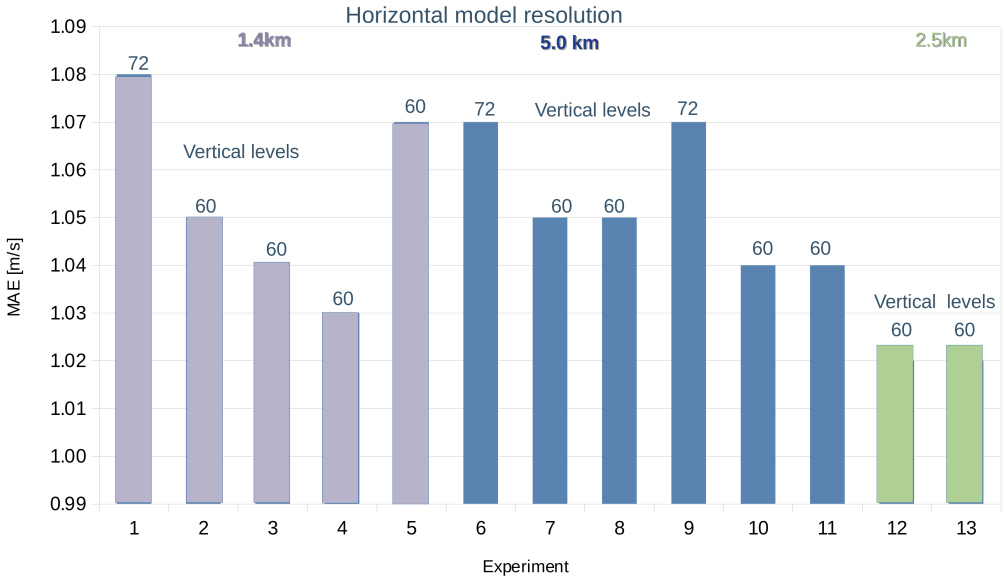


Figure 3.1: Mean absolut error statistics (MAE) from the sensitivity analysis at the Danish Testsite at Østerild for different setups of the high-resolution model system .

Table 3.4: Root mean square statistics (RMSE) in [m/s] of the sensitivity experiments for five selected ensemble members. The "Best Guess" is the MSEPS ensemble member with the lowest RMSE, the Mean is the mean of 5 selected MSEPS ensemble members.

Experiment	**Best Guess**	**Mean**	**Selected MEMBERS**				
	(m/s)	(m/s)	**1**	**2**	**3**	**4**	**5**
1	1.39	1.39	1.43	1.46	1.45	1.43	1.41
2	1.36	1.38	1.40	1.36	1.45	1.41	1.41
3	1.34	1.34	1.38	1.36	1.42	1.36	1.35
4	1.34	1.34	1.38	1.36	1.43	1.35	1.35
5	1.38	1.38	1.42	1.36	1.44	1.41	1.42
6	1.38	1.40	1.42	1.38	1.51	1.43	1.43
7	1.36	1.37	1.39	1.36	1.46	1.39	1.40
8	1.36	1.36	1.37	1.37	1.42	1.41	1.39
9	1.37	1.38	1.41	1.37	1.43	1.42	1.40
10	1.33	1.33	1.42	1.36	1.40	1.37	1.33
11	1.33	1.33	1.40	1.36	1.41	1.39	1.33
12	1.30	1.30	1.40	1.34	1.49	1.36	1.30
13	1.31	1.31	1.42	1.35	1.41	1.37	1.31

Wind speed increases because of air parcels from higher altitudes sink and cause other warmer air parcels with low momentum to lift. A possible explanation is that there is never equilibrium with 72 levels, whereas with 60 levels or less the mean wind speed rather constant. Most forecast users

find a noisy result inconvenient although the variability maybe important for correct simulation of frictional forces. The pattern is consistent with the fact that the vertical diffusion equations in the NWP models require an implicit solver to not blow up numerically. diffusion process is often a source to instability. The complexity of the coast line would be a possible explanation of wind speed variability on short time scales. There are wind directions where the upstream surface pure sea, but flow from these directions show the same variability as other wind directions. The source of the variability must be the friction process and not the surface characteristics. Nevertheless we conducted experiments to evaluate the impact of detailed resolution of the model and the surface. The best forecast in high resolution out of 13 simulations had an error of 1.02m/s. The best simulation used a 2.5km resolution with 60 level and semi-lagrangian advection using a smooth climate data set. Note that the difference in MAE error between the best and worst is only 6cm/s. All high resolution experiments perform from a weather forecast user's point of view similar. The difference is invisible except in monthly verification. Another note is that the score of the individual 5 members of experiment number 12 is among the poor, but the mean of the members perform best of all. From a deterministic model perspective experiment 12 would not be ranked best, but from an ensemble perspective it is most likely better. The list of experiments does not include an experiment in the highest resolution inclusive five different condensation schemes and physics each time step. This would have been the most costly experiment and was therefore not conducted.

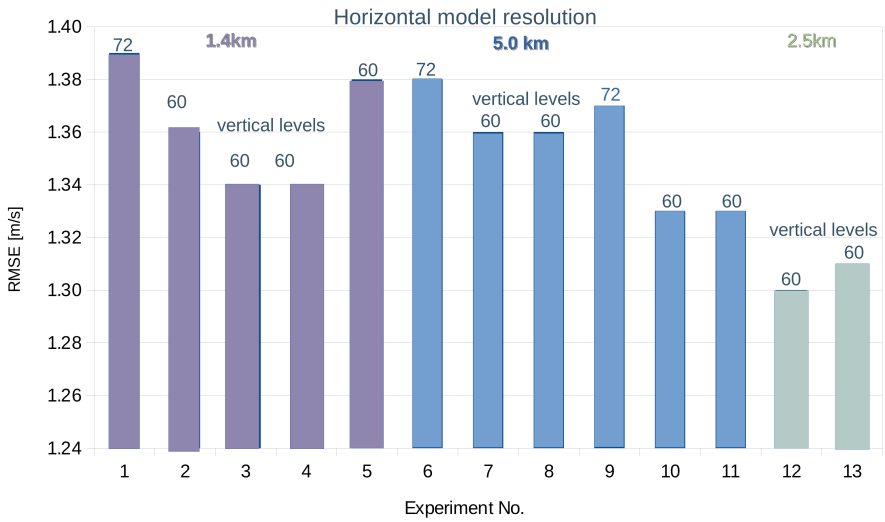


Figure 3.2: Root mean square error statistics (RMSE) from the sensitivity analysis at the Danish Testsite at Østerild for different setups of the high-resolution model system .

The 10 minute variability is responsible for background error in all results and it could be considered useful to time smooth the mast data and to obtain a more meaningful synoptic scale score difference between the experiments. However time smoothing does not alter the the absolute difference between ensemble members should not change from time smoothing measurements.

The verification results are robust because the background error from variability should be common

for all experiments. It is interesting that modelling can get close to an MAE 1m/s at 100m in the full time-resolution in a windy period.
It should be noted that 75% of the period has westerly and north-westerly wind from the Northsea side. The influence of measurements in upstream direction is therefore very low. The results are therefore raw measures of the performance of details of the ensemble forecasts.
The verification scores can be regarded as general measures of high resolution forecast performance in open land and sea during late summer. It is the time of the year where the sea surface temperature is highest and the boundary layer at sea is unstable. This is especially so because the wind is 75% from the Northsea side. Conditions could be stable a few hours around noon. Such conditions are relatively difficult weather conditions.
The benchmark period at Østerild provided a clean result in well-defined conditions. The strong agreement between AQ510 and Met mast also increases confidence in the verification scores. There are also several strong wind speed changes, which will penalize forecasts with incorrect phase.
None of the other demonstration benchmarks of the project could provide equally idealized data suited for plain model statistics.

Lessons Learned 3.2 — Østerild experiment take-aways:. The fundamentals from the Danish Test center experiments are:

1. The very highest resolution does not perform better statistically
2. Error difference from best to worst is not significant...
3. High-resolution with 72 levels shows similar variability as SODAR data, but is not in phase with measurements
4. All 13 experiments were clearly better than the 22km run with 32 levels, confirming that resolution does pay off.

3.2 Evaluation of Experiment at WINSENT Testsite

The demonstration experiment at Stötten was carried out in cooperation with the Center for Solar- and Hydrogen Research (ZSW) in Stuttgart, Germany and Anemos-Jakob Gmbh, a consultancy company for resource assessment and monitoring in Germany that was willing to test a new AQ510 SODAR for a period of three months against the met masts at the test center WINSENT and a scanning LIDAR from University of Stuttgart.



Figure 3.3: Picture of the AQ510 SODAR and the windscanner of University Stuttgart and ZSW for the testperiod at the WINSENT test site.

Unfortunately, only one met mast provided trustworthy data for the entire test period and the wind scanner was only available foe ca. 4 weeks. Additionally, the site is close to a hostel from the local environmental association, where it was necessary to stop the SODAR over 4 weekends throughout the test period, due to the noise from the beeping signals.
The SODAR and Lidar were place right behind the ridge of the slope behind some trees at the edge of the slope. Figure 3.3 shows the two instruments. This location was selected due to the required distance of the AQ510 to the met mast's steel construction that can deflect the echo and a requirement of the LIDAR to be connected to electricity.
Fig. 2.5 in section **??** shows both the topographic characteristics and Fig. 2.6 shows the cross section of the steep hill in the prevailing wind direction for the 2 wind turbines and hence the met masts.
The demonstration phase revealed a number of important aspects for both the SODAR development and the forecast development using remote sensing data for gap-filling and ultra-shortterm forecasting and especially the difficulty in evaluating different NWM model configurations.

3.2.1 Instrument comparison

The measurement campaign for the AQ510 SODAR started on November, 2 in 2023 and ended on March 5, 2024. The Windscanner LIDAR was only available from 23^{rd} of January 2024 and the north-west met mast cup anemometer was on and off many times until the 8th of December and had several outages until the comparison campaign with the LIDAR started (23/01/2024).

The statistics for the model system against the AQ510 SODAR was therefore carried out for two periods: period 1 of ca. 12 weeks, where met mast data and SODAR data were available and period

Type	Mean	Bias	MAE	RMSE	STDV
min	5.86	-0.17	2.03	2.64	2.63
p10	6.48	0.45	2.03	2.63	2.59
p20	6.77	0.75	2.09	2.69	2.58
p30	6.99	0.96	2.14	2.75	2.58
p40	7.18	1.16	2.21	2.83	2.58
p50	7.37	1.34	2.28	2.92	2.59
p60	7.57	1.55	2.38	3.02	2.59
p70	7.79	1.77	2.49	3.15	2.60
p80	8.05	2.03	2.65	3.32	2.63
p90	8.42	2.40	2.88	3.57	2.64
max	9.24	3.21	3.51	4.20	2.70
SODAR	6.03	0.00	0.00	0.00	0.00
LIDAR	6.06	0.03	0.88	1.23	1.23
MetMast NV	6.43	0.40	0.79	1.08	1.00

Table 3.5: Wind speed forecasts from the MSEPS as minimum, percentiles p10..p90, maximum and measurements from the AQ510 SODAR, the Windscanner LIDAR, the Met mast North-West at the WINSENT test site at approximately 100m for the common period 23/01/2024 00:00 – 04/03/2024 23:00. The Met mast measurement from a cup anemometer was at 97m, but at a 8m higher altitude than the remote sensing instruments.

2 of 6 weeks, where all three instruments were available.

It should be noted that the mast and the remote sensing instruments were approximately 150m apart from each other and the met mast is placed at ca. 8m higher altitude, which means that there is a discrepancy of ca. 8m in measurement height. In addition some effect of shadowing trees with a wind direction dependent effect.

For the verification with the MSEPS forecast this is less relevant, but an important aspect when comparing the instruments, shown in Table 3.5 and 3.6. Here, we can see that the LIDAR and the SODAR have nearly the same mean and the LIDAR has almost no BIAS against the SODAR, whereas the met mast cup anemometer has a higher mean and a lightly positive BIAS. Both the cup and the LIDAR have a 0.8m/s mean absolut error (MAE) and a root mean square error (RMSE) of approx. 1m/s in comparison to the SODAR, which is consistent with the visual inspection of the data. This error calculations is made with the official 10 minute time stamps.

Fig. 3.4 shows a typical day, where the amplitude and the phase of the instruments and the forecast varies. The time scale of the variability varies.

Table 3.7 compares forecasts and measurements of wind speed in 100m altitude. Also wind speed transformed to wind power with the same power curve is included.

The results are based in the full common period between AQ510 and mast data.

The data from WINSENT has been handled independently for the two time series. WEPROG fetched therefore data from independent databases. The native time stamps from AQ-online and the WINSENT database differs 10 minutes, which is equivalent to an MAE error of 0.15m/s. All numbers in 3.7 are computed inclusive the time stamp correction.

From the MSEPS forecast we have used a low percentile to limit the bias. Nevertheless the MAE is twice the error of the best results for Østerild.

It is characteristic that the MSEPS forecast score against AQ510 is better than against Met mast. This phenomena is opposite of Østerild, where the forecast fitted wind speeds from the mast better. The difference can be explained by AQ510's loss of difficult high wind speed extremes at WINSENT. Some difficult events are therefore not present in the AQ510 time series.

We cannot use the lower MSEPS forecast error to conclude that AQ510 match MSEPS better. Given

Curve	Mean	Bias	MAE	RMSE	STDV
min	6.57	0.24	2.05	2.66	2.65
p10	7.15	0.82	2.12	2.76	2.63
p20	7.45	1.11	2.21	2.87	2.64
p30	7.67	1.33	2.30	2.97	2.65
p40	7.86	1.53	2.38	3.06	2.66
p50	8.04	1.71	2.47	3.17	2.66
p60	8.24	1.91	2.57	3.29	2.67
p70	8.46	2.13	2.70	3.43	2.68
p80	8.73	2.40	2.87	3.62	2.69
p90	9.09	2.76	3.12	3.88	2.73
max	9.84	3.51	3.72	4.47	2.76
SODAR	6.33	0.00	0.00	0.00	0.00
MetMast NW	6.54	0.21	0.92	1.29	1.28

Table 3.6: Wind speed forecasts as percentiles p10..p90 and measurements from the AQ510 SODAR, the Met mast North-West at the WINSENT test site at 100m for the common period 08/12/2023 00:00 – 04/03/2024 23:00. The Met mast measurement from a cup anemomenter was at 97m, but at a 8m higher altitude than the remote sensing instruments.

Reference	**Forecast**	**Type**	**BIAS [m/s]**	**MAE [m/s]**
Met mast	MSEPS	ws	-0.157	2.015
Met mast	AQ510	ws	-0.318	0.678
AQ510	MSEPS	ws	0.160	1.990

Reference	**Forecast**	**Type**	**BIAS [MW]**	**MAE [MW]**
Met mast	MSEPS	pwr	-0.394	18.154
Met mast	AQ510	pwr	-2.545	6.146
AQ510	MSEPS	pwr	2.150	17.769
Data loss=821 Delivered data=7284				

Table 3.7: Statistics of the WINSENT demonstration at 100m above ground for wind speed (ws) and reference wind power (pwr) computed from met mast wind speed

the data loss of 821 values in 100m we can in any case not argue the AQ510 fully match the Met Mast at WINSENT.

Another lesson from the comparison is that MAE errors in power have approximately the characteristic error of a wind power site which is extremely difficult to forecast. Out of 100 wind farms, one would normally have en error of 18-19%.

The BIAS of AQ510 against the MET mast can probably be explained by a 8m lower+shadows from some trees. A similar bias was found for the wind scanner.

3.2.2 Filtering Process in the processing of SODAR signals

The comparison with the LIDAR and the met mast cup anemometer revealed an issue in the signal processing of the SODAR data that was found to have a significant influence on the performance of the SODAR for the certification at the Irish test site, where the wind conditions were much more variable than at any of the other test sites.

The default filtering configuration of the SODAR caused that signals with a large ramp of greater than 6m/s within one loop interval were rejected. For resource assessment this is an acceptable

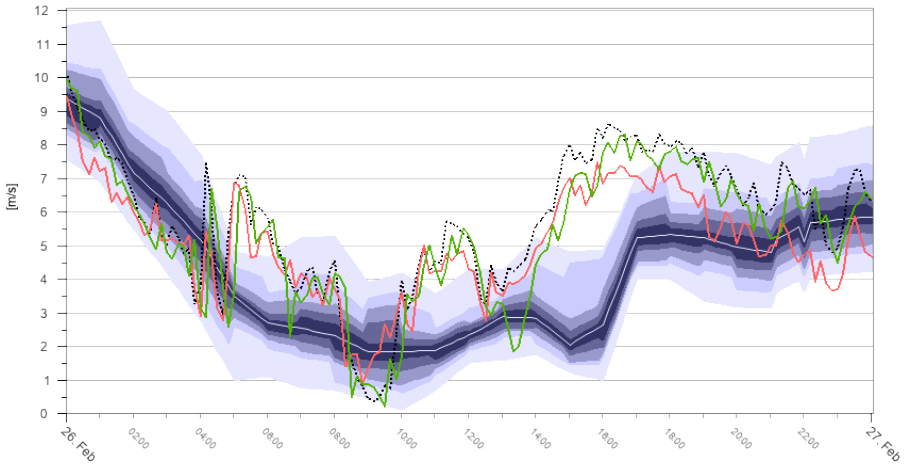


Figure 3.4: Typical differences in amplitude and phase of the three instruments at the WINSENT test site at Stötten in comparison to the forecasts. Forecasts are shown as coloured percentile bands from the MSEPS, each representing a 10% percentile, the met mast cup anemometer as black dashed line, SODAR as green line and LIDAR as red line) .

criterie to avoid data errors. However, for real-time forecasting purposes, such assumptions are unwanted. This is because sudden changes can lead to that critical changes in the power generation.

Fig. **??** shows the example, where we discovered the side effect of filtering. By setting a higher threshold value for the filter, we found that the AQ510 was able to produce a realistic wind speed. Our recommendation is no filtering for real time delivery of data. The end-user should rather filter data. More details in the case analysis of the extreme event in Ireland 4.4.

> **Lessons Learned 3.3 — SODAR – LIDAR comparison.** What we learned from the comparison was that the filter settings of the signal processing of the instruments are a tunable that may be necessary to investigate via sensitivity studies for different applications.

3.3 Evaluation of Windscanner Test at DTU Risø Campus

DTU has validated the measurement data by running co-located SODAR-LiDAR experiments and contributed with met mast reference data for the SODAR experiments regarding rain, snow and traditional wind speed. DTU suggested a turbulence algorithm, which is now being implemented in the SODAR software. The relevant constants for this algorithm are based on extensive analysis of all in all six sites and has been partially presented at [9, 4] and is reported in detail in [3, 6].
Further, DTU was responsible for testing how well the SODAR measured during rough weather [2]. This work showed unexpectedly that the SODAR itself can measure rainfall intensity. DTU and UU teams used a new combination of models and measurements to show that the SODAR measures mean wind speed with high accuracy and precision [8].

IV AQ520 Certification

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4. AQ520 Certification at Irish Wind Farm

4.1 Background

The International Energy Agency (IEA) have published a study in autumn 2024 on the requirements and challenges of renewables integration and defined 6 phases[17]. From phase 4 onwards, i.e. when control zones reach more than 30% of their electricity from wind (and solar) power production plants, the weather conditions become drivers for the power system.
In Ireland, the provision of real time meteorological data from wind and solar plants greater than 10MW [15] has been established as an additional obligation for renewable energy facilities.
The requirement is important for the stability of the Irish power system, because Ireland is exposed to the Atlantic from where intense low pressure systems can reach the coast and cause strong wind power ramping. And, Ireland's plan to reach a near fossil fuel free power system, means that it will not stop at 40% or 50%, but increase to 80-90% of power production.
The following sections describe in detail, why such data is important in e.g. Ireland, but also discuss the benefits from such information for power systems in phase 4 – 6 in general (see also [11]). By going through the steps in the certification process, we will also look into the need for alternative instrumentation, that has its rationale in the increasing hub heights, where the operation of met masts are expensive and require planning permission. Here, we also dive into the requirements and the need for investment for manufacturers, when entering a new market with different requirements and in general evaluate remote sensing as alternatives to met masts in the operational phase of wind farms.

4.1.1 The importance of real-time wind speeds for grid stability

In Ireland, the combination of coastal capacity gradients, small scale intense low pressure systems and a relatively small electrical grid justifies the need of real-time wind speed information by wind farm. The coastal regions provide the best wind resource, but in fact, each corner of Ireland has a strong wind resource, because there is an approximately 270 angle to the sea instead of 180 at the straight coast lines. The wind farms in these corners of Ireland form 3 main clusters (NW, SW and SE). There is also wind power capacity in the center of Ireland, but it is the coastal areas which cause the strongest risk of instability in the power system, because these clusters can cause stronger ramps than the more dispersed wind power in the center of Ireland [14].
Due to strong wind speed gradients, it is almost daily observed during the winter months, that one or two of the clusters ramp up to full generation and down to almost no generation. Ramp up and down times are visible in the aggregated generation of Ireland, because each cluster represents a

local capacity center.

A new interconnection to Europe is planned for end of 2026 with a 700MW peak capacity corresponding to half of one wind farm cluster. This will double the total transmission capacity seen from the Republic of Ireland. However, 700MW is only equivalent to 10% of the renewable energy capacity, which is 8GW as of March 2026[1] and a peak demand of ca. 6GW[2].

The expected impact of extra transmission capacity assumes savings of some contingency reserves in Ireland and export of more renewable energy from Ireland to central Europe. Ireland will from time to time be able to run the grid with 100% renewable energy, but will remain an island with a high renewable energy capacity and strong ramps every day.

Given the above mentioned circumstances, remote sensing has the potential to provide savings in environmental footprint compared to a met mast and also to provide wind speed measurements at higher altitudes than met masts are typically able to without disturbing the wind turbines in the prevailing wind direction. Therefore, we started a benchmark of the AQ510 SODAR in the Northwestern wind farm cluster in the hope that the quality of the wind speed would meet the performance criteria.

4.2 Certification Procedure

The certification procedure has to follow the requirements for meteorological measurements for wind farms with a size exceeding 10MW, set out by the Irish system operator EIRGRID [15]. The opening for alternatives to measuring with met masts lies in the increased hub height of wind turbines, where met masts need planning permission and is the rationale behind the certification of the AQ510 SODAR [14]. EIRGRID in fact publishes a list of alternative instruments to provide a choice for wind farm operators and for manufacturers to be certified once [16].

The requirements and quality of met data delivered through the SCADA system of wind farms are monitored by the system operator on a quarterly basis and failures that have impact on the system or forecast accuracy are communicated to the wind farms and followed up. The preparation for the certification therefore requires that the instrument is able to deliver the required quality and availability throughout the entire year.

There are three main tests to be performed:

1. **Delivery tests of measurement data**
   The test are based on an overall system delivery rate that takes account for system issues and check on:
   - Outages of SCADA data
   - hanging SCADA data
2. **Quality test of the delivered data** The quality checks look at the mean, BIAS, MAE and correlation for the variables wind speed and direction, temperature, pressure and separate on
   - corrupt data
   - bad data
   - out-of-range SCADA data
3. **Improvement tests**
   The improvement tests evaluate, whether the measured wind speed converted to power output from the wind farm with a standarised method show MAE statistics that are at least 5% lower than the equivalent with forecasted wind speed.

For an instrument to be certified for delivery of met data to the power system, a specific procedure has to be followed with an onsite demonstration period that is monitored by the system operator.

[1] see https://www.gov.ie/en/department-of-climate-energy-and-the-environment/press-releases/ireland-reaches-8gw-of-onshore-renewable-electricity-generation-securing-our-future-with-homegrown-renewables/

[2] see https://www.eirgrid.ie/did-you-know

4.3 Preparation for the Certification process

The following sections describe the preparation for the certification process with the operator for both the instrument and describes the tests that need to be carried out to ensure that an instrument not only performs in the certification, but also in the operational environment and in all four quarters (seasons) of a calendar year. The wind speed measurements are also used to evaluate potential generation of dispatched generation and therefore ideally need to be independent of the wind farm's power production.

4.3.1 Selection of a benchmark site

It is difficult to find a wind farm operator with an interest in participating in a benchmark for a new instrumentation type. In Ireland, there are also a lot of sites in complex terrain. The wind farm that agreed to support our benchmark case is also located in complex terrain and the wind farm contains many wind turbines and varying wake effects throughout the farm due to changing slopes. These circumstances turned out to add complexity, which was not trivial to bypass.

The wind pattern varies across the wind farm. Such variations are not well described by a single wind speed signal regardless of the type of instrument. The larger the number of turbines, the longer the physical distance across the wind farm and the altitude difference of the wind turbines, the less good a single wind instrument can represent the wind generation of all wind turbines. It is mostly the peak, which has focus in variable wind, but there are calm periods in between the peak as well. The timing of these play a role for how accurate the power generation of the wind farm can be predicted from a single source within the wind farm. In general, the wind speed signal is not important for the operation in the range between 5–11m/s unless the wind farm is curtailed. In all other circumstances the wind speed is more important to determine the actual wind conditions.

4.3.2 Simulation of wind generation from a single nacelle wind speed

For the certification, the wind speed accuracy target is that the wind speed provided by the wind measurement shall be 5% better on calculating the wind farm's power output than a NWP forecasted wind speed using the same technique of calculating power for both wind speed time series. The 5% is an idealized target while 3% is an accepted improvement.

During the benchamark, we also experienced outages at the closest met mast. Therefore the power output of the wind farm should be localized based on the nacelle wind speed of a *reference turbine* with the shortest distance to the location of the SODAR. This localization effectively moved the capacity centre to the reference wind turbine.

Use of nacelle wind to simulate the reference turbine's power generation ensure that the power curve calibration cannot know the truth and include wake and various outages. The nacelle wind + conversion to power contains the sum of internal and external contributions to wake effects at the reference turbine. The forecasted power of the reference turbine will be smoothed by the training for best possible fit to the actual wind farm power and in that way, the total power generation of the reference turbine will over time match the total wind farm power.

The power generation becomes a fully independent time series, because it is strongly related to the actual wind at the reference turbine and all influence due to the terrain and other wind turbines. The reference wind power is in that way suitable to use as a benchmark of the wind instrument, because it is a time series of valid wind power generation.

4.4 Improvement Analysis against the wind farm's power signal

For the certification and instrument acceptance requirements in Ireland [15], the direct correlations between the predicted wind speed and the observed wind should not be less than 0.65 and there must be an improvement relative to forecast measured in power of 5% MAE. For larger wind farms at least 3% MAE. The same applies for wind farms that are in very complex terrain (see also sections 4.1 and 4.2).

4.4.1 Comparison of the SODAR versus a reference wind power forecast

For the comparison of power output converted from SODAR wind speeds and MSEPS forecasts, we achieved a correlation of 0.87, which indicates that both forecast and measured values are of higher accuracy than required on correlation.

There are also requirements to BIAS and MAE. They are easily met by a BIAS of 0.76m/s and MAE of 1.75m/s for the 3 months during winter. The metrics are not alone good measures of quality. The purpose of the validation framework with several criteria (see section 4.2) is to catch all disturbing errors by testing different metrics.

The reference turbine and the SODAR will not experience the same wake, because of a 400m distance and some additional altitude differences. The correlation of the nacelle wind of the reference turbine and the SODAR was found to be 0.96. This is a strong correlation compared to the correlation of forecast to nacelle wind, taken into consideration that the SODAR provides an independent wind signal.

Source 1	Source 2	Correlation in [m/s]
AQ510 SODAR	Nacelle	0.96
Forecast	Nacelle	0.85
Forecast	AQ510 SODAR	0.87

Table 4.1: Correlation between SODAR measured 40m winds and nacelle wind.

The correlations in tab. 4.1 indicate that the nacelle wind of the reference turbine contains some wind to power related information. In fact, the AQ510 signal is more correlated to the reference turbine than the forecast, which is a good sign. The correlation result also indicates that the AQ510 describes the local wind well, while the forecast seems to rather provide a wind, which represents an average over a larger area. The difference in correlation also suggests that the onsite wind speeds are influenced by the local roughness conditions.

4.4.2 Data transformations from wind speed to wind power

A fundamental test and verification criteria in Ireland, is the comparison between measured and forecasted wind speed converted into wind power generation and compared with the wind farms power output.

Fig. 4.1 describes all the data transformations required from single turbine power back to nacelle wind to the final power forecast comparison between measured and forecasted techniques. The data flow in the light gray box on top is required to localize the power generation to the reference turbine.

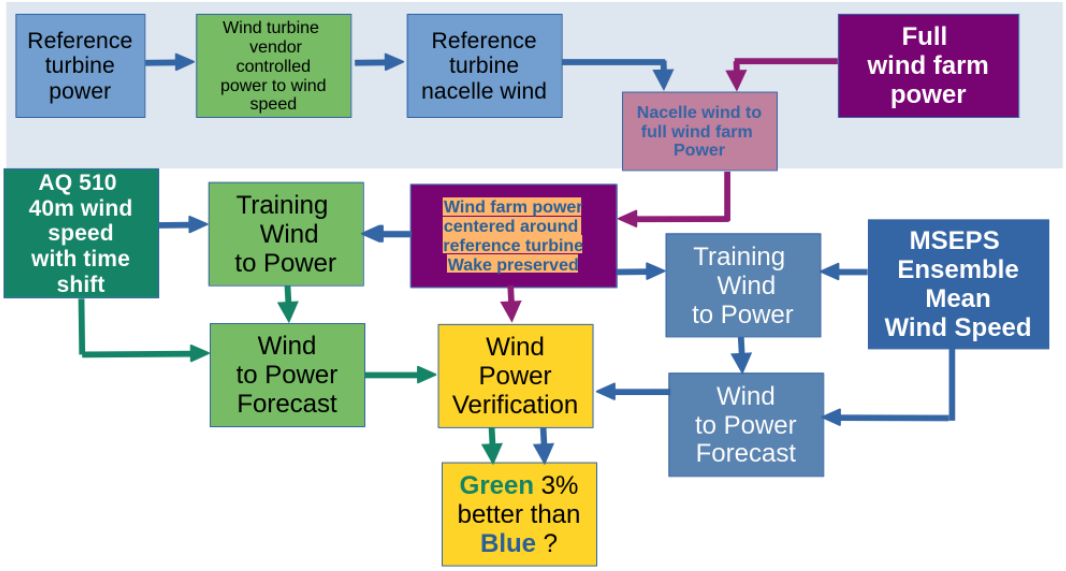


Figure 4.1: *Schematic diagram of the data processing steps. The transformation of power to wind speed is a wind turbine vendor controlled process based on power generation and anemometer data from the nacelle. The remaining data transformations follow the guidelines defined by EirGrid [15]*

The wind farm operator has, for this benchmark, selected the reference turbine and position of the AQ510 in order to validate the wind speed of the AQ510. The power generation of the reference turbine was not disclosed. The transformations on Fig. 4.1 was therefore a required step to conduct a comparison of the AQ510 SODAR and forecast transformed into wind power.

Table 4.2: Bias and MAE error for Forecast and AQ510.

Source	**BIAS in [m/s]**	**MAE in [m/s]**	**Improvement in [%]**
Forecast	0.75	12.16	reference
AQ510	-0.90	5.36	6.8

The final result of the evaluation of 10.502 10-minute intervals is shown in Tab. 4.2 and implies that the power forecast based on the AQ510 wind is more than 6% better than the forecasted power when validated against the localized power signal from the wind farm. The AQ510 has a distance of more than 400m to the reference turbine. The result would be at least as good, if more wind turbines would be centred around the AQ510, which would be the optimal position for high best possible accuracy.

An improvement of 6% would be achievable for smaller wind farms and is a rather high improvement compared to similar large wind farms in Ireland. The same improvement cannot be expected for larger wind farms, where this threshold is relaxed to 3% improvement in comparison to a forecast. Experience from other wind farms indicate that the larger the area of the wind farm, the better the forecast relative to measured wind. The reason is that the forecasted wind is by definition an area average. In complex and semi-complex terrain, the details of a single local wind speed measurement is not representative to wind turbines situated differently in the terrain. The wind speed needs, in that case, to be recorded at multiple locations to be representative for the power generation of the full wind farm.

4.5 Conclusions from the Certification Preparations

With an improvement of 6% in comparison to the forecasted wind speed, our improvement analysis against the wind farm's power signal revealed that the AQ510 SODAR was well capable of outperforming forecasts by the required 3% for the large wind farm in a highly complex topographic location. The AQ510 also manages the 5% improvement for the average conditions as set out in the official grid code requirements [15].
Our data availability and data loss analysis revealed that data loss occurs for the AQ510 40m wind speed mainly during severe weather, where wind farms are in a cutoff state.

Future Improvements

Supplementary information such as rain intensity, temperature and wind speed in 2m altitude would strengthen the value of the AQ510 during extreme weather. The precipitation signals investigated by DTU has shown first promising results on how a signal processing step could look like to such data [2]. Such information can help to improve the utilization of ensemble forecasts during extreme weather in a minute-scale forecasting system [7, 1, 13]. The likelihood that some of the AQ510 data fit to some of the already generated ensemble forecasts and variables is therefore high. The ultra short-term forecast would then follow these selected ensemble members.
Ensemble forecasts can also be used to compute quality flags of each recorded value. In addition, the gap-filling approach can be used to estimate related data values. The gap-fill process is not limited to values recorded by AQ510, but could as well provide an estimate of the temperature profile.

> **Lessons Learned 4.1 — Certification Preparation.** From our data-loss analysis and improvement study (see section 4.4, we can conclude, that the AQ510 SODAR has potential to add value in real-time minute-scale forecasting and situational awareness, and, that the combination of AQ510 and ensemble weather forecasts can deliver detailed site specific data of a vertical profile without visual impact and with low environmental footprint (see section 4.1.1). To conclude: the AQ510 SODAR is ready to be added to the list of alternatives for the Irish grid code on met measurement for renewable power plants [16].

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5. Conclusions and Outlook

AQ System has demonstrated that the enhancements carried out for the AQ510 throughout the project has improved the reliability and accuracy of the instrument's data output for both resource assessment and real-time forecasting applications and, most important, how to prepare and configure the instrument's software for the respective task.
WEPROG has demonstrated that it is possible to produce consistent multi-year time series based on a few months of onsite measurements with the AQ510. That means, after 3 months of recording it is possible to estimate historic power generation of a very large wind turbine and thereby compute the economic value backward in time. The total cost of such an estimate is now at a level, where it is possible to do site screenings and select the best. Combined with quality control with the MSEPS ensemble, it is now possible to produce significantly more reliable wind speeds and also provide a quality measure of each reported value, especially above 100m, where data loss increases during combined strong wind and rain.
It is fair to say that, besides the known reference site in Sweden, the project's four demonstration sites were challenging for all partners, being pushed into unknown territory with some of the measured data. Nevertheless, each project partner has gained important knowhow on their respective scientific area from the demonstrations.
The result has become an **E**nsemble-based integrated **A**nalysis of **R**emote **S**ensing data, which we refer to as the **EARS-Approach**.

Project Output 1 — EARS-Approach. We developed the **E**nsemble-based integrated **A**nalysis of **R**emote **S**ensing data and validated it using the AQ510 SODAR and the MSEPS ensemble data from five demonstration sites. It performs a meteorologically consistent analysis of the raw minute-scale data from the SODAR and the MSEPS ensemble. The output is a complete time series of the wind profile in 5m vertical resolution in minute-scale of very high accuracy.

5.1 Outlook of Technology Enhancements

In the following sections, we will outline the new applications and describe how the **EARS-Approach** can be applied in each application area. We first describe the two core inputs to the **EARS-approach**:

1. 1-minute data from the AQ510 SODAR, which is based on 11 vertical sound scans, which is used to produce various wind related measurements for each 5m from 40-300m above ground. Besides wind, temperature and humidity is being recorded from the AQ510 SODAR itself.
2. 75 member high-resolution ensemble in minute scale resolution to provide robust data of 60 weather variables from the PBL (Planetary Boundary Layer).

An AQ510 SODAR is often sited in extreme conditions with rapid weather changes and strong turbulence, but also in conditions, where recording can lead to incorrect values or no response.

The MSEPS ensemble data is used to validate the recorded values. The objective is to accept the realistic values and discard any unrealistic values. Both, changes in time and absolute values are checked against the extremes in the MSEPS ensemble spread. Values are discarded, if they fail on all tests. Finally, any gaps are filled on the basis of cross covariances computed from the MSEPS ensemble between accepted measurements and gaps. The cross covariances determine the influence of accepted measurements on each gap.

The mean absolute error of the gap-fill process range from 0.2m/s for sparse losses to 0.5m/s in cases, where no data were recorded. The mean error with a data loss of 10% is therefore only 2-5 cm/s (0.02-0.05m/s), which is below the measurement uncertainty. This means, the accuracy impact from using the **EARS-Approach** on the data accuracy can be ignored for nearly all applications and the output can be regarded as a valid measurement data point.

5.1.1 Early Warning of wind speed ramps by EARS-approach

The demonstration in Ireland confirmed that wind speed measurements from 100m-200m can contribute to improve wind power forecasting. Periods with increasing wind from southerly and south-westerly direction are often not detectable at low altitudes from NWP wind speed forecasts. The warm wind blows above the lower cold and stable boundary layer. This can lead to a sudden increase in the wind power generation, because wind turbines sometimes manage to mix the stronger wind down to lower altitudes. The **EARS-Approach** is required in these cases, because there is some data loss due to high wind speeds in the upper range.

5.1.2 Utilising the EARS-approach for early detection of cutoff events

In this project we have demonstrated the application of 1-minute wind speed data from the AQ510 SODAR to be feasible in combination with ensemble-based forecasts.

Besides many months of data analysis at five demonstration sites, we especially studied an extreme event of about 30m/s in Ireland. The extreme happened while the mean wind speed was about 6.5m/s. We found temporal 1-minute changes between 3.5m/s and 29.6m/s in 40m altitude. Without detailed intra-hour ensemble forecasts at hand, the extreme wind speed ramp would have been discarded by the signal processing filters of the SODAR. The wind farm went in cutoff approximately 15 minutes later.

Project Output 2 — Early detection of extreme events. The **EARS-Approach** led to an important warning of a critical event. An event, a nacelle anemometer is unlikely to detect before it is too late, even though it is a critical event for the wind farm.

5.1.3 EARS-Approach as wind turbine control alternative

We found that the **EARS-Approach** provides a more accurate wind speed than reported from the nacelle anemometer of wind turbines, especially in strong wind. The physical dimensions of the nacelle grow with wind turbine capacity. The nacelle wind is an estimate around a single height above ground, whereas the AQ510 provides a wind profile and covers the entire swept area of the wind turbine. We are convinced that there is a potential application for the SODAR and remote sensing devices in general, also for turbine control, because the cost of adding a AQ510 to an operating multi MW-class wind turbine is rather low compared to the total investment.
The potential for increased power generation using the reported wind direction in the altitude which contributes most to power generation, needs to be investigated. This point would normally lie above the centre of the rotor. The benefit of using the SODARs wind direction increases with the length of the blades and physical size of the nacelle. Today, the only other instruments than nacelle anemometer are scanning LIDARS installed at the nacelle, which are more expensive and also suffer from the turbulence and wakes due to the rotation of the blades in front. We have demonstrated in this project that the **EARS-Approach** provides a serious alternative to state-of-the-art.

5.1.4 EARS-Approach as large wind farm control alternative

For larger wind farms, knowing the wind profile at each corner of the wind farm would add significant value to the wind farm control and operation. Applying the **EARS-Approach**, the wind farm's SCADA system would be able to predict the optimal nacelle direction at each minute and thereby avoid unnecessary load on the turbine blades and reduce turbulence generation within the wind farm.
Although wind turbine vendors primarily rely on proprietary ad-hoc solutions, they could still benefit from cutoff warnings and increased power generation. However, integrating new technology into their systems remains challenging.

Project Output 3 — Wind Turbine Control Alternative. Nacelle measured wind is an estimate around a single height above ground, whereas the SODAR provides a wind profile and covers the entire swept area of wind turbines. We have demonstrated in this project that the **EARS-Approach** provides a serious wind turbine control alternative to state-of-the-art.

5.1.5 EARS-approach provides ease of maintenance

The **EARS-Approach** can provide the wind speed profile in 5m steps. Delivering the equivalent with a met mast would require a significant amount of instrumental maintenance. The AQ510 SODAR requires much less maintenance and can deliver, via the **EARS-Approach**, cost-efficient, accurate data with low environmental footprint.
Besides the unrealistic setup of a met mast with instruments at 5m or even 10m distance and the increased costs, the quality assessment requirements of the data would be the same.
In other words, there are benefits and drawbacks for all instrumentations. Looking at the development of wind turbines growing height and capacity, the remote sensing devices offer advancements regarding the wind profile that are important and therefore should be encouraged for real-time operation, forecasting and other control services.

5.1.6 EARS-Approach as enabler for increased Peak Wind Power Feed-in

The demonstration in Ireland has shown that the **EARS-Approach** provides a better, and truly independent, alternative to a nacelle wind speed measurement in Ireland, which is limited in accuracy and lacks independence [14]. It is commercially sensitive information, how nacelle wind is produced and therefore difficult for forecasting approaches to rely on the data. We have proven in this project that remote sensing technology is a feasible alternative solution without impact on the wind power potential at the site.

With more independent measurements, the Irish system operator EirGrid will experience higher certainty of the power generation forecast, especially in strong wind, with risk for power cutoffs that are today, to a large extent, mitigated with curtailment in the up-ramping phase. The **EARS-Approach** will be able to deliver wind profiles ranging above existing masts. If more wind farms choose to use a remote sensing device as alternative, there would be a higher certainty in the wind speed range 12-25m/s. The expected impact is a lift of the allowed threshold percentage of wind power (non-synchronous generation) feed-in to meet demand.
What we have learned in this project is that strong and stable wind should allow the bulk of generated wind power being used in *any* power system. This is where curtailment should be avoided until the point, where there is no other alternative. Today, transmission system operators (TSO) fear this kind of weather, because high wind speeds imply also risk of fast changes and strongly ramping production - in both directions.

Project Output 4 — Forecast Reliability for increased peak wind power feed-in. The reliability of wind speed forecasts above 15m/s cannot be increased to a satisfactory level without onsite wind speed measurements and a forecasting system that can make use of such measurements. The **EARS-Approach** can deliver the required additional accuracy needed to increase the peak wind penetration.

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Additionally, we are very grateful for the support of the Irish wind farm's operator to find an appropriate space within the wind farm for the AQ510 experiment and for providing data from the nearest met mast and wind turbine's nacelle wind measurements for the test period. Without that possibility, we would not have been able to carry out the necessary tests for the certification for the Irish Grid code requirments.
We also want to thank our project partners for providing important measurement data from their own test sites: DTI from their Turbine Test Centre in Østerild and at the Risø Campus in Roskilde, AQ system's test site at Moholm, Sweden and the data from University of Uppsala's Hornamossen experiment.
Without the support from the owners and operators of the test facilities and wind farm, we would not have been able to test our developments and to some extent also not been able to find the necessary solutions to make our developments robust.

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