Advancing wind resource assessment in complex terrain with scanning lidar measurements

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IEA Wind Task 32 online seminar – 2 July 2020
Outline
What to expect in this seminar

- Standard Wind Resource Assessment (WRA) for complex terrain sites and related challenges → some introduction
- How we tackled these challenges in EWiNo → very brief project overview
- The developed approach → combining scanning lidar measurements with flow modelling (with results of demonstration campaigns)
- Some words on the business case, and conclusions
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Standard WRA procedure
According to Technical Guideline (TR) 6 by FGW

| Wind data pool | Wind potential modelling | Energy yield calculation |
|----------------|--------------------------|--------------------------|
| 1. Short-term wind data | 3. Wind field modelling | 5. Yield calculation |
| o Wind measurements | o Flow model | o Wind turbine power curve |
| o Wind turbine yield data | o Input data | 6. Wind farm wake effects |
| | o Horizontal and vertical extrapolation | o Wake model |
| | | o Wind turbine thrust coefficients |
| 2. Long-term correction | 4. Wind potential calculation adjustments | 7. Yield reductions |
| o Long-term data source | o Reconciliation with wind turbine yield data and/or wind measurements | o Operating modes and/or wind turbine cut-out times and other technical losses |
| o Consistency test | o Discussion of reconciliation | |
| o Reproduction algorithm | | |

Components of an energy yield assessment (EYA) – and WRA, respectively – with reference to corresponding sections of TR 6

- **on-site data**
  - spatial extrapolation
- **temporal extrapolation**
Standard WRA procedure
According to Technical Guideline (TR) 6 by FGW

Components of an energy yield assessment (EYA) – and WRA, respectively – with reference to corresponding sections of TR 6

→ on-site wind measurements and flow model are key components (possibly making the difference)
Standard WRA procedure  
According to Technical Guideline (TR) 6 by FGW

| Wind data pool                  | Wind potential modelling                  | Energy yield calculation                |
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| o Wind turbine yield data       | o Input data                               | 6. Wind farm wake effects              |
| 2. Long-term correction         | 4. Wind potential calculation adjustments  | o Wake model                           |
| o Long-term data source         | o Reconciliation with wind turbine yield data and/or wind measurements | o Wind turbine thrust coefficients      |
| o Consistency test              | o Discussion of reconciliation             |                                        |
| o Reproduction algorithm        |                                          |                                        |

Where do **scanning lidar measurements** fit in?  
- ...
## Standard WRA procedure

According to Technical Guideline (TR) 6 by FGW

| Wind data pool       | Wind potential modelling                                      | Energy yield calculation                          |
|----------------------|----------------------------------------------------------------|--------------------------------------------------|
| 1. Short-term wind   | 3. Wind field modelling                                       | 5. Yield calculation                              |
| data                 | o Wind measurements                                           | o Wind turbine power curve                        |
| o Wind turbine yield | o Flow model                                                  | 6. Wind farm wake effects                         |
| data                 | o Input data                                                  | o Wake model                                      |
| 2. Long-term         | 4. Wind potential calculation adjustments                     | o Wind turbine thrust coefficients                 |
| correction           | o Long-term data source                                      |                                                  |
| o Consistency test   | o Reconciliation with wind                                    |                                                  |
| o Reproduction       | turbine yield data and/or wind measurements                  |                                                  |
| algorithm            | o Discussion of reconciliation                                |                                                  |

### Where do scanning lidar measurements fit in?

- **As substitute for the more standard on-site wind measurement** (must be at least 12 months according to TR 6)

- **As an additional short-term wind measurement** (according to TR 6)

- …
Standard WRA procedure
According to Technical Guideline (TR) 6 by FGW

| Wind data pool          | Wind potential modelling                        | Energy yield calculation                  |
|-------------------------|-------------------------------------------------|------------------------------------------|
| 1. Short-term wind data | 3. Wind field modelling                         | 5. Yield calculation                     |
| o Wind measurements     | o Flow model                                     | o Wind turbine power curve                |
| o Wind turbine yield data | o Input data                                      | o Wind farm wake effects                 |
| 2. Long-term correction | 4. Wind potential calculation adjustments       | 6. Wake model                            |
| o Long-term data source | o Reconciliation with wind turbine yield data and/or wind measurements | o Wind turbine thrust coefficients       |
| o Consistency test      | o Discussion of reconciliation                   |                                          |
| o Reproduction algorithm |                                               |                                          |

Where do **scanning lidar measurements** fit in?

- As substitute for the more standard on-site wind measurement (must be at least 12 months according to TR 6)
- As an additional short-term wind measurement (according to TR 6)
- Where it best improves the WRA (EYA) result… depends essentially on estimated uncertainties and business case

*Fig. 2–1: Generalised structure of energy yield assessments*
Overview of joint R&D project EWiNo

Entwicklung eines zweistufigen Verfahrens für die Beurteilung von Windstandorten hinsichtlich ihres Windpotenzials nach der EEG-Novelle 2017

(Development of a two-stage procedure for the assessment of wind sites with regard to their wind potential after the EEG [German Renewable Energy Law] amendment 2017)

- Funded by BMWi for project duration 10.2017 – 03.2020
- Coordinated by Fraunhofer IWES, with GEO-NET Umweltconsulting GmbH and four associated partners (windwärts, Naturstrom, Energiequelle, ENERTRAG)
- Focus on moderately complex (typical German) terrain → some hills, roughness changes, forest, and not too large wind farms
Overview of joint R&D project EWiNo

Some of the project conclusions

- CFD tools more and more gaining ground but not without an on-site measurement
- Short-term measurements neither to replace the standard 1-year campaign nor to inform in an early project phase (acceptance, costs)
- Scanning lidar technology is of interest but related costs challenge the business case
Overview of joint R&D project EWiNo

Some of the project conclusions

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- Scanning lidar technology is of interest but related costs challenge the business case

More than a compromise: **use most cost-efficient scanning lidar approach to maximise value of flow modelling** (and with this optimise WRA / EYA result)
... what this means in terms of uncertainties...

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**Uncertainty assessment**

*Fig. 2-1: Generalised structure of energy yield assessments*
what this means in terms of uncertainties…

| Wind data pool          | Wind potential modelling                          | Energy yield calculation                   |
|------------------------|--------------------------------------------------|-------------------------------------------|
| **1. Short-term wind data** | 3. Wind field modelling                          | 5. Yield calculation                      |
| Wind measurements      | Flow model                                       | Wind turbine power curve                  |
| Wind turbine yield data| Input data                                       | Wind farm wake effects                    |
|                        | Horizontal and vertical extrapolation            | Wind model                                |
|                        |                                                  | Wind turbine thrust coefficients          |
| **2. Long-term correction** | 4. Wind potential calculation adjustments        | 7. Yield reductions                       |
| Long-term data source  | Reconciliation with wind turbine yield data and/or wind measurements | Operating modes and/or wind turbine cut-out times and other technical losses |
| Consistency test       | Discussion of reconciliation                     |                                           |
| Reproduction algorithm |                                                  |                                           |

**Uncertainty assessment**

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Fig. 2–1: Generalised structure of energy yield assessments
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- Some words on the business case, and conclusions
For complex-terrain sites (orography variations, roughness variations)

- Poor representativeness of reference conditions
- Increased uncertainty of flow modelling

Use additional measurements to evaluate the performance of flow model and minimize uncertainties

WRA
According to TR6
Scanning lidar technology

Measuring principle

- Measured wind speed is the projection on the LoS of the respective beam
- Pulsed lidars: simultaneous measurements in multiple “Range gates”
- Scanning: 2 degrees of freedom (elevation + azimuth)
Scanning lidar technology

Measuring principle

- Measured wind speed is the projection on the LoS of the respective beam
- Pulsed lidars: simultaneous measurements in multiple “Range gates”
- Scanning: 2 degrees of freedom (elevation + azimuth)

- Benefit in combination with standard wind measurements:
  - Multi-location time series (reconstruction approach)
**Scanning lidar technology**

**Measuring principle**

- Measured wind speed is the projection on the LoS of the respective beam.

- Pulsed lidars: Simultaneous measurements in multiple “Range gates”

- Scanning: 2 degrees of freedom (elevation + azimuth)

- Benefit in combination with standard wind measurements:
  - Multi-location time series (reconstruction approach)
  - Flow visualization (snapshots)
Integrating scanning lidar in WRA

- Virtual scanning lidar method (VSL)
  - Create a simulation of the scanning lidar measurements in flow model

Direct comparison of measured and modelled wind fields (stability, terrain effects) by projection.
Virtual scanning lidar method

- Infrastructure:
  - Wind flow model (for preselected wind sectors) (microscale)
  - On-site 1 year measurements
  - Parallel PPI scanning lidar measurements over POI* (few weeks)

* Positions of interest
Virtual scanning lidar method

Constructing VSL

Simulated wind field projected on the LOS geometry
Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry
- For a reference wind direction:
Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry
- For a reference wind direction:
  1. Extract simulated wind vector at LoS locations
Virtual scanning lidar method

Constructing VSL

- Simulated wind field projected on the LOS geometry
  - For a reference wind direction:
    1. Extract simulated wind vector at LoS locations
    2. Project simulated vector on LoS geometry
Virtual scanning lidar method
Calibration of flow model

- Compare VSL and actual scanning lidar measurements

VSL

Scanning lidar
Virtual scanning lidar method
Calibration of flow model

- Compare VSL and actual scanning lidar measurements

- Identify mismatches (larger than measurement statistical uncertainty)
Virtual scanning lidar method
Calibration of flow model

- Compare VSL and actual scanning lidar measurements
- Identify mismatches (larger than measurement statistical uncertainty)
- Tune flow model (terrain, stability) to reduce disagreement
Demonstration campaigns

- Two demonstration campaigns during EWiNO project

- Sites in Germany:
  1. Herleshausen (site in Hessen)
  2. Lügde (site in Nord-Rhine Westphalia)

- Sites with moderately complex terrain
- Pre-construction stage

- Simulations by two steady state microscale models:
  - FITNAH (GEO-NET)
  - FIWind (Fraunhofer IWES)

*both models had good performance over the site but here we only show FIWind
Setting up the infrastructure

Scanning lidar

Galion 4000 – Scanning lidar

- Range 0-4 km (along „Line of Sight“ [LoS])
- Pulsed LiDAR: Simultaneous measurements „Range Gates“
- Flexible Geometry (Azimuth, Elevation)
- Measured quantity is fraction of the wind speed along beam direction (LoS)
- Verified at Fraunhofer IWES premises
Setting up the infrastructure

Model

- FIWind: Fraunhofer IWES Wind simulation environment

- IWES in-house development: Flow solver based on open source code OpenFOAM with own optimizations for wind energy applications (forest, stratification, complex terrain, ...)

- FIWind was validated at different locations in complex terrain (Kassel, NEWA project¹) →

¹Chang, Chi-Yao, et al. “A consistent steady state CFD simulation method for stratified atmospheric boundary layer flows.” Journal of Wind Engineering and Industrial Aerodynamics 172 (2018): 55-67
Results

Infrastructure

**Model**
- Steady state microscale flow model (FIVwind)

**Input/Initial conditions**: 
- Neutral stratification
- 36 (Site 1) / 12 (Site 2) directional sectors
- 25 x 25 m mesh resolution
- Terrain maps
- Landcover maps
Results

Infrastructure

| Model | Scanning lidar |
|-------|----------------|
| Steady state microscale flow model (FIWind) | ![Scanning lidar image] |

Input/Initial conditions:
- Neutral stratification
- 36 (Site 1) / 12 (Site 2) directional sectors
- 25 x 25 m mesh resolution
- Terrain maps
- Landcover maps

| Measurement | Value |
|-------------|-------|
| Beams in scan | 36 |
| Azimuth $\varphi$ [°] | 0-360 |
| $\Delta \varphi$ [°] | 10 |
| Elevation $\theta$ [°] | 20 |
| Completion time (min:sec) | 1:25 |
## Results

### Infrastructure

| **Model** | **Scanning lidar** | **Reference instrument** |
|-----------|--------------------|-------------------------|
| - Steady state microscale flow model (FIVind) | | - Profiling lidar |

**Input/Initial conditions:**

- Neutral stratification
- 36 (Site 1) / 12 (Site 2) directional sectors
- 25 x 25 m mesh resolution
- Terrain maps
- Landcover maps

**Scanning lidar:**

| Beams in scan | Azimuth θ [°] | Δθ [°] | Elevation φ [°] | Completion time (min:sec) |
|---------------|---------------|--------|----------------|--------------------------|
| 36            | 0-360         | 10     | 20             | 1:25                     |

**Reference instrument:**

- 1 year data (not overlapping with scanning lidar campaign)
- SoDAR
- 1 month (overlapping with scanning lidar campaign)
## Results

### Infrastructure

### Model
- Steady state microscale flow model (FIWind)

### Input/Initial conditions:
- Neutral stratification
- 36 (Site 1) / 12 (Site 2) directional sectors
- 25 x 25 m mesh resolution
- Terrain maps
- Landcover maps

### Scanning lidar

| Site 1 | Site 2 |
|--------|--------|
| **Beams in scan** | 36 | 36 |
| **Azimuth φ [°]** | 0-360 | 0-360 |
| **Δ φ [°]** | 10 | 10 |
| **Elevation ϑ [°]** | 20 | 34 |
| **Completion time (min:sec)** | 1:25 | 1:25 |

### Reference instrument

- Profiling lidar
  - 1 year data (not overlapping with scanning lidar campaign)
- SoDAR
  - 1 month (overlapping with scanning lidar campaign)
- Profiling lidar
  - 1 year data (overlapping period with scanning lidar campaign)
Results

Example single timestamp – Site 2

- Select common cases in the measured wind conditions capture matrix ($\alpha$: shear exponent, Dir: inflow direction)
- 30 minute ensembles from reference and scanning lidar measurements

Capture matrix Herleshausen.
Results

VSL vs Scanning lidar

Choose VSL for the sector corresponding to the reference measured direction.
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
- Any big structures still visible in the scanning lidar measurement?

Example case for Herleshausen
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
- Any big structures still visible in the scanning lidar measurement? NO
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
- Any big structures still visible in the scanning lidar measurement? NO
- Terrain / landcover mismatches?
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction

- Identify deviations larger than measurement uncertainty (discussed later)

- Any big structures still visible in the scanning lidar measurement? NO

- Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
- Any big structures still visible in the scanning lidar measurement? NO
- Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)
- Atmospheric stability mismatch?
Results

VSL vs Scanning lidar

- Choose VSL for the sector corresponding to the reference measured direction
- Identify deviations larger than measurement uncertainty (discussed later)
- Any big structures still visible in the scanning lidar measurement? NO
- Terrain / landcover mismatches? YES - Over speeding in front and behind hill (on average 30% over prediction)
- Atmospheric stability mismatch? NO (Equal distribution of contours)
Results

Clustering of cases

- Cluster cases with similar wind conditions
- Compare cluster’s average with VSL
  - Assess errors related to different wind conditions (shear profile)
Results

Clustering of cases – Example 240°

\[ \alpha = 0.1 \]  
\[ \alpha = 0.3 \]  
\[ \alpha = 0.5 \]

Scanning lidar

Averaged clusters for 240° sector at Herleshausen
Results
Clustering of cases – Example 240°

Averaged clusters for 240° sector at Herleshausen

*Scanning lidar*

\[ \alpha = 0.1 \]

\[ \alpha = 0.3 \]

\[ \alpha = 0.5 \]
Results

Clustering of cases – Example 240°

Mismatch in the blind zone increases with $\alpha$.

Include different stability classes in the model.

Good model performance for POI.

Averaged clusters for 240° sector at Herleshausen.
Results

Clustering of cases – Example 240°

Scanning lidar

\[ \alpha = 0.1 \quad \alpha = 0.3 \quad \alpha = 0.5 \]

Mismatch in the blind zone increases with \( \alpha \)

Include different stability classes in the model

Good model performance for POI

Averaged clusters for 240° sector at Herleshausen

Give more trust to the wind flow models by giving them a fair evaluation method

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Outlook

- Integrating a single scanning lidar only costs ~1.7 times more than conventional WRA
- VSL can be used:
  - to evaluate wind flow model performance
  - to quantitatively measure model uncertainty at POI
Conclusions (on use and business case)
How many scanning lidars will we see in future WRA campaigns?

Consider…

- German onshore market (starting point for EWiNo project)
- Costs of technology (how many devices)
- Use case / integration with WRA process and flow modelling in particular
- Significance of results (in the end, the estimated uncertainties decide)
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