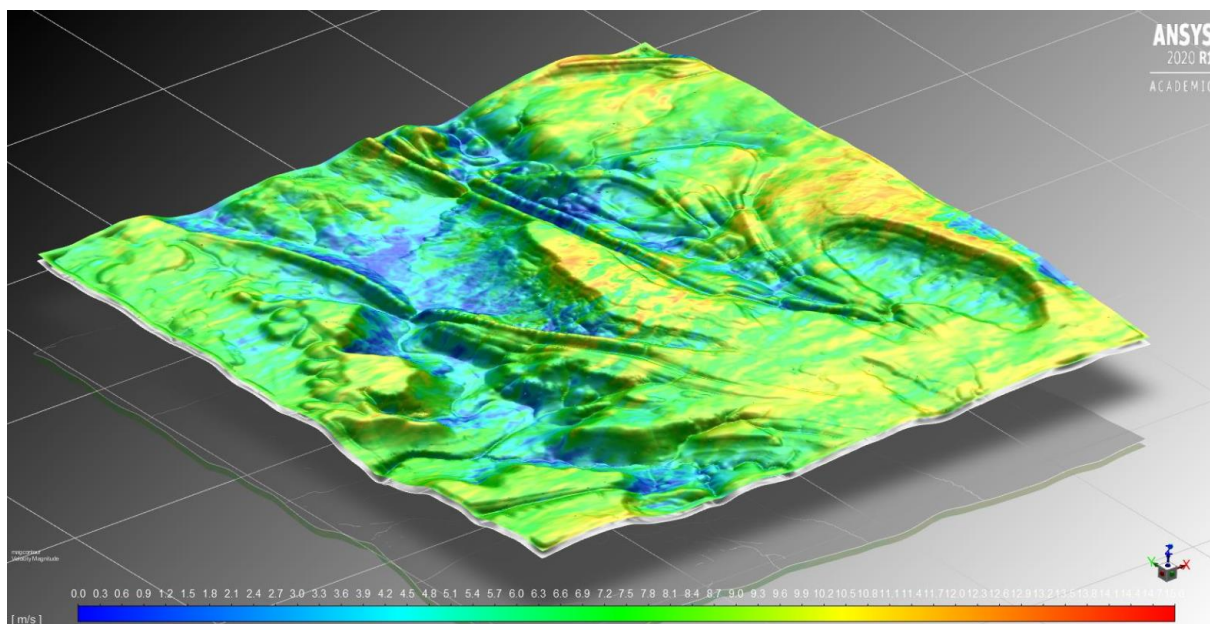




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A new process for the pragmatic choice of wind models in complex terrain



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The authors bear the entire responsibility for the content of this report and for the conclusions drawn therefrom.



Summary

In this work, a new industry-relevant process for selecting the wind model that gives the best results with the least computational effort and costs for any given wind energy project has been developed, with a focus on complex terrain. This will help modellers decide which model is optimal for each application, e.g. for Wind Resource Assessments (WRA) where the wind model accuracy has an enormous effect on the project's expected rate of return. The final result of the project is the design of a new commercial decision tool, which is being tested as part of the on-going SFOE-funded project "Comparison metrics simulation challenge".

In order to achieve this goal, a large number of simulations with different wind modelling tools and WRA workflows have been carried out at four complex terrain wind energy sites, followed by a detailed analysis of the results. The project was carried out by OST and Meteotest in collaboration with the Hochschule Esslingen, who are implementing a separate German-funded project with the same goal at two mutual wind energy sites (Stötten and Enercon). This collaboration has enabled us to develop the modelling and WRA workflow methods together and to compare our results with a wider range of different tools than would otherwise have been possible. The wind modelling tools applied in this project by the research partners include *WindPro*, *WindSim* and *PALM* (Meteotest), *Fluent* and *Palabos LBM* (OST), as well as *CFX* (HSE).

The project was split into two main parts: (1) Design of the decision process; (2) Demonstration and validation of the decision process.

For part (1), the test site Stötten in Germany was focused on, because data was available to all project partners including Hochschule Esslingen. In this part, WRAs were carried out using different combinations of wind modelling tools and WRA workflows, and the results compared and analysed in detail. Based on this, automated WRA processes were developed for the wind modelling tools used in this project. For *Fluent* and *CFX*, this resulted in a library of automated scripts, which enabled the other sites to be efficiently simulated and easily compared to each other. These libraries can be applied in future projects. Following this, a set of parameters (called "Comparison Metrics") for deciding the most optimal wind modelling tool and WRA workflow were developed. This resulted in several publications, a new SFOE-funded project studying the topic in more detail ("Comparison metrics simulation challenge"), as well as a new publicly-available template for estimating the Comparison Metrics.

In part (2), three other sites (ewz, Enercon and ADEV) were used to demonstrate and validate the Comparison Metrics parameters and method. This was done by firstly applying the new automated WRA processes to each of these sites and analysing the results. Finally, a comparison and evaluation of all the results at all four sites enabled the new decision tool to be designed, as well as several improvements to the WRA process and to the Comparison Metrics method to be suggested. The decision tool with the suggested improvements will be developed and tested as part of the on-going SFOE-funded project "Comparison metrics simulation challenge".



Zusammenfassung

In dieser Arbeit wurde ein neues branchenrelevantes Verfahren zur Auswahl des Windmodells entwickelt, das für jedes beliebige Windenergieprojekt die besten Ergebnisse mit dem geringsten Rechenaufwand und den geringsten Kosten liefert, wobei der Schwerpunkt auf komplexem Gelände liegt. Dies wird Modellierern helfen zu entscheiden, welches Modell für die jeweilige Anwendung optimal ist, z.B. für Wind Resource Assessments (WRA), bei denen die Genauigkeit des Windmodells einen enormen Einfluss auf die erwartete Rendite des Projekts hat. Das Endergebnis des Projekts ist der Entwurf eines neuen kommerziellen Entscheidungstools, das im Rahmen des laufenden BFE-finanzierten Projekts "Comparison metrics simulation challenge" getestet wird.

Um dieses Ziel zu erreichen, wurde eine grosse Anzahl von Simulationen mit verschiedenen Windmodellierungstools und WRA-Workflows an vier Windenergiestandorten mit komplexem Gelände durchgeführt, gefolgt von einer detaillierten Analyse der Ergebnisse. Das Projekt wurde von OST und Meteotest in Zusammenarbeit mit der Hochschule Esslingen durchgeführt, die ein separates, von Deutschland finanziertes Projekt mit demselben Ziel an zwei gemeinsamen Windenergiestandorten (Stötten und Enercon) durchführen. Diese Zusammenarbeit hat es uns ermöglicht, die Modellierungs- und WRA-Workflow-Methoden gemeinsam zu entwickeln und unsere Ergebnisse mit einer breiteren Palette von verschiedenen Tools zu vergleichen, als es sonst möglich gewesen wäre. Zu den von den Forschungspartnern in diesem Projekt eingesetzten Windmodellierungstools gehören WindPro, WindSim und PALM (Meteotest), Fluent und Palabos LBM (OST) sowie CFX (HSE).

Das Projekt wurde in zwei Hauptteile aufgeteilt: (1) Entwurf des Entscheidungsprozesses; (2) Demonstration und Validierung des Entscheidungsprozesses.

Für Teil (1) wurde der Teststandort Stötten in Deutschland genutzt, da die Daten für alle Projektpartner einschliesslich der Hochschule Esslingen verfügbar waren. In diesem Teil wurden WRAs mit verschiedenen Kombinationen von Windmodellierungstools und WRA-Workflows durchgeführt und die Ergebnisse detailliert verglichen und analysiert. Darauf aufbauend wurden automatisierte WRA-Prozesse für die in diesem Projekt verwendeten Windmodellierungstools entwickelt. Für Fluent und CFX resultierte dies in einer Library von automatisierten Skripten, die es ermöglichten, die anderen Standorte effizient zu simulieren und einfach miteinander zu vergleichen. Diese Libraries können in zukünftigen Projekten verwendet werden. Im Anschluss daran wurde eine Reihe von Parametern (genannt "Comparison Metrics") für die Entscheidung über das optimale Windmodellierungstool und den WRA-Workflow entwickelt. Dies resultierte in mehreren Publikationen, einem neuen BFE-finanzierten Projekt, das das Thema genauer untersucht ("Comparison metrics simulation challenge"), sowie einer neuen öffentlich zugänglichen Vorlage für die Abschätzung der Comparison Metrics.

In Teil (2) wurden drei weitere Standorte (ewz, Enercon und ADEV) genutzt, um die Parameter und die Methode der Comparison Metrics zu demonstrieren und zu validieren. Dies geschah, indem zunächst die neuen automatisierten WRA-Prozesse auf jeden dieser Standorte angewendet und die Ergebnisse analysiert wurden. Durch den Vergleich und die Auswertung aller Ergebnisse an allen vier Standorten konnte schliesslich das neue Entscheidungstool entworfen werden, und es wurden mehrere Verbesserungen des WRA-Prozesses und der Comparison Metrics-Methode vorgeschlagen. Das Entscheidungswerkzeug mit den vorgeschlagenen Verbesserungen wird im Rahmen des laufenden BFE-finanzierten Projekts "Comparison metrics simulation challenge" entwickelt und getestet.



Dans ce projet, un nouveau processus pertinent pour l'industrie a été développé pour sélectionner le modèle de vent qui donne les meilleurs résultats avec le minimum d'effort de calcul et de coûts pour n'importe quel projet d'énergie éolienne, avec une attention particulière pour les terrains complexes. Cela aidera les modélisateurs à décider quel modèle est optimal pour chaque application, par exemple pour les évaluations des ressources éoliennes (ERE) où la précision du modèle de vent a un effet énorme sur le taux de rendement attendu du projet. Le résultat final du projet est la conception d'un nouvel outil commercial de décision, qui est testé dans le cadre du projet en cours financé par l'OFEN "Comparison metrics simulation challenge".

Afin d'atteindre cet objectif, un grand nombre de simulations avec différents outils de modélisation du vent et de méthodes d'ERE ont été effectuées sur quatre sites éoliens ayant un terrain complexe, suivies d'une analyse détaillée des résultats. Le projet a été réalisé par OST et Meteotest en collaboration avec la Hochschule Esslingen, qui a monté un autre projet financé par l'Allemagne avec le même objectif, utilisant deux sites éoliens communs (Stötten et Enercon). Cette collaboration nous a permis de développer ensemble les méthodes de modélisation et de flux des tâches ERE et de comparer nos résultats avec une gamme plus large d'outils, qui n'aurait pas été possible autrement. Les outils de modélisation du vent utilisés dans ce projet par les partenaires de recherche comprennent WindPro, WindSim et PALM (Meteotest), Fluent et Palabos LBM (OST), ainsi que CFX (HSE).

Le projet a été divisé en deux parties principales: (1) Conception du processus de décision ; (2) Démonstration et validation du processus de décision.

Pour la partie (1), le site d'essai de Stötten en Allemagne a été privilégié, car les données étaient disponibles pour tous les partenaires du projet, y compris la Hochschule Esslingen. Dans cette partie, les ERE ont été effectuées en utilisant différentes combinaisons d'outils de modélisation du vent et de flux des tâches ERE, et les résultats ont été comparés et analysés en détail. Sur cette base, des processus automatisés d'ERE ont été développés pour les outils de modélisation du vent utilisés dans ce projet. Pour Fluent et CFX, cela a abouti à une bibliothèque de scripts automatisés, qui ont permis aux autres sites d'être simulés efficacement et facilement comparés les uns aux autres. Ces bibliothèques peuvent être appliquées dans de futurs projets. Ensuite, un ensemble de paramètres (appelés "métriques de comparaison") ont été développés permettant de déterminer l'outil de modélisation du vent et le flux des tâches ERE les plus optimaux. Cela a donné lieu à plusieurs publications, à un nouveau projet financé par l'OFEN qui étudie le sujet plus en détail ("Comparison metrics simulation challenge"), ainsi qu'à un nouveau modèle disponible publiquement pour estimer les paramètres de comparaison.

Dans la partie (2), trois autres sites (ewz, Enercon et ADEV) ont été utilisés pour démontrer et valider la méthode et les paramètres "métriques de comparaison". Pour ce faire, nous avons tout d'abord appliqué les nouveaux processus automatisés d'ERE à chacun de ces sites et analysé les résultats. Enfin, la comparaison et l'évaluation de tous les résultats obtenus sur les quatre sites ont permis de concevoir le nouvel outil de décision et de suggérer plusieurs améliorations du processus ERE et de la méthode des métriques de comparaison. L'outil de décision avec les améliorations suggérées sera développé et testé dans le cadre du projet en cours financé par l'OFEN "Comparison metrics simulation challenge".



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1 Introduction

1.1 Background information and current situation

In wind energy, the accuracy of the estimation of the wind resource has an enormous effect on the expected rate of return of a project. Due to the complex nature of the weather and of the wind flow over the earth's surface, it can be very challenging to measure and model the wind resource correctly. For a given project, the modeller is faced with a difficult choice of a wide range of simulation tools with varying accuracies and costs. If this choice is made incorrectly, either many resources are wasted in needless high accuracy simulations, or the rate of return is incorrect and investors risk losing large amounts of money. As there are currently no guidelines or tools available to the modeller to help with this choice, it is usually left to gut feeling – and this can be catastrophic for investors or acquirers of wind parks.

1.2 Purpose of the project

The goal of this project is to develop a new decision tool to help modellers choose the most appropriate model for a particular wind-energy related project. It involves applying various simulation tools to a test site, defining appropriate comparison metrics and developing a draft process. In a second step, the simulation tools are applied to a number of demonstration sites in order to validate, demonstrate and improve the decision process.

1.3 Objectives

The two main objectives of this project are to (1) design the new decision process, and (2) validate and demonstrate the new decision process.

The outcomes of objective (1) were:

- Results of simulations using different tools at the test site Stötten in Germany.
- Complete Wind Resource Assessment (WRA) process including libraries of scripts¹.
- Results and evaluation of comparison metrics analysis for the Stötten site.
- Definition of Comparison Metrics parameters for evaluating the decision process.

The outcomes of objective (2) were:

- Results of simulations using different tools at three demonstration sites using the automated WRA processes.
- Results and evaluation of Comparison Metrics analysis for three demonstration sites.
- Evaluation of the methods and suggestions for improvements.
- Design of final decision tool.

2 Procedures and methodology

¹ Note: the WRA process is not the same as the decision process. The WRA process is the automated process designed in order to carry out Wind Resource Assessment.



The time plan of this project involved completing objective (1) in the first year (2019) and objective (2) in the second year (2020). Part (2) was slightly delayed, and this final report has been submitted on April 30th, 2021.

The methodologies used for reaching these two objectives are described below.

Part (1) of the project (design of new decision process) was approached as follows:

- Initial study and investigation of Comparison Metrics at the Bolund Hill site.
- Initial definition of Comparison Metrics for evaluating the decision process.
- Initial simulations at the Stötten site.
- Development of automated WRA processes for the wind modelling tools applied.
- Application of the automated WRA processes and detailed analysis of the Stötten site.
- Evaluation of the Comparison Metrics method for the Stötten site.
- Summary of part (1).

Part (2) of the project (demonstration of new decision process) was approached as follows:

- Application of the automated WRA processes at three sites:
 - ewz site.
 - Enercon site.
 - ADEV site.
- Detailed analysis of the simulation results.
- Evaluation of the Comparison Metrics for the sites mentioned above.
- Comparison of results for all sites and evaluation of the methods.
- Development of the new decision tool to help modellers choose the most appropriate model for a particular wind-energy related project.



3 Activities and results

3.1 Part (1): design of new decision process

In this part of the project, the new decision process was designed based on studies at the Bolund Hill [1] and Stötten sites. In this section, the initial study at the Bolund Hill site followed by the initial definition of Comparison Metrics for evaluating the decision process is first introduced. Next, initial simulations at the Stötten site are described, followed by the development of automated WRA processes. Then, the automated WRA processes are applied to the Stötten site and the results analysed and evaluated. Finally, part (1) of the project is summarised.

3.1.1 Initial study and investigation of comparison metrics at the Bolund Hill site

Details of this initial study can be found in the following two presentations as part of a Mini-Symposium "Pragmatic choice of wind models" at the Wind Energy Science Conference in Cork, Ireland, in June 2019, as well as in the last yearly report of this project:

The results of the first presentation (Sarah Barber), "A new process for the pragmatic choice of wind models in complex terrain – quantification of "skill score" and "cost", [2] showed that this new method has a high potential to be successful, although the parameters and their weightings need to be studied in more detail.

The results of the second presentation (Alain Schubiger), "Evaluation of the Lattice Boltzmann Method for wind modelling in complex terrain", [3] showed that the Lattice Boltzmann Method (LBM) requires far more development to be applied effectively in this project. The work on this topic as part of this project lead to a publication in the Wind Energy Science Journal [4]. LBM is a computational fluid technique based on the Boltzmann transport equation with high potential for reducing the computational cost of high-fidelity wind flow simulations in complex terrain. It is generally used to study complex phenomena such as turbulence, because it describes motion at the mesoscopic level in contrast to the macroscopic level of conventional Computational Fluid Dynamics (CFD) approaches, which solve the Navier–Stokes (N–S) equations. Other advantages of the LBM include its efficiency; near-ideal scalability on high-performance computers (HPCs); and ability to easily automate the geometry, the mesh generation and the post-processing. However, LBM has been applied very little to wind modelling in complex terrain for wind energy applications, mainly due to the lack of availability of easy-to-use tools as well as the lack of experience with this technique. In this paper, the capabilities of the LBM to model wind flow around complex terrain are investigated using the Palabos framework and data from a measurement campaign from the Bolund Hill experiment in Denmark. Detached-Eddy Simulations (DES) and Large Eddy Simulations (LES) in *Fluent* are used as a numerical comparison. The results show that there is in general a good agreement between simulation and experimental data, and the LBM performs better than RANS and DES. Some deviations can be observed near the ground, close to the top of the cliff and on the lee side of the hill. The computational costs of the three techniques are compared, and it has been shown that the LBM can perform up to five times faster than DES, even though the set-up was not optimised in this initial study. It can be summarised that the LBM has a very high potential for modelling wind flow over complex terrain accurately and at relatively low costs, compared to solving Navier–Stokes equations conventionally.

Following this work, further studies involving the application of Palabos to full-scale wind sites showed that there are some challenges with this, including cell refinement and wall modelling, leading to computational mesh sizes that are far too large to handle. It was concluded that Palabos is not a suitable tool for carrying out this project. We are currently preparing a new research project proposal looking into the details of applying LBM for WRA in complex terrain.



3.1.2 Initial definition of comparison metrics for evaluating the decision process

Based on the results of the initial Bolund Hill study, the Comparison Metrics initially defined were studied further and completely re-worked. Additionally, some useful inputs were provided by the wind energy community at the IEA Wind Task 31 annual meeting at Amherst, USA in October 2019. The results of these activities were (and are described in [5] and [6] in more detail:

- Definition of a **new Comparison Metrics method** for estimating the skill and costs scores before and after carrying out the simulations, shown in Figure 1 below.
- A **final definition of the parameters used to estimate the skill and cost scores** for both wind speed and Annual Energy Production (AEP). A summary is shown in Figure 2 and a more detailed description including the definition of the scaling of the skill score parameters seen by the user is shown in Appendix 1(a), (b) and (c). The scaling helps the user decide which score on a scale of 0-100% to assign to their answers. For example, the answer to A1 may be "Linear model" or "CFD RANS". The scale tells the user that "linear model" gives an answer of 0% and "CFD RANS" gives an answer of 50%. The Bolund Hill study has been used to guess some suitable parameter weightings for the skill score parameters, but these will be refined during the project.
 - For the **skill scores**, a lot of thought has gone into the parameter definition in order to be able to include all the steps in the WRA process in the scores (see Section 3.1.4). This includes parameters related to the wind model, the input data quality, the calibration and validation methods, the AEP calculation method, the skill of the user and the robustness of the model.
 - For the **cost scores**, the so-called "Actual Total Costs" are estimated by splitting the costs up into the categories described in the table and adding up the totals. The software costs are estimated by dividing the total license and support costs by the number years of usage, and dividing this by the number of projects carried out per year. The time to learn and training costs are estimated by adding the staff costs for the time taken to learn how to use the tool to any training costs, and dividing this by the number of projects carried out per year and the estimated number of years of usage. The simulation set-up effort costs are estimated by recording the number of hours required to set up the simulations and multiplying this by the hourly staff rate (for all calculated wind directions). The simulation run time costs are estimated by recording the run-time of the simulations and the number of cores that they were run on, and multiplying this with the computational cost per core per hour (for all calculated wind directions). The post-processing effort costs are estimated by recording the number of hours required to post-process the results and multiplying this by the hourly staff rate (for all calculated wind directions). In order to compare the results with each other fairly, the following parameters should be normalised: Number of years of usage of the software; Number of projects per year; Staff hourly rate; Computational cost per core per hour = \$0.04/hour/core; Number of cores; Processor clock speed = 2 GHz.
- A **set of Google Forms** for participants to describe their model set-up and to enter their skill and cost parameter estimations [7].
- A new section is introduced in one of the Google Forms ("Model description") for **classifying the terrain complexity**. This is because we expect the weightings of the comparison metrics to be dependent on the terrain complexity. For this, new parameters have been defined based on previous work on terrain classification related to lidar measurements [8] This splits complex flow into the following categories: (a) Complex terrain (e.g. definition in IEC 61400-12-1 [9]); (b)



Surface roughness (e.g. forested land, changes in ground cover); (c) Presence of obstacles (e.g. buildings, towers and wind turbines); (d) Local meteorology (e.g. low-level jets, divergent flows and fronts). The parameters used for this work should not be too difficult or time-consuming to calculate, and the site classification given in IEC 61400-12-1 and 61400-12-2, for example, are too complex for this application. Therefore the following parameters are used here in order to simplify the process:

- General terrain complexity - how steep are the slopes on average?
- General terrain complexity - how many slopes are there?
- Validation mast position - in how many 30° sectors is there a positive slope steeper than 30° less than 250 m away from the validation position in any direction?
- Surface roughness complexity - approximately how many different surface roughness regions are you using?
- Surface roughness - how rough is the surface in general?
- Atmospheric stability - what is the average value of the vertical temperature gradient? (if relevant)
- Atmospheric stability - are low-level jets present?
- Degree of turbulence - what is the approximate Reynolds number, calculated based on the input flow velocity and the distance from the inlet to the calibration met mast?

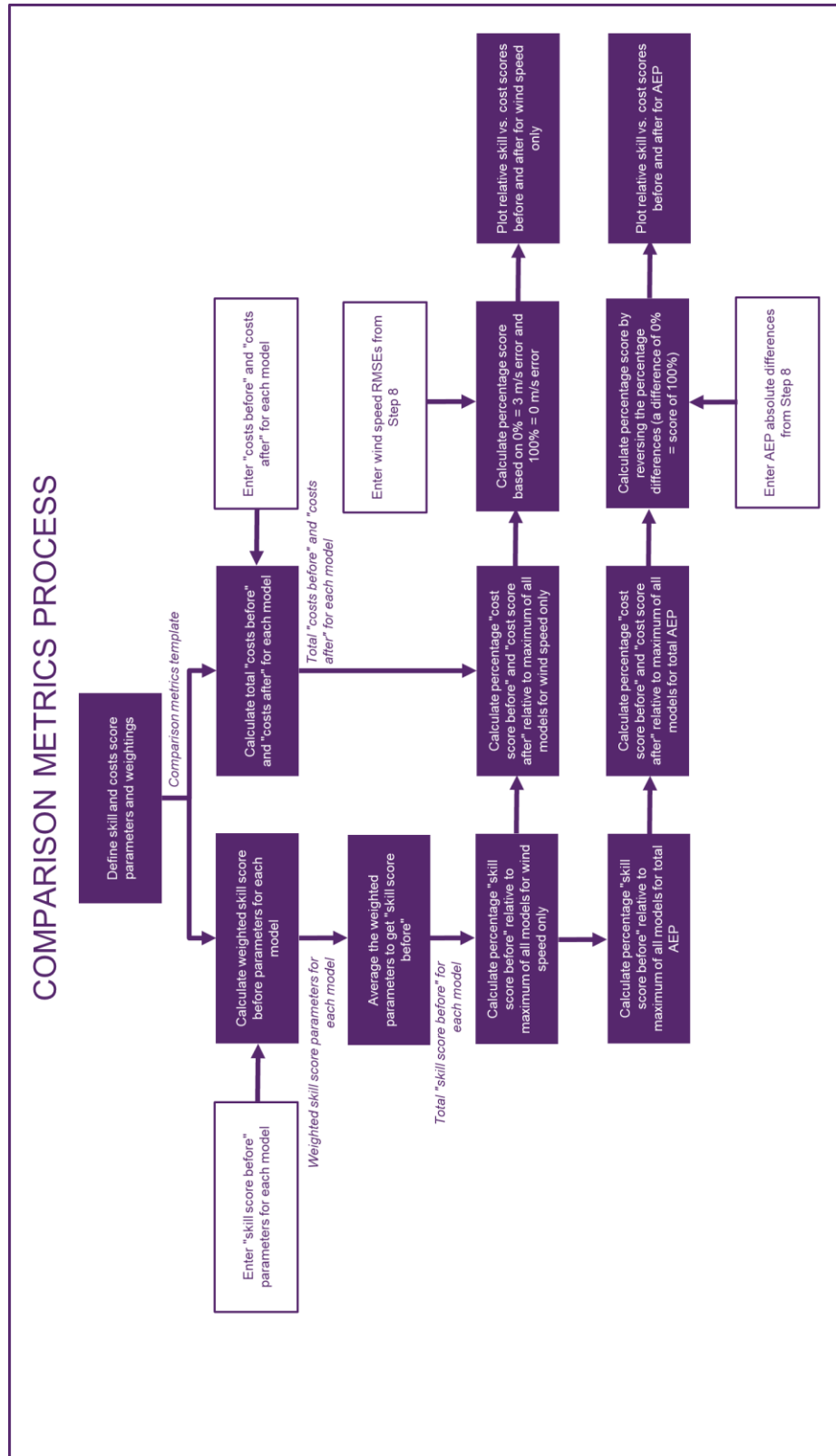


Figure 1. Comparison Metrics method.



List of parameters for skill score estimation	
Skill A. Model parameters	
A1. Mathematical model - what is the complexity of the underlying aerodynamic equations?	
A2. Mathematical model - what is the complexity of the underlying thermodynamic equations (including temperature and coriolis force modelling)?	
A3. Time step - how well does your chosen time step conform to the recommendations for your model and set-up?	
A4. Simulation period - how well does the simulation period reflect the entire measurement period?	
A5. Grid quality - how well are the software recommendations regarding orthogonal quality, skewness and aspect ratio fulfilled?	
A6. Grid quality - has grid independency been proven via a grid study?	
A7. Grid quality - are the estimated y+ values within the software recommendations of the applied boundary layer model?	
A8. Domain size - how well do the domain dimensions allow the flow to be properly captured?	
A9. Convergence - how well does your model convergence meet the required convergence criteria?	
A10. Operating envelope - if you are using WASP or a linear model, what is the average dRIX value for all wind sectors at the validation mast 1?	
A11. Operating envelope - if you are using WASP or a linear model, what is the average dRIX value for all wind sectors at the validation mast 2 (if applicable)?	
A12. Operating envelope - if you are using WASP or a linear model, what is the average dRIX value for all wind sectors at the validation mast 3 (if applicable)?	
Skill B. Input data quality	
B1. Measurement data - how do you assess the general quality of wind data you have been provided with?	
B2. Measurement data - how well did you filter the measurement data?	
B3. Quality of terrain data - what is the ratio of horizontal resolution as a % of your domain length?	
B4. Quality of land cover data - how well does the land cover data you have been provided with depict the real situation?	
B5. Quality of atmospheric data - how do you assess the general quality of atmospheric data you have been provided with?	
Skill C. Wind model calibration and validation	
C1. Validation of model - if you have previously validated the wind model for other sites, what was the average deviation between simulations and measurements for a site of similar complexity?	
C2. Wind speed calibration quality - which wind speed calibration method did you use? (please describe in detail in the model description)	
C3. Wind speed calibration quality - how well does your input data method capture the wind profile actually measured at the calibration mast?	
Skill D. AEP calculations	
D1. Wind sectors - which wind sector extrapolation method are you applying?	
D2. Wind sectors - how are different wind speeds in different sectors taken into account?	
D3. How well did you account for flow turning?	
D4. Long-term AEP - which long-term extrapolation method is applied?	
D5. Rotor area extrapolation - which rotor area extrapolation method is applied?	
Skill E. Other parameters	
E1. Skill of user - how many years of experience does the user have with the applied model?	
E2. Skill of user - on a scale of 0-100%, how do you rate your own ability to apply the chosen model correctly?	
E3. Robustness of model - what is the status of the applied model?	
List of parameters for cost score estimation	
Software costs	
Time to learn and training costs	
Simulation set-up effort costs	
Simulation run time costs	
Post-processing effort costs	

Figure 2. Parameters for skill and cost scores for the new comparison metrics estimation.



3.1.3 Initial simulations at the Stötten site

Site description

The test site chosen for this work was a complex terrain, partly-forested site close to Stötten in southern Germany, whose central feature is a steep incline above 30% and a main wind direction of 270°-300°. Wind speed and direction data was available from a met mast located about 1 km away from the incline, as well as a lidar, as described in [10]. In this paper, the met mast data from four cup anemometers with an accuracy 1% and three 3D sonic anemometers with an accuracy of 1.5% were used for calibration, and the wind speed data recorded using the SWE-Scanner, a fast pulsed lidar wind scanner based on a Leosphere Windcube V1 system with an adapted scanner unit, were used for validation. For the measurement campaign used in this work, the lidar was positioned approximately 300 m west of the met mast for approximately one year (March 2015 - February 2016). An overview of the site and the wind rose from the met mast at 98 m over the entire measurement period of 16 months (March 2015 - July 2016) are shown in Figure 3. A close-up of the terrain contours near to the met mast and lidar locations is shown in Figure 4. The plot is stretched in the vertical direction in order to show the terrain more clearly.

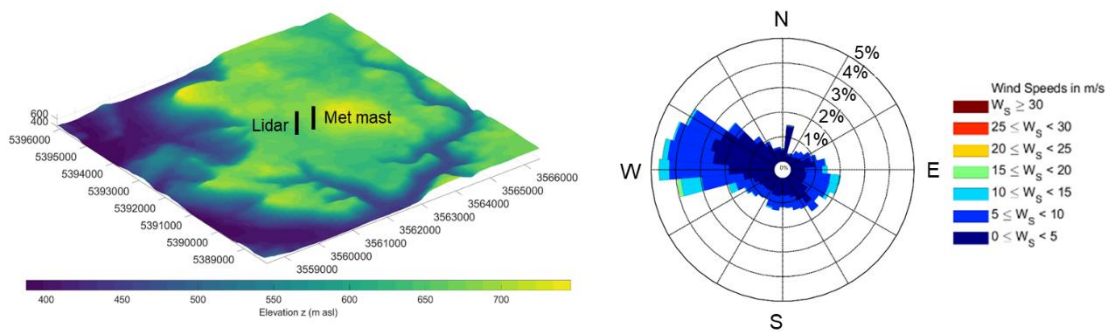


Figure 3. Stötten site: terrain contours (left) and wind rose (right).

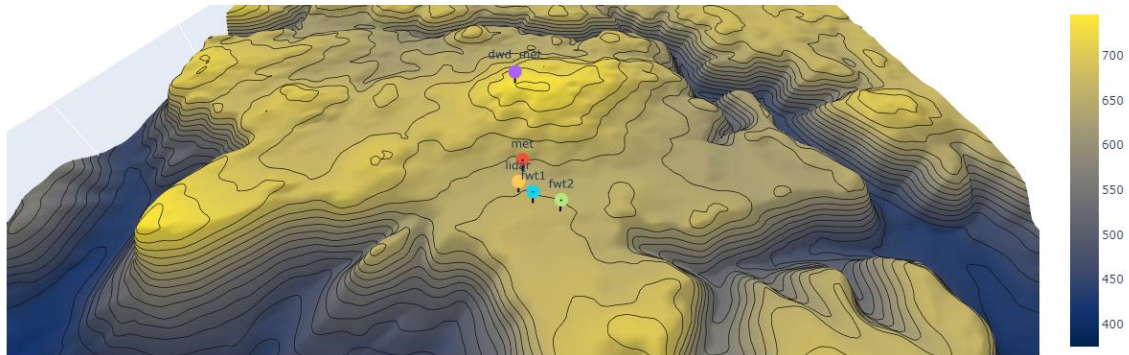


Figure 4. Close-up of Stötten terrain near the met mast and lidar locations. "met" refers to the met mast, "dwd-met" refers to a nearby weather station (not used in this work), "fwt1" and "fwt2" refer to the planned wind turbine locations (not used in this work) and "lidar" refers to the lidar location. The plot is stretched in the vertical direction in order to show the terrain more clearly.

In this work, a geostrophic wind speed of 10 m/s at a height of 500 m and a logarithmic profile down to the ground was used, and simulations with the commercial CFD solvers *ANSYS Fluent* and *ANSYS CFX* (Version 19.2) as well as with a wind industry tool, *WindSim*, were carried out as described in the next sections. It should be noted that the *ANSYS* add-on *WindModeller* has not been considered here, as the focus was on entirely generic tools. For all the simulations, a digital elevation model and surface roughness from the Copernicus database [11] were used with a horizontal resolution of 25 m, and a neutral Atmospheric Boundary Layer (ABL) was assumed. Based on the average roughness value (z_0) at the inlet of the domain, the inlet profiles of mean wind speed, turbulent kinetic energy and specific turbulence dissipation rate were imposed, using the equations by [12]. The ground boundary conditions were set to no-slip and individual roughness lengths were attributed to each land use of the domain according to the work of Wieringa [13] and Silva et al. [14] for all simulations. The average wind profile over the entire measurement period from the met mast data was used to define the initial wind profile shape, but because the met mast was not located at the inlet, the resulting wind speeds at the met mast deviated from the input profile. In order to recreate wind conditions equivalent to the average conditions over the entire measurement period, the ratio between the simulated wind speed at the met mast location for the 98 m height and the average wind speed at this height over the entire measurement period was calculated. This ratio was then used to linearly scale all of the simulated wind speeds in the entire domain (see Section 3.1.4 for more details). The lidar data were used to check the accuracy of the simulations by comparing the average RMSE between measurements and simulations (for overlapping time periods only).

The set-ups for each wind modelling tool applied here are described below and summarised in Table 1. Varying grid sizes and set-ups were chosen deliberately in order to be able to compare their effects on the total costs.

WindSim

WindSim is a Computational Fluid Dynamics (CFD) model based on the PHOENICS code, a 3D Reynolds Averaged Navier Stokes (RANS) solver from the company CHAM. The RANS equations govern the transport of the averaged flow quantities, and can model the whole range of turbulence



fluctuations using turbulence modelling. The approach is very popular for engineering applications because it allows reasonably accurate modelling of a wide range of flow phenomena, but with significantly lower computational effort than other approaches such as Large Eddy Simulations (LES). In this work, the simulation of the Stötten site was conducted using the standard k-epsilon turbulence model [15]. Based on the experience of the user and the guidelines of the tool, an 8 km by 8 km by 5 km domain was created with about 4.5 million cells with a horizontal resolution of 25 m and a stretched grid on the vertical axis providing four layers in the lowest 100 m and then 31 more layers to the model roof. The boundary condition at the top was fixed pressure. The wind rose measured at the met mast was used as an input in order to simulate all wind sectors.

ANSYS Fluent

ANSYS Fluent is a commercial CFD tool for modelling the flow in industrial applications and can be set up to solve the RANS equations, as well as for the Large Eddy Simulations (LES) or Detached Eddy Simulations (DES) approach. In this work, Fluent was first set up to solve the RANS equations with the SST k- ω turbulence model [15], and then the results were used to initialise DES, which was performed unsteadily with an adaptive time stepping procedure ensuring $CFL^2 \leq 1$. After an additional unsteady initialisation, the wind speeds were averaged over 10 minutes. Following a mesh sensitivity study, a 10 km by 10 km by 1.5 km structured mesh with a horizontal resolution of 20 m and 20 million cells was created. The first cell height was chosen to be 1 m and the average growth rate 1.2. The Delayed Detached Eddy Simulation (DDES) model was applied, which ensures that RANS is preserved, even in high-aspect ratio boundary layers. In order to introduce fluctuating velocities at the inlet, the Fluent Synthetic Turbulence Generator was used. The wind rose measured at the met mast was used to choose the three main wind directions, and only these directions were simulated. In order to obtain results for all wind sectors, the three main wind directions were scaled linearly according to their measured average wind speeds and frequency distributions.

ANSYS CFX

The all-purpose CFD software *ANSYS CFX* (version 19.2) was applied using a URANS (Unsteady RANS) approach in combination with the k- ϵ model [16]. The equation system was extended to an anelastic formulation whereby the density is influenced by buoyancy forces using the Boussinesq approximation [17]. The Earth's rotation was considered with additional terms in the momentum equation to describe the Coriolis force at a given angular velocity. Forested areas were considered through a canopy model [18]. Individual roughness lengths of the canopy were attributed to each land use and are chosen according to the work of Wieringa [13]. These methods have previously been applied successfully to another application [19]. A structured mesh of about 17 million cells was created over an area of 22 km by 20 km reaching a height over ground of 2 km. The first layer above the ground was adjusted to a height of 3 m. Further layers up to a height of 60 m were dimensioned to a growth rate from 1.3 to 1.5, giving 36 cell layers in total. Static boundary conditions were applied around the resolved volume for the chosen wind direction and wind speed, forming a Taylor Spiral. Since the upper boundary condition of the domain is flat, but the ground surface is not, the mass flow rate was balanced at the top surface of the domain in order to prevent an acceleration due to mass conservation of the setup. The wind rose measured at the met mast was used to choose the three main wind directions, and only these

directions were simulated. In order to obtain results for all wind sectors, the three main wind directions were scaled linearly according to their measured average wind speeds and frequency distributions.

Table 1. Summary of simulation set-ups for the wind modelling tools used in the initial Stötten study.

Set-up	WindSim	Fluent	CFX
Type	CFD RANS	CFD DDES	CFD URANS
Turbulence model	$k-\epsilon$	SST $k-\omega$	$k-\epsilon$
Grid dimensions	8 km by 8 km by 5 km	8 km by 8 km by 1.5 km	20 km by 22 km by 2 km
First layer cell height	4.8 m	1 m	3 m
Total number of cells	4.5 million	20 million	17 million
Atmospheric model	None	None	Non-hydrostatic anelas- tic formulation
Earth's rotation	None	None	Additional term for Cori- olis force
Forest model	None	None	Canopy model

The roughness maps used by each wind modelling tool are shown in Figure 5. The differences are due to the varying domain sizes and scale colours.

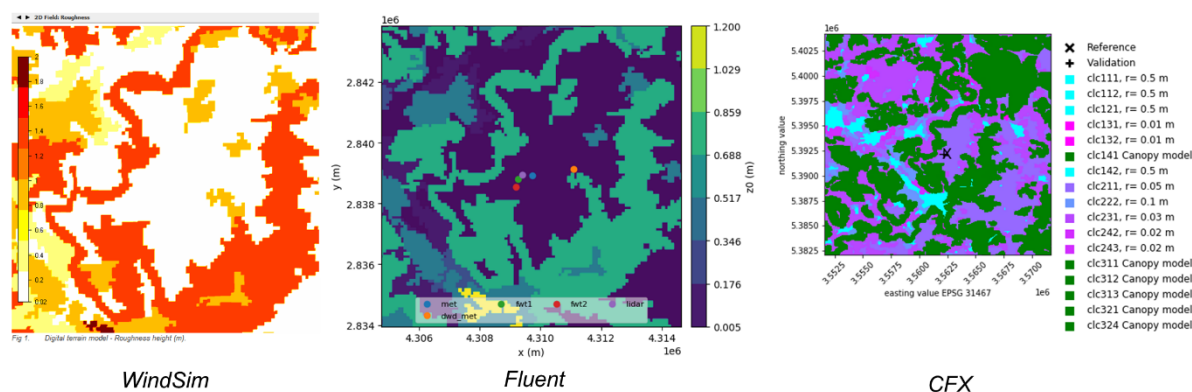


Figure 5. Roughness height z_0 (m) used for each tool.

Simulation results

The initial simulation results were used to investigate the costs related to the entire WRA process. The simulation set-up effort and post-processing effort were found to be very large for the two commercial CFD tools, *Fluent* and *CFX*, as shown in Table 2. The Actual Total Costs (ATC) were defined as the sum of the software costs, the time of learn and training costs, the simulation set-up effort, the simulation run time and the post-processing effort (see Section 3.1.2 for more details). It can be seen that the ATCs for the *Fluent* and *CFX* simulations are very similar, and approximately twice as high as the *WindSim* simulations. The main cost saving potential was therefore identified to be in the terrain and mesh creation process, as well as in the post-processing.



In order to get these results, the costs were normalised according to the following assumptions:

- Number of years of usage of the software = 10.
- Number of projects per year = 12.
- Staff hourly rate = \$80/hour.
- Computational cost per core per hour = \$0.04/hour/core.
- Number of cores = 100.
- Processor clock speed = 2 GHz.

The results are displayed as a percentage relative to the maximum ACT (in this case for *Fluent*).

Table 2. Summary of Relative Actual Total Costs for each wind modelling tool used in the initial Stötten study.

Cost category	WindSim	Fluent	CFX
Software costs	0.6%	3.9%	3.9%
Time to learn and training costs	0.3%	0.7%	0.9%
Simulation set-up effort	14.9%	55.9%	32.6%
Simulation run time	0.04%	2.4%	4.7%
Post-processing effort	5.6%	37.2%	55.9%
Relative Actual Total Cost (ATC)	21.4%	100.0%	97.9%

Due to these results, it was decided to take the time to generate automated process for *Fluent* and *CFX* within this current project, as described in the next section.

3.1.4 Development of automated Wind Resource Assessment (WRA) processes

Firstly, a general process was generated as shown in Figure 6(a). In this process, the wind data, such as met mast measured wind speeds and directions, are first processed in order to create input wind profiles for the simulation set-up (step 5), for comparison data for the post-processing (step 7) as well as in order to create the 3D digital model at the required angle (step 3). Next, the site data, such as the terrain and land cover data, is processed to produce raster data that can be used to create a 3D digital model in the next step. Then the mesh is created for the required wind directions and input into the simulation set-up space, which is combined with initial parameters as well as additional source terms, if being used. This produces a simulation file, which can then be used to actually carry out the simulations. The results are then combined with any available comparison data in a post-processing step, and the quality of the results are checked using additional comparisons with measurement data. Steps 3-5 are then repeated for all selected wind directions. The post-processing includes the calibration process as well as the linear scaling of non-simulated wind speeds using the wind rose as discussed.

In the remainder of this project, the following three wind modelling tools were applied by the research partners, as well as the three tools already introduced above (*WindSim*, *Fluent* RANS and *CFX*).

- **WindPro:** The industry leading software suite for design and planning of wind farm projects. It uses the linear solver WAsP for modelling the wind field [20].
- **Fluent SBES:** A technique called "Stress-Blended Eddy Simulation" (SBES) was applied. SBES is a new model that offers improved shielding of RANS boundary layers and a more rapid RANS-



LES 'transition', amongst other things. However, due to the long computational time, not all sectors could be simulated. Instead, the most frequent sectors were simulated and complemented with the *Fluent* RANS simulations.

- **PALM:** The model *PALM* is based on the non-hydrostatic, filtered, incompressible Navier-Stokes equations in Boussinesq-approximated form (an anelastic approximation is available as an option for simulating deep convection). Furthermore, an additional equation is solved for either the subgrid-scale turbulent kinetic energy using Large-Eddy Simulations (LES) [21]. In this work, due to the long computational time, not all sectors could be simulated. Instead, the most frequent sectors were simulated and complemented with the *WindSim* simulations.

Following the generation of this general process, individual processes were developed for its implementation in *WindPro*, *WindSim*, *Fluent*, *CFX* and *PALM* separately as shown in Figure 6(b)-(e). Each process is based on the general process, but is slightly different in the way the steps are implemented. For example, the *WindPro* and *WindSim* processes are largely included inside the tool already, whereas scripts had to be developed by the research partners for *Fluent*, *CFX* and *PALM*.

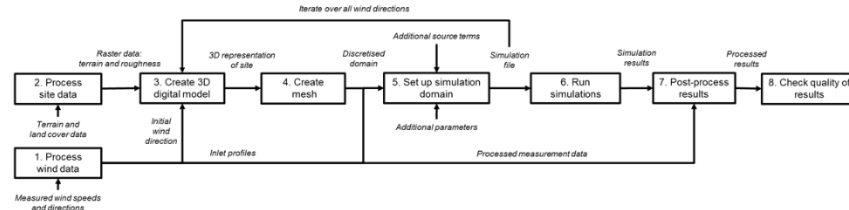
The separate steps are shown in Figure 7 (steps 1-6), Figure 8 (step 7) and Figure 9 (step 8) and described in more detail in Appendix 2.

In this project, step 1 was carried out by OST, Meteotest and HSE together using OST's *MATLAB* pre-processing tool, in order to ensure that the same input data was used for the simulations.

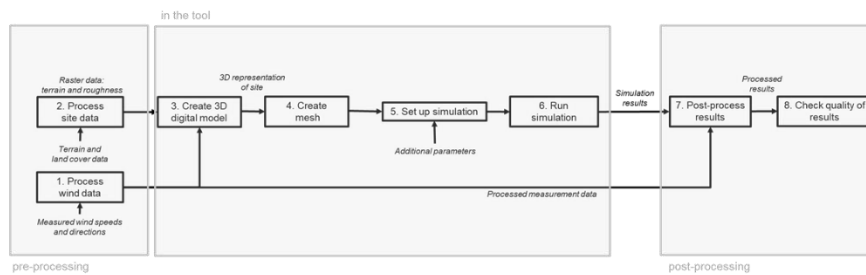
For *PALM*, a slightly different method was applied in order to reduce the computational time in a pragmatic way. This involved firstly searching for a time period in the met mast data for which the wind speed remained relatively stable at the average wind speed for each wind direction sector. For this time period, *COSMO-D2* data [22] was taken for the *PALM* boundary conditions by reading the data from a dynamic input file (offline nesting). Finally, this time period is simulated with *PALM* and the average wind speed is extracted for the calibration and validation positions at the reference height.



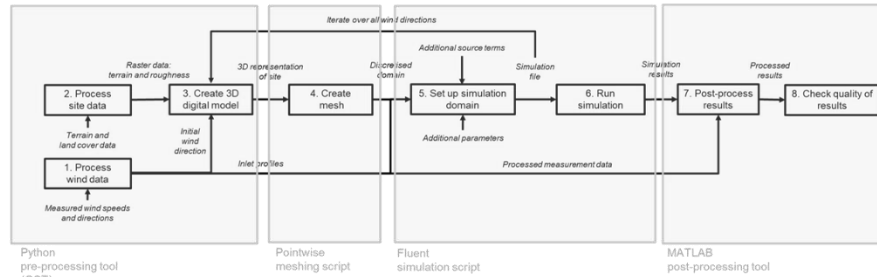
(a) General Process



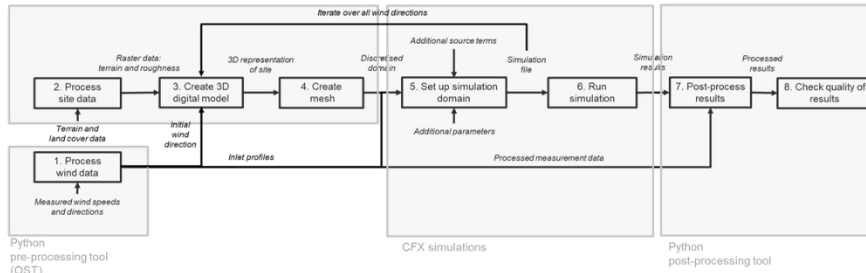
(b) WindSim and WindPro Process



(c) Fluent Process



(d) CFX Process



(e) PALM Process

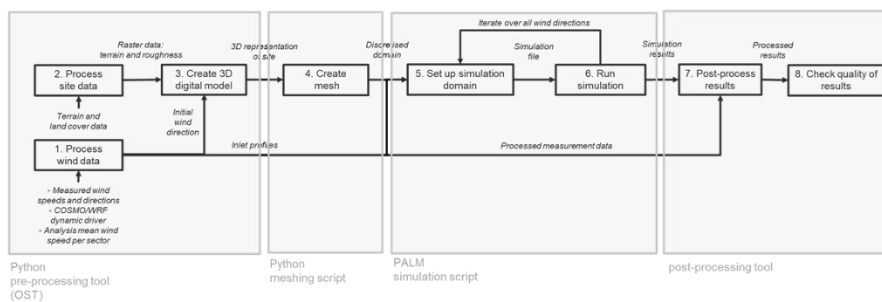


Figure 6. Automated processes: (a) General process; (b) *WindSim* and *WindPro* process, (c) *Fluent* process; (d) *CFX* process, (e) *PALM* process.

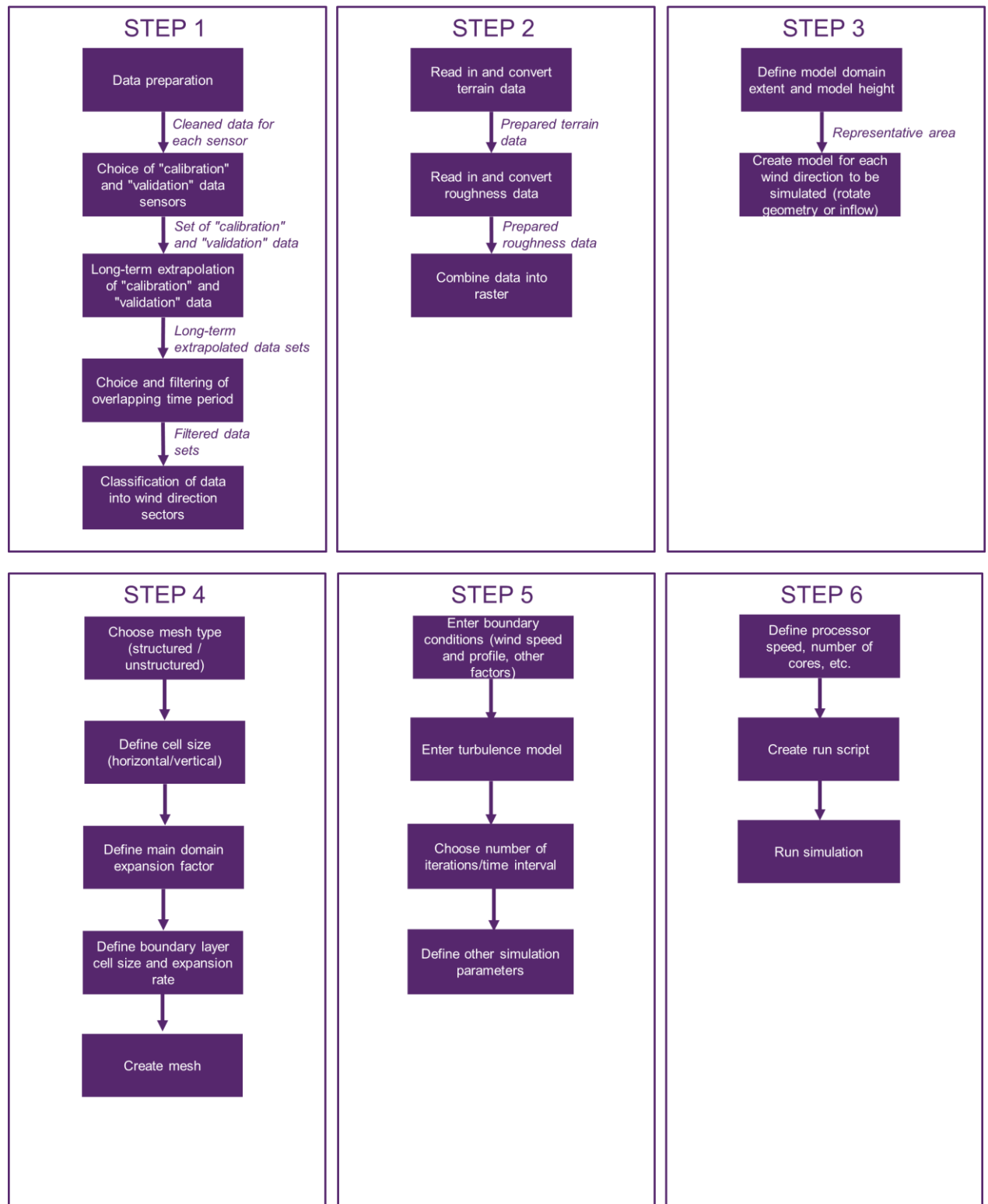


Figure 7. Steps 1-6 of the automated WRA process.

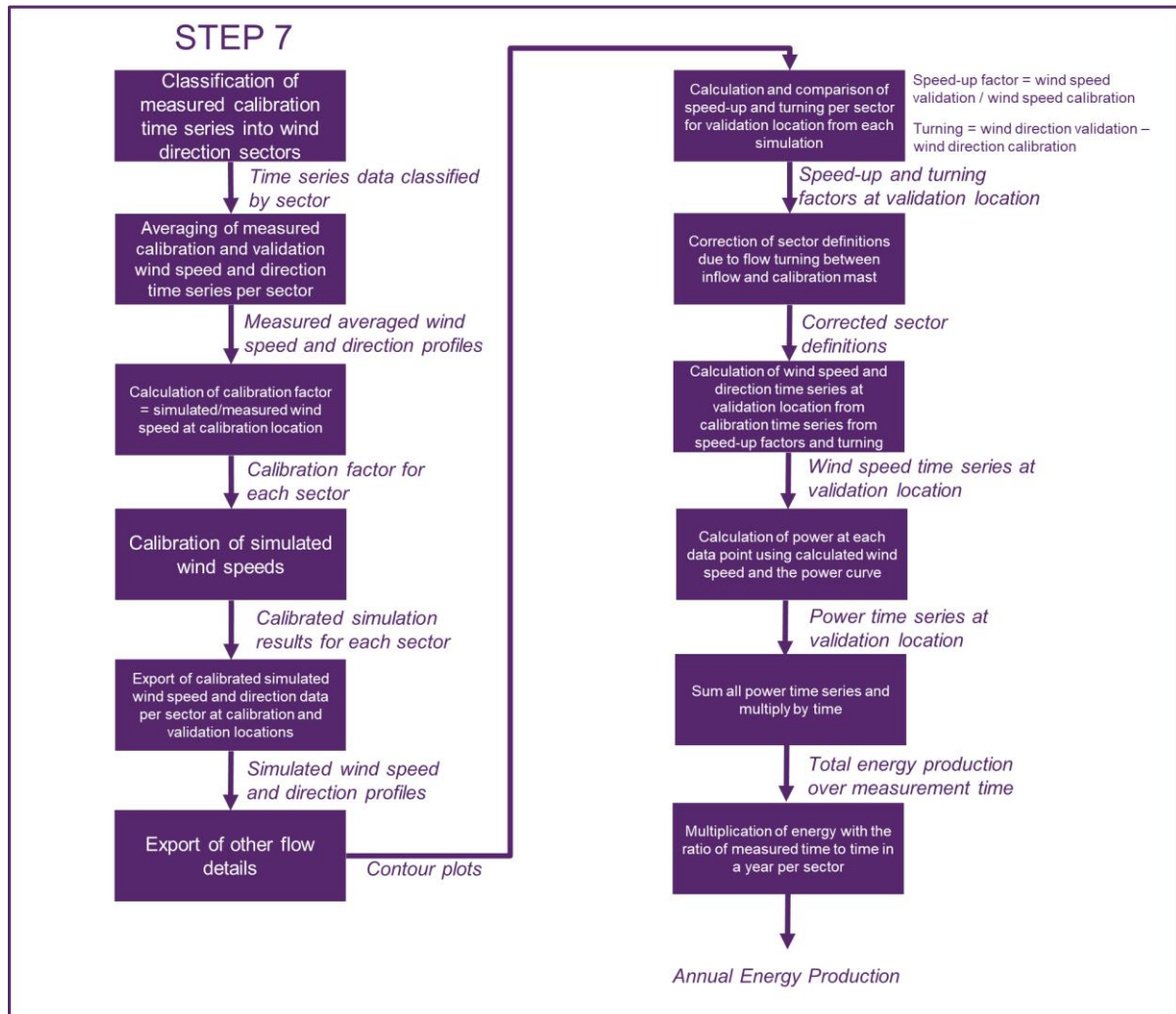


Figure 8. Step 7 of the automated WRA process

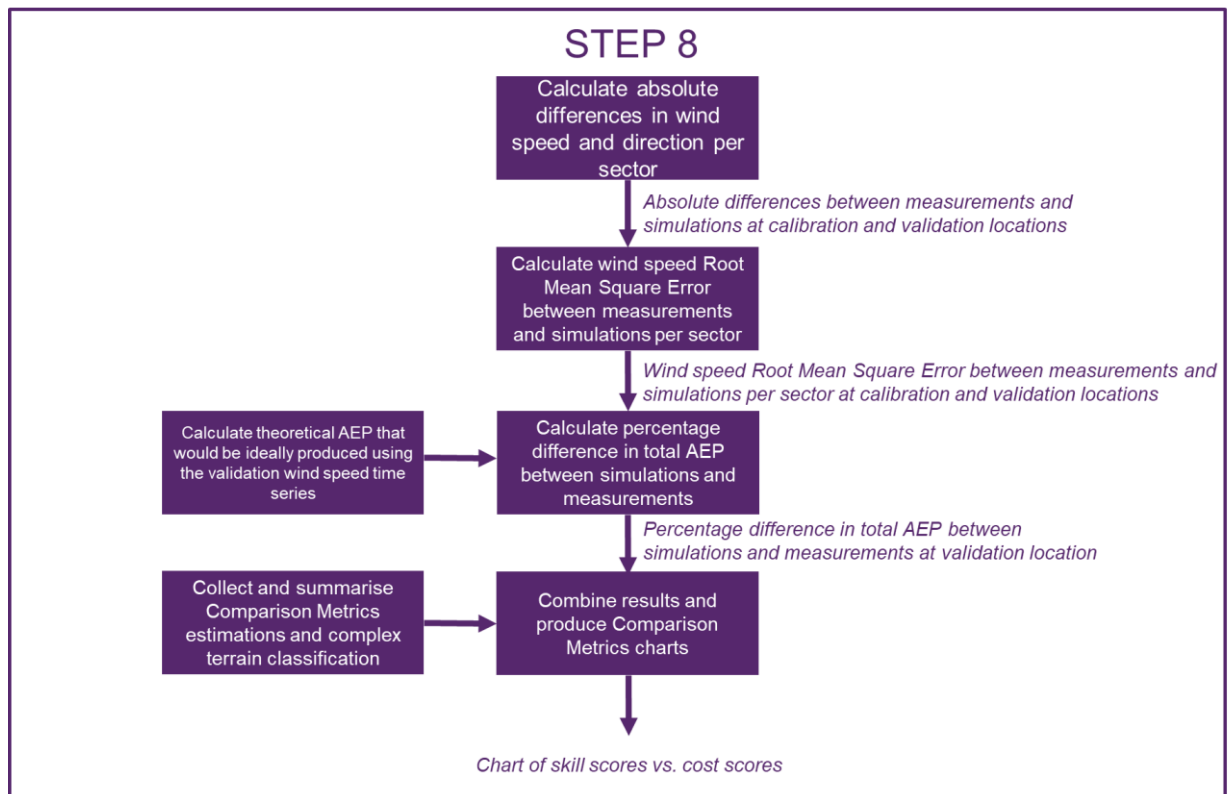


Figure 9. Step 8 of the automated WRA process.



Reduction in Actual Total Costs

The same simulations as described in Section 3.1.3 above were repeated using these new automated processes (except for *PALM*, which had not been completed when this work was carried out). The relative Actual Total Costs for the simulations carried out with the new processes are compared to those for the manual processes in Figure 10.

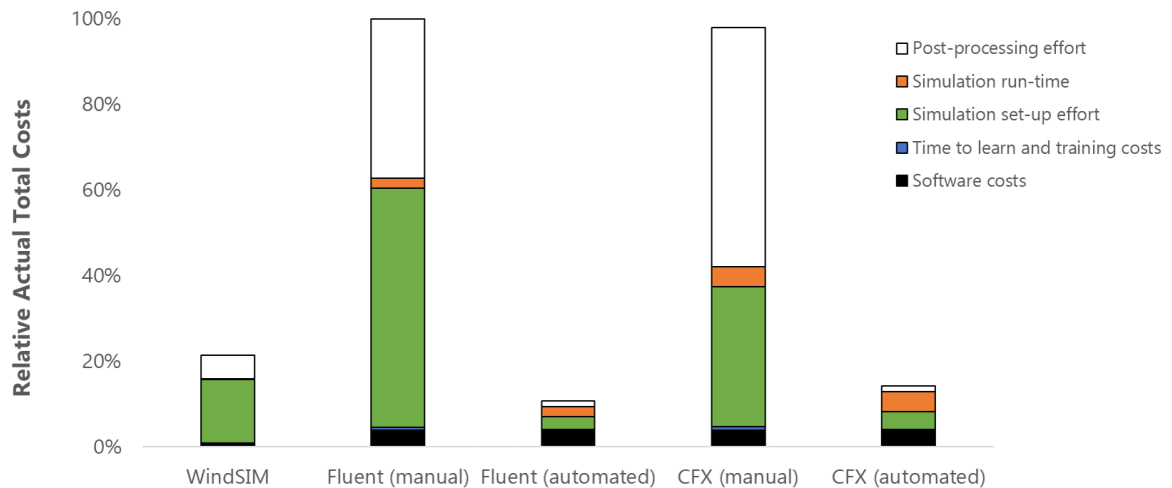


Figure 10. Actual Total Costs for the automated processes compared to the manual processes for the initial Stötten study.

In this plot, the dominating costs of the simulation set-up effort and post-processing effort are clear to see for the manual *Fluent* and *CFX* simulations. The new automated processes have led to a significant drop in relative ATC (12 times cheaper for *Fluent* and 7 times cheaper for *CFX*). It is very interesting that these new processes have allowed the ATCs to be reduced even below those of *WindSim*, despite the higher software / license costs. This is because the *WindSim* simulations require a certain amount of set-up effort that the new automated processes do not. As the different set-ups and user skills will significantly affect the costs, it is important to note that these results should not be used to directly compare the general costs of different tools with each other, but only to compare specific simulation set-ups with each other. This can be useful in helping modellers choose the most appropriate tool for a certain project, when combined with skill scores as described in the introduction. In other words, the results should not be interpreted as the costs of the tools themselves, but as a combination of the user, the tool and the set-up. This is a great strength of this method for real applications, because in reality the costs always result from the combination of user, tool and set-up. Nevertheless, the manual and automated processes can be directly compared with each other, as the set-up and user was the same, and therefore **it can be concluded that these new processes have significantly reduced the total simulation costs and are likely to have a large effect on the choice of the most cost effective model for a given wind energy project.** This will be investigated further for the other sites.



3.1.5 Application of the automated WRA process and detailed analysis of the Stötten site

In this section, the new automated WRA processes were applied to the Stötten site, already described in Section 3.1.3 above.

Workflows applied

The set-ups for the six wind models applied in this work are summarised in Table 3. Due to the fact that the applied wind modelling tool is only a small part of the entire WRA process, the different set-ups are referred to from now on as "workflows". The names of the various workflows applied are thus named WF-1, WF-2, etc. It is important to remember that any comparisons of the results are not comparing the wind modelling tools themselves, but rather the entire workflow.

Table 3. Summary of set-ups for final Stötten simulations.

	WF-1	WF-2	WF-3 and WF-3T	WF-4	WF-5a and WF-5b	WF-6
Wind model	WindPro	WindSim	CFX	Fluent RANS	Fluent SBES	PALM
Institution	Meteotest	Meteotest	HSE	OST	OST	Meteotest
Model type	Linear wind model	Steady-state RANS CFD, k-epsilon	Unsteady RANS CFD, k-epsilon model	Steady-state RANS CFD, k-omega SST	Unsteady SBES CFD, k-omega SST, average over 1800s	LES model
Grid dimensions (resolution)	9 x 9 km (25 m)	9 x 9 x 5 km (25 m)	20 x 22 x 2.5 km (25 m)	10 x 10 x 1.5 km (20 m)	10 x 10 x 1.5 km (20 m)	6 x 6 x 6.5 km (10m)
Number of cells	129'600	4.5 million	17 million	20 million	20 million	54 million
Input profile	None	Log profile at inlet	Taylor Spiral at all boundaries with α , B i.o.w. B Klose, Meteorologie, 2nd edition 2015	Log profile at inlet ($z_0 = 0.75$ m)	Log profile at inlet ($z_0 = 0.75$ m)	Offline Nesting in COSMO-D2 model
Turbulence intensity	None	Calculated by the model (standard k-epsilon)	10 % at all boundaries	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Moeng Wyngaard turbulence closure
Other models	None	None	Non-hydrostatic anelastic formulation, Additional models for impacts through earth rotation and forest	None	Synthetic Turbulence Generator	Land Surface Model, Radiation Model
Wind directions	12 sectors	12 sectors	12 sectors	12 sectors	WF-5a = 3 sectors (270°, 300°, 120°) WF-5b = 7 sectors (0°, 30°, 60°, 90°, 270°, 300°, 120°)	7 sectors (0°, 30°, 60°, 90°, 270°, 300°, 120°)
Other workflow steps	Includes steps 1-8 specific to <i>WindPro</i> .	Includes steps 1-8 specific to <i>WindSim</i> . Preparation of roughness data for all partners is done in this WF.	Includes steps 1-8 specific to <i>CFX</i> . WF-3T is without turning, WF3b is with turning considered.	Includes steps 1-8 specific to <i>Fluent</i> .	Includes steps 1-8 specific to <i>Fluent</i> .	Includes steps 1-8 specific to <i>PALM</i> .

For WF-5 (*Fluent SBES*), two variations were compared: WF-5a with seven sectors simulated in *Fluent SBES* and the rest in *Fluent RANS*, and WF-5b with three sectors simulated in *Fluent SBES* and the rest in *Fluent RANS*. For *PALM*, the same seven sectors were simulated as for WF-5b, and the remaining sectors were obtained using *WindSim* results. Note the variation in grid size and resolution between the models. It should also be noted that the preparation of the roughness data for all the partners was mainly done as part of WF-1 (*WindPro*) and WF-2 (*WindSim*), leading to higher costs than if the time for doing this had been split up amongst all partners. Note also that WF-3 considers flow turning in the AEP calculation, whereas WF-3T does not.



Input data

For this site, the sensor chosen for the reference data was the met mast sensor at a height of 100 m. This was because it was the closest height to the fictitious wind turbine hub height (S&G Engineering SG750.54) chosen to be examined as if it was placed at the lidar position. This wind turbine was chosen because it is the model that is being planned to be installed at the site. We assume that it will be placed at the lidar location so that we can use the lidar data (at a height of 100 m) as the validation sensor, and compare the AEP estimations as well as the wind speeds.

The overlapping time period can be seen in Figure 11: blue shows the met mast data and orange shows the lidar data. The data availability of the met mast data is reasonable (60%) but very poor for the lidar (40%), giving an overlap of 34% of the total time. As well as resulting in a relatively small amount of data in each wind direction sector (566 points, or 3%, for the least frequent sector and 3'551, or 20%, for the most frequent sector), the resulting time series is broken up and probably doesn't represent real wind conditions well. Therefore, the results of this study need to be handled with care.

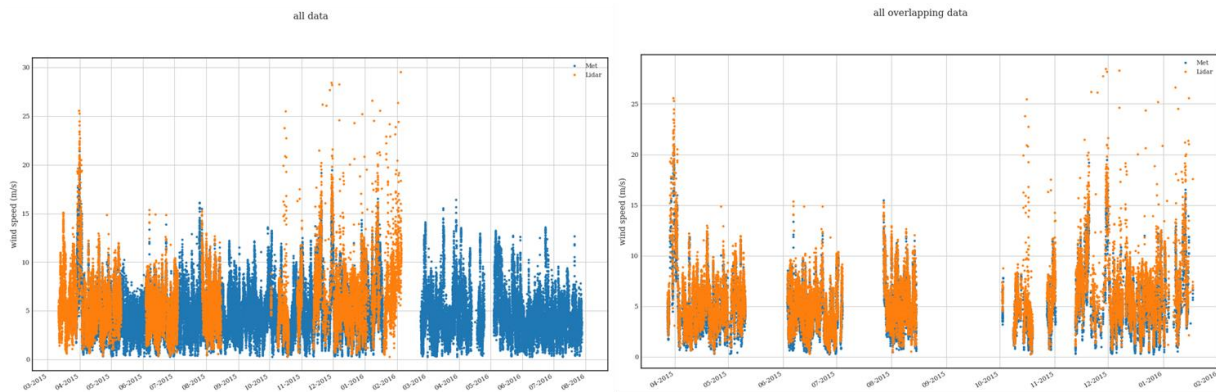


Figure 11. Data used for Stötten simulations: (a) All data; (b) Overlapping periods only.

A second difficulty encountered with this data was an apparent offset between the met mast and lidar data. Figure 12 shows the average wind speeds over the overlapping time period for the met mast in blue and the lidar in red. The error bars show the standard deviations of the measurements, which are remarkably large. This offset is not expected due to the small distance between the met mast and the lidar (only 1 km). Regardless of this, this site has been very useful for us to design our processes and methods.

Due to the short time period with overlapping data, no long-term extrapolation was carried out for this project. For all analyses, the cleaned data of the met mast and the lidar have been used.

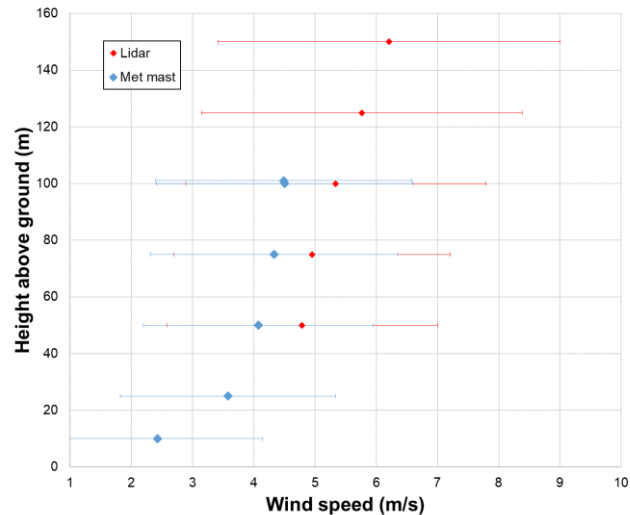


Figure 12. Average wind profiles for overlapping period for met mast and lidar.

Results

Wind speed profiles

The results for each wind model and wind direction sector are shown in Appendix 3(a) for the met mast (calibration location). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). The middle plot shows the percentage difference between the measurements and the simulations for each height and sector. It is clear to see that most of the tools have the largest error at the lowest height. This is as expected, because the simulations have been calibrated at the highest point and the area near to the surface is harder to resolve correctly. The workflows could be improved in the future by carrying out an iterative calibration involving altering the input profile shape until the profile is achieved at the calibration location. The right-hand plot shows the differences between measurements and simulations per sector in terms of the difference at hub height (blue), the Root Mean Square Error (RMSE) using all the measured heights (red) and the RMSE without the lowest height (green). It can be seen that the RMSE with the lowest height included (red) is particularly large in the sectors between 150° and 240°, and can be reduced significantly by removing the lowest height (green). It is more representative of the real situation to exclude the lowest height in any case, because it is not relevant for the Annual Energy Production calculation (as this point is not within the rotor area).

The same results are shown for the lidar (validation location) in Appendix 3(b). For the right-hand plots, the three colours represent hub height (blue), the RMSE over the whole measurement range (red) and the RMSE over the rotor area (green).

In general, the match is worse than at the met mast, as expected, because the met mast was used for calibration. The difference between the simulations and the measurements at the reference height of 100 m represent the real accuracy of the simulations in calculating the speed-up from the reference sensor to the validation sensor.

Figure 13 shows a summary of the RMSE results for each workflow for the met mast (top) and the lidar (bottom), by taking a simple average of the individual RMSEs of all simulated sectors (left) and by



weighting the average according to its relative frequency from the met mast data. This gives more weighting to more frequent wind speeds in order to provide a number more relevant for the AEP. The different colours represent the different heights taken to calculate the RMSE as discussed above. It can be seen that the RMSE of the met mast simulations decreases with decreasing number of heights taken. This corresponds to the results discussed in the first paragraph of this section. For the lidar, however, the RMSEs are much less sensitive to the number of points. This indicates that the entire profiles are offset compared to the measurements. Combined with the unexpected offset of the lidar measurement data mentioned above, this strengthens the conclusion that the results at this site should be treated with care.

The RMSE values at the validation location are used for the Comparison Metrics analysis below.

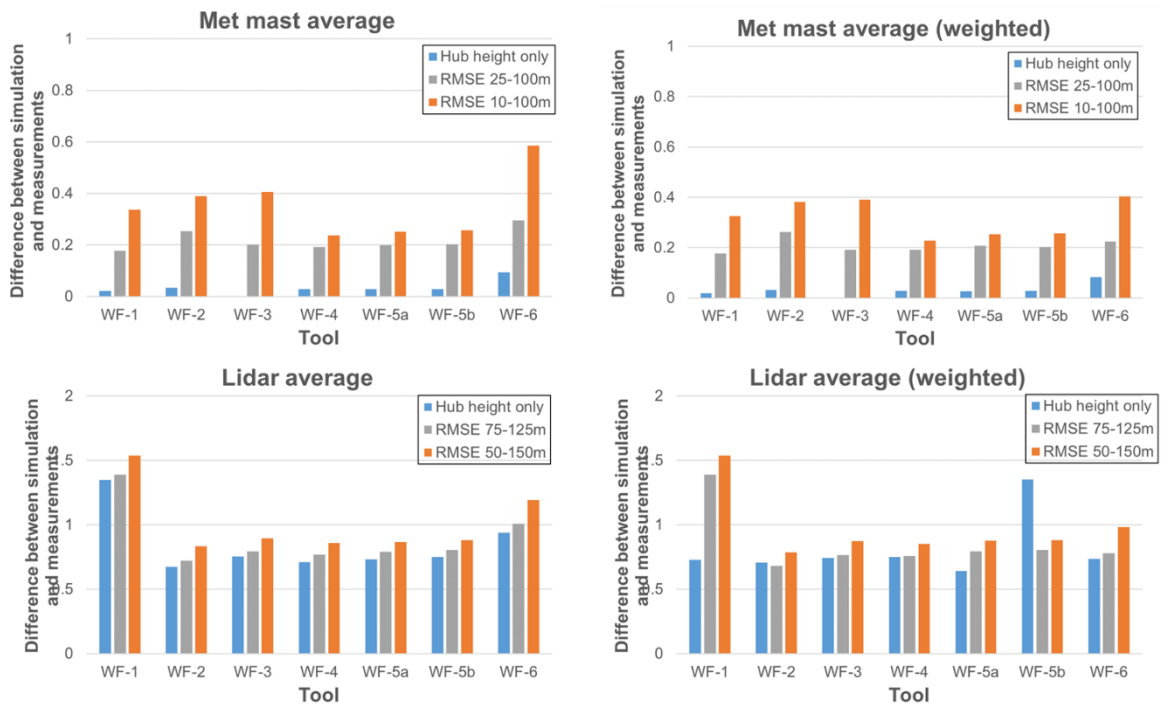


Figure 13. Average Root Mean Square Errors for each workflow for met mast (top) and lidar (bottom), both for a simple average (left) and a frequency-weighted average (right).

Wind speed contours

As well as examining the wind profiles, we compare the absolute wind speed contours at a height of 100 m above the ground level for the *WindSim*, *Fluent RANS*, *Fluent SBES* and *CFX* simulations in Appendix 3(c), Appendix 3(d), Appendix 3(e) and Appendix 3(f) for the three most frequent wind speed direction sectors, 120°, 270° and 300°. Unfortunately, the 120° sector data for *Fluent SBES* is missing due to an error with the data exporting. These plots were obtained by exporting the data from a fixed grid of simulation points at a fixed area in the domain close to the wind farm and interpolating the results to get a smooth display of data. It can be seen that the results are generally very similar. All the wind models that the calibration and validation locations experience very similar flows. In particular, *CFX* shows clear flow sections, or streaks, caused by flow separation behind various hills. The two locations remain within the same streaks for all three main wind directions. This agrees with the low speed-up factors from the



measurements as discussed below. The larger flow turning observed in Figure 27 for various sectors are not visible in the wind speed contours, because these sectors are not the three most frequent sectors. Additionally, some small differences between the different wind models can be seen. For example, *CFX* over-predicts the recirculation zones behind hills compared to *Fluent*.

Wind direction profiles

The simulated wind direction profiles are compared to the measurements at the calibration location in Appendix 3(g) and at the validation location in Appendix 3(h) (except for *WindPro*, for which this information wasn't available). It can be seen that the deviations in wind direction between the simulations and the measurements are very low for the calibration location and height, as expected. At lower heights, the wind direction deviates by less than 10° in most sectors, and up to 20° for some sectors. Except for *CFX*, there are no deviations larger than ±15° at the calibration height, and therefore only the *CFX* data has to be re-assigned to new sectors as described in Section 3.1.4. This is the case due to the consideration of the Earth's rotation that has been introduced without calibrating for wind direction at the calibration height. As expected, the deviations between the simulations and measurements are slightly higher at the validation location (lidar), although they mainly remain within the same sector.

Speed-up factors and turning

The speed-up factors and turning between the validation and calibration locations are shown for each workflow and sector in Figure 14, where: Speed-up factor = wind speed at calibration location / wind speed at validation location; Turning = wind direction at calibration location – wind direction at validation location. The "theoretical" value refers to the measurements. The speed-up factor of the measurements varies between about 1.1 to 1.3 depending on the sector. The speed-up factor of each workflow varies from about 0.9 (WF-6, 270°) to 1.5 (WF-6, 90°). There is no particular pattern regarding models and sectors that can be recognised. The turning of the measurements is very small, equally about 1° for each sector. Except for WF-6 (*PALM*), the turning of each model also remains between 0° and 2°. WF-6 (*PALM*) predicts turning between 4° and 16°, depending on the sector. This difference may be due to the method used in *PALM* of using *COSMO-D2* data as a boundary condition.

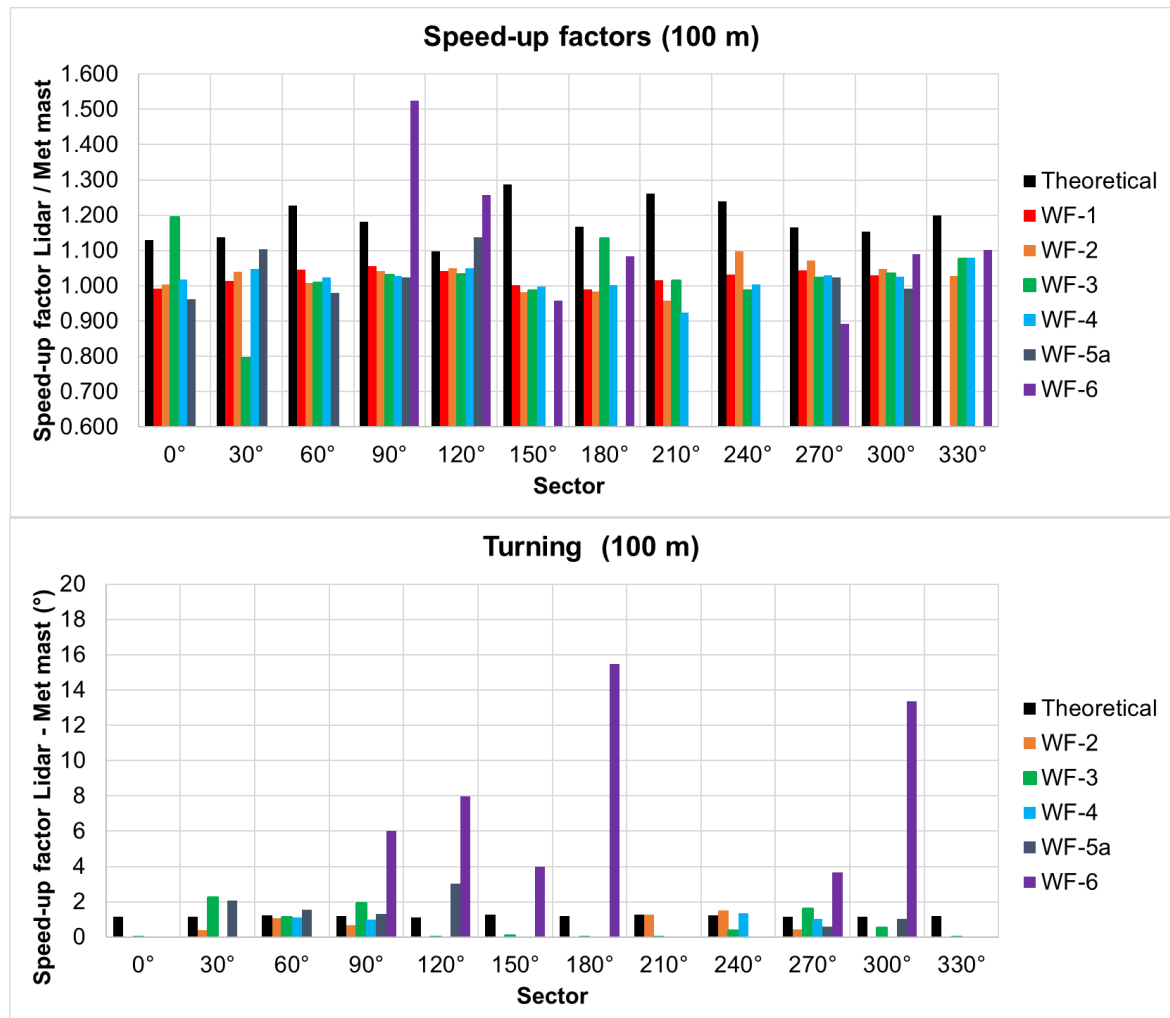


Figure 14. Speed-up factors and turning for Stötten.

AEP at validation location

As the wind turbines have not yet been built at this site, the AEP of a wind turbine positioned at the validation location was calculated, in order to allow us to examine the effects of the simulated wind speeds on the AEP. The wind turbine chosen was a S&G Engineering SG750.54 with a hub height of 100 m, because this is the type planned for this site (construction expected to start soon). This wind turbine has a rated power of 750 kW and a rated wind speed of 11 m/s. For comparison purposes, the theoretical AEP that would be achieved for the measured wind conditions at the validation location was calculated.

In order to calculate the AEP, each research partner implemented their own script according to the "time series method" described in Section 3.1.4. For validation purposes, in a first step these methods were compared to each by inputting the same wind speed data. For this comparison, the *WindSim* speed-up factors were chosen as an input to the AEP calculations. As well as comparing the different "time series methods", the so-called "Weibull" method from OST and *WindSim* were also included. This method works by creating frequency distributions of the calibration location data for each sector and fitting a Weibull distribution to them, then by multiplying the wind speeds in each wind speed bin by the simulated



speed-up factor according to the sector. Finally, the effect on the AEP of interpolating the power curve between the provided points instead of using the bin-averaged values was investigated. The different methods are shown in Table 4 and the resulting AEPs in Figure 15. The orange bars show the energy production over the overlapping time period, and the blue bars show the AEP (scaled for one year).

The first thing to note is the large difference of all the simulation results compared to the measurements. It is likely that this comes from the unexpected offset in the measurement results as discussed in Section 3.1.3. The next thing to notice is that all of the simulation results except for the Meteotest time series method match well (maximum variation of 2%), giving us confidence in the methods. After significant investigation, the deviation between the Meteotest time series method and the other methods was not clear, but should be considered in the later analysis of the *PALM* results.

Furthermore, the scaling factor between the overlapping period and the full year is the same for all methods, indicating that the upscaling to one year is correct. As well as this, it can be seen that the difference between the Weibull method and the time series method is fairly small (3.4% for the OST method), and that the difference between the power curve bins and the interpolation is small (1.2% for the OST method, 0.6% for the HSE method, 0.1% for the *WindSim* method).

Next, the AEPs were calculated by each research partner using their own simulation results and their own methods. The results are shown in Figure 16. Again, all the results are significantly lower than the theoretical value. The differences in AEP are due to the differences in speed-up factors as well as the differences in the AEP method. For *CFX*, a comparison was additionally made with and without the effects of turning (as described in Section 3.1.4). A very small difference was observed. These results were used for the comparison metrics comparison, which are discussed in the next section.

The percentage differences in AEP between the simulated and theoretical values at the validation location are used for the Comparison Metrics analysis below.

The variation of the AEP for each sector is shown for each model in Figure 17. A large variation between model and sector can be seen, without a particular trend. The effect of the flow turning can be clearly seen in sectors 11 and 12.

Table 4. Set-ups investigated for AEP method at Stötten.

Calculation number	Simulation results	Script written by	Frequency distribution method	Power curve method
1	WindSim	OST	Weibull	Bins
2	WindSim	OST	Time series	Bins
2.1	WindSim	OST	Time series	Interpolated
3	WindSim	HSE	Time series	Bins
3.1	WindSim	HSE	Time series	Interpolated
4	WindSim	WindSim	Time series	Bins
4.1	WindSim	WindSim	Time series	Interpolated
5	WindSim	WindSim	Weibull	Bins
5.1	WindSim	WindSim	Weibull	Interpolated
6	WindSim	Meteotest	Time series	Bins
6.1	WindSim	Meteotest	Time series	Interpolated

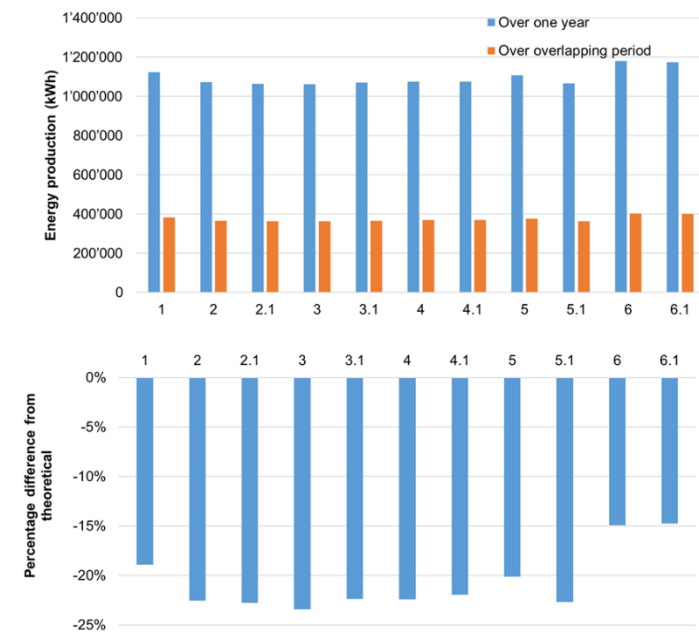


Figure 15. Energy production calculated with the methods described in Table 4 for the WindSim simulation results (energy production at top, percentage difference from theoretical at bottom) for Stötten at validation location (lidar).

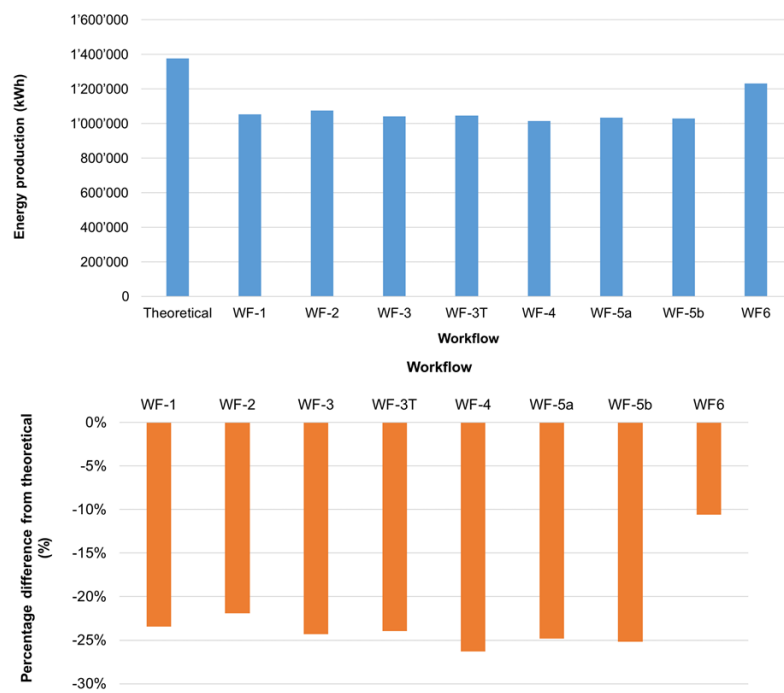


Figure 16. Energy production calculated for each tool (energy production at top, percentage difference from theoretical at bottom) for Stötten at validation location (lidar).

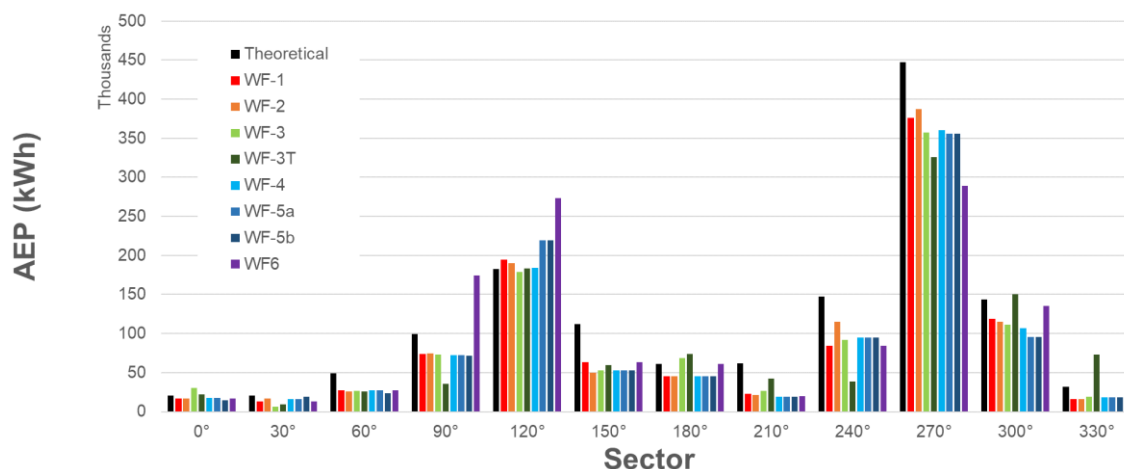


Figure 17. AEP per sector for each model applied (Stötten at validation location).

3.1.6 Evaluation of the comparison metrics for the Stötten site

In this section, the skill scores and cost scores before and after carrying out the simulations are examined and discussed according to the process shown in Figure 1 above.

Definition of skill and costs score parameters and weightings

The skill and cost score parameters were used as described in Section 3.1.2. However, the skill score parameter weightings were adjusted in order to get a good match with the "skill score after". These weightings were then kept constant for the other sites in order to test their suitability.

The resulting weightings according to each score listed in Figure 2 are shown in Figure 18. The parameters with strong weightings are A1 (complexity of the underlying aerodynamic equations), A2 (complexity of the underlying thermodynamic equations), C2 (wind speed calibration method), C3 (input data method) and D1 (wind sector extrapolation method).



Figure 18. Skill score weightings used at Stötten.



Comparison Metrics results

The main results are shown in Figure 19. The upper plot shows the relative skill vs. cost scores both before and after running the simulations for each model, marked by a coloured circle (before: empty circle; after = filled circle). The "before" results show that WF-1 (*WindPro*) was predicted to be the least accurate and least expensive model. WF-2 (*WindSim*) was expected to be slightly more expensive but much more accurate. WF-3 (*CFX*), WF-4, (*Fluent RANS*) and WF-5a and 5b (*Fluent SBES*) were expected to have an accuracy somewhere between the two, but at higher costs. WF-6 (*PALM*) was expected to be much more expensive but not more accurate, due to the special method applied as explained in Section 3.1.4. The reality matched these expectations quite well, partly due to the weightings that were adjusted as described above. At the end of the day, the most optimal models appear to be WF-2 (*WindSim*) and WF-4 (*Fluent RANS*), as they offer a good performance with low costs. A decision tool based on the "skill score before" and "cost score before" would therefore work as expected, choosing WF-2 (*WindSim*) as the most optimal model. It is important to note that this analysis does not rate the applicability or accuracy of the flow models themselves, as many different steps are included in the overall workflow.

The lower plot is slightly different due to the conversion of wind speeds in each sector to AEP using the process described in Section 3.1.4. The skill scores are much closer together, indicating that the wind modelling tool does not have a great effect on the accuracy. This is due to the many steps that are required to carry out a WRA, which all seem to have a relatively large effect on the results. The most interesting feature of this plot is how close the cost and skill scores of WF-1 (*WindPro*) and WF-2 (*WindSim*) are to each other, and that WF-4 (*Fluent RANS*) has the lowest relative cost score. Again, the predictions "before" seem to predict well that WF-1 (*WindPro*), WF-2 (*WindSim*) and WF-4 (*Fluent RANS*) are expected to offer the best compromise, even though the exact scores do not match "before" and "after".

For comparison purposes later in 3.2.4, the ability of the Comparison Metrics estimation method to successfully predict the most effective workflow for this site has therefore been given a quality rating of 8 out of 10 for the wind speed and 8 out of 10 for the AEP.

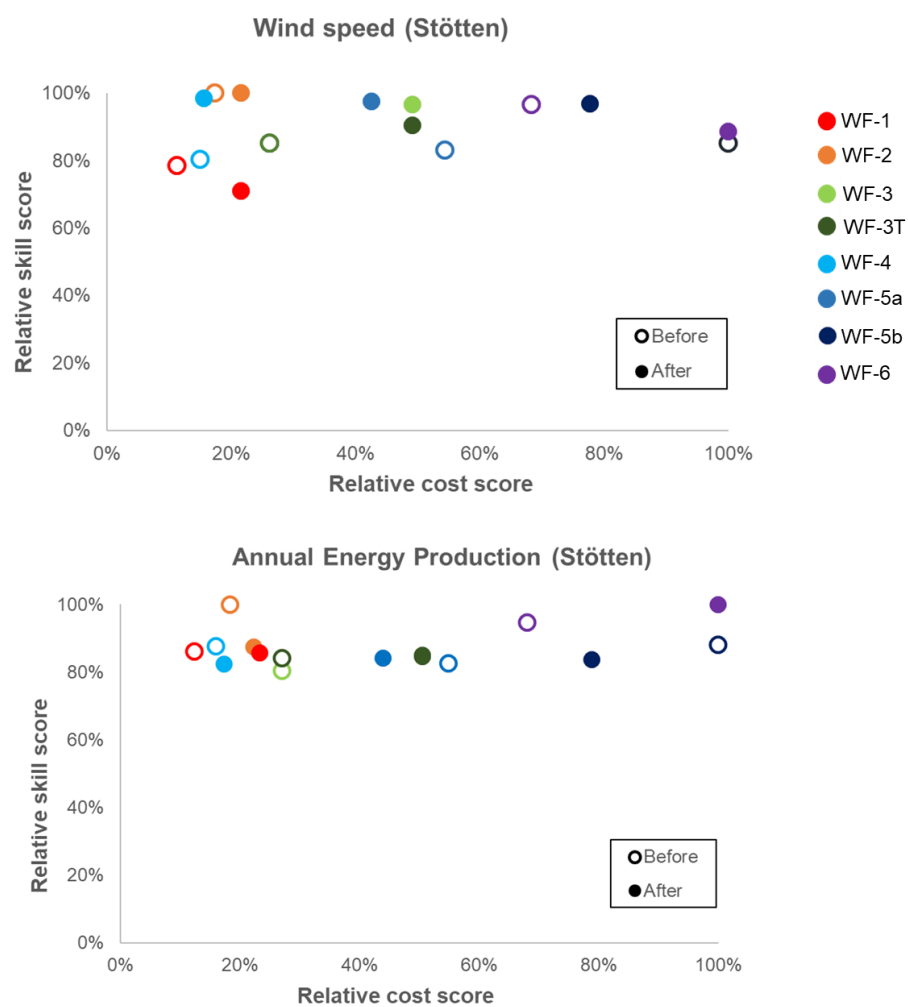


Figure 19. Comparison Metric results for Stötten (top: wind speed, bottom: AEP)



It is interesting to compare the split of the different costs contributing to the cost scores "after". The results are shown in Figure 20. They are normalised in the sense that the same staff hourly rate and processor power have been used, as described in Section 3.1.2. For WF-1 (*WindPro*), WF-2 (*WindSim*) and WF-6 (*PALM*), the simulation set-up effort costs dominate. For WF-3a and -3b (*CFX*) and for WF-4, WF-5a and WF-5b (*Fluent*), the simulation run-time costs dominate. This will be investigated for the other sites in this work.

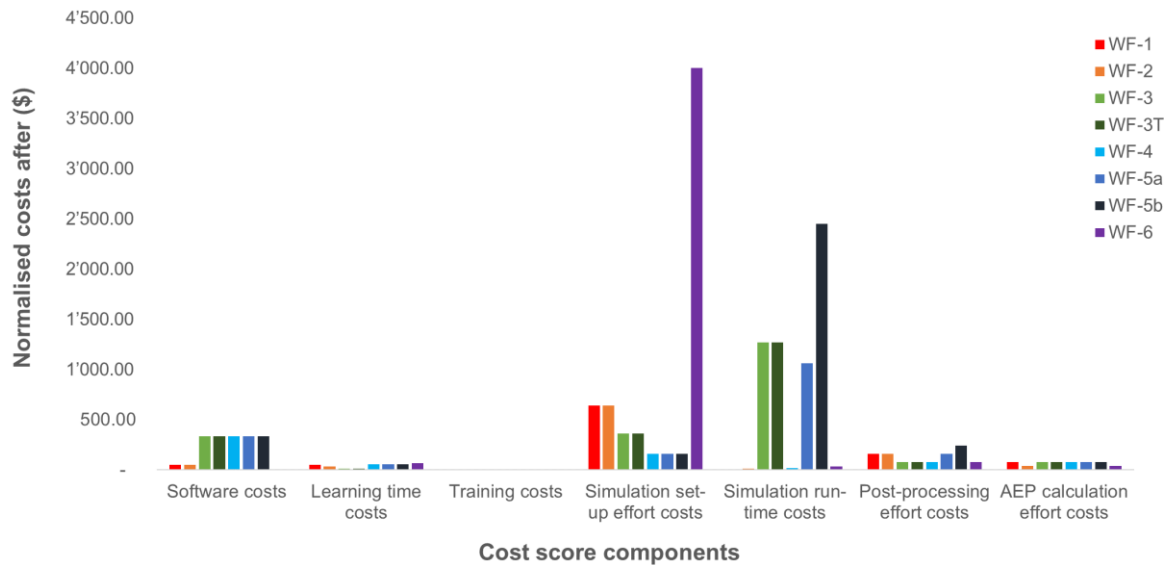


Figure 20. Cost score components for Stötten.

Complex terrain classification

As mentioned in Section 3.1.2, we hypothesize that some of the skill score weightings and costs are affected by the complexity of the terrain at the site. Therefore the terrain complexity needs to be classified in some way for the planned decision tool. The results of the answers to the questions presented in Section 3.1.2 are shown by each research partner organisation in Figure 21. This shows that the agreement between the three organisations is fairly good; small differences can be seen in answers to the questions "*How many slopes are there?*" and "*How rough is the surface in general?*". This will be examined further for the other sites.

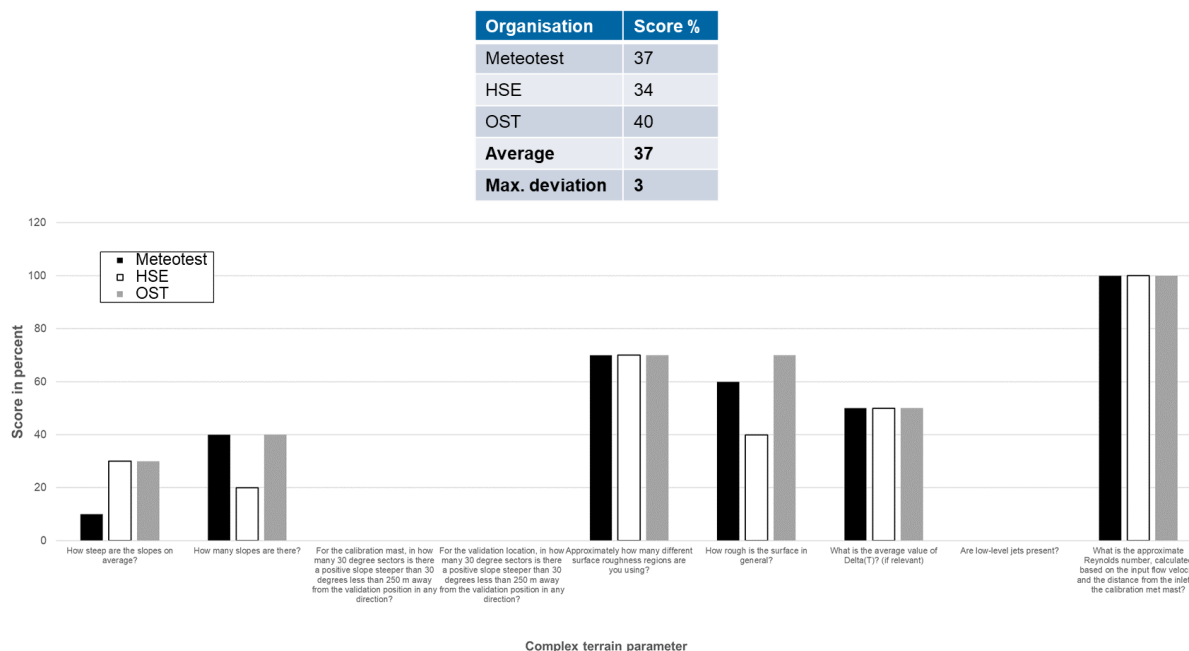


Figure 21. Complex terrain classification results for Stötten.

3.1.7 Summary of part (1)

In this part of the project, the new decision process was designed starting with an initial study at the Bolund Hill site in order to design the Comparison Metrics method and going on to study the Stötten site in order to develop and test automated WRA processes as well as to assess the Comparison Metrics method.

The main findings were:

- The entire WRA process required for estimating the AEP involves many steps as well as the wind modelling itself. Each step has a large influence on the final results, and therefore the performance of the wind modelling tool itself is less important than expected.
- Automated processes using generic CFD tools greatly save overall WRA project costs due to the savings in simulation set-up effort.
- It is difficult to capture the effects of all these steps on the simulated wind speeds and AEP estimations in one skill score. Further sites will be investigated in Part (2) of the project.
- For the Stötten site, the proposed method for estimating and comparing the skill and cost scores for different models for choosing the optimal model for the given application appears to work well. However, the parameter weightings were adjusted in order to get good results. The method needs to be tested on more sites (see Section 3.2).
- The results of this study should be handled with care, as the validation measurements (lidar) has an offset that we were not able to explain within the scope of this project.



3.2 Part (2): validate and demonstrate the new decision process

In this part of the project, the new decision process is demonstrated. In this section, the application of the automated WRA processes at three sites (ewz, Enercon and ADEV) is first described and the results analysed and evaluated. The BKW site is not presented here due to simulation delays, but will be completed by the end of June on request of BKW. The results are not essential for reaching the goals of the project. However, the results can be provided later if required. Finally, the results are assessed and used to develop a new decision tool to help modellers choose the most appropriate model for a particular wind-energy related project.

3.2.1 Application of the automated WRA processes to the ewz site

Site description

The ewz site used in this project is an existing wind farm site in Norway surrounded by a terrain of hills, lakes and forests. The wind farm consists of seven Siemens SWT-DD-130 wind turbines with a hub height of 115 m located on a small hill as shown on the left-hand side of Figure 22. The circles on this figure refer to met masts and wind turbines as can be seen on the legend: "maka_83m", "liat_83m", "stig1_49m" and "stig2_83m" refer to met masts and "wtg_1", "wtg_2", etc. to wind turbines. Another wind farm consisting of 22 wind turbines is located on the hill to the north of the wind farm, near to the met masts "maka_83m" and "liat_83m". The two main wind directions are SE and NW, as can be seen on the wind rose from the met mast STIG2 in Figure 22. A close-up of the terrain contours near to the wind farm location is shown in Figure 23. The plot is stretched in the vertical direction in order to show the terrain more clearly.

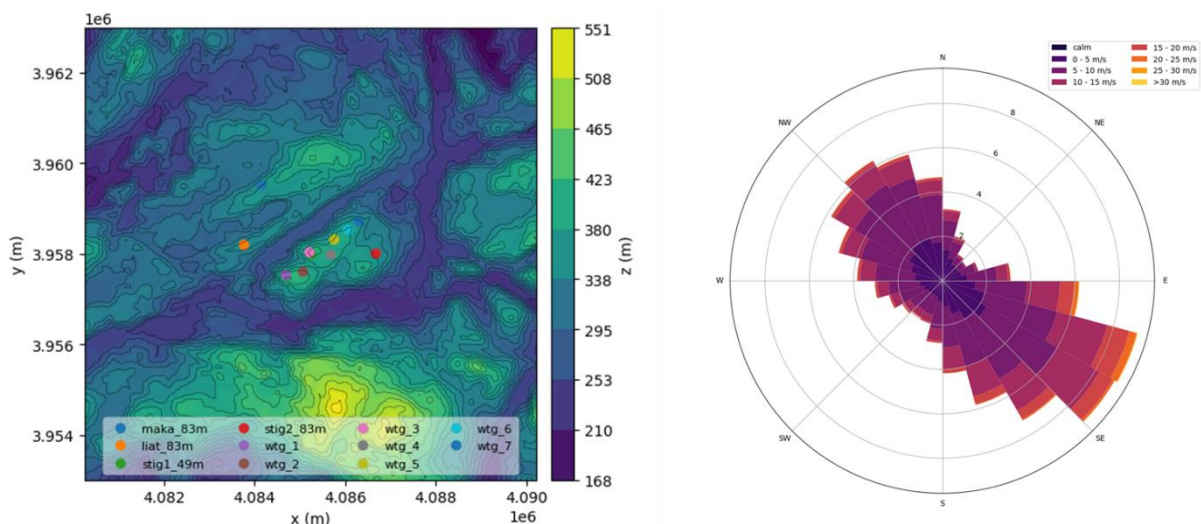


Figure 22. ewz site: terrain contours (left) and wind rose (right). "maka_83m", "liat_83m", "stig1_49m" and "stig2_83m" refer to met masts.

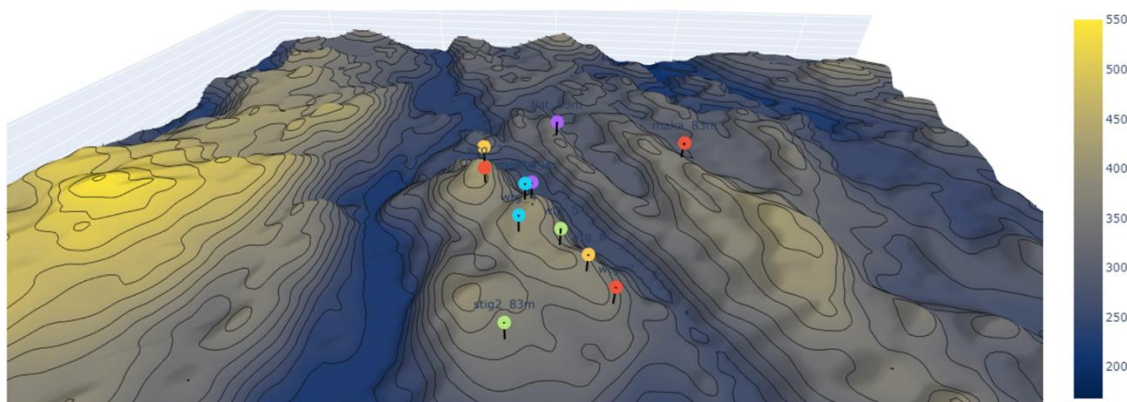


Figure 23. Close-up of ewz terrain near the wind farm location. The plot is stretched in the vertical direction in order to show the terrain more clearly.

Workflows applied

The set-ups for the workflows applied in this work are summarised in Table 5. *CFX* was not applied because HSE were not granted access to the data. For WF-5a (*Fluent SBES*), only the variation with the three most frequent sectors simulated in *Fluent SBES* (90°, 120° and 330°) and the rest in *Fluent RANS*. For WF-6 (*PALM*), the four most frequent sectors were simulated (90°, 120°, 300° and 330°), and the remaining sectors were obtained using *WindSim* results. The domain was split into two nested grids: a larger one with 100 m resolution and a smaller one closer to the wind farm with 20 m resolution. Note the variation in grid size and resolution between the models. It should also be noted that the preparation of the roughness data for all the partners was done mainly as part of WF-1 (*WindPro*) and WF-2 (*WindSim*), leading to higher costs than if the time for doing this had been split up amongst all partners.



Table 5. Summary of set-ups for ewz simulations.

	WF-1	WF-2	WF-4	WF-5a	WF-6
Wind model	WindPro	WindSim	Fluent RANS	Fluent SBES	PALM
Institution	Meteotest	Meteotest	OST	OST	Meteotest
Model type	Linear wind model	Steady-state RANS CFD, k-epsilon	Steady-state RANS CFD, k-omega SST	Unsteady DDES CFD, k-omega SST, average over 1800s	LES model
Grid dimensions (resolution)	25 x 25 km (25 m)	5 x 5 x 5 km (25 m)	10 x 10 x 1.5 km (20 m)	10 x 10 x 1.5 km (20 m)	20 x 20 km x 4 (100m) 6 x 6 x 3.6 km (20m)
Number of cells	1.0 million	1.9 million	20 million	20 million	1.6 million 16.2 million
Input profile	None	Log profile at inlet	Log profile at inlet (z0 = 0.75 m)	Log profile at inlet (z0 = 0.75 m)	Offline Nesting in WRF model
Turbulence intensity	None	Calculated by the model (standard k-epsilon)	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Moeng Wyngaard turbulence closure
Other models	None	None	None	Synthetic Turbulence Generator	Land Surface Model, Radiation Model
Wind directions	12 sectors	12 sectors	12 sectors	3 sectors (90°, 120°, 330°)	4 sectors (90°, 120°, 300°, 330°)
Other workflow steps	Includes steps 1-8 specific to <i>WindPro</i> .	Includes steps 1-8 specific to <i>WindSim</i> . Preparation of roughness data for all partners is done in this WF.	Includes steps 1-8 specific to <i>Fluent</i> .	Includes steps 1-8 specific to <i>Fluent</i> .	Includes steps 1-8 specific to <i>PALM</i> .

The roughness maps used by each wind modelling tool are shown in Figure 24. The differences are due to the varying domain sizes and scale colours.

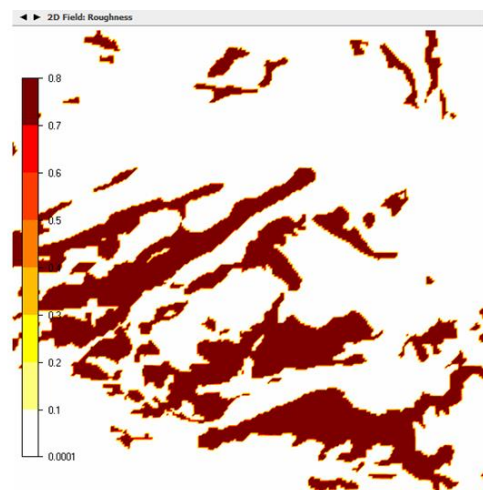
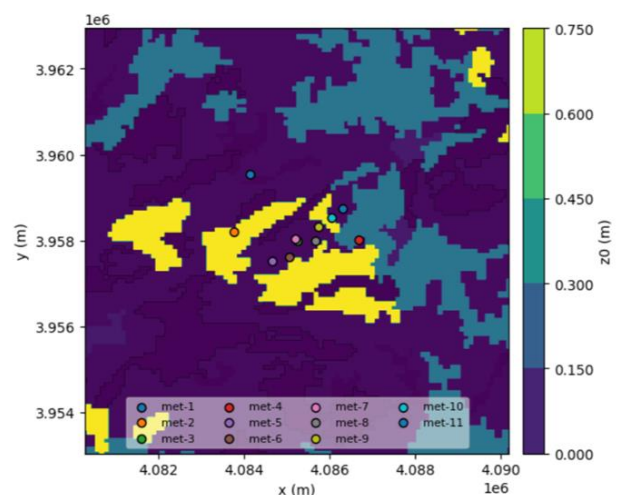
*WindSim / WindPro / PALM**Fluent*

Figure 24. Roughness maps for the ewz site.



Input data

In this project, the two met masts close to the wind turbines, "STIG1" and "STIG2", are used, on request of ewz. For STIG1, wind speed measurement data is available at the five heights up to 50 m shown in Figure 25 from January 2007 to May 2016 (9½ years). For STIG2, wind speed measurement data is available at the five heights up to 83 m shown in Figure 25 from December 2013 to January 2016 (2 years). STIG1 has three sensors at very similar heights (48 m, 49 m and 50 m), whereas STIG2 has two sensors at similar heights (82 m and 83 m). An examination of the time series of the measurement data showed that the sensors at 47 m, 48 m and 82 m contained some errors, and therefore the sensors at these heights were not used. The two wind speed profiles shown in the figure show a relative offset. Contrary to the Stötten site, however, this offset is expected due to the relative locations of the two masts on opposite sides of the hill.

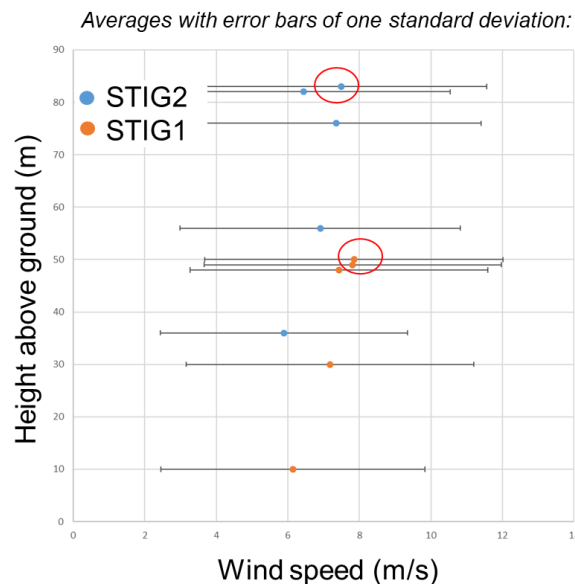


Figure 25. Measurement data STIG1 and STIG2 over entire measurement periods for ewz.

In order to use one set of data for the calibration and one set for the validation, an overlapping time period has to be found. For the two highest sensor locations on each mast, there were a total of 17,916 overlapping data points. This is a large number of points and lead us to the conclusion that the quality of the conclusions of this project should be higher than the Stötten project.

The STIG2 met mast was chosen as the calibration mast and STIG1 as the validation mast, due to the higher maximum measurement height of STIG2, which is closer to the hub height of the wind turbines (83 m compared to 115 m). However, due to the measurement length of the STIG1 met mast time series, this met mast was used for the long-term extrapolation of the STIG2 met mast data that is required in order to calculate a long-term AEP as described in Step 7 of the WRA process in Section 3.1.4. The STIG2 data at 83 m for overlapping data points was extrapolated using the MCP ("Measure-Correlate-Predict") method using the STIG1 data at 50 m for the reference time series. For the long-term extrapolation of STIG2 the regression method of the MCP module of *WindPro* was used to correlate the long-term data of STIG1 with the data of STIG2. For the overlapping time period a transfer function between STIG1 and STIG2 was determined and from this a long-term adjusted dataset for the location STIG2 was calculated. For all further calculations, this long-term adjusted dataset was used for the location STIG2.



Results

Wind speed profiles

The results for each model and wind direction sector are shown in Appendix 4(a) for the met mast STIG2 (calibration location). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). As opposed to the Stötten site, there is only one wind speed measurement used in the comparison, because the other heights were not extrapolated using the MCP method and therefore are not comparable on the same plot. The right-hand plot shows the absolute difference between the measurements and the simulations at this height for each sector. The differences are almost zero because this is the calibration location. Small differences result from rounding errors.

The same results are shown for the met mast STIG1 (validation location) in Appendix 4(b). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). The middle plot shows the absolute difference between the measurements and the simulations for each height and sector. The errors are not larger at lower heights, as they are for the Stötten site. This is probably because the chosen logarithmic input profile matched to the real conditions better than at the Stötten site. The right-hand plot shows the differences between measurements and simulations per sector in terms of the difference at 50 m only (orange), the Root Mean Square Error (RMSE) using all the measured heights (green) and the RMSE without the lowest height (blue). The results are similar for all heights. In general, the match is not as good as at the met mast, as expected, because the met mast was used for calibration. The results are fairly good for all models, with deviations mainly below 1 m/s. The difference between the simulations and the measurements at the reference height of 50 m represent the real accuracy of the simulations in calculating the speed-up from the reference sensor to the validation sensor.

Figure 26 shows a summary of the RMSE results for each model for STIG2 (top) and STIG1 (bottom), by taking a simple average of the individual RMSEs of all simulated sectors (left) and by weighting the average according to its relative frequency from the met mast data (right). This gives more weighting to more frequent wind speeds in order to provide a number more relevant for the AEP. The different colours represent the different heights taken to calculate the RMSE as discussed above. It can be seen that the RMSE of STIG2 is very low. This corresponds to the results discussed in the first paragraph of this section. For STIG1, the RMSEs all remain below 1 m/s. *WindSim* and *WindPro* are closer to the measurements than *Fluent* and *PALM*. The reasons for this are examined in the next sections.

The RMSE values at the validation location are used for the Comparison Metrics analysis below.

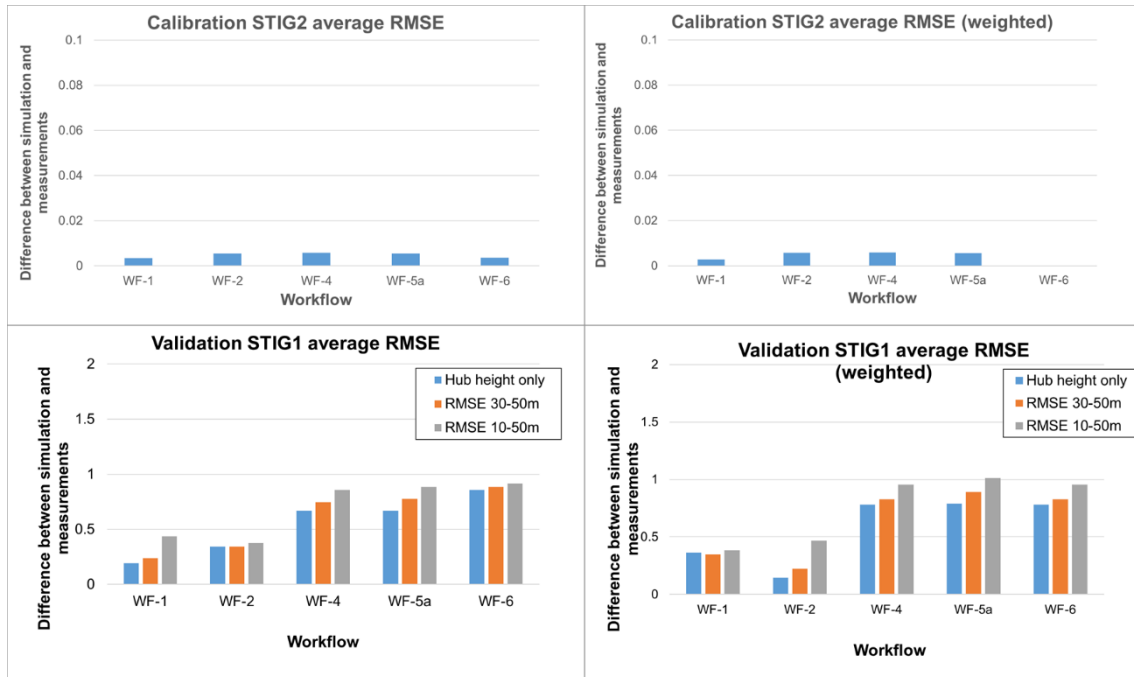


Figure 26. Average Root Mean Square Errors for STIG2 (top) and STIG1 (bottom) for ewz, both for a simple average (left) and a frequency-weighted average (right).

Wind speed contours

As well as examining the wind profiles, we compare the absolute wind speed contours at a height of 100 m above the ground level for the *WindSim*, *Fluent RANS*, *Fluent SBES* simulations in Appendix 4(c), Appendix 4(d) and Appendix 4(e) for the three most frequent wind speed direction sectors, 90°, 120° and 330°. These plots were obtained by exporting the data from a fixed grid of simulation points at a fixed area in the domain close to the wind farm and interpolating the results to get a smooth display of data. All the simulation results show clear flow sections, or streaks, caused by flow separation behind various hills. It can be seen that the results are generally very similar on the main hill (where the wind turbines and the STIG1 and STIG2 masts are located). These streaks are generally broken up by the main hill. STIG1 is located roughly in the middle of the hill, and STIG2 is located further to the right. The two met mast locations remain within similar colour streaks for all three main wind directions. This agrees with the low speed-up factors from the measurements as discussed below. The larger flow turning measured in Figure 27 for various sectors is not really visible in the 90° and 330° sectors in the plots of *u*- and *v*- components, because the wind models do not pick up this turning well. However, some small differences between the different wind models can be seen. For example, *Fluent SBES* seems to "smear" the recirculation zones behind hills compared to *Fluent RANS*, due to the varying averaging methods.

Wind direction profiles

The simulated wind direction profiles are compared to the measurements at the calibration location in Appendix 4(f) and at the validation location in Appendix 4(g) (except for *WindPro*, for which this information wasn't available). It can be seen that the deviations in wind direction between the simulations and the measurements are low for the calibration location and height, except for *PALM*. The maximum deviation of *PALM* is 22° for the 90° sector, due to the input conditions as described in Section 3.1.4.



This deviation is higher than 15° and therefore the data points in this input sector actually "land" in a different sector at the calibration mast, as explained in Section 3.1.4. The lower heights cannot be compared because the long-term extrapolation has not been carried out for the other heights.

As expected, the deviations between the simulations and measurements are slightly higher at the validation location (STIG1). For *WindSim* and *Fluent RANS*, the deviations are especially high in the 330°, 0° and 30° sectors. This needs to be investigated further, and could be due to problems with the averaging method requiring extra care to be taken when averaging values that jump over the 360° limit (e.g. the average of 1° and 359° should not give a result of 180°, but 0°)!

Speed-up factors and turning

The speed-up factors and turning between the validation and calibration locations are shown for each workflow and sector in Figure 27 where: Speed-up factor = wind speed at calibration location / wind speed at validation location; Turning = wind direction at calibration location – wind direction at validation location. The speed-up factor is calculated for the highest mast positions of 50 m (STIG1) and 83 m (STIG2). For the turning, the wind direction measurements are located at slightly different heights: 43 m (STIG1) and 83 m (STIG2). The "theoretical" value refers to the measurements. The speed-up factor of the measurements remains very small (about 1.1) for all sectors, indicating that there is a very small difference in average wind speeds between the two masts. However, the simulated speed-up factors of each workflow are generally over-estimated: they vary from about 0.6 (WF-6, 330°) to 1.3 (WF-4, 300°). There is no particular pattern regarding models and sectors that can be recognised.

The turning of the measurements is much larger than for Stötten for some sectors: 38° for the 0° sector, 23° for the 60° sector and 32° for the 90° sector. The wind modelling tools are not capable of capturing this turning well at all: the simulated turning remains below about 4° for all workflows. However, this does not have a large effect on the overall AEP.

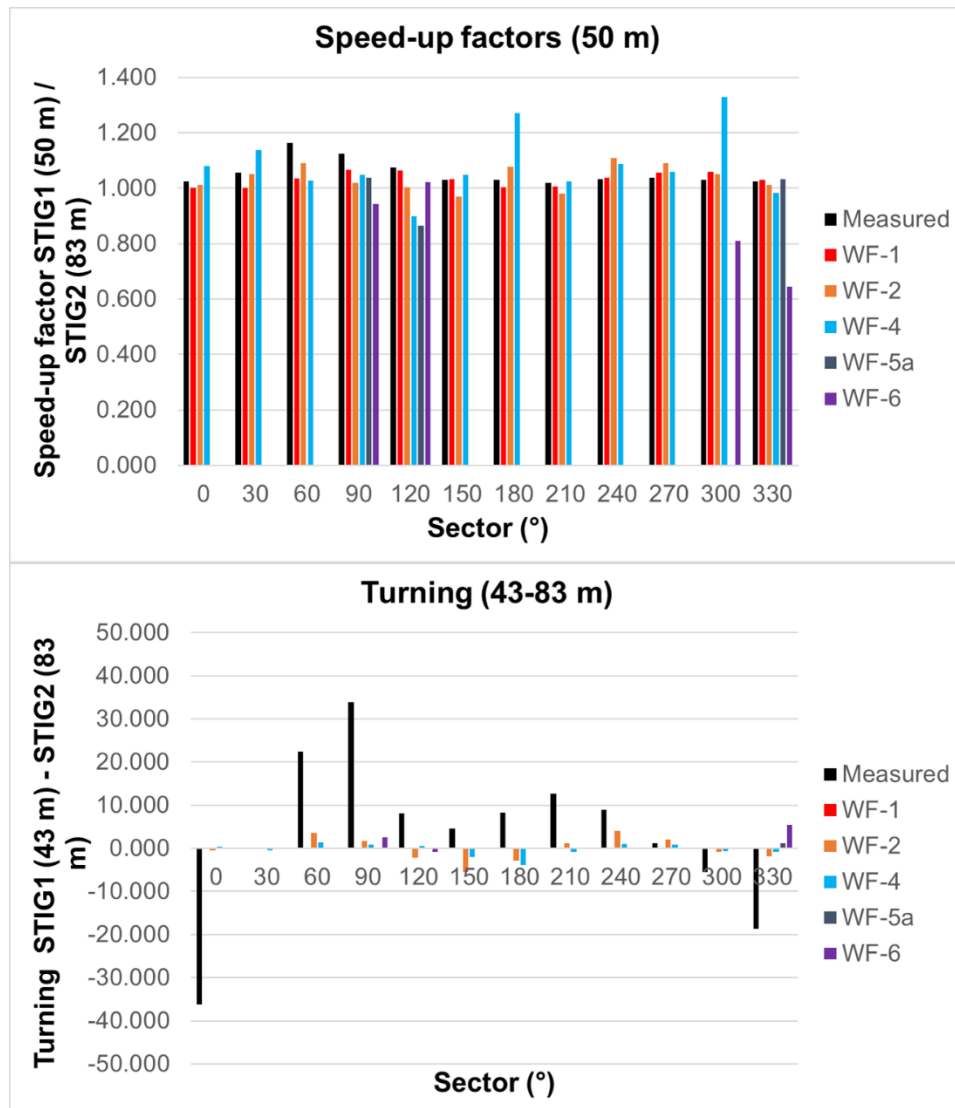


Figure 27. Speed-up factors and turning for ewz.

AEP at validation location

Contrary to the Stötten site, the wind turbines at this site have been built and we have access to monthly production data between August 2020 and February 2021. However, this data has not been used directly for the Comparison Metrics study in this project, because the simulations predict the gross AEP without any losses, and some inaccuracies will result due to assumptions made regarding the losses. For the Comparison Metrics study therefore, the AEP has been calculated at the validation location using the power curve of the Siemens SWT-DD-130 wind turbine. This allows the effects of the simulated wind speeds on the AEP to be examined. A hub height of 50 m instead of the real hub height of 115 m was used in order to avoid additional inaccuracies due to the wind speed profile vertical extrapolation. This wind turbine has a rated power of 3.9 MW and a rated wind speed of 13 m/s.

The resulting AEPs calculated using the method described in Section 3.1.4 are shown in Figure 28. The results match very well for WF-1 (*WindPro*), WF-2 (*WindSIM*), WF-4 (*Fluent RANS*) and WF-5a



(*Fluent SBES*), with deviations less than 3%. The WF-6 (*PALM*) result is significantly lower, with a deviation of 32%. This is due to the under-predicted wind speed shown above.

The percentage differences in AEP between the simulated and theoretical values at the validation location are used for the Comparison Metrics analysis below.

The variation of the AEP for each sector is shown for each workflow in Figure 29. This shows that the AEP is under-predicted in the three most frequent sectors (120°, 270° and 300°), leading to an overall under-prediction of AEP. For WF-6 (*PALM*), the 270° and 300° sectors are especially strongly under-predicted, explaining the large deviation compared to the theoretical AEP.

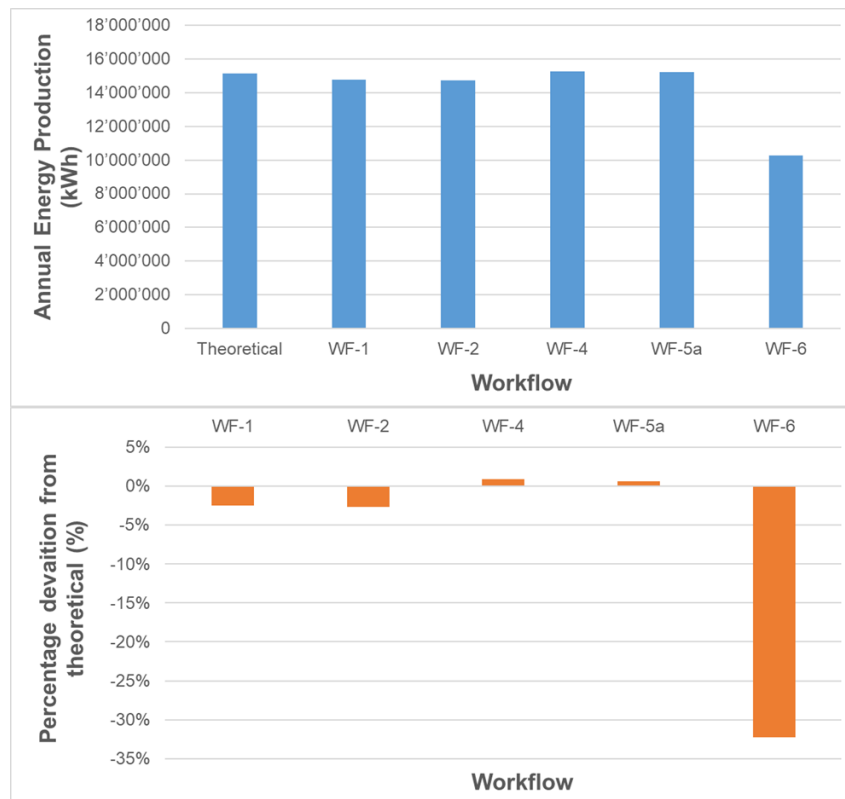


Figure 28. AEP calculated with each workflow (top) and percentage deviation from the theoretical value (bottom) at the validation location (STIG1).

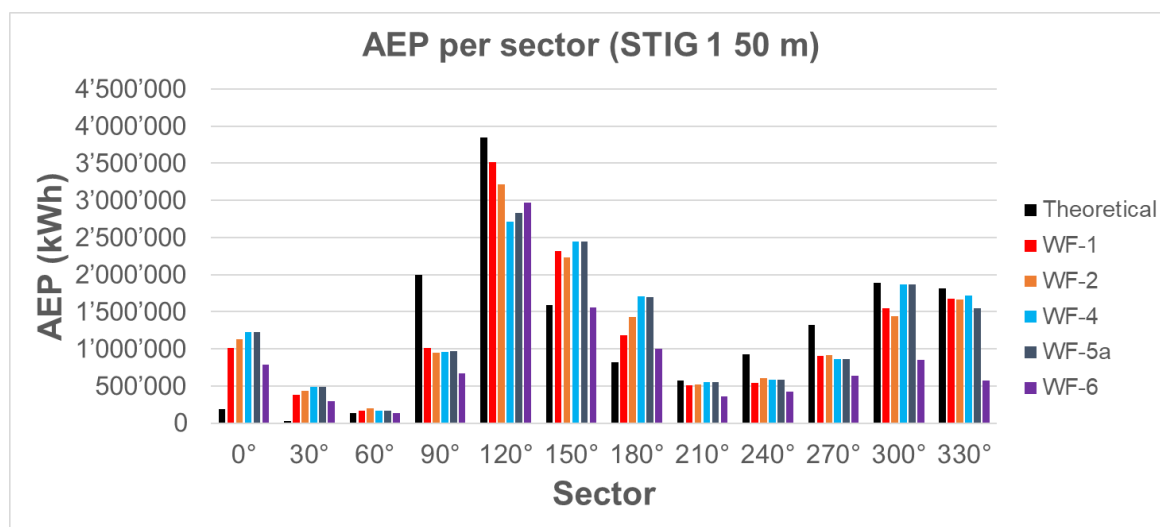


Figure 29. AEP per sector for each workflow applied (ewz at validation location).

Comparison to measured production data

At the request of ewz, the simulations were used to estimate the long-term AEP at the seven wind turbine locations and compare the results to the measured production data. These results were not used for the Comparison Metrics analysis below. The monthly net AEPs derived from the power fed into the grid for the time period between August 2020 and February 2021 were provided by ewz, as shown in Figure 30 (top left). In order to compare these values to the long-term gross AEPs estimated in this work, the following steps were undertaken:

- The net values were corrected for the expected total losses of 16.8% from the original WRA provided by ewz. It should be noted that these losses include wake effects, and represent the total wind farm losses. The individual wake losses at each wind turbine are expected to be slightly different. However, this effect will not be large, as the wind farm is oriented perpendicular to the two main flow directions and wake effects are therefore generally small.
- The expected monthly variation of energy production at the wind turbine WEA01 location was exported from *WindSim* time series at this location (Figure 30 top right).
- From this, the expected proportion of AEP for the months of August to February was calculated to be 64%.
- The total energy production of each wind turbine over the period of August to February was scaled to a full year by dividing the total energy production by 64% (Figure 30 bottom). The proportion was not calculated for each individual wind turbine because the values were found to be the same.

The resulting gross AEP values are compared to the simulation results at each wind turbine location in Figure 31. It can be seen that the match is very good: the AEP for WEA01 and WEA02 is slightly under-predicted by the simulations, and for WEA07 slightly over-predicted (especially *PALM*). Looking at the wind speed contour plots in Appendix 4(c)-(e), it can be seen that AEPs for each wind turbine are generally very similar because the main hill on which they are located breaks up the various different flow streaks, leading to very similar wind speeds at all positions on the hill. The slightly lower AEP of WEA01 occurs because it is located at the edge of the hill, where it is slightly negatively affected by the flow separation behind a neighbouring hill. This is clear to see on the 90° sector plot of absolute wind speed for all three wind models.

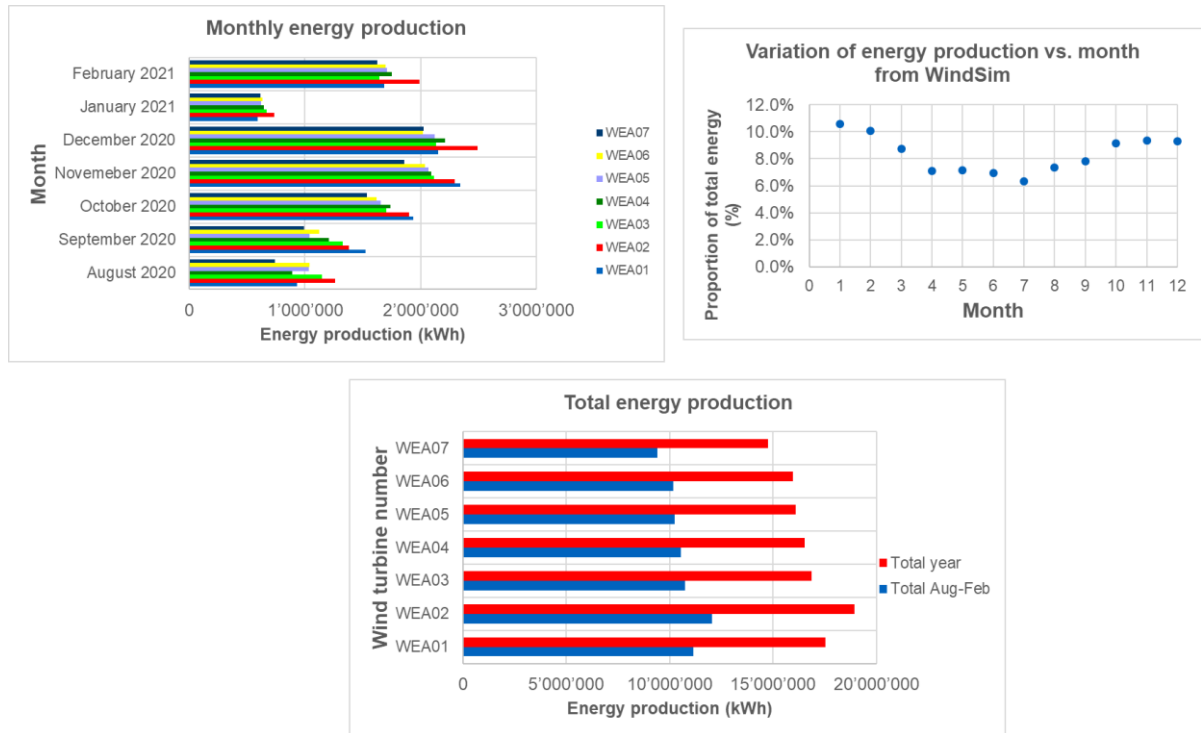


Figure 30. Analysis of ewz production data.

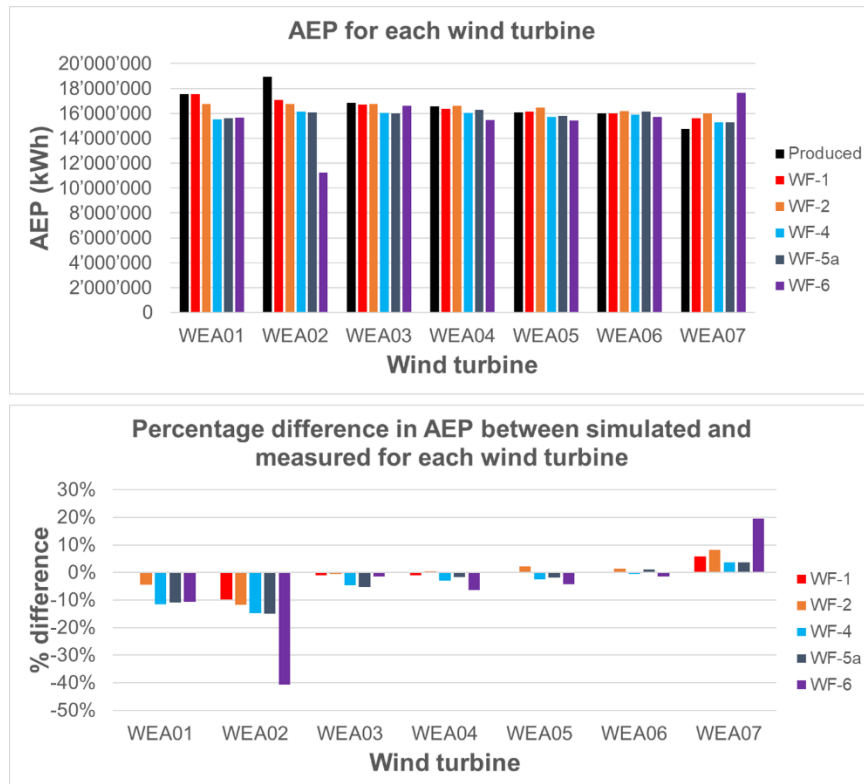


Figure 31. AEP for each wind turbine compared to measured production (top) and the percentage difference (bottom) for each workflow for ewz.



Comparison Metrics

In this section, the skill scores and cost scores before and after carrying out the simulations are examined and discussed according to the process shown in Figure 1.

The main results are shown in Figure 32. The upper plot shows the relative skill vs. cost scores both before and after running the simulations for each model, marked by a coloured circle (before: empty circle; after = filled circle). The "before" results show that WF-1 (*WindPro*) was predicted to be the least accurate and least expensive model. WF-2 (*WindSim*) was expected to be more expensive and more accurate. WF-4 (*Fluent RANS*) and WF-5a (*Fluent SBES*) were expected to be somewhere in between these two workflows in terms of skill and cost scores. WF-6 (*PALM*) was expected to be much more expensive and more accurate. The reality matched these expectations quite well. The main differences were that (a) WF-1 (*WindPro*) performed much better than expected and (b) WF-6 (*PALM*) performed much worse than expected. This leads to the conclusion that the skill score parameters do not fully capture the accuracy of the WF-6 (*PALM*) method. Some resulting improvements to the skill score definitions are suggested in Section 3.2.4. The choice of optimal workflow is not entirely clear for the "before" scores, as there is no sudden flattening-off of the curve. The best compromise between cost and skill is probably WF-2 (*WindSim*). This means that a decision tool based on these predictions would choose WF-2 (*WindSim*) as the most suitable workflow. However, the most suitable workflow in reality ("after") is clearly WF-1 (*WindPro*). This means that the skill score definitions need to be improved, as suggested in Section 3.2.4. They will be further examined for the other two sites.

The lower plot is slightly different due to the conversion of wind speeds in each sector to AEP using the process described in Section 3.1.4. Small difference in the predictions ("before") lead to WF-5a (*Fluent RANS*) probably being the most optimal workflow for this application. The larger differences in the "after" results, leading to much closer performance of WF-2 (*WindSim*) and WF-4 and WF-5a (*Fluent*) compared to WF-1 (*WindPro*), lead to the most optimal workflow being WF-4 (and WF-1) as well. In this case, the decision tool has worked effectively.

As mentioned in the Stötten analysis above, these results should not be used to compare wind models directly, rather to compare the entire workflows.

For comparison purposes later in 3.2.4, the ability of the Comparison Metrics estimation method to successfully predict the most effective workflow for this site has therefore been given a quality rating of 5 out of 10 for the wind speed and 7 out of 10 for the AEP.

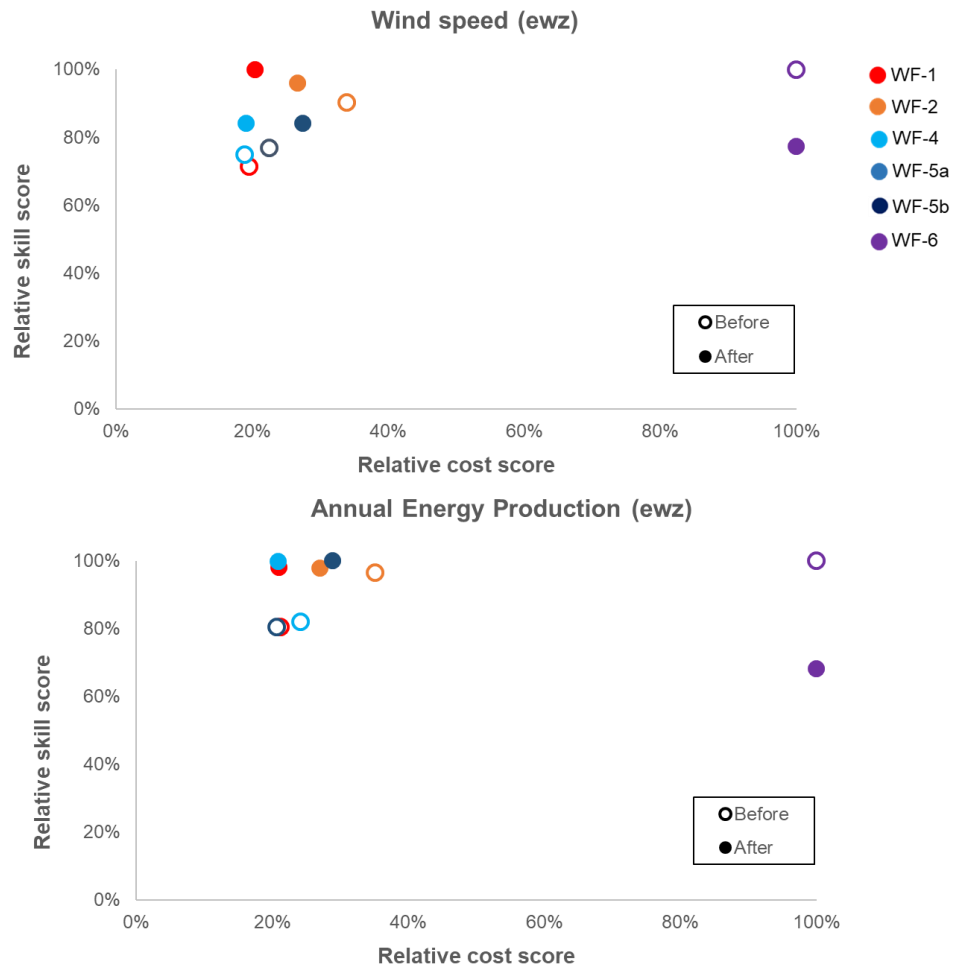


Figure 32. Comparison Metrics results for ewz.



The split of the different costs contributing to the cost scores "after" are shown in Figure 20. They are normalised in the sense that the same staff hourly rate and processor power have been used, as described in Section 3.1.2. For WF-1 (*WindPro*), WF-2 (*WindSim*), WF-4 (*Fluent RANS*) and WF-6 (*PALM*), the simulation set-up effort costs dominate. WF-6 has very high simulation set-up costs compared to the other workflows, because for this site WRF data has been used for the boundary conditions instead of COSMO-D2 data as for Stötten. The process to include WRF-data in the workflow is summarised in the set-up costs. For WF-5a (*Fluent SBES*), the simulation run-time costs are approximately equal to the set-up effort costs. This will be investigated for the other sites in this work.

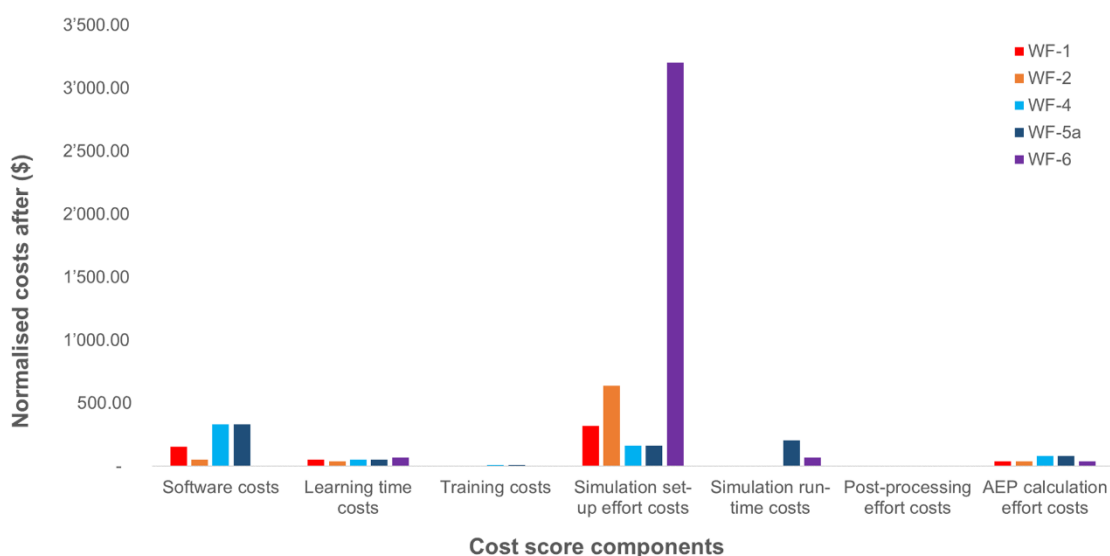


Figure 33. Cost score components for ewz.

Complex terrain classification

The results of the complex terrain classification questions presented in Section 3.1.4 are shown by each research partner organisation in Figure 34. This shows that the agreement between the three organisations is fairly good. The main difference is in the answer to the question "*How steep are the slopes on average?*", and small differences can be seen in answers to the questions "*How many slopes are there?*", "*Approximately how many different surface roughness regions are you using?*" and "*How rough is the surface in general?*". This shows that although the final result agrees well between the three organisations, it is difficult to put a number to such a subjective question. This will be examined further for the other sites.



Organisation	Score %
Meteotest	43
HSE	43
OST	38
Average	41
Max. deviation	2

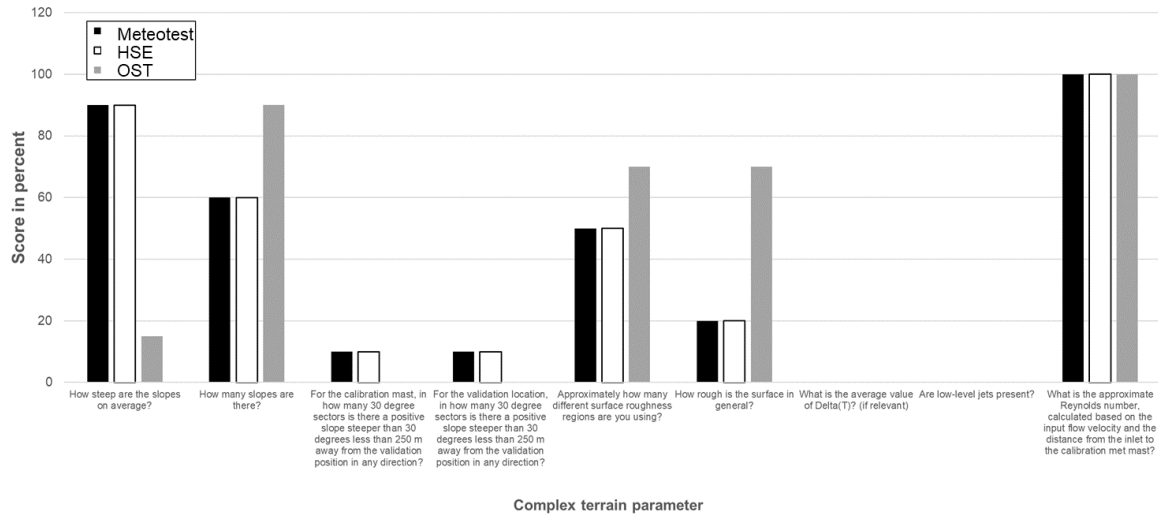


Figure 34. Complex terrain classification results for ewz.



3.2.2 Application of the automated WRA processes to the Enercon site

Site description

The Enercon site used in this project is an existing wind farm site in Spain situated in complex terrain. The wind farm consists of 15 Enercon E-40 wind turbines with a hub height of 50 m located at the top of a steep ridge as shown on the left-hand side of Figure 36. The circles on this figure refer to met masts and wind turbines as can be seen on the legend: "west" and "east" are met masts, whereas "wtg_1", "wtg_2", etc. are wind turbines. The two main wind directions are E and NNW, as can be seen on the wind rose on the right-hand side of the figure. A close-up of the terrain contours near to the wind farm location is shown in Figure 35. The plot is stretched in the vertical direction in order to show the terrain more clearly.

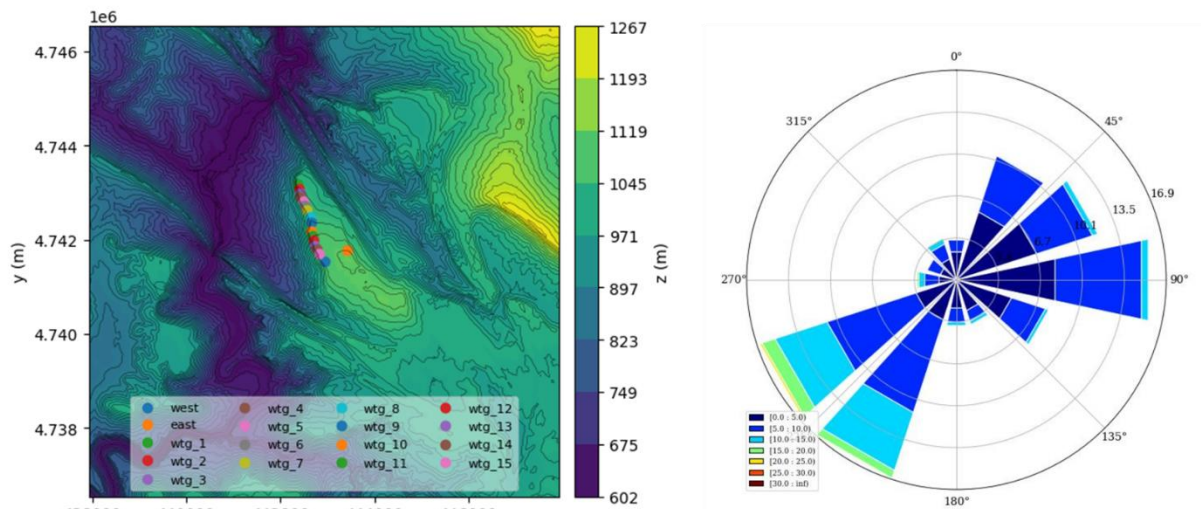


Figure 36. Enercon site: terrain contours (left) and wind rose (right). "east" and "west" refer to met masts.

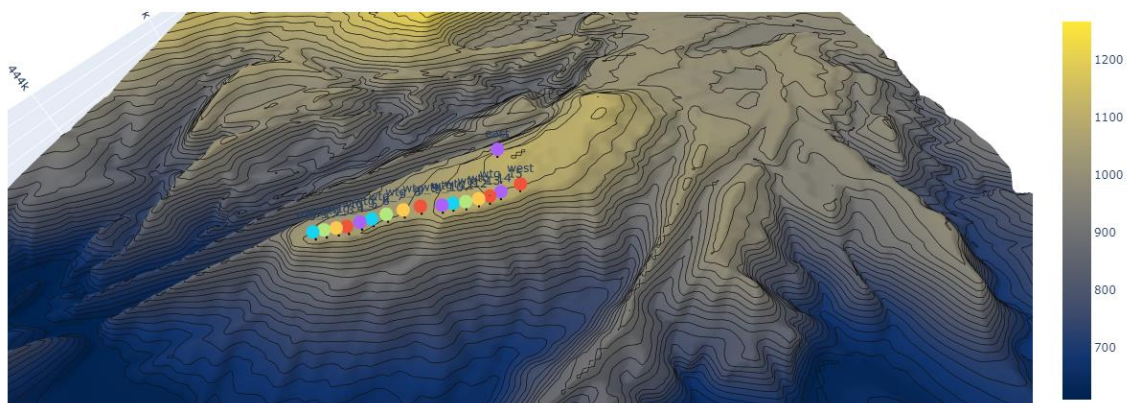


Figure 35. Close-up of Enercon terrain near the wind farm location. The plot is stretched in the vertical direction in order to show the terrain more clearly.



Workflows applied

The set-ups for the workflows applied in this work are summarised in Table 6. *CFX* could be applied because HSE were granted access to the data. Additionally, simulations were carried out by Enercon using their in-house OpenFOAM-based tool *E-Wind* (WF-7). Note that the grid resolution was poor and therefore the results are not expected to be of high quality. For WF-5a, *Fluent SBES* could only be applied with the three most frequent sectors simulated in *Fluent SBES* (30°, 60° and 240°) and the rest in *Fluent RANS*. For WF-6 (*PALM*), the five most frequent sectors were simulated (0°, 30°, 60°, 210° and 240°), and the remaining sectors were obtained using *WindSim* results. The domain was split into two nested grids: a larger one with 100 m resolution and a smaller one closer to the wind farm with 10 m resolution. It should also be noted that the preparation of the roughness data for all the partners was done mainly as part of WF-1 (*WindPro*) and WF-2 (*WindSim*), leading to higher costs than if the time for doing this had been split up amongst all partners (except for WF-7).

Table 6. Summary of set-ups for Enercon simulations.

	WF-1	WF-2	WF-3T	WF-4 and WF-4T	WF-5a and WF-5aT	WF-6	WF-7
Wind model	WindPro	WindSim	CFX	Fluent RANS	Fluent SBES	PALM	E-Wind
Institution	Meteotest	Meteotest	Meteotest	OST	OST	HSE	Enercon
Model type	Linear wind model	Steady-state RANS CFD, k-epsilon	LES model	Steady-state RANS CFD, k-omega SST	Unsteady DDES CFD, k-omega SST, average over 1800s	Steady-state anelastic RANS, k-epsilon	Steady-state RANS based on OpenFOAM, k-epsilon
Grid dimensions (resolution)	20 x 20 km (25 m)	10 x 10 x 8 km (25 m)	20 x 20 x 4 km (100m) 6 x 6 x 3.2 km (10m)	10 x 10 x 1.5 km (20 m)	10 x 10 x 1.5 km (20 m)	18 x 18 x 10 km (25 m)	20 km diameter (50 m)
Number of cells	640'000	13.8 million	1.6 million 32.4 million	20 million	20 million	17.6 million	600,000
Input profile	None	Log profile at inlet	Offline Nesting in WFR model	Log profile at inlet per sector	Log profile at inlet per sector	Ekman-spiral at all boundaries	Neutral ABL
Turbulence intensity	None	Calculated by the model (standard k-epsilon)	Moeng Wyngaard turbulence closure	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Turbulent Kinetic Energy and Specific Dissipation Rate specified	10 % at all boundaries	Neutral ABL
Other models	None	None	Land Surface Model, Radiation Model	None	Synthetic Turbulence Generator	canopy, coriolis force	Temperature equation for buoyancy effects; Coriolis force
Wind directions	12 sectors	12 sectors	5 sectors (0°, 30°, 60°, 210°, 240°)	12 sectors	3 sectors (30°, 60°, 240°)	12 sectors	12 sectors
Other workflow steps	Includes steps 1-8 specific to <i>WindPro</i> .	Includes steps 1-8 specific to <i>WindSim</i> . Preparation of roughness data for all partners is done in this WF.	Includes steps 1-8 specific to <i>CFX</i> . WF-3T is with turning.	Includes steps 1-8 specific to <i>Fluent</i> . WF-4T is with turning considered in the AEP calculation.	Includes steps 1-8 specific to <i>Fluent</i> . WF-5aT is with turning considered in the AEP calculation.	Includes steps 1-8 specific to <i>PALM</i> .	Includes steps 1-8 specific to <i>E-Wind</i> .



The roughness maps used by each wind modelling tool are shown in Figure 37. The differences are due to the varying domain sizes and scale colours.

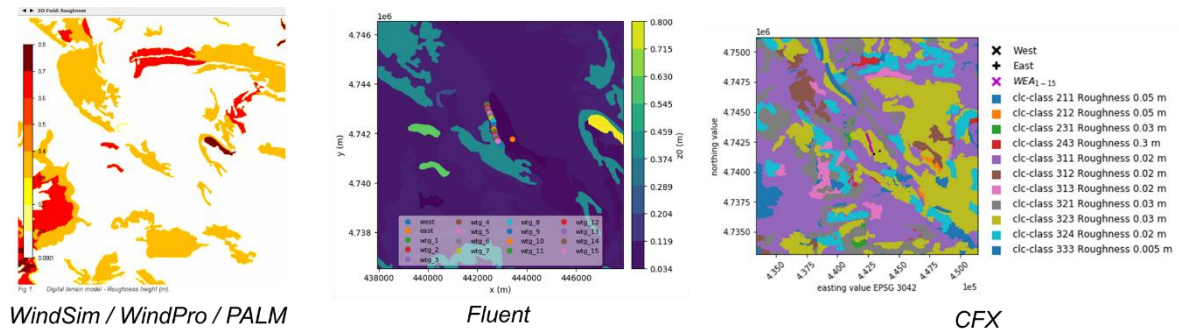


Figure 37. Roughness maps for the Enercon site.

Input data

In this project, data from two met masts "EAST" and "WEST" were used. For both of these masts, measurement data was provided at a range of heights up to 50 m from September 2009 to September 2010. Due to the high amount of overlapping data points (48,941), they can be used for the calibration and validation data reliably. The MERRA-2³ reanalysis dataset was used for the long-term adjustment of both met mast data sets. From the MERRA-2 data, a factor of the mean wind speed during 10 years to the mean wind speed over the measurement period was determined. For the long-term adjusted data sets at both locations, the measurement series were extrapolated with this factor. The WEST mast was used for calibration and the EAST mast for validation.

Results

Wind speed profiles

The results for each model and wind direction sector are shown in Appendix 5(a) for the met mast WEST (calibration location). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). As for the ewz site, there is only one wind speed measurement used in the comparison, because the other heights were not corrected for long-term and therefore are not comparable on the same plot. The right-hand plot shows the absolute difference between the measurements and the simulations at this height for each sector. The differences are almost zero because this is the calibration location. Small differences result from rounding errors.

The same results are shown for the met mast WEST (validation location) in Appendix 5(b). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). For this site, there is only one measurement point at the validation location because the other heights have not been extrapolated for long-term. The middle plot shows the absolute difference between the measurements and the simulations for each sector. The right-hand plot shows the differences between measurements and simulations per sector for the validation mast compared to the calibration mast. The deviations are fairly low (below 1 m/s) for

³ <https://gmao.gsfc.nasa.gov/reanalysis/MERRA/>



most sectors; however, all the models show a larger deviation of around 1.5 m/s for the 330° sector. This will not be further investigated, as this sector occurs very infrequently (only 8% of the time).

Figure 38 shows a summary of the RMSE results for each model for WEST (left) and EAST (right), by taking a simple average of the individual RMSEs of all simulated sectors (blue) and by weighting the average according to its relative frequency from the calibration mast data (orange). This gives more weighting to more frequent wind speeds in order to provide a number more relevant for the AEP. Note that in this case, the RMSE is equal to the absolute difference, as only one height is used. This corresponds to the results discussed in the first paragraph of this section. For EAST, the RMSEs are almost zero, and for WEST, they all remain below 1 m/s.

The RMSE values at the validation location are used for the Comparison Metrics analysis below.

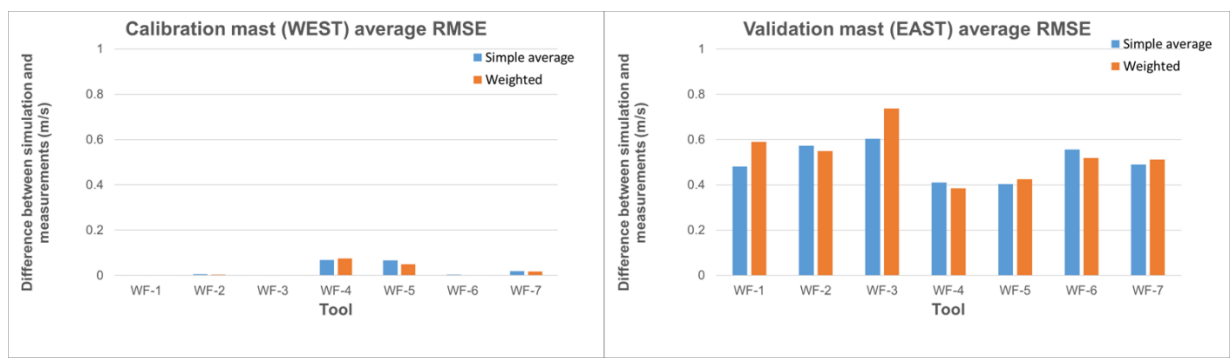


Figure 38. Average Root Mean Square Errors for WEST (left) and EAST (right) for Enercon, both for a simple average (blue) and a frequency-weighted average (orange).

Wind speed contours

As well as examining the wind profiles, we compare the absolute wind speed contours at a height of 100 m above the ground level for the *WindSim*, *Fluent RANS*, *Fluent SBES* and *CFX* simulations in Appendix 5(c), Appendix 5(d), Appendix 5(e) and Appendix 5(f) for the three most frequent wind speed direction sectors, 30°, 60° and 240°. Unfortunately, the 30° sector data for *Fluent SBES* is missing due to an error with the data exporting. These plots were obtained by exporting the data from a fixed grid of simulation points at a fixed area in the domain close to the wind farm and interpolating the results to get a smooth display of data. As for the ewz site, all the simulation results show clear flow sections, or streaks, caused by flow separation behind various hills. The two met masts are located at the bottom right of the wind turbine row: WEST on the ridge next to the wind turbines and EAST further back on the hill. For all wind models, the flow at the two mast locations is similar for the three sectors shown, explaining the low speed-up factors shown in Figure 39 (except for sector 330°, which is discussed in the next section). There are slight differences between the models, mainly due to the location of WEST near to the edge of the ridge. Some small differences between the different wind models can be seen. For example, *Fluent SBES* seems to "smear" the recirculation zones behind hills compared to *Fluent RANS*, due to the varying averaging methods. This pattern is similar to the ewz site.



Wind direction profiles

The simulated wind direction profiles are compared to the measurements at the calibration location in Appendix 5(g) and at the validation location in Appendix 5(h) (except for *WindPro*, for which this information wasn't available). It can be seen that the deviations in wind direction between the simulations and the measurements are low for the calibration location, remaining below 10° for all models and sectors. The lower heights cannot be compared because the long-term extrapolation has not been carried out for the other heights.

As expected, the deviations between the simulations and measurements are slightly higher at the validation location (EAST), although they remain below 15°.

Speed-up factors and turning

The speed-up factors and turning between the validation and calibration locations are shown for each workflow and sector in Figure 39 where: Speed-up factor = wind speed at calibration location / wind speed at validation location; Turning = wind direction at calibration location – wind direction at validation location (both at a height of 50 m). The "theoretical" value refers to the measurements. The speed-up factor of the measurements varies between 0.9 (120° sector) and 1.3 (330° sector), indicating that there is a very small difference in average wind speeds between the two masts, except for in the 330° sector. For the wind direction of 330°, the met mast WEST is probably affected negatively by the presence of the wind turbines in the measurements, explaining why the measured speed-up factor is so high, but this is not picked up by the simulations. In general, the simulated speed-up factors of each workflow are under-estimated: they vary from about 0.8 (WF-2, 270°) to 1.15 (WF-6, 240°). There is no particular pattern regarding models and sectors that can be recognised.

The turning of the measurements is larger than for Stötten but smaller than ewz, staying within 7° for all sectors. The models are partly able to capture this turning; however, there are some sectors in which the turning is slightly over-predicted, e.g. 210° for WF-4 (*Fluent RANS*) and 270° for WF-2 (*WindSim*).

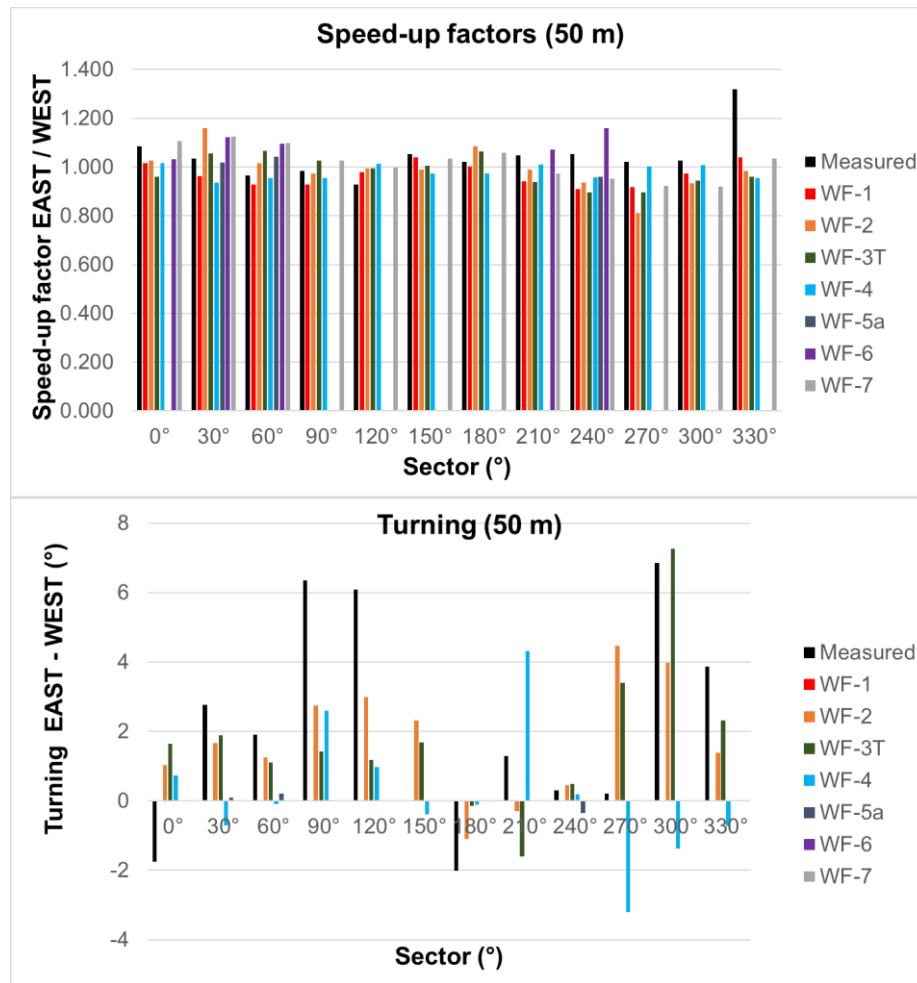


Figure 39. Speed-up factors and turning for Enercon.

AEP at validation location

The measured production data was not available for this site, therefore the AEP has been calculated at the validation location using the power curve of the Enercon E-40 wind turbine. This allows the effects of the simulated wind speeds on the AEP to be examined. This wind turbine has a rated power of 0.6 MW and a rated wind speed of 12 m/s. A hub height of 50 m was assumed.

The resulting AEPs calculated using the method described in Section 3.1.4 are shown in Figure 40 (top: AEP, bottom: percentage difference from theoretical value). The results are all under-estimated, due to the under-estimations of wind speeds in the most frequent sectors. The under-estimation is quite consistent for all models (between 10% and 15%) except E-Wind, which under-estimates the AEP by 24%.

The percentage differences in AEP between the simulated and theoretical values at the validation location are used for the Comparison Metrics analysis below.

The variation of the AEP for each sector is shown for each workflow in Figure 41 (except for WF-7, for which this information was not available). This shows that the AEP is significantly under-predicted in the most frequent sector (240°), leading to an overall under-prediction of AEP. There is no particular



pattern in the variation of AEP between each workflow. The very small effect of flow turning on the WF-4 and WF-5a (*Fluent*) results can be seen for some sectors.

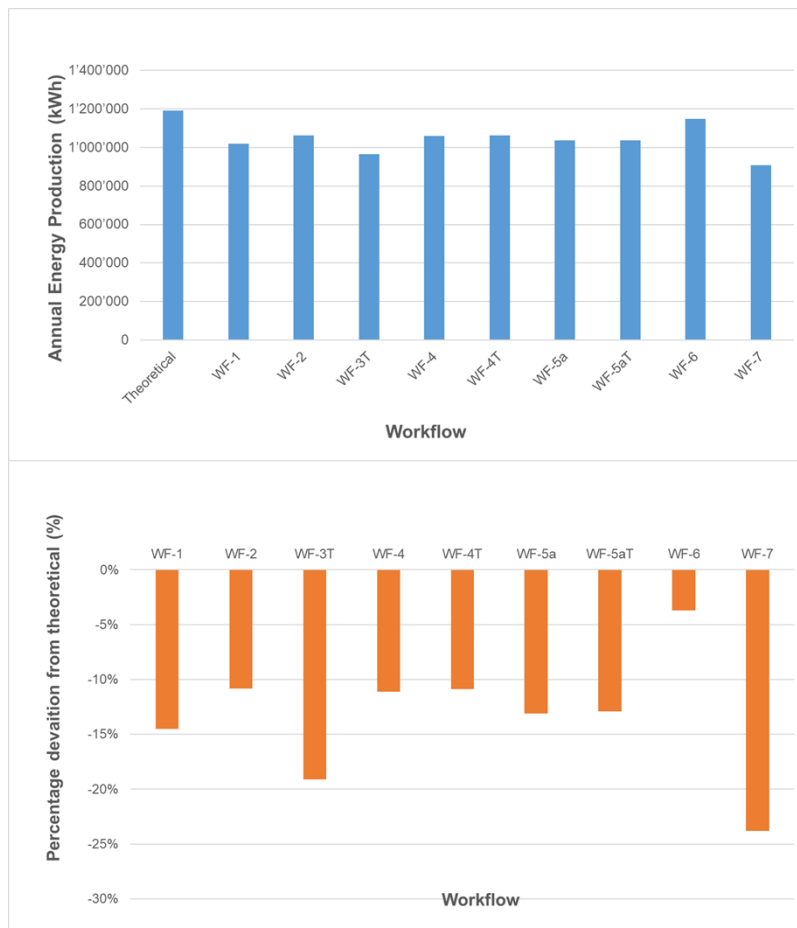


Figure 40. AEP calculated with each workflow (top) and percentage deviation from the theoretical value (bottom) at the validation location (EAST) for Enercon.

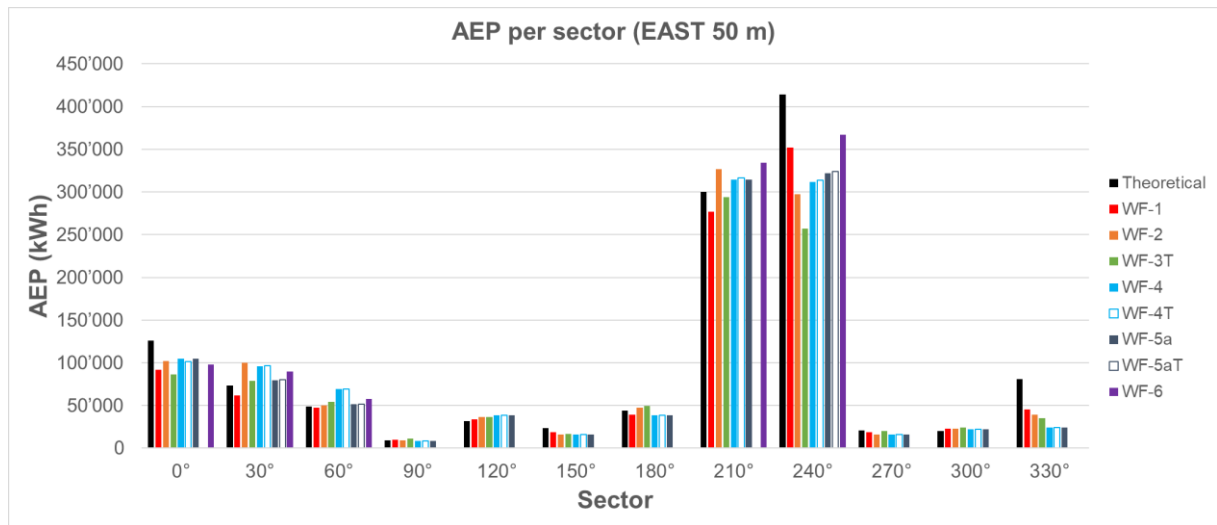


Figure 41. AEP per sector for each workflow applied (Enercon at validation location).

Comparison of AEP estimations at wind turbine locations

Although the measured production data was not available, a comparison of the estimated AEPs at the wind turbine locations was still possible. This analysis was not used for the Comparison Metrics results in the next section; however, the results may be interesting for Enercon, and also demonstrate the potential what can be done with the simulation results.

The calculated AEP values for each of the 15 wind turbines at the site for each workflow are shown in Figure 42. The order of the results for each wind turbine from left to right is: Theoretical, WF-1, WF-2, WF-3T, WF-4, WF-4T, WF5a, WF-5aT, WF-7, where "Theoretical" refers to the theoretical AEP at the validation location (met mast EAST). WF-6 (PALM) is not included in this analysis due to the high effort of extracting the results. The following observations can be made:

- For each workflow, the AEP of WTGs1-7 are very similar to each other. Looking at the wind speed contours for the three most frequent sectors in Appendix 5(a)-(c), distinct areas of different wind speeds can be seen on the hill on which the wind turbines are located. In particular on the *Fluent RANS* plot, it can be clearly seen that the first seven wind turbines are located in one distinct area with constant wind speed for two of the three main wind directions (60° and 240°).
- For WTGs1-7, the AEPs estimated with all the *Fluent* workflows (WF-4, WT-4T, WF-5a, WF-5aT) are significantly lower (approximately 50%) than WF-1, WF-2 and WF-3T. The AEPs of WF-1, WF-2, WF-3T and WF-7 match each other fairly well ($\pm 20\%$). The AEP split into each sector shown in Figure 43 for each workflow for WTG1 demonstrates clearly that this happens due to the much lower energy production in the 210° and 240° sectors. Further examination of the flow for the 240° sector simulated using *Fluent RANS* in Figure 44 clearly demonstrates the low wind speed for the WTGs1-7, which shows wind speed contours on a surface 100 m above the ground, with the wind turbine and mast locations marked by vertical lines. It can be seen that the WTGs1-7 on the left experience low speeds (coloured in blue).
- In general, the AEPs of WTGs10-15 are slightly higher than the other WTGs. Again, this can be seen well on the contour plots, and is highlighted even more in Figure 44 by the particularly high wind speeds (coloured in yellow/orange) at the locations of WTGs10-15.



- The effect of flow turning is small. This is because the flow turning only results in very few measurement points from the calibration mast (WEST) to be re-assigned to a neighbouring sector. An example for WTG15 is shown in Figure 45. This demonstrates the small changes in the wind rose at the calibration location (upper left, applied to WTG15 when turning is not considered) compared to the wind rose predicted at WTG15 by WF-4T (upper right, with turning considered) for the 210° and 240° sectors, as well as the small difference in speed-up factors for WTG15 per sector (highlighted in red). For the other sectors, there are no differences in the wind rose and therefore no effect of turning on the results.

Further analysis is underway together with Enercon.

Comparison Metrics

In this section, the skill scores and cost scores before and after carrying out the simulations are examined and discussed according to the process shown in Figure 1.

The main results are shown in Figure 46. The WF-4 (*Fluent RANS*) and WF-5a (*Fluent SBES*) results with turning considered have been used (WF-4T and WF-5aT). The upper plot shows the relative skill vs. cost scores both before and after running the simulations for each workflow, marked by a coloured circle ("before": empty circle; "after" = filled circle). The "before" results show that WF-1 (*WindPro*) and WF-4T and WF-5aT (*Fluent*) are expected to have similarly low cost and skill scores, whereas WF-2 (*WindSim*) is expected to be most expensive and WF-6 (*PALM*) most accurate.

There are several differences that can be observed between the predicted and actual scores. Firstly, all the skill scores are similar, meaning that all the workflows performed very similarly. However, WF-7 (*E-Wind*) cost less and performed much better than expected. This means that some of the expected inaccuracies due to the low resolution of the grid and sub-optimal set-up did not actually translate into a lower actual accuracy. This needs to be investigated further. Some resulting improvements to the skill score definitions are suggested in Section 3.2.4. The choice of optimal workflow is not entirely clear for the "before" scores, as there is no sudden flattening-off of the curve. The best compromise between cost and skill is represented by WF-1 (*WindPro*), WF-4T (*Fluent RANS*) and WF-5aT (*Fluent SBES*), which all show similar results. A decision tool based on these predictions would choose WF-1 (*WindPro*) as the most suitable workflow. However, the most suitable workflows in reality ("after") are clearly WF-7 (*E-Wind*) and WF-4T (*Fluent RANS*), although WF-1 (*WindPro*) comes next. This means that the skill score definitions need to be improved, as suggested in Section 3.2.4. They will be further examined in Section 3.2.3 for the ADEV site.

The lower plot is slightly different due to the conversion of wind speeds in each sector to AEP using the process described in Section 3.1.4. The predicted most optimal workflows are WF-1 (*WindPro*), WF-4T (*Fluent RANS*) and WF-3T (*CFX*). In reality, the most optimal workflows for this application are either WF-7 (*E-Wind*), WF-1 (*WindPro*) or WF-4T (*Fluent RANS*). Therefore the decision tool has worked fairly well, with some improvements required. This will be discussed later in Section 3.2.4.

As mentioned for the other sites above, these results should not be used to compare wind modelling tools directly, rather to compare the entire workflows.

For comparison purposes later in 3.2.4, the ability of the Comparison Metrics estimation method to successfully predict the most effective workflow for this site has therefore been given a quality rating of 3 out of 10 for the wind speed and 3 out of 10 for the AEP.



Figure 42. AEP for each Enercon wind turbine WTG1-15 for each workflow (each time from left to right: Theoretical, WF-1, WF-2, WF-3T, WF-4T, WF-5aT, WF-6, WF-7).

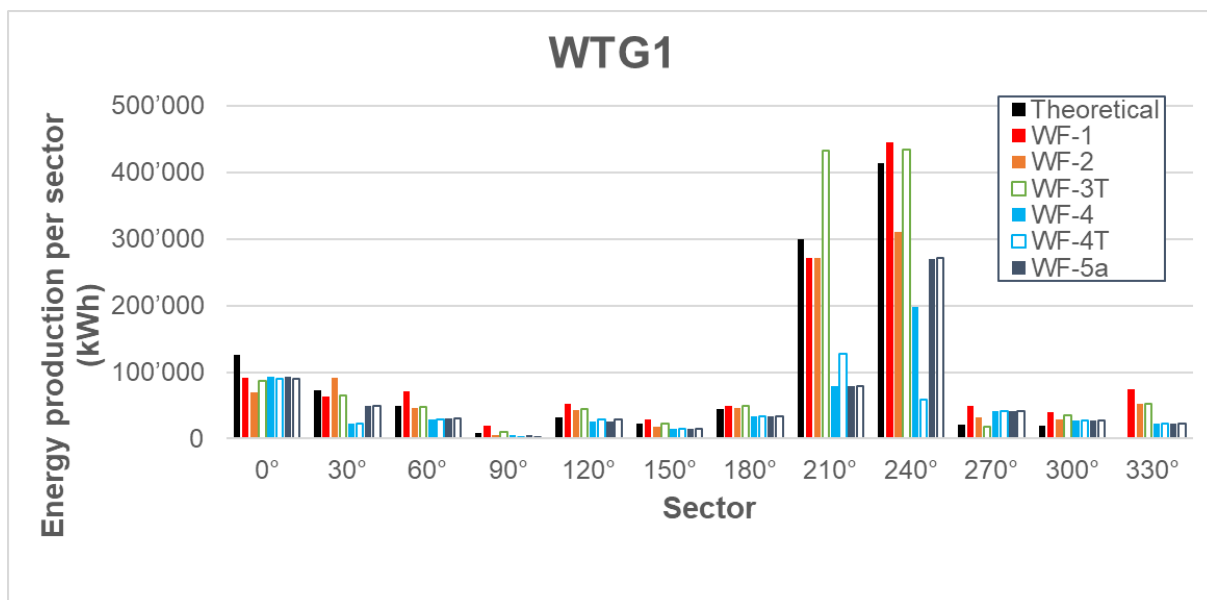


Figure 43. AEP split up into sectors for each workflow for WTG1 for Enercon.

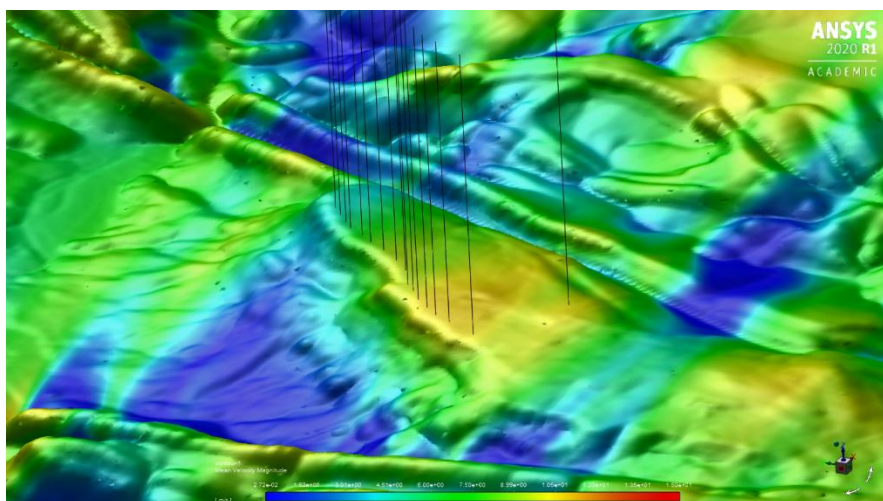


Figure 44. Wind speed contours at 100 m height above the ground for the *Fluent* RANS simulations for the 240° sector (Enercon). The wind turbine and mast locations are marked by vertical lines.

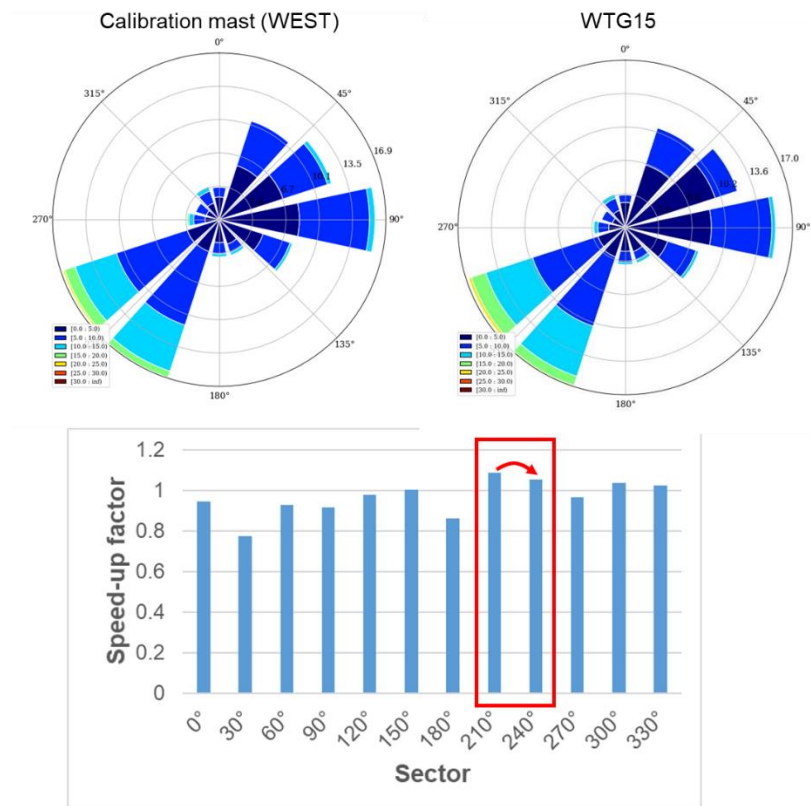


Figure 45. Wind rose for calibration data (top left) compared to for WTG15 (top right) using *Fluent RANS*. The bottom plot shows the speed-up factor between WTG15 and the calibration location for each sector. The 210° and 240° sectors are marked in red.

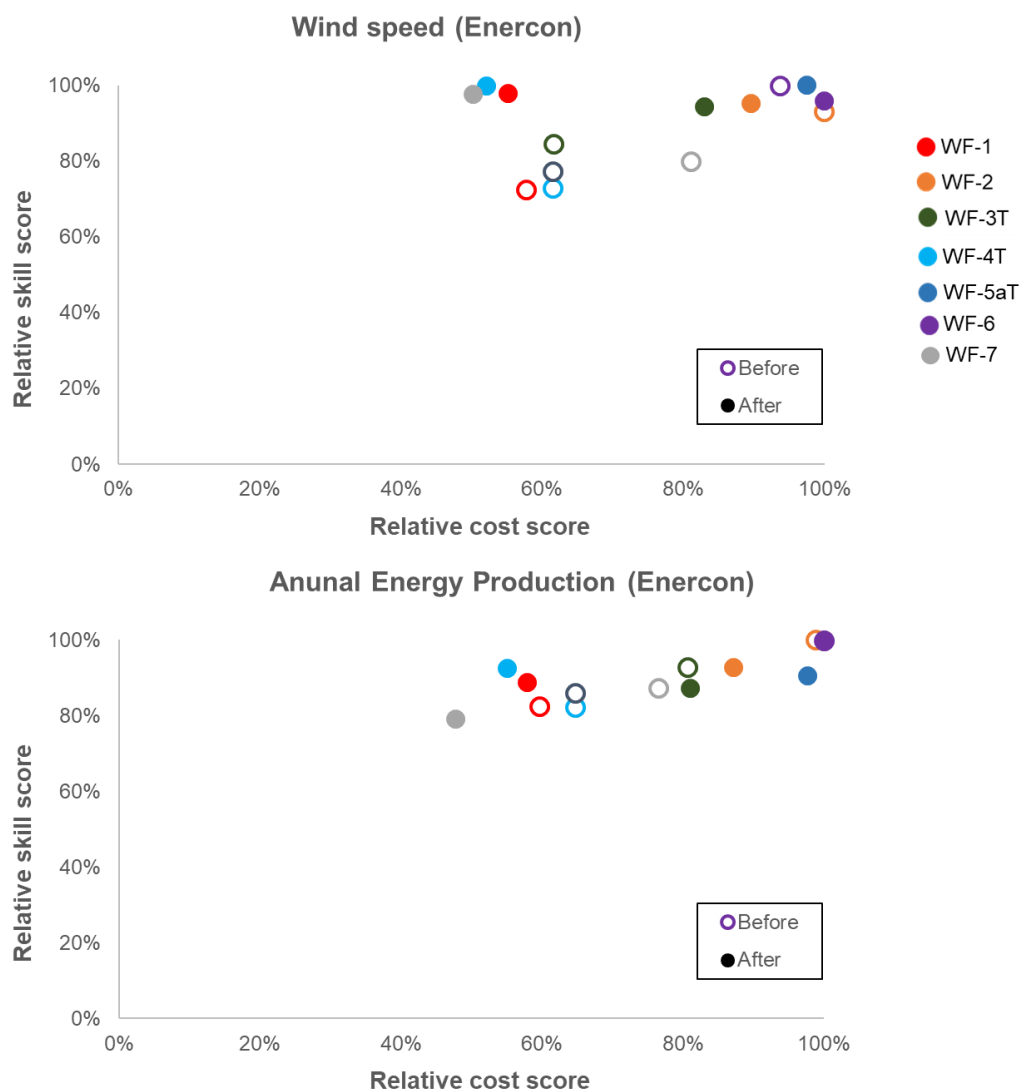


Figure 46. Comparison Metrics results for Enercon.

The split of the different costs contributing to the cost scores "after" are shown in Figure 20. For this project, the simulation set-up effort costs no longer dominate. This is because the set-up effort has been reduced during the course of the project by the learn effect of the other projects.

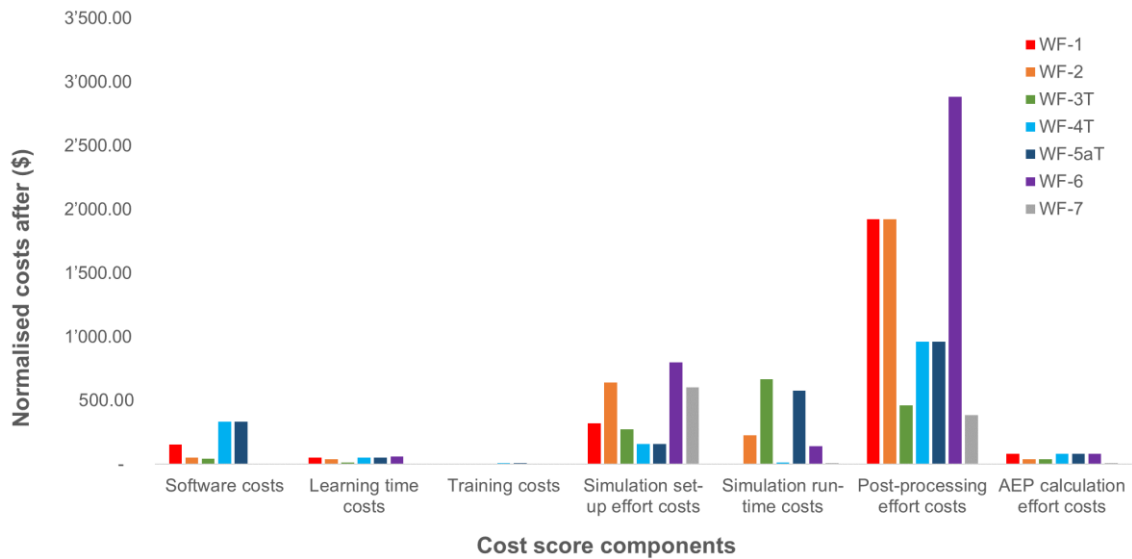


Figure 47. Cost score components for Enercon.

Complex terrain classification

The results of the complex terrain classification questions presented in Section 3.1.4 are shown by each research partner organisation in Figure 48. This shows that the agreement between the four organisations is not particularly good. There is a maximum deviation from the average value of 50%. The main differences are in the answers to the questions "In how many 30° sectors is there a positive slope steeper than 30° less than 250 m away from the validation position in any direction?", and "How many slopes are there?" As well as it being difficult to put a number to subjective questions, this shows that the question can easily be misunderstood or interpreted differently between different people. It is therefore clear that this classification method needs to be improved, as discussed further in Section 3.2.4.

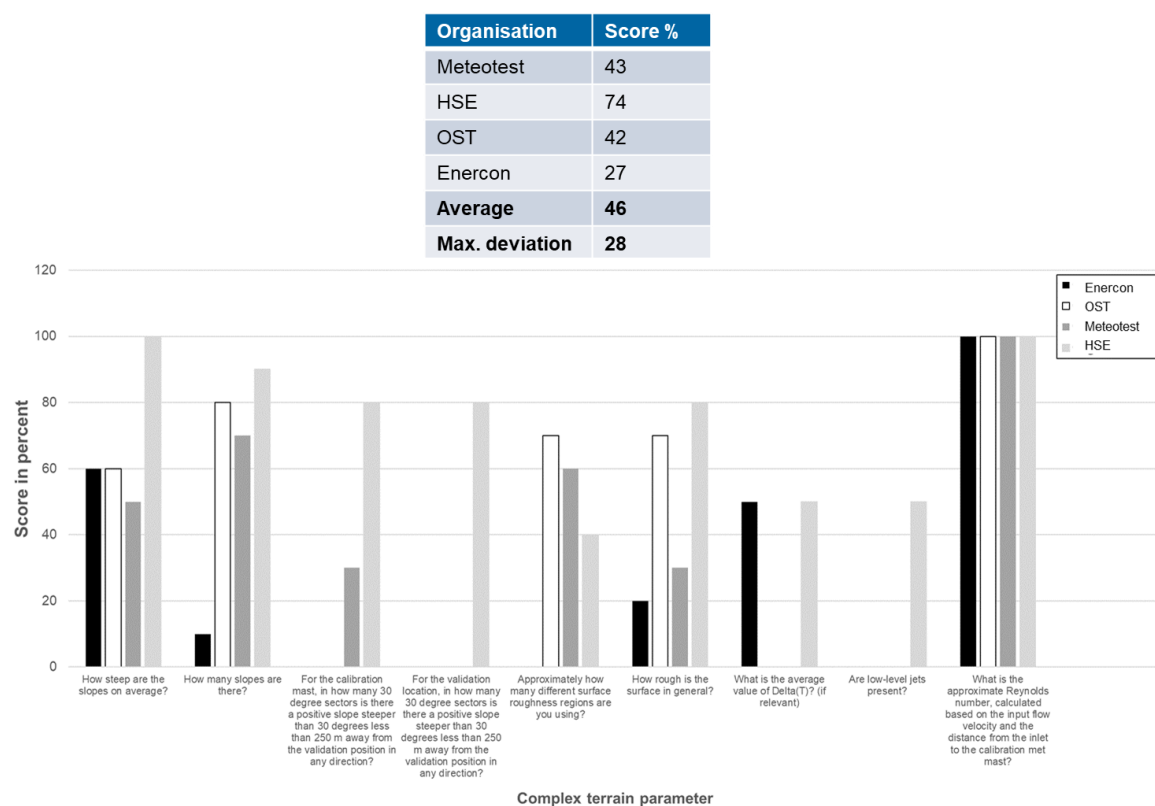


Figure 48. Complex terrain classification results for Enercon.



3.2.3 Application of the automated WRA processes to the ADEV site

Site description

The ADEV site used in this project is the existing St. Brais wind farm site in Switzerland situated in complex terrain. The wind farm consists of two Enercon E-82 wind turbines with a hub height of 78 m located as shown on the left-hand side of Figure 49. The main wind direction is NW, as can be seen on the wind rose on the right-hand side of the figure. A close-up of the terrain contours near to the wind farm location is shown in Figure 50. The plot is stretched in the vertical direction in order to show the terrain more clearly.

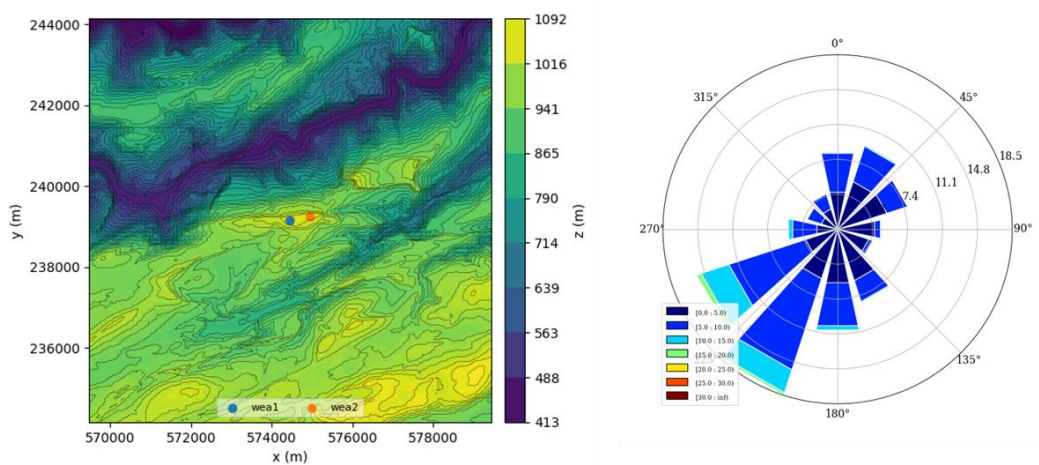


Figure 49. ADEV site: terrain contours with the two wind turbines marked (left) and wind rose of WEA1 (right).

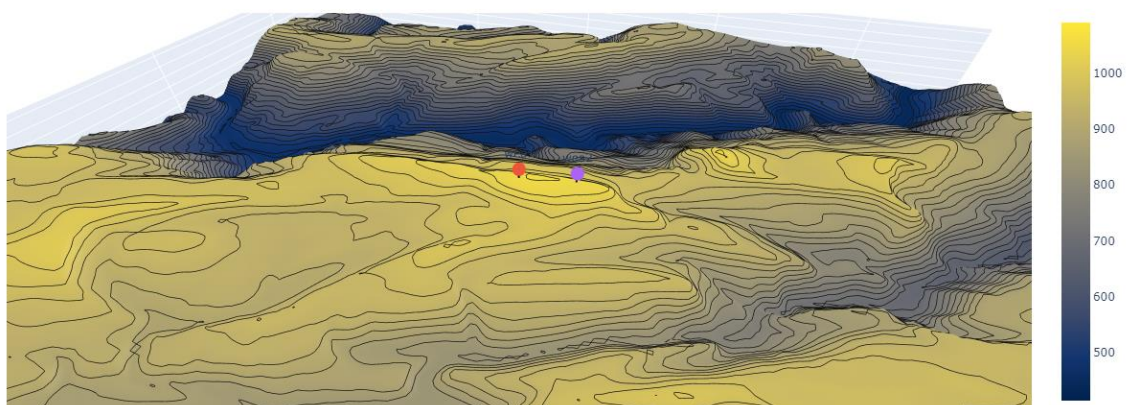


Figure 50. Close-up of ADEV terrain near the wind farm location. The plot is stretched in the vertical direction in order to show the terrain more clearly



Workflows applied

The set-ups for the workflows applied in this work are summarised in Table 7. *CFX* could not be applied because HSE were not granted access to the data. *PALM* has not been applied. For WF-5a, only the variation with the three most frequent sectors simulated in *Fluent SBES* (180°, 210° and 240°) and the rest in *Fluent RANS*. It should also be noted that the preparation of the roughness data for all the partners was done mainly as part of WF-1 (*WindPro*) and WF-2 (*WindSim*), leading to higher costs than if the time for doing this had been split up amongst all partners.

Table 7. Summary of set-up of ADEV simulations.

	WF-1	WF-2	WF-4 and WF-4T	WF-5a and WF-5aT
	WindPro	WindSim	Fluent RANS	Fluent SBES
Institution	Meteotest	Meteotest	OST	OST
Model type	Linear wind model	Steady-state RANS CFD, k-epsilon	Steady-state RANS CFD, k-omega SST	Unsteady DDES CFD, k-omega SST, average over 1800s
Grid dimensions (resolution)	9 x 9 km (25 m)	10 x 10 x 10 km (25 m)	10 x 10 x 1.5 km (20 m)	10 x 10 x 1.5 km (20 m)
Number of cells	129'600	10.2 million	20 million	20 million
Input profile	None	Log profile at inlet	Log profile at inlet	Log profile at inlet
Turbulence intensity	None	Calculated by the model (standard k-epsilon)	Turbulent Kinetic Energy and Specific Dissipation Rate specified	Turbulent Kinetic Energy and Specific Dissipation Rate specified
Other models	None	None	None	Synthetic Turbulence Generator
Wind directions	12 sectors	12 sectors	12 sectors	3 sectors (180°, 210°, 240°)
Other workflow steps	Includes steps 1-8 specific to <i>WindPro</i> .	Includes steps 1-8 specific to <i>WindSim</i> . Preparation of roughness data for all partners is done in this WF.	Includes steps 1-8 specific to <i>Fluent</i> . WF-4T is with turning considered in the AEP calculation.	Includes steps 1-8 specific to <i>Fluent</i> . WF-5aT is with turning considered in the AEP calculation.

The roughness maps used by each wind modelling tool are shown in Figure 51. The differences are due to the varying domain sizes and scale colours.

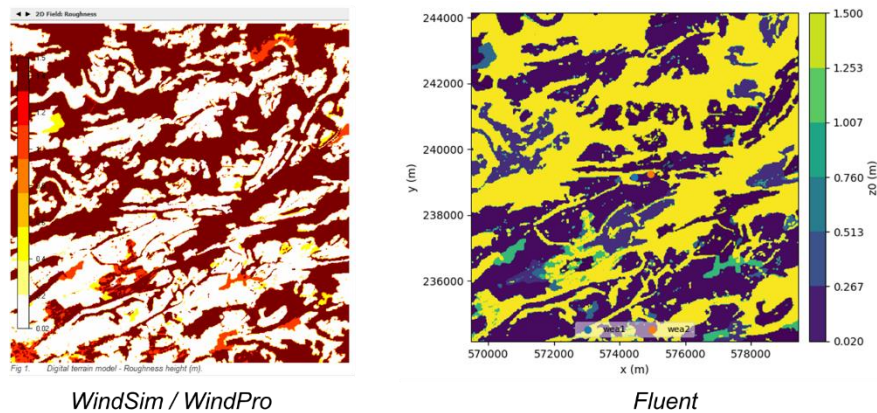


Figure 51. Roughness maps for the ADEV site.

Input data

In this project, wind speed and direction data from the two wind turbines "WEA1" and "WEA2" were used, because no met mast data was available. The measurement location on the nacelle of the wind turbines (hub height 78 m) means that the data will be influenced by the wind turbine rotors, and the measurements will not correspond to the freestream wind speed. It is not known if the measurement results delivered by ADEV include any kind of correction for this effect or not. However, it is nevertheless possible to use one wind turbine as the calibration location and the other as the validation location. The absolute values of the wind speeds may not be correct, but the ratios will still be valid, assuming that there are no large discrepancies in the operation of the wind turbines.

For both of these wind turbines, measurement data was provided from January 2010 to December 2020, a time period of 10 years. Due to the high amount of overlapping data points (554,045), they can be used for the calibration and validation data reliably. A long-term extrapolation was not done because it could be assumed that this measurement period is already very long. The wind turbine WEA1 was used for calibration and WEA2 for validation. In order to check the quality of the input data, a correlation between the WEA1 and WEA2 data is shown in Figure 52, showing that the data correlates well and therefore can be used reliably.

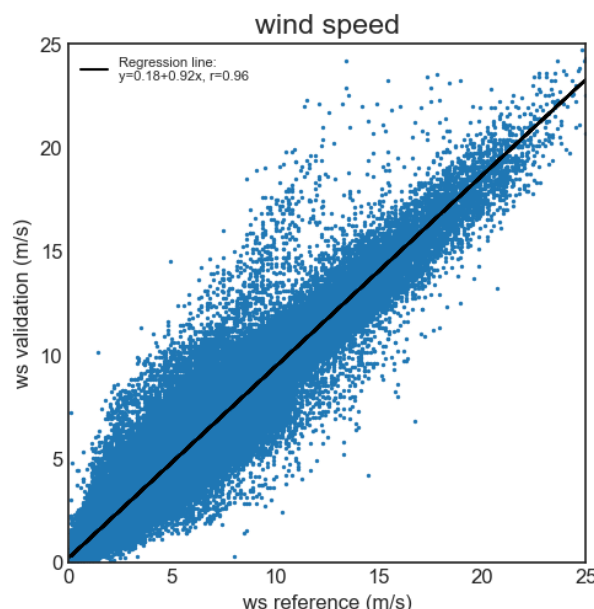


Figure 52. Correlation of WEA1 ("reference") and WEA2 ("validation") wind speed data for ADEV.

Results

Wind speed profiles

The results for each model and wind direction sector are shown in Appendix 6(a) for WEA1 (calibration location). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). As for the Enercon site, there is only one wind speed measurement used in the comparison, this time because measurement data was only available at hub-height. The right-hand plot shows the absolute difference between the measurements and the simulations at this height for each sector. The differences are almost zero because this is the calibration location. Small differences result from rounding errors.

The same results are shown for WEA2 (validation location) in Appendix 6(b). The left-hand plot for each model shows the average wind speed profiles vs. height for each sector (coloured lines) compared to the measurements (coloured diamonds). For this site, there is only one measurement point at the validation location because measurement data was only available at hub-height. The middle plot shows the absolute difference between the measurements and the simulations for each sector. The right-hand plot shows the differences between measurements and simulations per sector for the validation mast compared to the calibration mast. The deviations are fairly low (mainly below 1 m/s); however, Fluent SBES shows a larger deviation of around 1.5 m/s for the 60° and 330° sectors. These sectors do not occur very frequently (sector 60° 9% of the time and sector 330° 4% of the time) so may not have a large influence on the AEP.

Figure 53 shows a summary of the RMSE results for each model for WEA1 (left) and WEA2 (right), by taking a simple average of the individual RMSEs of all simulated sectors (blue) and by weighting the average according to its relative frequency from the calibration mast data (orange). This gives more weighting to more frequent wind speeds in order to provide a number more relevant for the AEP. Note that in this case, the RMSE is equal to the absolute difference, as only one height is used. The results



correspond to the results discussed in the first paragraph of this section. For WEA1, the RMSEs are almost zero, and for WEA2, they all remain below 1 m/s.

The RMSE values at the validation location are used for the Comparison Metrics analysis below.

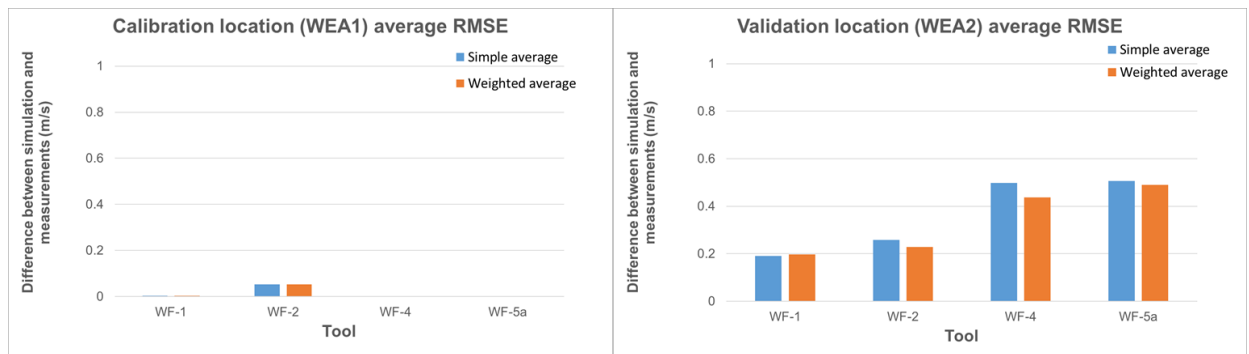


Figure 53. Average Root Mean Square Errors for WEA1 (left) and WEA2 (right) for ADEV, both for a simple average (blue) and a frequency-weighted average (orange).

Wind speed contours

As well as examining the wind profiles, we compare the absolute wind speed contours at a height of 100 m above the ground level for the *WindSim*, *Fluent RANS* and *Fluent SBES* simulations in Appendix 6(c), Appendix 6(d) and Appendix 6(e) for the three most frequent wind speed direction sectors, 180°, 210° and 240°. These plots were obtained by exporting the data from a fixed grid of simulation points at a fixed area in the domain close to the wind farm and interpolating the results to get a smooth display of data. Similar to the ewz site, it can be seen that the two wind turbines are located on a hill, which shields them from the wind speed streaks caused by flow separation over nearby hills. This explains the low speed-up factors between the two wind turbines as discussed below and shown in Figure 54. Some small differences between the different wind models can be seen. For example, *Fluent SBES* seems to "smear" the recirculation zones behind hills compared to *Fluent RANS*, due to the varying averaging methods. This pattern agrees with the previous sites.

Wind direction profiles

The simulated wind direction profiles are compared to the measurements at the calibration location in Appendix 6(f) and at the validation location in Appendix 6(g) (except for *WindPro*, for which this information wasn't available). It can be seen that the deviations in wind direction between the simulations and the measurements are low for the calibration location, remaining below 10° for all models and sectors.

As expected, the deviations between the simulations and measurements are higher at the validation location (WEA2). In particular, *Fluent* under-predicts the flow turning for the 90°, 120°, 150°, 300° and 330° sectors. As none of these correspond to the three most frequent wind directions, it may not have a significant influence on the total AEP.



Speed-up factors and turning

The speed-up factors and turning between the validation and calibration locations are shown for each workflow and sector in Figure 54 where: Speed-up factor = wind speed at calibration location / wind speed at validation location; Turning = wind direction at calibration location – wind direction at validation location (both at a height of 78 m). The "theoretical" value refers to the measurements. The speed-up factor of the measurements varies very little (between 0.9 and 1.0), indicating that there is a very small difference in average wind speeds between the wind turbines. The simulated speed-up factors match fairly well, except for the 60° and 330° sectors, which are over-estimated by WF-4 (*Fluent RANS*), and the 90° and 120° sectors, which are under-estimated by WF-4 (*Fluent RANS*).

The measurements show a constant turning of about -10°. This indicates an offset in the orientation of the wind turbines, rather than a real effect, especially because this turning cannot be observed in the simulations. This does not have any effect on the final results.

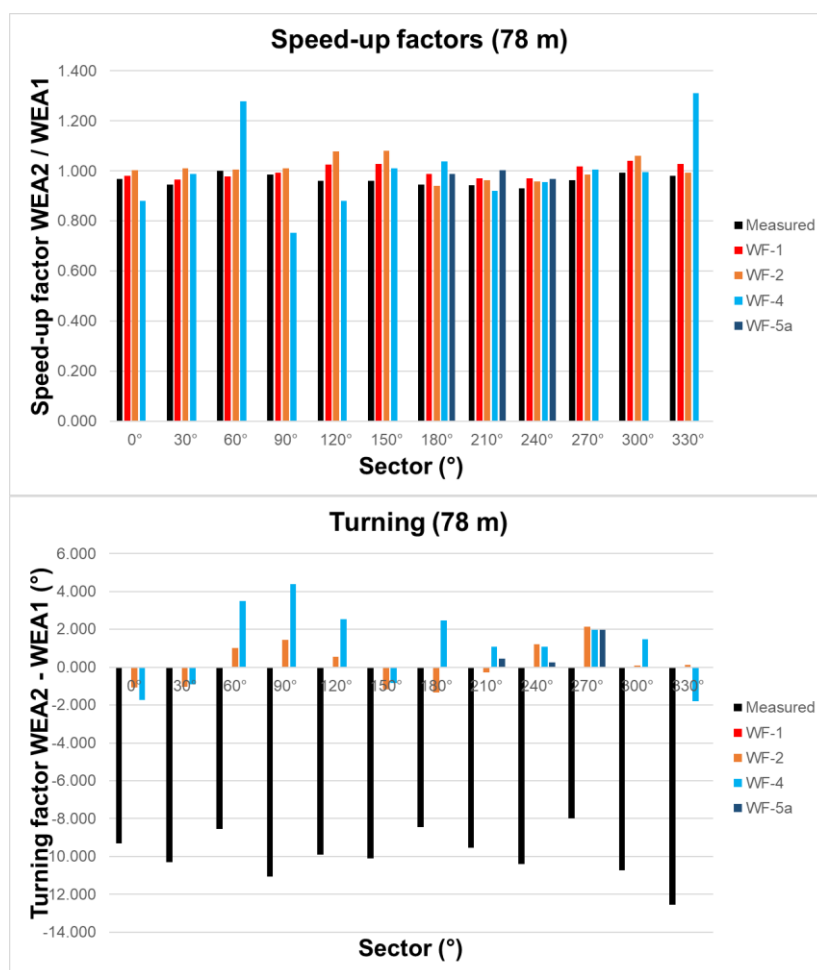


Figure 54. Speed-up factors and turning for ADEV.

AEP at validation location

The measured production data was not available for this site, therefore the AEP has been calculated at the validation location using the power curve of the Enercon E-82 wind turbine. This allows the effects of the simulated wind speeds on the AEP to be examined. This wind turbine has a rated power of 2 MW and a rated wind speed of 12.5 m/s. The hub height is 78 m.



The resulting AEPs calculated using the method described in Section 3.1.4 are shown in Figure 55 (top: AEP, bottom: percentage difference from theoretical value). As opposed to the Enercon site, the results are all over-estimated, due to the over-estimations of wind speeds in the most frequent sectors. The over-estimation is largest for WF-4 (*Fluent RANS*), and the *SBES* simulation in WF-5a reduce this slightly. The effect of flow turning is minimal. The over-estimation is small for WF-1 (*WindPro*) and WF-2 (*WindSim*).

The percentage differences in AEP between the simulated and theoretical values at the validation location are used for the Comparison Metrics analysis below.

The variation of the AEP for each sector is shown for each workflow in Figure 56. The results for the *Fluent* workflows are shown only with turning, as the difference was minimal. This indicates that the large over-prediction in AEP by the WF-3 and WF4 workflows mainly occurs because of the over-prediction in the 240° sector, because this is the most frequently occurring sector. Additionally, it can be seen that an under-prediction of WF-1 (*WindPro*) and WF-2 (*WindSim*) in the 210° sector is probably compensated for by the over-prediction in 240°, because both of these sectors occur for a similar proportion of time.

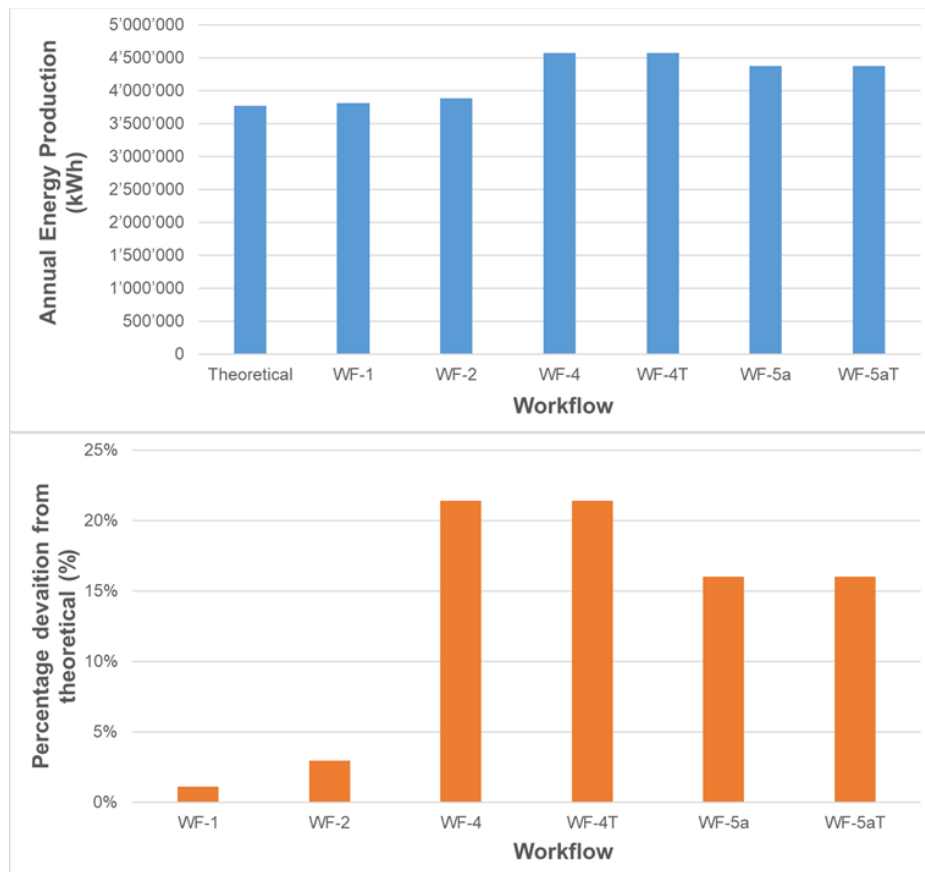


Figure 55. AEP calculated with each workflow (top) and percentage deviation from the theoretical value (bottom) at the validation location (WEA2) for ADEV.

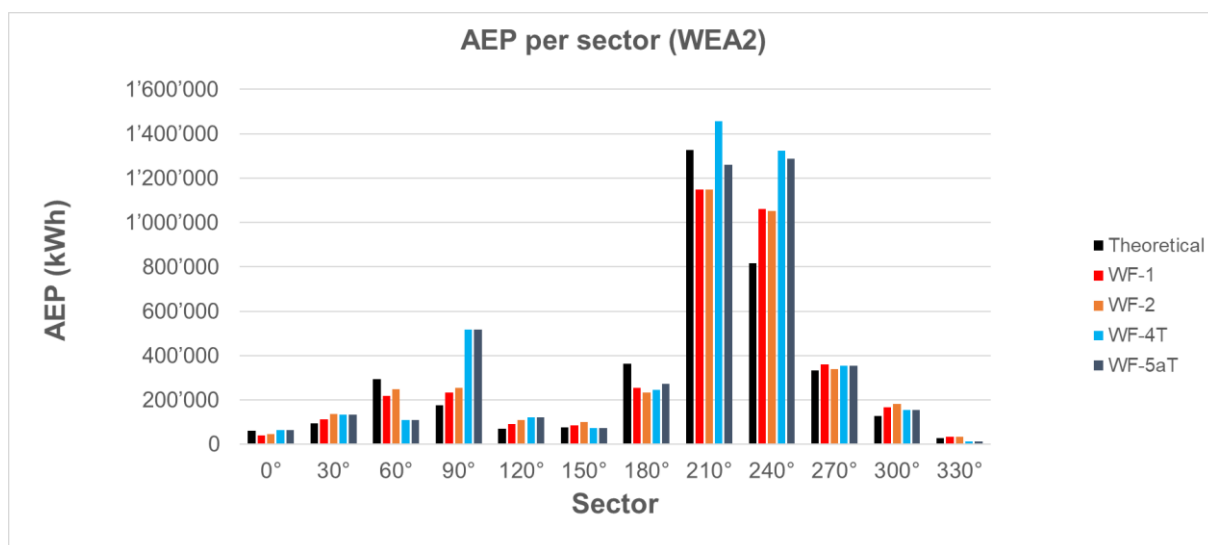


Figure 56. AEP per sector for each workflow applied (ADEV at validation location)

Comparison Metrics

In this section, the skill scores and cost scores before and after carrying out the simulations are examined and discussed according to the process shown in Figure 1 above.

The main results are shown in Figure 57. The WF-4 (*Fluent RANS*) and WF-5a (*Fluent SBES*) results with turning considered have been used (WF-4T and WF-5aT). The upper plot shows the relative skill vs. cost scores both before and after running the simulations for each workflow, marked by a coloured circle ("before": empty circle; "after" = filled circle). The "before" results show a very nice shaped curve, with *WindSim* clearly expected to be the most optimal workflow. Note that this plot looks different to the others because WF-6 (*PALM*) is not included, which has relatively high costs and therefore causes the relative cost scores of the other workflows to be used. At this site, the most expensive workflow is expected to be WF-5aT (*Fluent SBES*).

There are several differences that can be observed between the predicted and actual scores. The shape of the "after" curve is similar to the "before" curve; however WF-1 (*WindPro*), WF-2 (*WindSim*) and WF-4T (*Fluent RANS*) have swapped places. The results indicate that WF-1 (*WindPro*) would be the optimal workflow for this application, whereas the decision tool predicts WF-2 (*WindSim*). Therefore further work is required on the optimisation of the skill score predictions.

The lower plot is very similar to the wind speed plot. This indicates that the AEP estimation procedure does not have a large influence on the accuracy or on the costs. This is contrary to the other sites, which showed a large variation between the wind speed and AEP charts. This will be discussed further in Section 3.2.4.

As mentioned for the other sites above, these results should not be used to compare wind modelling tools directly, rather to compare the entire workflows.

For comparison purposes later in 3.2.4, the ability of the Comparison Metrics estimation method to successfully predict the most effective workflow for this site has therefore been given a quality rating of 5 out of 10 for the wind speed and 3 out of 10 for the AEP.

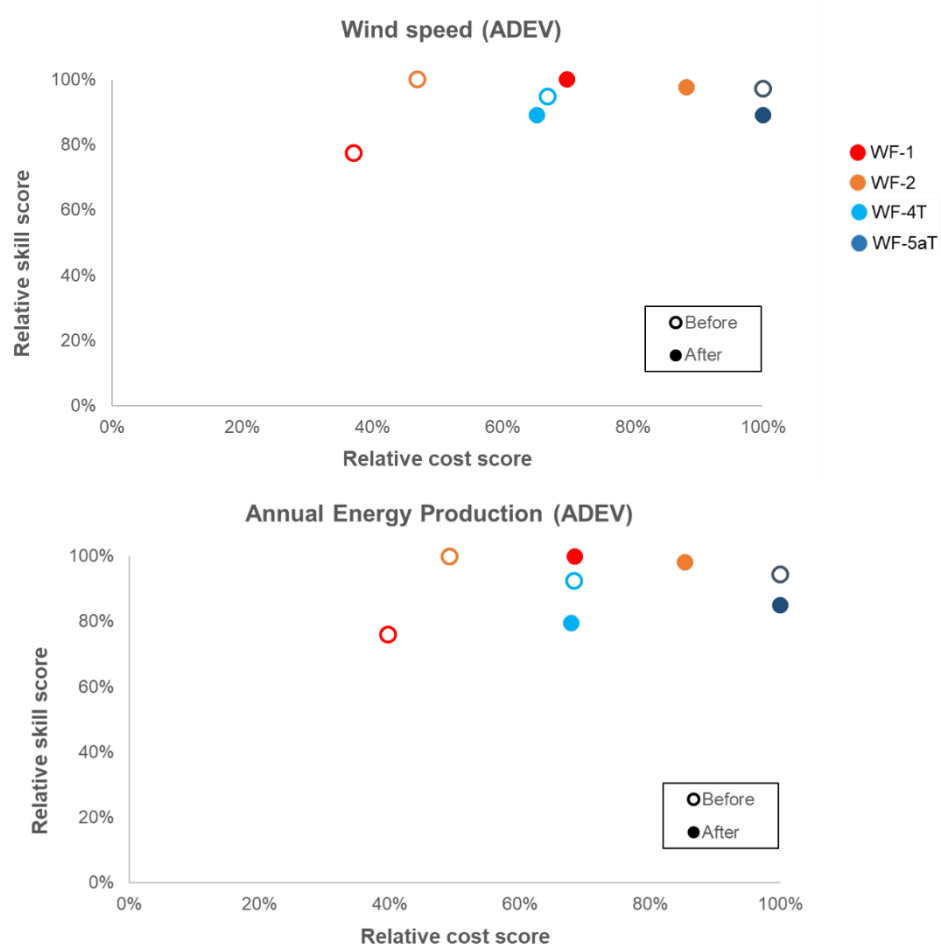


Figure 57. Comparison Metrics results for ADEV.

The split of the different costs contributing to the cost scores "after" are shown in Figure 20. The plot seems so different to the previous projects because the very high set-up costs for WF-6 (*PALM*) are not included. Additionally, this site was the last one to be simulated in this project, and therefore the one with the highest learn effect and therefore the lowest set-up costs.

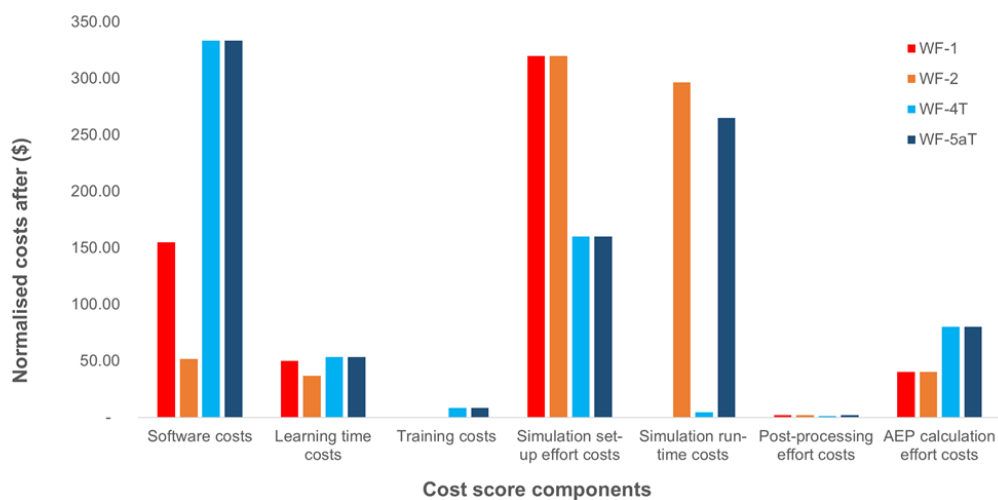


Figure 58. Cost score components for ADEV.

Complex terrain classification

The results of the complex terrain classification questions presented in Section 3.1.5 are shown by each research partner organisation in Figure 59. It is difficult to assess these results because data is only available from two organisations, Meteotest and OST. The variation between the predictions is quite low. In Section 3.2.4, we examine how the classification estimations can be used in the decision tool.



Organisation	Score %
Meteotest	55
OST	40
Average	47
Max. deviation	8

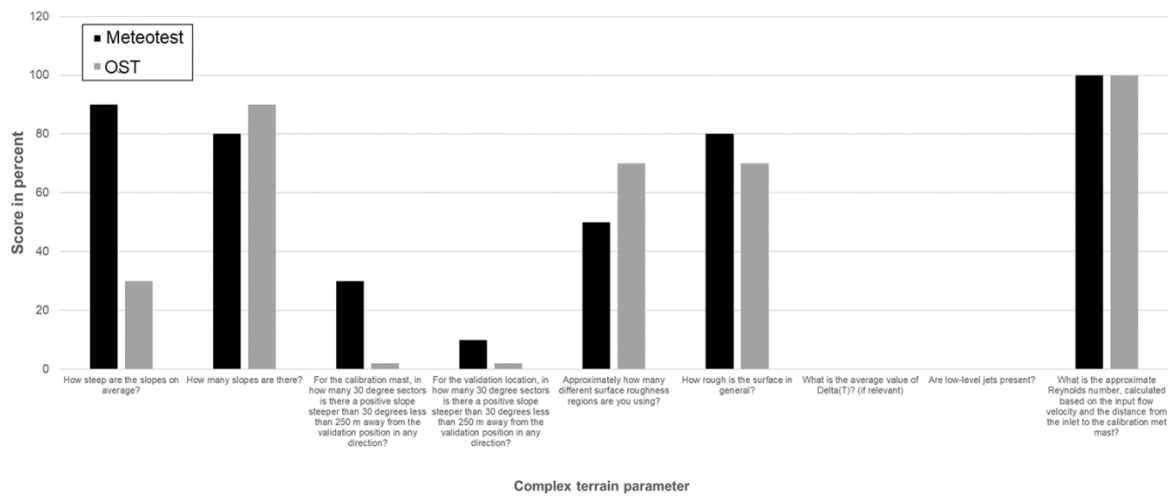


Figure 59. Complex terrain classification results for ADEV.



3.2.4 Development of the new decision tool to help modellers choose the most appropriate model for a particular wind-energy related project.

In this section, the following steps were carried out towards the development of a new decision tool to help modellers choose the most appropriate model for a particular wind-energy related project:

- (1) Evaluation of the WRA process.
- (2) Comparison of the results from each site.
- (3) Evaluation of Comparison Metrics method.
- (4) Description of new decision tool.

(1) Evaluation of the WRA process

The WRA process developed in this project was described in Section 3.1.5. This process is not part of the final decision tool, but was necessary for the generating the results of this project. The automated processes developed for *Fluent* and *CFX* can be used in the future for carrying out WRAs and further investigating the effects of different input parameters.

The following improvement possibilities to the WRA process itself were identified:

- The process should set criteria for an automated quantification of the quality of the input data, using correlation coefficients, number of overlapping time periods and a general comparison of the different data sources.
- The process should allow the sector centres to be chosen at the start of the project, e.g. starting at either 0° to 30° (with 15° in the centre) or -15° to +15° (with 0° in the centre).
- The process should allow a grid-dependency study to be carried out automatically. In order to guarantee the quality of a CFD simulation and ensure that the grid does not influence the results, grid dependency studies are usually carried out. This was not done in this project at all, and it also not part of industry tools such as WindSim.
- A comparison and evaluation of different steps within the process should be automatically made to allow the user to choose the best set-up, e.g. different turbulence models, grid sizes, geometry rotation methods, calibration methods. *Note: this functionality would be very time-consuming and difficult to implement!*
- A guideline for the most optimal choice of these steps could be included in the future.
- The calibration process needs improving. It is not surprising to us that a linear scaling of one point in the domain does not allow particularly accurate simulations to be carried out, although this is the method that is used by industry tools such as *WindSim*. An iterative process could be developed that involves altering the inflow conditions until the entire wind speed and direction profile matches well at the calibration mast location.
- The process of summarising and comparing the results, calculating the speed-up factors and turning, producing the wind speed and direction profile plots, calculating the RMSE values, and comparing the AEP results still needs to be automated. In this project, this part was carried out in Excel, and this was incredibly inefficient and time-consuming.
- The process could be coupled with a weather model in order to allow simulations with more realistic boundary conditions.



- The process should be compared to and validated against other available open-source processes such as OpenOA⁴ (developed by NREL). This could be part of a further project.

As well as this, the development of the process allowed several observations to be made that are relevant to the development of the decision tool:

- Carrying out a WRA consists of a large range of tasks as well as the wind flow simulations. The results of this project show that the choice of method for these tasks can have a very large effect on the quality of the result, in some cases making the actual choice of wind model not important.
- A detailed examination of the results shows that simulation results that match measurements well can be achieved by coincidence; when, for example, an over-prediction of the energy production in one sector cancels out the under-prediction in another sector. In some cases, the quality of the results appears to be random, rather than strongly correlated with any input parameter or set-up choice.

(2) Comparison of results from each site

Figure 60 shows a summary of the wind speed and AEP Comparison Metrics plots for all the sites simulated in this project. The average and maximum deviation values of the complex terrain classification that were estimated by the users are given on the left. The charts vary considerably between the different sites and it is difficult to detect a pattern. A more detailed analysis of the results (not shown here) shows that there are some difficulties with correctly estimating both the skill and cost scores, which is discussed below in part (3).

However, if the quality rating of the ability of the Comparison Metrics estimation method to successfully predict the most effective workflow for each site already assigned in Sections 3.1.6, 3.2.1, 3.2.2 and 3.2.3 for wind speed and AEP is plotted against the complex terrain classification average and maximum deviation, a negative correlation can be clearly seen. These relationships are shown in Figure 61. Therefore it can be concluded that the score estimations need adjusting depending on the complex terrain classification score. This idea will be developed further in step (4) below.

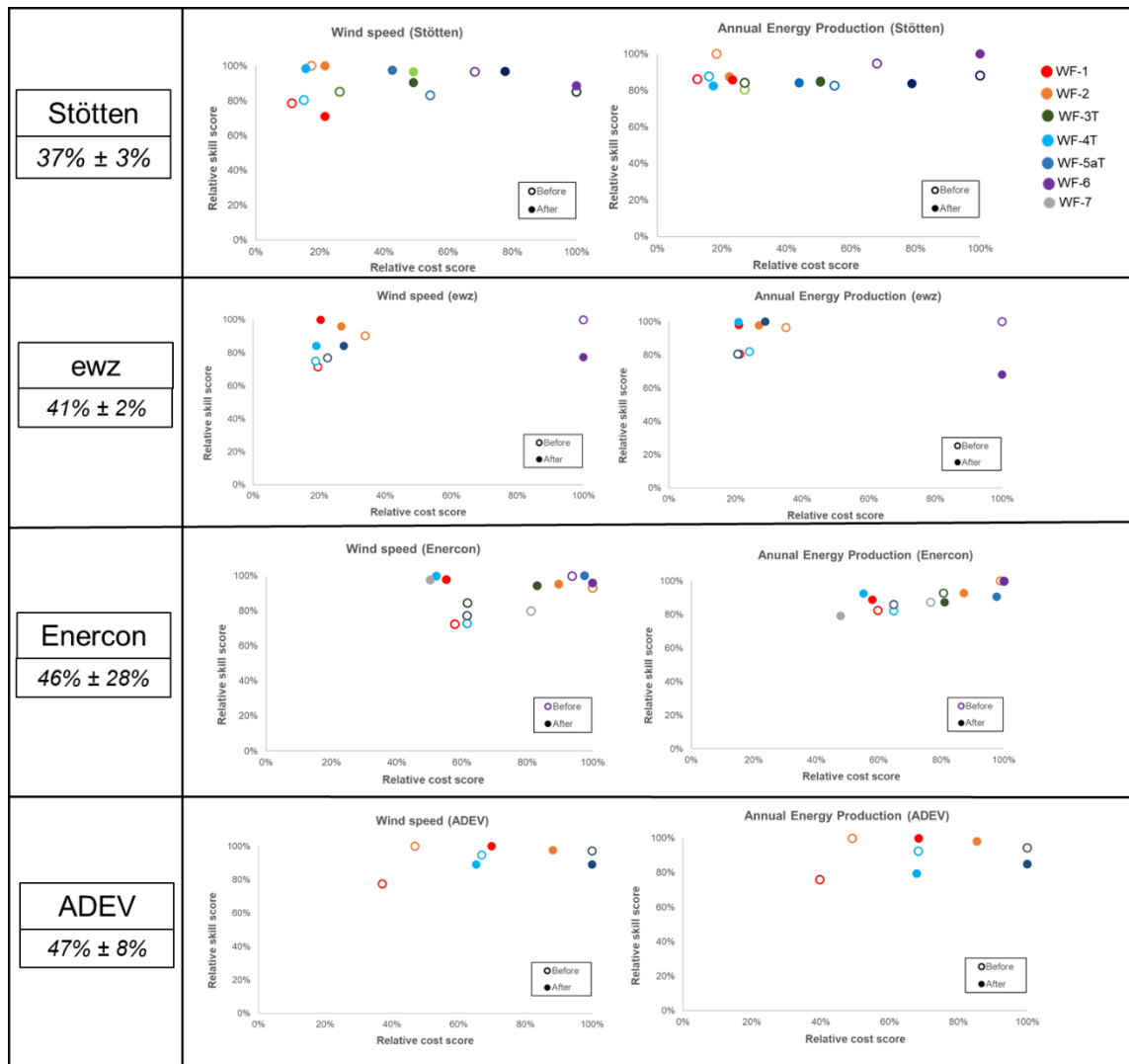


Figure 60. Summary of results of Comparison Metrics for each site. Complex terrain classification average and maximum deviation given on the left.

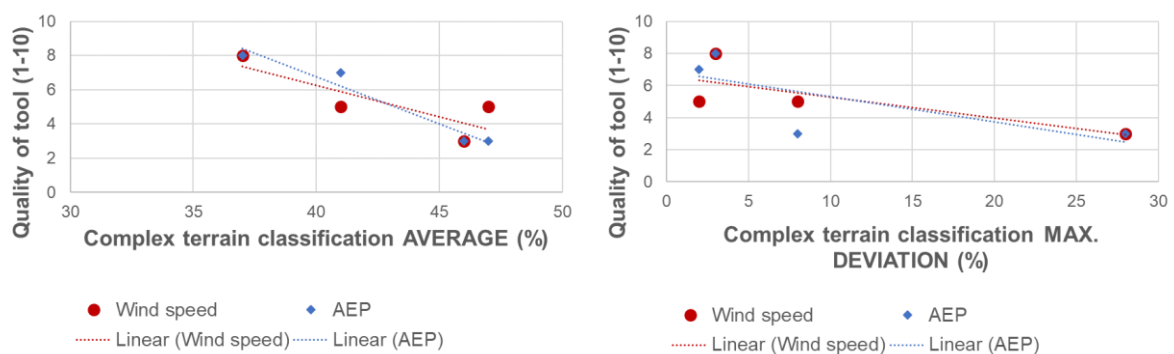


Figure 61. Relationship between the quality of the tool and the complex terrain classification score, both in terms of the average score (left) and the maximum deviation from the average (right) for all sites.



(3) Evaluation of Comparison Metrics method

The results show that the Comparison Metrics method works fairly well for sites with lower complexity (even though the complexity classification scores themselves are associated with some inaccuracies). However, several improvements are required before this can be used in a commercial decision tool. In particular, the skill scores need to better reflect the different set-up steps and choices, and the cost score definitions need some re-thinking. The following improvements to the Comparison Metrics method are suggested here:

- General method:
 - The process of defining the Model Description in a Google Form and then estimating the skill and cost score parameters in a separate Google Form turned out to be sub-optimal. It requires the user to firstly enter the set-up details, and then to estimate the skill parameters related to these details. This is not only time-consuming and confusing, but it also leaves a large room for interpretation. The final decision tool should therefore only collect parameters related to the set-up, and then automatically convert this to a skill score in a consistent way.
 - The values entered into the Google Forms were transferred to an Excel template by hand. This template then had to be adjusted for each project. A commercial decision tool has to do these steps automatically.
- Skill score before estimation:
 - Many of the parameters can only be estimated once the simulations have been fully set up. However, the whole point of this method is to be able make an estimation of the most optimal model without carrying out any simulations. Therefore the skill score parameters need to be adjusted so that the user can estimate their values. As well as this, each parameter should have a confidence score associated with it, so that the tool can be applied even if very little information about the set-up is known.
 - The weightings need to be improved and some of them should be dependent upon the terrain complexity classification.
 - Some of the parameter descriptions were confusing or unclear, including (see Appendix 1 to refer to the parameter numbers and scales):
 - A1: DNS should not be included on the scale, but instead DDES and LES. Also, it should be differentiated between different turbulence models on the scale.
 - A2: "0%" should refer to "incompressible". "100%" should refer to Anelastic formulation, Moisture, Non- adiabatic ground and Radiation. "Coriolis force modelling" should not be included.
 - A3: it should be made clear that "not applicable" refers to "steady state".
 - A5: nesting for local refinement should be included in the scale.
 - A6: more details should be given on the scale, e.g "40%" refers to "some sectors suffer from missing convergence".
 - A7: absolute values of y^+ could be used, where "100%" refers to a value of 1 and "0%" refers to a value above 30.
 - A8: the scale should be changed according to whether the simulated terrain represents the wider area or not.



- B3: should be dependent on terrain complexity.
 - C1: the scale should represent actual results of previous validation studies.
 - D4: the scale should be distributed according to IEC recommendations.
- Cost scores before and after:
 - It turned out to be very difficult to define the Actual Total Costs related to carrying out a WRA project. For example, it was not always clear if an activity was contributing to learning the tool or to the set-up of a particular project. Also, in this project, there were some tasks carried out by Meteotest (e.g. the roughness definition), which contributed to their cost scores but were used by OST and HSE and did not contribute to their cost scores. Also, the staff hourly cost and number of projects per year had to be normalised for a fair comparison. These parameters therefore require further consideration for the final version of the tool.
 - It was very interesting that the set-up effort costs dominated for most of the projects and tools. These costs actually decreased during the project as we became more efficient. This effect skews the results and reduces the accuracy of any comparisons between different sites.
- Complex terrain classification:
 - The results showed that it was difficult to classify the complexity of the terrain by asking questions that the participants could easily answer. Many of the questions were difficult to understand and interpret. Therefore these definitions need to be worked on further.

(4) Design of decision tool

Following the evaluation in the three previous steps, a decision tool was developed as summarised in Figure 62. The tool will use the *Flask* web application, in which an input mask can be created where the user inserts all necessary data, and the tool then calculates the scores automatically and presents the results in the web application.

The user inputs consist of:

- **Site details:** The user enters details of the site complexity, such as the number and steepness of the slopes, similar to the questions asked in the Model Description related to site classification in the existing model. The questions will be improved to make them easier to quantify and less open to interpretation.
- **Model description:** For each model, the user enters details of the planned model set-up, based on the information already given in the existing Model Description. However, the fields will be directly related to the skill score parameters, and the tool will calculate the parameters automatically, without the user having to interpret (or misinterpret) the parameter description and scale. The improvements will be added as discussed above.
- **User experience with model:** For each model, the user answers questions similar to the questions in the skill score parameters (Skill E).
- **Cost estimations:** For each model, the user estimates the costs using the categories introduced in this work. Few improvements are required to this part.
- **Optimisation constraints:** The user defines what they are trying to optimise and what the constraints are. This helps the decision tool to automatically choose the optimum tool for a given



application. In this work so far, this "choice" was only done by looking at the Comparison Metrics charts and assessing which tool offers the best compromise of costs and accuracy. The user may choose, for example, to always choose the model that is furthest towards the top left of the chart (maximum skill, minimum costs), or to always choose the model that has the highest skill below a certain cost limit.

- **Confidence scores:** Every one of the fields related to the site details, model description, user experience with model and cost estimations will also require a confidence score. This will allow users to apply the decision tool without knowing many details of the planned set-up. The more details that are known, the higher the confidence score will be and the more accurate the final decision will be.

The tool consists of:

- **Complexity classifier:** The tool will automatically calculate a complexity score based on the site details input by the user. This will be a number from 0-100%. The user can optionally upload the digital map of the site.
- **Skill score calculator:** For each model, the model description and user experiences inputs made by the user will be converted to a skill score by converting the user inputs to scores, weighting them according to the in-built weightings, and averaging them to get one score between 0% and 100%. Some of the weightings will be altered for the complexity class. The weightings can be adjusted by the decision tool operator but not by the user.
- **Skill score confidence class calculator:** For each model, the confidence scores that have been input by the user will be combined to give an overall confidence score.
- **Cost score calculator:** For each model, the total costs will be calculated using the inputs made by the user.
- **Cost score confidence class calculator:** For each model, the confidence scores that have been input by the user will be combined to give an overall confidence score.

The results consist of:

- **Complexity class:** The complexity score will be converted to a number between one and four. This number will be used to scale certain weightings that are dependent upon the complexity class. The details of this step have to be developed in more detail.
- **Skill score:** For each model, the skill score will be presented to the user.
- **Skill score confidence class:** For each model, the skill score confidence score will be converted to a class (a number between one and four) and presented to the user.
- **Cost score:** For each model, the cost score will be presented to the user.
- **Cost score confidence class:** For each model, the cost score confidence score will be converted to a class (a number between one and four) and presented to the user.

The decision is made as follows:

- For all the models considered, the resulting relative skill and cost scores are displayed on a chart of skill score vs. cost score (relative to the maximum score amongst the considered models). This chart is similar to the Comparison Metrics charts displayed in this project, but without the "after" scores (because the simulations have not been carried out). Each point represents one model, and will have error bars associated with it that relate to the confidence scores.

- Depending upon the optimisation constraints entered by the user as described above, a decision will be made regarding the most optimal tool for the application, together with a confidence score.

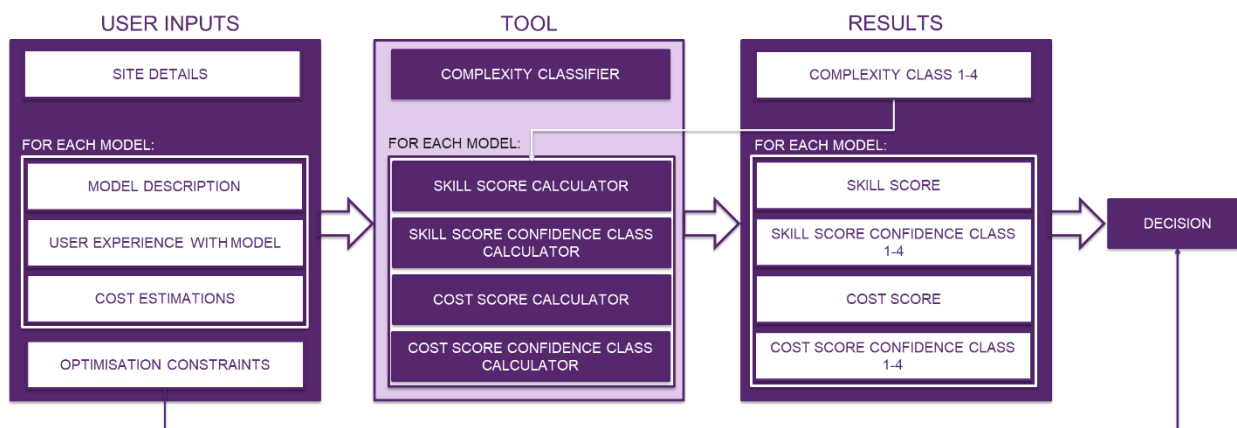


Figure 62. Overview of new decision tool.

A proposed schema for the design of the tool is shown in Figure 62. This tool will be developed and tested, along with the suggested improvements to the Comparison Metrics process, as part of the ongoing SFOE-funded project, "Comparison metrics simulation challenge".

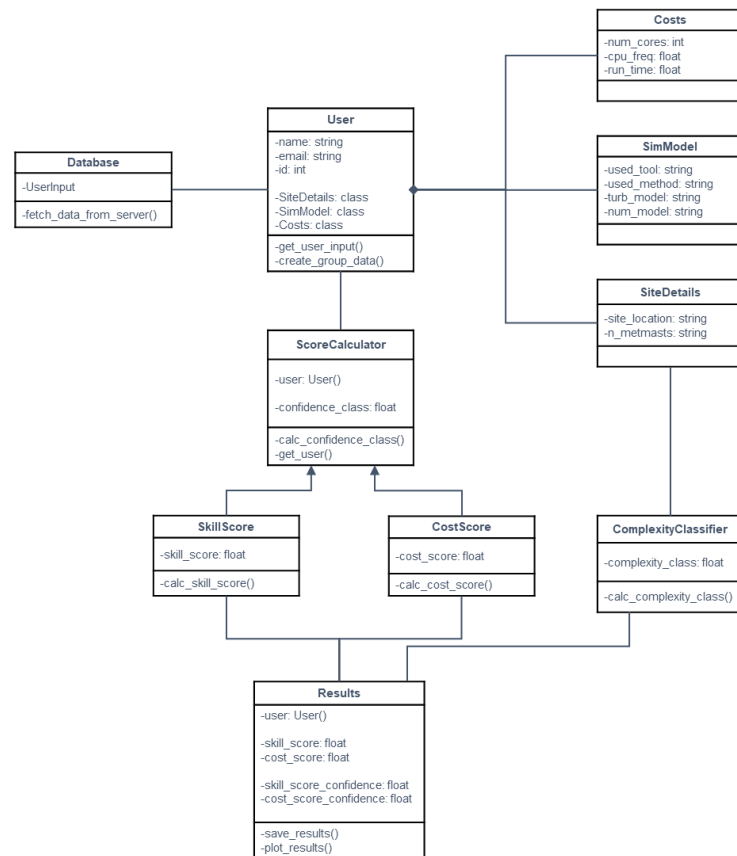


Figure 63. Proposed schema for decision tool.



4 Evaluation of results

In this work, a new industry-relevant process for selecting the wind model that gives the best results with the least computational effort and costs for any given wind energy project has been developed, with a focus on complex terrain. This will help modellers decide which model is optimal for each application, e.g. for Wind Resource Assessments (WRA) where the wind model accuracy has an enormous effect on the project's expected rate of return. The result of the project is the design of a new commercial decision tool, which will be tested as part of the on-going SFOE-funded project "Comparison metrics simulation challenge".

As well this, a large amount of simulation results for four complex terrain sites have been generated. Further analysis is required in order to understand the effects of all the different input variables on the results. As mentioned in Section 3.2, the BKW site is still being analysed. Even though the results are not expected to have an influence on the conclusions of this work, they can be provided later if required.

Furthermore, the automated WRA processes created for *Fluent* and *CFX* will be very useful for further projects, and we intend to publish the scripts on *GitLab*.

The project was very successful, but also very challenging. The large number of simulations carried out by three organisations (four, in the case of Enercon) required significant coordination.

5 Next steps

This project has been completed successfully. The next steps planned are:

- Complete the analysis of the BKW site (30.06.2021).
- Hold presentations at the WESC2021 conference as part of Sarah Barber's Mini-Symposium "The Pragmatic Choice of Wind Models in Complex Terrain" (May 2021):
 - Sarah Barber: "The Pragmatic Choice of Wind Model in Complex Terrain – Decision Tool Development"
 - Andreas Rumpf: "The effect of flow turning on Annual Energy Production estimations in complex terrain"
- Hold a presentation at the WESC2021 conference as part of Andrew Cliftons's Mini-Symposium "Demystifying Complex Terrain" (May 2021):
 - Sarah Barber: "Reducing the uncertainty of Wind Resource Assessments through a new complex flow scoring system"
- Submit a journal paper to the Special Issue "Consistent Computational Approaches for Wind Energy Applications" of the Sustainability Journal⁵ (July 2021)
- Submit a journal paper to Wind Energy Science on the topic of complex terrain classification (June 2021).
- Submit abstracts to the TORQUE2022 conference (Autumn 2021).
- Apply and test the new decision tool in the SFOE-funded project "Comparison metrics simulation challenge" (30.09.2021).

⁵ https://www.mdpi.com/journal/sustainability/special_issues/approaches_wind_energy



- Find a commercial partner to implement the decision process (31.12.2021).

6 National and international cooperation

This project is being carried out in collaboration with Hochschule Esslingen in Germany, who have received funding from DBU. Information and data from the Stötten site has been provided by partners in the WindForS research cluster, including the University of Stuttgart and ZSW (Zentrum für Sonnenenergie- und Wasserstoff-Forschung). The project is being partially funded by ewz (CH), ADEV (CH), Enercon (DE) and BKW (CH).

Furthermore, discussions are already underway for continuing this work on comparison metrics and decision processes as part of IEA Wind. In connection with this, we are contributing to a publication on the topic planned for next year, lead by Andrew Clifton, Operating Agent of IEA Wind Task 32.

7 Publications

The following work relating to this project has been published or is planned:

Published:

- WESC2019 presentation "A new process for the pragmatic choice of wind models in complex terrain – quantification of "skill score" and "cost"" by Sarah Barber [2].
- WESC2019 presentation "Evaluation of the Lattice Boltzmann Method for wind modelling in complex terrain" by Alain Schubiger [3].
- Wind Energy Science Journal Paper, "Evaluation of the Lattice Boltzmann Method for wind modelling in complex terrain" by Alain Schubiger [4]
- Journal of Physics: Conference Series paper, "IEA Wind Task 31: Design of a new comparison metrics simulation challenge for wind resource assessment in complex terrain Stage 1" [5].
- Journal of Physics: Conference Series paper, "Cost reduction of generic modelling tools for wind resource assessment in complex terrain" by Sarah Barber [6].

Planned:

- Presentations at the WESC2021 conference as part of Sarah Barber's Mini-Symposium "The Pragmatic Choice of Wind Models in Complex Terrain" (May 2021):
 - Sarah Barber: "The Pragmatic Choice of Wind Model in Complex Terrain – Decision Tool Development"
 - Andreas Rumpf: "The effect of flow turning on Annual Energy Production estimations in complex terrain"
- Presentation at the WESC2021 conference as part of Andrew Clifton's Mini-Symposium "Demystifying Complex Terrain" (May 2021):
 - Sarah Barber: "Reducing the uncertainty of Wind Resource Assessments through a new complex flow scoring system"



- Journal paper for the Special Issue "Consistent Computational Approaches for Wind Energy Applications" of the Sustainability Journal⁶ (July 2021)
- Journal paper for Wind Energy Science on the topic of complex terrain classification (June 2021).
- Abstracts for the TORQUE2022 conference (Autumn 2021).

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