Research challenges and needs for the deployment of wind energy in ~~atmospherically complex locations~~hilly and mountainous regions

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Abstract. The continuing transition to renewable energy will require more wind turbines to be installed and operated ~~in many new locations on land as well as offshore. The need to have geographic diversity, as well as limited availability of landin historically "good" locations for wind energy, means that~~ on land and offshore. On land, wind turbines will ~~also need to~~ increasingly be deployed in hilly or mountainous regions, ~~often known as "complex terrain"~~which are often described together as “complex terrain” in the wind energy industry. These areas can ~~also experience challenging weather and climate conditions and may experience~~ experience complex flows that are hard to model, and cold climate conditions that lead to instrument- and blade icing ~~that~~ and can further impact ~~their~~ wind turbine operation. This paper – a collaboration between several IEA Wind Tasks and research groups based in mountainous countries – sets out the research and development needed to improve the financial competitiveness and ease of integration of wind energy in hilly or mountainous regions~~and in regions subject to icing~~. The focus of the paper is on the interaction between the atmosphere, terrain, land cover, and wind turbines, ~~and covers~~ during all stages of a project lifecycle. The key needs include collaborative research and development facilities~~,~~; improved wind and weather models that can cope with mountainous terrain~~,~~; frameworks for sharing data; and a common, quantitative definition of site complexity. Addressing these needs will be essential for the affordable and reliable large-scale deployment of wind energy in many countries across the globe. And, because of the widespread nature of complex flow and icing conditions, addressing these challenges will have positive impacts on the risk and cost of energy from wind energy globally.

1 Introduction

~~The global installed capacity of wind turbines has increased by more than than 10% year-on-year for the last decade. Of the 743 GW of installed wind energy capacity at the end of 2020, around 95% was on land, while the rest is offshore (?).~~

Until the early 2000s, wind energy development generally took place at sites in flat and windy terrain (e.g., Denmark, northern Germany, parts of California~~and~~, the wind corridor in the Midwestern United States and Canada, and the plains of

China). ~~Such areas continue to be popular for~~ These areas were popular for the early deployment of wind energy for many reasons including ~~the wind resource~~ strong wind resources and the relative ease of transportation, installation, and planning.

~~Regional and global wind resource mapping exercises have shown that significant wind resources can be found in hilly or mountainous locations. Around 30% of the global land surface can be considered to be mountainous (see e.g. **?**, and Figure 1) .~~

~~The global distribution of mountains.~~

~~The ongoing transition to low-carbon energy sources in almost all nations means that such sites are likely to need to be developed as well as flatter sites to meet the increasing demand and to avoid transmission congestion. Also, some regions or nations simply do not possess sufficient areas of flat terrain and as a result have to build~~

1.1 The importance of mountainous and hilly sites

As the demand for low-emission energy has grown, the installed generating capacity of wind turbines has increased by more than than 10% year-on-year for the last decade. Of the 743 GW of installed wind energy capacity at the end of 2020, around 95% is on land, while the rest is offshore (**?**). Not all of these turbines have been built in flat locations; some developers have built turbines in hilly or mountainous ~~locations if they wish to develop low-carbon energy supplies.~~

1.2 ~~The challenges related to hilly or mountainous locations~~

~~Experience shows that despite the high wind speeds that can be found at~~ terrain, which is often known in the wind energy industry as ‘complex terrain’. Although sites in hilly or mountainous locations ~~, the conditions often bring additional challenges for wind energy development, compared to flat terrain at lower elevations. For example, they can bring complex flow phenomena such as flow separation, high turbulence, and sudden changes in wind speed and direction that can be difficult to model and also negatively impact turbine performance. They can also bring difficult~~ might also have good wind resources due to localised speed up over ridges or escarpments (e.g., **??**), or through passes (e.g., **?**), they bring extra challenges in understanding the wind conditions in such locations (sometimes called ‘complex flow’) and may be prone to extreme weather conditions such as storms~~or icing that make it difficult to forecast plant performance, and can prevent site operations. And, such locations might be more costly or difficult to develop because of steep slopes, narrow roads or poor infrastructure, and snow.~~ , snow, or ice formation. These characteristics can increase the cost and uncertainty of measurements, are difficult to predict, may lead to high variability between nearby locations (**?**), and can lead to increased wind turbine costs and reduced lifetime. Even the perception of risk may result in increased financing costs, adding to the overall project costs. As a result of these challenges, these types of sites are sometimes avoided by wind energy developers.

~~Although a range of flow, meteorological and access conditions all contribute to the challenges of developing and operating a wind plant in such areas, they are often described simply as "complex terrain" sites. The use of such a broad term makes it difficult to be precise about the challenges and potential solutions and associated~~ The global transition to low-carbon energy sources means that wind energy now needs to be deployed in all regions, and not just in historically preferred locations. In Europe, scenarios suggest that between 500 GW and 1300 GW of new wind energy capacity will be needed by the year 2050, which is two to four times the existing capacity; about one third of this new capacity will be installed offshore, while the balance will be installed on land (**?**). This requires installing new wind capacity on land at two to five times the average rate for the period 2015 to 2020 (**?**). Many national and regional governments have policies that encourage distributed development, rather than focusing on areas with the most favourable conditions. This distribution reduces the risk of transmission congestion and provides geographical variability that improves the reliability of energy from weather-driven renewable energy (e.g., **?**).

Together, these trends mean that more wind turbines will need to be built in mountainous and hilly locations that can experience complex flow or cold climates, or both. And, research and development ~~(R&D) needs. Instead, in this paper we refer deliberately to~~ will be required to support this deployment.

1.2 Qualitative definitions

Understanding how important these different aspects of complexity ~~as follows~~are to the deployment of wind energy first requires some qualitative definitions:

- **Hilly and mountainous terrain** is characterised by steep slopes and significant changes in elevation over small distances. This could take the form of mountain ranges or hills, but could also include escarpments, ridges, valleys and gorges. Such terrain is found over large parts of the earth's surface; according to the definitions used by **?**, at least 30% of the earth's land surface can considered to be mountainous. The definition used is provided in Appendix **??**. These regions are plotted in Figure 1.

- Hilly and mountainous terrain is one type of **complex terrain**. Complex terrain is a catch-all label used in the wind energy community that has different meanings depending on the application (see Section **??**).

- **Complex flow** refers to wind conditions that cannot be described by simple heuristic wind models such as logarithmic or power law profiles with sufficient accuracy for wind energy applications. Complex flow is not well described by simple heuristic wind models because it exhibits unusual profiles, curvature, or is inclined. Complex flows also usually show modified turbulence intensity and spectra compared to winds over flat terrain. These flow characteristics may be caused by winds flowing ~~through a mountain pass or over a ridge or other features, but~~ over or through hilly or mountainous terrain because of effects such as deflection, detached or separated flows, compression, and channelling. As a result, they are likely at any time in hilly or mountainous terrain.

  Complex flows may also form in flat terrain or offshore ~~. Highly-sheared flows can also be introduced by coastal winds or the diurnal cycle, for example in the Midwestern United States where low-level jetsoccur~~ because of variation in surface roughness, or because of atmospheric stability. This can lead to the development of internal boundary layers and low level jets, which have been found over flat terrain ~~(?), in~~ in Iowa (**?**) and Northern Germany (**?**), ~~or~~ and over the North Sea (**?**). As atmospheric stability is partially driven by diurnal or seasonal temperature differentials between the boundary layer and ground or water, these phenomena may come and go over timescales from hours to months. As well as this, complex flow can ~~also be found as wakes that form~~ be found in the form of wakes behind obstacles such as wind turbines, buildings, islands or mountains. ~~Complex flow might also arise over flat terrain because of variation in surface roughness, leading to the development of internal boundary layers. Such complex flows usually show increased turbulence compared to winds over a smooth, flat, and uniform surface and also may have a different turbulence spectrum compared to idealised boundary layer turbulence. Using the above definition, complex flow may be reasonably expected to occur over mountainous or hilly terrain, within 30 km of coasts (where sea breezes act), and in forested regions. Therefore, aspects of complex flow could well be very common in wind energy development sites worldwide.~~ The location and presence of such wakes is dependent on mesoscale and local conditions.

– **~~Complex terrain~~Cold climate** ~~is terrain that leads to complex flow conditions, or that leads to other challenges when developing or operating a wind farm. Terrain can lead to complex flow because of its orography through effects such as deflection, detached flows, compression, and channelling. This is often associated with mountains or hilly regions but can also be caused by blockages or gaps.~~ locations experience weather and climate phenomena associated with air temperatures near or below freezing. Here we define cold climates using the criteria set out by IEA Wind Task 19 in **?**, whereby a cold climate can be an icing climate and / or a low temperature climate:

  – **~~Complex weather and climate~~** ~~are meteorological conditions such as snowfall, icing , lightning, and storms that impact the operation of a wind farm. It could also include phenomena such as sea breezes, or thermally-driven valley- and slope wind systems, or outflow jets. These may be driven by local terrain (e.g. through elevation)~~ Icing climates (IC) have instrumental icing during more than 1% of the year (88 hours), or meteorological icing during more than 0.5% of the year (44 hours). Icing can be caused by rime or glaze ice at temperatures at or below 0 °C, but may also ~~simply be an effect of location, with locations at higher latitudes being more prone to low temperatures~~ be associated with wet snow accretion at temperatures from 0 to +3 °C. ~~Complex weather is not unusual; a~~

  – Low temperature climates (LTC) have air temperatures less than -9 °C on more than 9 days per year, or annual average air temperature less than 0 °C.

In the mid latitudes such conditions might occur at all elevations during winter or year-round in hilly or mountainous regions, while in the high latitudes they may occur anywhere, year-round. Many wind turbines have been built in cold climates. A recent IEA Wind Task 19 expert group market forecast ~~showed~~ estimated that around 22% of ~~current~~ wind energy development sites are in ~~"cold climate " locations~~ cold climate locations (**?**). That corresponds to more than 150 GW of capacity in 2020, or 78,000 turbines~~(?).~~ . Of this, around 119 GW was in an icing climate (Figure 2) while 74 GW was in low temperature climate locations; some regions may experience both low temperatures and icing.

– In this paper~~we refer to sites that might have one or more of these characteristics as “complex sites”. These characteristics can increase the cost and uncertainty of measurements, are difficult to predict, may lead to high variability between nearby locations (?), and can lead to increased wind turbine costs and reduced lifetime. Even the perception of risk may result in increased financing costs, adding to the overall project costs. As a result of these challenges, these types of sites~~

~~are often avoided by developers.~~ , we define wind energy development locations in hilly or mountainous terrain that may experience complex flow or cold climates as **complex locations**.

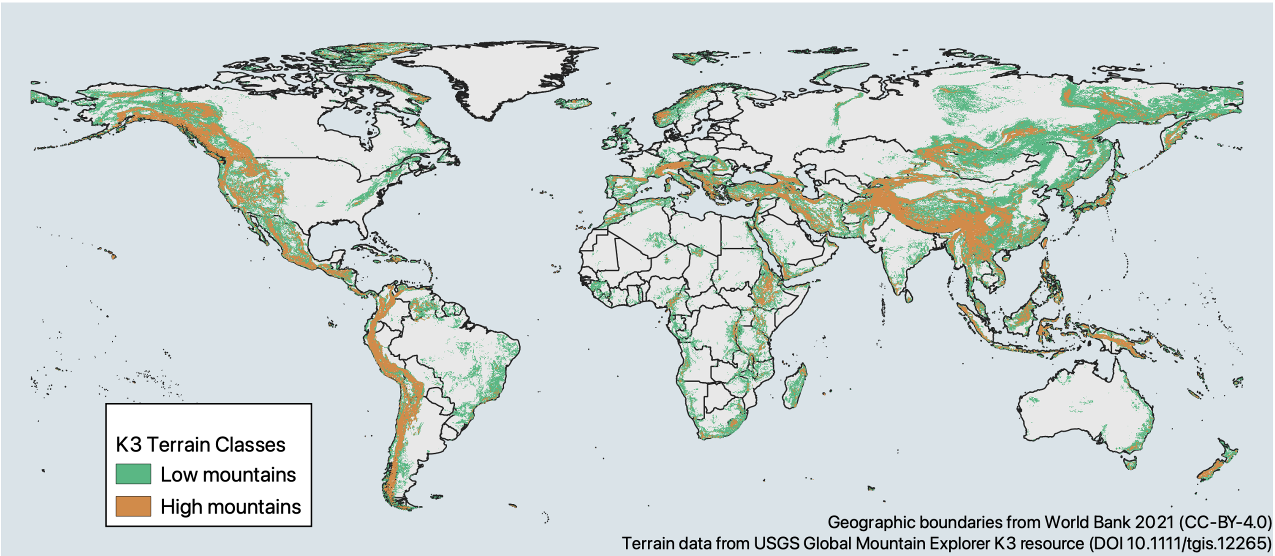

Figure 1. Around 30% of the global land surface can be considered to be mountainous. Data are plotted by the authors from the Global Mountain K3 Datafiles (**?**). The definition of mountainous terrain used for this figure is provided in Appendix **??**. An interactive version of the map is available at https://rmgsc.cr.usgs.gov/gme/gme.shtml.

1.3 ~~Mitigating the challenges of hilly, mountainous or forested locations~~

~~In order to fully exploit the potential of~~

1.3 Research and development needs

In recent years the wind ~~energy,~~ energy industry has taken stock of the ~~increased costs and uncertainties resulting from the particular challenges related to hilly , mountainous or forested locations must be overcome. Mitigating these challenges through~~ research and development (R&D) challenges that it faces. In 2016 **?** proposed a curiosity-driven research agenda for wind energy (**?**), while in 2019 **?** identified three "Grand Challenges" in the science of wind energy that needed to be addressed (**?**). These papers have been useful in raising awareness of significant challenges and in helping set research strategies for wind energy. In this paper, we continue in that vein by identifying the challenges specifically facing wind energy in hilly and mountainous terrain and identifying the R&D ~~is therefore not just of academic interest or relevant for a few developers or wind plant owners, but essential for a successful transition towards a sustainable energy sector~~required to overcome them. We anticipate that this paper will be particularly relevant for researchers and funding agencies in countries with significant areas of hilly or mountainous terrain.

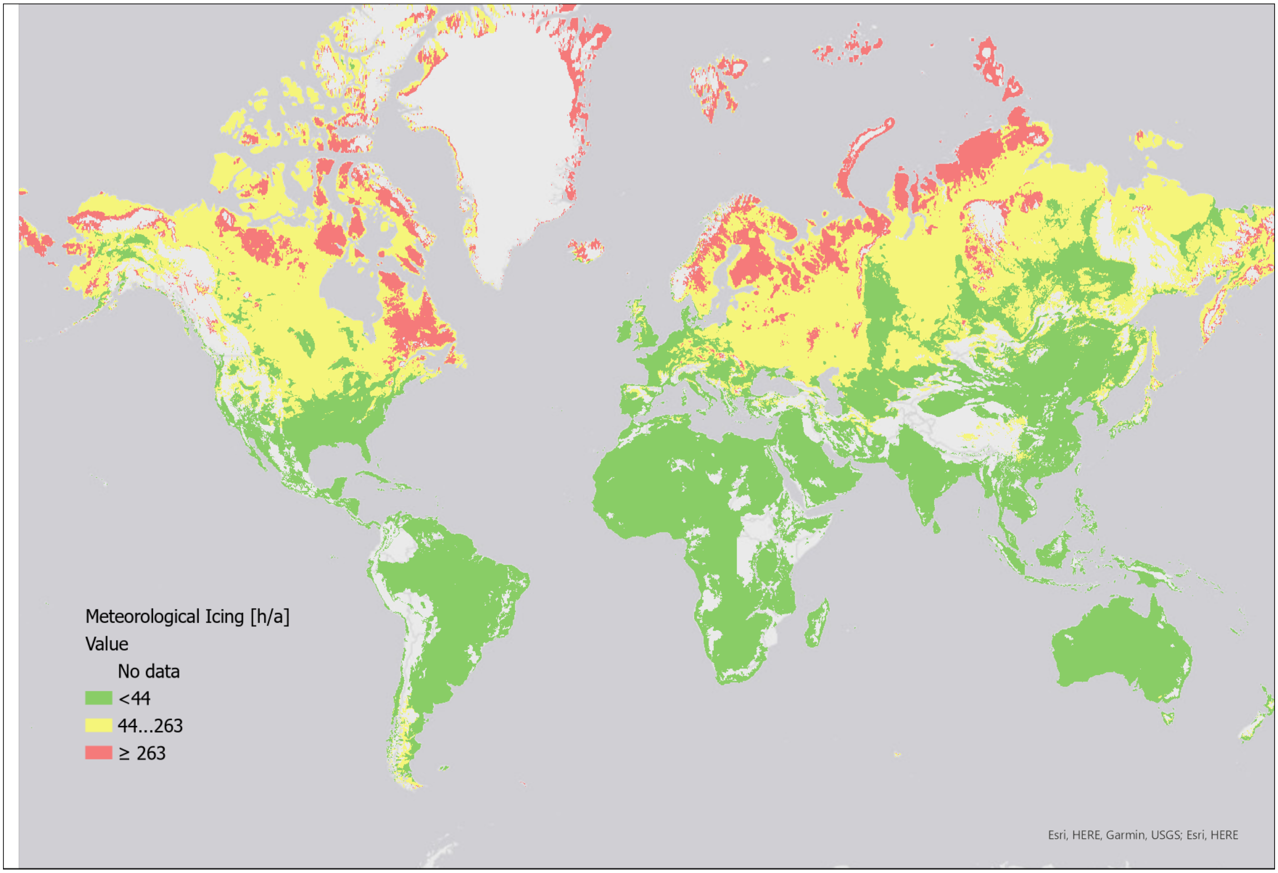

Figure 2. The Technical Research Centre of Finland (VTT) Wind Power Icing Atlas (WIceAtlas), showing the number of hours per year of meteorological icing. IEA Wind Task 19 considers areas with more than 44 hours of meteorological icing to be in an icing climate, which is a subset of cold climate. An interactive version of the map is available at http://virtual.vtt.fi/virtual/wiceatla/.

This paper ~~aims to support this mitigation process by considering the R&D required~~ considers the challenges at each stage ~~of wind energy development~~in the lifecycle of a wind energy project, focusing on the interaction of terrain, wind turbine, wind farm and atmosphere. ~~Section 2~~ Pre-construction issues are explored in sections 2 to 5; section 2 looks at the challenges ~~of~~ in site prospecting, section ~~3~~ 3 at the challenges ~~of~~ for resource assessment, section ~~4~~ 4 at the challenges ~~of~~ for project planning, ~~section 5~~ and section 5 at the challenges ~~of~~ for wind turbine design~~, section 6~~. Section 6 looks at the challenges ~~of~~ for operational wind plants~~and section 7 at general challenges. The conclusions are discussed in section 8.~~. General challenges facing wind energy in complex locations are discussed in **??**. The associated research needs are discussed for each challenge. We also consider the potential impact that addressing the R&D need would have on a wind energy project's negative risks, and the potential impact (either positive or negative) on the ultimate levelised cost of energy of a wind energy development. These are documented in tables at the end of each section together with an estimate of the relevance of the research for wind plant developments in complex locations. The information about impact and relevance allow the various stakeholders in the deployment of wind energy to identify their own priorities for e.g., further research or research funding allocation, or product development. The paper's conclusions are presented in section **??**.

Because of the widespread prevalance of hilly or mountainous terrain and icing, addressing these challenges will be essential for a successful transition towards sustainable energy in many countries.

2 Site prospecting

Site prospecting is a desktop exercise that the process of identifying sites that might be suitable for a wind energy project. It usually uses existing sources of information, such as wind resources, electrical transmission, and infrastructure to identify a potential area for a wind energy project.

At this stage of a wind energy the emphasis is usually on filtering out a assess a large number of candidate areas rapidly and cheaplyto allow the next stages of development to progress. As a result of the need for speed and to keep costs down, the tools that are used in this stage are often based on Geographical Information Systems (GIS)and might use data with coarse spatial or temporal resolution. However, such simplified data can be highly inaccurate in mountainous terrain or complex flow. The main challenges in this phase are: (1) Low accuracy of global or national wind data sets; (2) Low availability of local GIS data; (3) Lack of information about the risk of icing. These challenges , before moving on to wind resource measurements on the most promising sites (next section). The associated challenges and the resulting R&D research needs are discussed in the next sectionsthis section and summarised in Table 1.

2.1 Low accuracy of global or national wind data sets

Site prospecting often typically starts by using wind data from global or national data sets to identify sites with attractive wind conditions. These data sets are often known as wind atlases and include the Global Wind Atlas, New European Wind Atlas (NEWA), the Swiss Wind Atlas (SWA), and others (see review in ?)(see review in **?**). There are also a wide range of commercial products available. Because each country is at different stages in the national or regional deployment of wind energy and thus has different needs from an atlas, nationally-sponsored atlases can differ significantly. For example, it was common in the early days of wind energy deployment to simply plot the annual average wind speed as a map and use this for prospecting (see ?)(see e.g., **?**). Such maps are still often used useful to communicate the opportunity for wind energy . However, as wind energy adoption increases, there to the public or non expert audiences. In regions where wind might be a significant contribution to the energy supply, there often is a need for time-resolved atlases , while in complex terrain wind atlases to include time-resolved data to enable grid integration studies. These time-resolved data sets can be created using numerical weather prediction (NWP) models (see e.g., the WIND Toolkit, described in **?**). And, particularly in hilly or mountainous regions, higher spatial resolution and increased representation of physical processes such as buoyancy-driven flows is required to capture local effects. Without such stepsthese measures, atlases can under estimate the wind resources in complex terrain, under- or over estimate wind resources or hide potentially beneficial regional or seasonal correlations, and thus hide development opportunities . opportunities for wind energy might be missed.

Although many atlases are based on national research efforts, local-scale wind resource data can also be obtained from reanalysis data (e.g., COSMO-REA6 as described in ?). These time-series data products use physics-based modelling, but still lack the spatial resolution required to accurately model winds in complex terrain. Several studies have shown the potential effect of using time-series data from high-spatial and temporal resolution models, compared to time-averaged wind speed distributions from coarser models. To illustrate the effects for this study we created synthetic time series for one year. One data set has no diurnal variation in wind speed. The other data set has a realistic diurnal cycle added for 50 consecutive days. The diurnal cycles are based on data collected in a Swiss alpine valley (?). A comparison of a 48-hour subset of the data is shown in Figure ??. The difference in mean wind speed between the two data sets is about 4%. The wind speed data was then used to estimate the potential annual energy production (AEP) of a 2 MW wind turbine using a generic, realistic power curve. The AEP increased by more than 20% from 1.5 GWh to 1.8 GWh when the diurnal cycles were added. Although the effect of diurnal cycles will depend on the mean wind speed, the magnitude of the cycle, the turbine's power curve and other factors, this example shows the need to use highly-resolved data when making development decisions at all stages of the planning process. The 20% difference in AEP seen in this example could easily be significant enough to trigger government interest in supporting wind energy development in a region, or make the difference for a commercial developer deciding between further developing a site or not.

Examples of wind time series with similar mean values, with (in orange) and without (in blue) diurnal cycles

The accuracy of global or national wind data sets can be improved by taking into account local weather patterns. They have been shown to be simulated well using Large Eddy Simulations (LES) (e.g., ?). However, LES requires prohibitively large computational power as well as high quality input data from weather stations, and it is not feasible to apply the technique to entire regions (such as the Swiss Alps). For However, the use of NWP tools to create wind atlases can be prohibitively expensive. There may be opportunities to learn from other applications, where methods for maintaining the high accuracy of simulations but reducing the computational costs have included the Lattice Boltzmann Method (LBM) and machine learning approaches. LBM is a suitable model class for massively parallel simulations of such type of flows (turbulent, thermal, complex hilly or mountainous terrain, weakly compressible) with real time potential (e.g., ?). The separation of scales of participating phenomena also allows a partitioned approach if necessary (?). Some initial studies on applying LBM to wind flow modelling have been done recently (?); however, there are still a number of difficulties to overcome before it can be used effectively (including high Reynolds number and wall function challenges). Machine learning methods are being used increasingly for extrapolating wind fields (e.g., ?), for post-processing weather forecasts (?), and for downscaling weather data (see e.g. the analog ensemble approach of ?) but not yet for efficiently generalising the flow simulation results and projecting the key simulated flow features to all alpine valleys. terrain.

Therefore, new methods for the extremely computationally efficient prediction of local weather effects at complex sites are required in order to significantly increase the accuracy of wind energy potential estimations.

2.2 Low availability of local GIS data

~~As well as using wind atlases in the prospecting phase, local GISdata is required for planning wind farms~~Site prospecting relies heavily on Geographical Information Systems (GIS) to identify suitable sites. Data on land ~~coverage, zone plan~~cover, land use zoning, the grid connection, and slope steepness is ~~key for planning potential wind turbine locations and therefore for AEPpredictions~~combined with wind data sets to identify suitable sites and estimate annual energy production (AEP). Because these characteristics can change rapidly over small distances in ~~complex~~ hilly or mountainous terrain it is important to have ~~access to~~ this data at high spatial resolution~~, compared to flatter locations. This high resolution data is typically not available from governments or agencies and usually has to be purchased directly from third parties~~. This data can be hard to find and difficult to use.

The low availability of local GIS data can be addressed by developing data marketplaces to help find data, and digital tools that allow easier and standardised access. ~~This should be integrated into~~ These solutions should apply the new framework discussed in ~~Section ??~~§??.

2.3 Lack of local information about ~~the risk of~~ wind turbine icing

~~Wind turbine blade- and instrument icing can potentially result in reduced~~ Ice formation on wind turbine blades or measurement instruments can reduce turbine availability, or reduce the energy ~~production of~~ produced by an operating turbine. This can reduce the attractiveness of a potential development site, but may also ~~penalise sites~~ unfairly penalise sites during the prospecting stage if an overly-conservative prediction is used. It is therefore important to have accurate but low-cost icing models during the site prospecting phase to correctly account for the potential effects of icing on the wind turbines themselves. The ~~VTT~~ Technical Research Centre of Finland's (VTT) icing map (Figure 2) is one example of how this data can be condensed and made accessible for developers.

~~The VTT Wind Power Icing Atlas (WIceAtlas), showing the number of hours per year of meteorological icing. An interactive version of the map is available at http://virtual.vtt.fi/virtual/wiceatla/.~~

~~Site screening specifically needs simple tools to determine icing~~ Other tools are still needed to assess the risk of icing during the site prospecting phase. These should be able to detect and quantify icing conditions from existing measurements, and ~~that can~~ determine the existence of ice throw risk when the icing conditions and potential turbine locations are known. These tools need to be accessible and simple to use without need for complex and detailed simulations.

3 ~~Resource~~ Wind resource assessment

After the wind project site has been chosen in the site prospecting phase, the wind resource has to be assessed in more detail. This involves ~~firstly~~ measuring the wind potential~~over at least a year and then extrapolating this in time~~, extrapolating it to cover the ~~length of the planned operating period (usually 20 years). After this, the wind field is extrapolated horizontally and vertically in order~~ entire planned site, and extrapolating it to cover the ~~entire planned site. Complex sites pose several challenges in the resource assessment phase, including (1) Difficulty planning measurement campaigns; (2) Unknown instrument uncertainty and bias; (3) The sensitivity of remote sensing devices to flow inhomogeneities; (4)Choosing the right measurement instrument;~~

Table 1. Challenges and R&D needs for site prospecting for wind energy in complex locations. Each need is associated with a qualitative estimate of the impact on project risk (high, medium or low), including performance risk; the impact on the project's LCOE (high, medium, or low); and the relevance, which is the approximate proportion of complex locations for which this would be applicable (all sites, most sites, some sites, few sites). The cells are colored for easy overview, and the colours are consistent over each column. The color scale runs from light orange (least impact or lowest frequency of occurrence) to dark red (high impact or highest frequency). Situations where these are not applicable are indicated with '-'.

Challenge	R&D need	Impact on project risk	Impact on LCOE	Relevance
Low accuracy of wind atlases (§2.1)	Inclusion of local and seasonal weather effects	Medium	Medium	Most sites
	Time series databases	Low	Low	Most sites
	Increased spatial resolution	Medium	Low	Most sites
Low availability of local GIS data (§2.2)	Data marketplaces	Low	Low	Some sites
	Digital tools for easier data discovery and integration	Medium	Low	Some sites
	Data sharing frameworks	Medium	Low	Some sites
Lack of information about icing (§2.3)	Simple tools to assess icing severity and probability	Medium	Low	Some sites
	Tools to estimate ice throw risk	Medium	Low	Some sites

~~(5) Higher demands on wind field modelling tools; (6) Difficulties in predicting future wind climates.These~~ planned operating period (usually 20 to 25 years).The associated challenges and the resulting R&D needs are discussed in ~~the next sections~~this section and summarised in Table **??**.

3.1 Lack of guidelines and planning tools

245 Accurate and reliable on-site wind measurements are the basis for any wind energy development. They are required to assess the wind resources and ensure the suitability of wind turbine models. When not available from previous experience, it is therefore necessary to gather this information through on-site measurements. The wind energy industry has gained most of its experience

with wind measurements in simple terrain and this has been captured in industry guidelines such as the Fördergesellschaft Windenergie (FGW's) ~~Technical Guidelines for Determination of wind potential and energy yields~~ *Technical Guidelines for Determination of wind potential and energy yields* (TG 6). These and other documents make it relatively easy to design and execute a resource assessment campaign. They also reduce the time taken to plan and initiate a measurement campaign, as well as increase confidence in the results. However, there is a relative paucity of applicable, open knowledge about wind measurements for wind farms in ~~complex~~ hilly or mountainous terrain, and no applicable standards or guidelines.

Guidelines and experience can be embedded in planning software so that the campaign can be optimised to reduce cost, uncertainty, or meet some other goal. Some progress has been made towards this for wind lidar deployments with the Campaign Planning Tool (**?**), but this is limited to measurements using scanning wind lidar. There is therefore a clear need first for guidelines and standards for resource assessment in ~~complex terrain~~ hilly or mountainous terrain terrain that can then be used as the basis for other campaign planning tools.

3.2 Unknown instrument uncertainty and bias

The response of measurement instruments can be different in complex flow conditions compared to simple flow. For example, cup anemometers are by far the most commonly used devices for measuring wind speed. However, they suffer from increased uncertainty in inclined or highly-turbulent flows (**?**), and so standards have long limited their use to a narrow range of inflow angles ~~(e.g., **?**)~~(e.g., **?**). Three-dimensional sonic anemometers are designed to work with such complex flows, but historically it has been harder to analyse the data coming from these devices and they tend to be more expensive than cup anemometers. They are also less reliable in rain or freezing conditions, but can be modified to work effectively. Similarly, remote sensing devices may need to use data processing approaches that can account for flow heterogeneity (**?**). Furthermore, almost all measurement devices can become coated with ice, which can modify their readings or prevent them from working at all (**?**). These factors can increase the uncertainty of the measurements themselves as well as the uncertainty of the uncertainty predictions and bias estimates used to estimate project risks.

There is a need for tools to reliably predict the measurement uncertainty and biases. These should ideally build upon the methods used for optimising the measurement campaign, but apply on-site measurements as well as expected wind roses and data from GIS systems. Such tools could also leverage the tools used for wind ~~data extrapolation~~ modeling (see following).

3.3 The difficulty of using remote sensing devices to supplement or replace met masts

~~Remote sensing of wind using wind lidar~~

Meteorological towers can be used to measure wind speed, direction, and turbulence, as well as profiles of temperature, pressure, humidity, and other meteorological variables.

Remote sensing devices estimate the wind speed and direction by measuring the line-of-sight wind speed at different azimuth and elevation angles from the sensor. These data are then fit to a wind field model using a process called wind field reconstruction. This process often assumes a homogeneous wind field.

Remote sensing of wind speed and direction using vertically-profiling wind lidar or sodar is well established for wind resource measurements, power performance testing, and site monitoring in simple terrain and offshore . It is clear that the (?). Experience so far suggests that wind lidar can be used with confidence for such applications ().

The flexibility and ease of use of vertically-profiling wind lidar as well as the relatively small size make of the equipment itself, makes it ideal for use in complex sites as well, and offer advantages over meteorological towerslocations as well. However, remote sensing devices, wind lidar and sodar, use much larger measurement volumes than point measurement devices. This can mean that they measure in inhomogeneous flows in complex flow conditions the flow might not be homogeneous (Figure 3), which in turn may . This could introduce errors in the windfield reconstruction process if not accounted for (see e.g. ?). Complex flow conditions thus may introduce additional uncertainties to measurements with , and could also cause differences between wind data from colocated remote sensing devices .

Complex terrain can introduce flow inhomogeneity in the measurement volumes of remote sensing devices. In this illustration the terrain (green) causes local speed-up and inhomogenous flow (represented by grey streamlines) through a lidar's measurement volume (represented by the red cone), upwind of a wind turbine.

Processes have and anemometers. Processes have therefore been developed and tested to equate data from volumetric measurements made by profiling wind speed and direction data from vertically-profiling wind lidar to familiar point measurements made by meteorological towers. Experience so far suggests that wind lidar can be used with confidence in locations that conform to the manufacturer 's guidelines (?, see e.g.), but it is clear that , and experience suggests that these are reliable in flat terrain and hilly or mountainous terrain locations, within limits defined by the manufacturer (see e.g. ?). However, future wind energy developments may move take place in terrain or flow conditions that are outside of these existing guidelines.

the manufacturer's guidelines. Research is therefore ongoing into the use of vertical-profiling wind lidar in more complex locations complex flows or hilly and mountainous regions (see e.g., ??) . And, scanning lidar

To be able to replace a meteorological mast, wind lidar data would have to be able to be processed to provide wind turbulence information that is comparable to a cup anemometer. At this time there is no clear consensus about the steps that should be taken to equate wind lidar turbulence to the turbulence derived from a cup anemometer (see e.g., ???). Although there are many possibilities to post process wind lidar data to retrieve turbulence information, the lack of open data sets prevents these from being tested. There is therefore a need for a collection of open data sets consisting of colocated wind lidar and anemometers in well-described locations that could be used to validate data processing methods.

3.4 Barriers to the adoption of scanning wind lidar

Scanning wind lidars have been seen to be vary useful for measuring wind conditions in complex hilly or mountainous terrain in research projects (??). However, the The experience reported there suggests that such three-dimensional wind scanners must currently be considered research devices that and elsewhere suggests that scanning wind lidar require extensive monitoring and post-processing to obtain usable data, and so are currently mostly suited for research. This is unfortunate, given their tremendous measurement capabilities compared to fixed masts. Research is therefore needed into ways to simplify the use

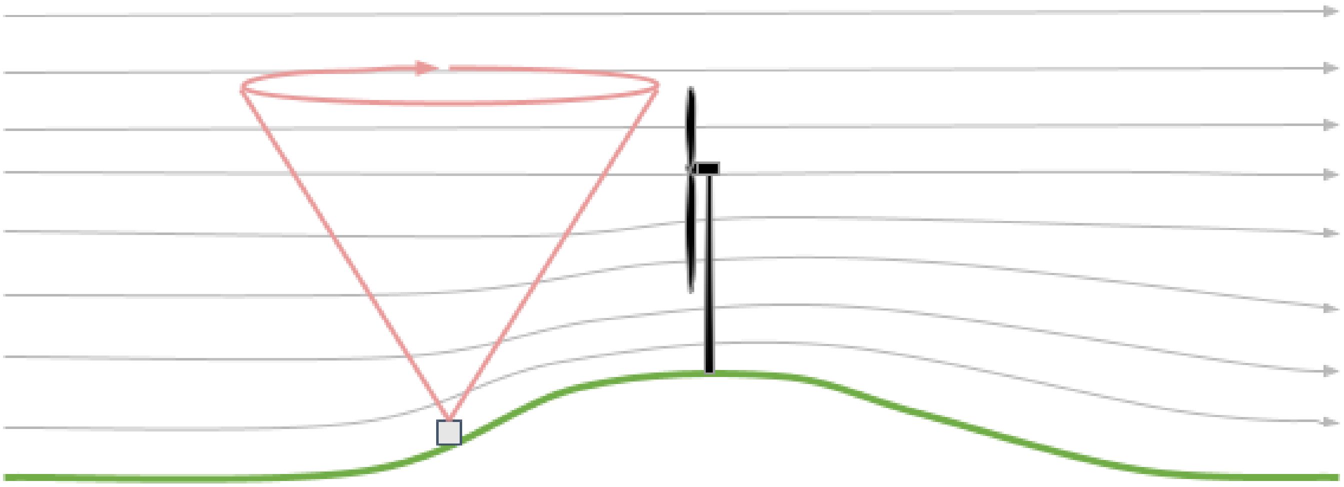

Figure 3. Terrain can sometimes introduce flow inhomogeneity in the measurement volumes of remote sensing devices. In this illustration the terrain (green) causes local speed-up and inhomogenous flow (represented by grey streamlines) through a lidar's measurement volume (represented by the red cone), upwind of a wind turbine.

of scanning lidar, as well as to process the results. Lidar manufacturers may also need to reduce the cost, weight, and power requirements of their devices to make them easier to deploy.

To truly replace meteorological masts, wind lidar would also have to be able to deliver reliable wind turbulence information. At this time there is no clear consensus about the ability of wind lidar to do this, or the steps that should be taken to equate wind lidarturbulence to the turbulence derived from a cup anemometer (see e.g. ???). Although there are many possibilities to post process wind lidar data to retrieve turbulence information , the lack of open data sets prevents these from being tested. We therefore suggest that there is a need for a collection of open data sets consisting of colocated wind lidar and anemometers in well-described locations that could be used to validate data processing methodsMultiple, overlapping scanning wind lidar (often known as multi lidar or dual Doppler wind lidar) might be capable of solving challenges with wind field reconstruction, and deliver turbulence information in complex flows, potentially without the need for synchronized sampling (see e.g., **??**). However multi lidar systems are expensive and difficult to use, and so are usually only used for academic research.

The variation in wind energy sites mean that it It is unlikely that one type of lidar and one processing approach will work for all sites. But, customised solutions are expensive. Instead we expect to see the development of flexible, digital, modular processes that allow appropriate solutions at each step of the process. This These should leverage available data frameworks such as the e-wind lidar data format (**?**) to build ad-hoc modular processes. This trend to modularisation of processes – enabled by common data formats – has been seen elsewhere in the wind energy industry and is part of the trend towards greater digitalisation of the wind energy industry.

Further research is needed to show the value added by single or multiple scanning wind lidar, as well as product development to reduce costs and improve ease of use. And, research is needed into how to benefit from the digitalisation to wind lidar.

~~Research is needed therefore into tools that make it easier to use wind lidarin complex flows, complex terrain, and complex weather. These should leverage available data frameworks such as the e-wind Lidar data format () to build ad-hoc modular processes.~~

3.5 Integrating airborne measurement systems

Although wind lidar partially mitigate the challenges of using meteorological masts in ~~complex~~ hilly or mountainous terrain, they ~~do not allow high spatial resolution measurements.~~ can also be challenging to deploy. They are also only able to measure wind data, meaning that other weather data might be missing. In contrast, ~~measurement systems~~ meteorological measurement systems can be mounted on unpiloted aerial vehicles (UAVs) including fixed-wing aircraft (**?**), helicopters (**?**), and multirotor drones (**?**)~~can all~~. This allows UAVs to be used to measure wind vectors and turbulence, as well as other parameters such as air pressure, temperature, and humidity. However, such systems can usually only measure for short periods of time ~~and only measure at one location.~~ (up to a few hours at most), and measurements can only be made locally to the UAV. It would therefore be advantageous in future to improve vehicles so that they can fly further or for longer, or carry more sensors. UAVs can be moved to sample other locations, but this leads to a patchy data set. Multiple drones can be flown simultaneously to cover multiple points or a larger area, but this adds complexity and requires more pilots. It may also be possible to combine the flexibility and access offered by drones with the remote wind sensing capability of lidar (**?**).

Research is needed into ways to fly multiple systems simultaneously and autonomously (sometimes known as ‘swarms’), and to combine the data from these airborne systems with other data sources. This process, known as ‘sensor fusion’, ‘data fusion’, or ‘data assimilation’ (when used as an input to models) is frequently used in weather forecasting but has not been an active area of research for wind resource assessment. However, given the known high spatial variability of winds in hilly or mountainous terrain UAVs combined with sensor fusion may be a beneficial tool and could reduce the uncertainty of wind resource estimates.

3.6 Choosing the right measurement instrument

The choice of optimal wind measurement device as well as its location and the measurement time period is a critical part of a wind resource assessment and site operations, and is especially challenging for complex sites due to the increased uncertainties as described above. There is currently no existing guideline, standard, or tool available to project planners for doing this. ~~Therefore the development of guidelines, standard or tools for choosing the right measurement instrument~~ These would be required to address this challenge.

3.7 ~~Higher demands~~ Demands on wind field modelling tools

Wind fields across planned wind farm sites are typically generated using a combination of on-site measurements with some form of flow model. The ~~modelling is~~ models are used to extrapolate from on-site data from a few locations that might only extend to a limited height above ground, to the tip of the potential wind turbines across the whole site. ~~This is often known as~~

horizontal and vertical extrapolationAccurate wind resource assessment is therefore strongly dependent upon the capability of the wind modeling tools.

There is broad academic consensus that the linear flow models that are often used in "simple" terrain simply cannot predict the winds and weather at complex sites because of the As was noted in the introduction, hilly or mountainous regions are associated with steep and changing slopes, forestry, and the effects of atmospheric stability. There is hope, however, that models that include additional physics may allow to capture effects such as . They can also have forestry, patchy ground over, and seasonal variation in ground cover. This can lead to highly localised complex flows with strong seasonal and diurnal cycles. These can be considered to be 'extra' physical processes compared to the flows found in flatter, more uniform, lowland sites. It is well established in the wind energy industry that neglecting these physical processes can lead to poor wind modeling, which has led to efforts to include buoyancy or forest canopy effects (see e.g., **??**). These models are often described collectively as Computational Fluid Dynamics (CFD) models. In turn, there are many different types and fidelities of CFD models, ranging from Reynolds-Averaged Navier Stokes (RANS) models, Detached Eddy Simulation (DES) models, Large Eddy Simulation (LES) models, and Lattice Boltzmann Method (LBM) models(**?**). where LES models are often used in the wind energy community for time-resolved simulations of complex turbulent flows as they offer the ability to resolve turbine-scale flows in realistic terrain (see e.g., **?**). in models (see **?**, for a review of ongoing research in this areas). More work is required to develop and test these and other physics models.

However, even high-fidelity LES models cannot overcome the greater difficulty of simulating the real flow. As an illustration Figure 4 shows the Root Mean Square Error (RMSE) of 10 m wind speed of the numerical weather prediction model ICON-D2 in March 2021 for sites below 100 m a Increased vertical and horizontal resolution can be helpful to capture the effect of land cover and terrain features, but this increases the computational requirement of a simulation. Similarly, some modeling approaches might require a time-resolved simulation, instead of assuming steady-state conditions. This further increases the computational cost, which increases the cost to the customer and can slow the process down. Research is needed into ways to make such high-resolution and time-resolved simulations both cheaper and faster. s.l., i.e. for rather flat terrain, and for sites above 800m a .s.l., i. e. in hilly and mountainous terrain. The RMSE is only calculated for sites which are accepted by the assimilation system. The wind speed at sites at higher elevations (i.e hilly and mountainous terrain) is less well predicted than sites at lower elevation.

RMSE of 10 m wind speed from the numerical weather prediction model ICON-D2 in March 2021 compared to observations at sites below 100m (red) and above 800 m a.s.l. (green). The ICON-D2 domain covers central Europe including most of France to Poland, and from northern Italy to Denmark and thus locations above 800 m are typically in hilly or mountainous terrain. For details of the ICON-D2 model, see **?**.

These more More complex flow models usually need realistic boundary conditions to deliver accurate results. These may include pressure gradients, surface temperature and moisture conditions, solar radiation or surface heat fluxes, upwind wind profiles, forestry parameters, and other data (**?**). Often these models have many "tuning" parameters, and it is not clear if one set which was successfully used in one case study is equally good for all weather situations at a different place. Different available topographical data might require different tuning parameters for some parameterizations of the model. As a result, complex models are harder to use than simpler models, both in terms of the data required and the knowledge required to assess the results.

Additionally, there is often no clear evaluation data available for such models, and therefore it is difficult for wind resource engineers to decide on the most effective model for a given site. Although software developers often provide site-specific case studies, the lack of a clear definition of complexity and an applicable, relevant comparison metric means that it is difficult to transfer experience from one site to another.

The main research need resulting from the challenge of modelling wind fields at complex sites is to improve atmospheric models . The high resolution time-resolved flow models used for wind resource assessment are often derived from forecasting models. Therefore, improvements to forecasting models would benefit wind energy directly. As an illustration of the potential for improvement in atmospheric models, Figure 4 shows the Root Mean Square Error (RMSE) of 10 m wind speed of the numerical weather prediction model ICON-D2 in March 2021 for sites below 100 m a.s.l., i.e. for rather flat terrain, and for sites above 800m a.s.l., i.e. in hilly and mountainous terrain. The wind speed at the higher elevations sites is less well predicted than sites at lower elevation.

Several research challenges for atmospheric models are clear:

- Major improvements for wind energy modelling can be expected from better boundary layer schemes and turbulence models. Schemes for the surface layer are often based on Monin-Obukhov theory, which is strictly valid only for homogeneous sites. Also, in turbulence schemes for atmospheric models horizontal gradients of fluxes and other second order moments are usually neglected compared to vertical gradients. It is not clear at which resolution in complex hilly or mountainous terrain this simplification is no longer valid. Direct numerical simulation of turbulence is too costly for wind energy assessment.

- All models have tuning constants with values obtained in comparing model results to experiments. However, care must be taken not to deteriorate model results when changing them (**?**). Especially for weather prediction models there can be conflicting interests. One quantity might improve, but, another one might deteriorate. Hence, changing established values must be done carefully even though it might be beneficial in complex terrainhilly or mountainous terrain, changing established values must be done carefully.

- Even at mesh sizes of only 2 or 3 kilometers, the subgrid-scale orographic drag must still be parameterized (**?**). The tuning constants of a sub grid scale scheme depend on the ratio of resolved to unresolved orography which depends on the resolution of the original data used to produce input fields for a subgrid scale scheme. This can be critical for the simulation of winds at typical hub heights.

- Accurate numerical schemes are always critical in complex hilly or mountainous terrain. Especially the calculation of horizontal pressure gradients should not yield spurious circulations in terrain-following coordinates (**?**).

A second research need resulting from the challenge of modelling wind fields at complex sites is to develop a decision tool for the optimal choice of wind modelling tool.

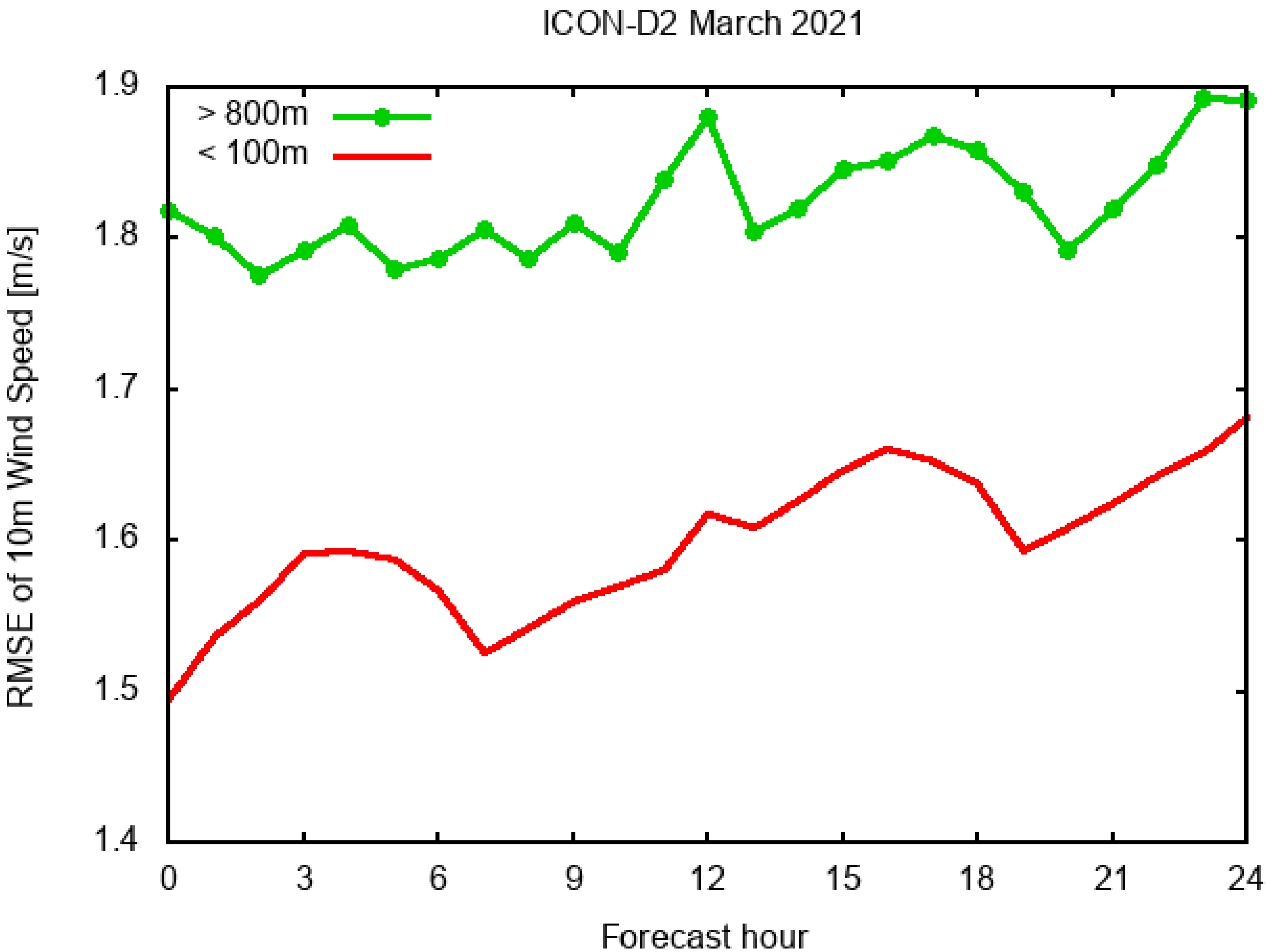

Figure 4. RMSE of 10 m wind speed from the numerical weather prediction model ICON-D2 in March 2021 compared to observations at sites below 100m (red) and above 800 m a.s.l. (green). The ICON-D2 domain covers central Europe including most of France to Poland, and from northern Italy to Denmark and thus locations above 800 m are typically in hilly or mountainous terrain. For details of the ICON-D2 model, see **?**.

Despite the potential for more accurate flow modeling, the required skill upgrade, cost of data, and the lack of evaluation data all act as barriers to the adoption of more advanced wind modelling tools. Research is therefore needed in ways to help people choose and use appropriate wind models. ~~There is a clear need for~~ This could take the form of software or services that ~~uses consistent~~ apply rules to set up and run such models, hiding the complexity ~~from the user~~ and thus making it easier for users to adopt them (see e.g., WindNinja [**?**] or WAsP CFD [**?**]). Furthermore, rules- or process-based modelling would give data consumers confidence that the tools have been used appropriately. ~~Recent work involved the development of~~ Research has started into a decision tool for the optimal choice of WRA tool for a given project at complex sites (**???**). However, in order to fully develop an effective decision tool, a much larger set of data related to different site complexities, model set-ups and costs is required. ~~The required skill upgrade, cost of data, and the lack of evaluation data all act as barriers to the adoption of more advanced wind modelling tools.~~

Finally, wind modelling needs to follow repeatable, auditable processes that provide the end user with confidence that the results are trustworthy and based on experience gathered at other sites, rather than each site being an independent study. This will require the wind energy industry to develop software and services to consistently set up wind flow models. This can be combined with the data sharing framework discussed in Section ~~??~~**??**.

3.8 ~~Difficulties in predicting~~ Predicting future wind climates

An important part of a wind resource assessment is predicting the future wind climates. This estimate may need to extend up to 30 years in the future. It is typically carried out by comparing site data to some kind of long-term reference weather data, such as observations from a nearby automated weather station or reanalysis models, and using this to predict the future wind resource. This process is known as measure-correlate-predict (MCP) and takes many forms.

Errors depend mainly on the length of the measurements, and the correspondence to the long time series at the reference site. Both sites must have a similar wind climate, e.g. a coastal station with frequent sea breezes can hardly be correlated with an inland mountain site.

Such extrapolations depend upon the regional climate in the future being comparable to the past. However, it is not clear if this will be true as climate change occurs. ~~On complex sites this also concerns changes in~~ Sites in mountainous regions or that depend on thermal winds may experience marked changes in wind regimes if long-term ~~and~~ or seasonal snow cover ~~in alpine and mountainous regions, which may affect surface temperatures and the associated valley wind systems that contribute to wind energy in some areas~~is reduced. Climate change may also result in changes to the frequency and intensity of storm systems and icing and extreme weather events. While many of the effects of climate change are negative, some may also have positive consequences for wind energy; it is, e.g., possible that turbines at higher elevations might experience less icing in future than previously, raising their energy production.

Although some attempts have been made to predict the effects of climate change on wind climates, results suggest that these effects may be strongly localised and site-specific and as such, cannot be captured using today's relatively coarse global climate models (**?**). Although regional climate models offer higher spatial resolution, they may be out of reach of developers and the wind industry because of the specialist knowledge required to use them.

The first research need related to improving the prediction of future wind climates at complex sites are affordable MCP processes that can account for the complex wind situations and climates found at complex sites. They need to be reasonably easy to use so that they can be applied quickly to different locations as part of the site design process. They also need to be validated using existing sites.

Furthermore, it will be important to develop MCP processes that include the effect of climate change on complex sites. Because the effects of climate change in mountainous regions are potentially highly localised and site-specific ~~, this might not be an automated process initially and could instead take the form of expert opinions for sites, identifying risks associated~~

with different weather conditions due to climate change. In any case, (?), this is often provided as expert opinions that tend to be expensive and time consuming. Longer term, the EU's Copernicus Climate Change Service (C3S) project - which aims "to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide." (?) – may make it easier for developers to access relevant data and tools. However, currently there are no industry-standard approaches to assessing the impact of climate change on wind energy developmentsat this time. . Research is therefore needed into methods for estimating the effect of climate change on wind farm performance.

The second research need related to improving the prediction of

4 Project planning

Following the resource assessment, an energy yield assessment is carried out by firstly using the results of the resource assessment to choose turbines' locations, and then estimating AEP. This information is then used for financial and risk estimations. Finally, public acceptance for the project has to be gained for it to proceed. The specific challenges related to these steps include (1) Increased uncertainty of wind turbine performance models; (2) Site-specific wind farm design; (3) Increased financial uncertainties; (4) Increased conflict potential between stakeholders. These challenges and the resulting R&D needs These challenges are discussed in the next sectionsthis section and summarised in Table ??.

4.1 Increased uncertainty of wind turbine performance models

The power produced by a wind turbine is a function of wind speed, air density, turbulence intensity, shear, veer and many other factors. Although it is common to apply a site density correction to the power curve according to IECfollowing the process set out in the International Electrotechnical Commision (IEC) 61400-12-1:2017 standard (?), the other factors are difficult to account for, and therefore less frequently considered. Studies have shown that such atmospheric conditions can affect the turbine output by 10% or more at the same wind speed, leading to a significant uncertainty in power prediction even if the wind speed and density are known (e.g., ???????)(e.g., ???????).

Tools that can predict performance at specific sites are therefore required. As well as wind speed, these need to take into account other atmospheric conditions at a turbine's location – such as shear, veer, and turbulence intensity – to estimate the power output at that location. They could be based on experience and leverage data sets from existing power performance tests to generate binned statistics (as explored by the Power Curve Working Group in ?)(as explored by the Power Curve Working Group in ?), or use physics-based approaches as in the IEC 61400-12-1:2017 standard (?). Physics-based approaches have the advantage of being repeatable and easily understood by people, but may not make the best use of the large amount of data available to the wind energy industry.

In contrast, machine learning has the potential to account for the effects of unknown or hard-to-model physics by using power performance data sets to train turbine performance models. These trained models can be used in place of power curves or physics-based models. Studies suggest that power predictions by machine learning tools trained on wind speed, turbulence, and other atmospheric parameters can reduce the error compared to simple power curves (??). The application of machine learning methods to real measurement data is on-going (see e.g., ?)(see e.g., ?). It may be possible to leverage data from power performance tests across a fleet to make more accurate machine learning models. However, machine learning approaches suffer from being "black boxes" in that it is often impossible for a human person to understand what they contain. This can make it hard to include them in a turbine supply agreement or a warranty, for example.

Collaboration between research and industry is required to develop and test more complex power performance prediction tools that use multiple parameters or machine learning, and mitigate the barriers to their adoption.

4.2 Site-specific Additional information required for wind farm design

Wind farms are usually designed with the goal of minimising the long-term cost of energy from the site, usually termed the Levelised Cost Of Electricity (LCOE). This is done by optimising the number, size, and layout of turbines on site to maximise energy production and minimise operating costs through an optimzation process to minimize the ratio of project cost to lifetime income (**?**). Accurate wind field models (§3.7) and long-term wind climate data (§3.8) are essential to this; they are foundational for the process of estimating turbine energy production or long-term viabilitytherefore foundational for this step.

Wind turbine energy production at a site is a function of the energy that can be harvested by a turbine, and the losses from that turbine. Wind resource data can be used to predict the energy available from a turbine using power curves (with and without adjustment for turbulence, shear, and veer) or aeroelastic models (e.g. NREL's FAST and others), while other models are required to predict the wakes from those turbines and their impact on downwind machines. It is also important to account for losses due to environmental effects such as blade soiling, and the formation of ice on the turbine blades or instrumentation. Knock-on effects such as turbine shutdowns to minimise ice throw, or slower maintenance in challenging weather should also be included in the plant energy yield assessment process.

Current wind turbine performance models are designed around inflow angles, shear, and turbulence that lie within standard ranges (defined in e.g., the IEC 61400-12-1:2017 standard). Although there has been some effort to develop power curves that cover a wider range of conditions, these have not been widely adopted or tested openly for complex sites (§5.3). Wakes from turbines have been extensively measured in simple terrain on land, and offshore. However, there are many fewer wake measurements from more complex hilly or mountainous terrain, where it is possible that increased turbulence and inclined flows may lead to faster dissipation (**?**).

The challenge is therefore to provide wind farm designers with the information that they need to optimise a wind plant at a complex site. This includes appropriate wind fields and an icing climatology for the location, turbine performance models that can account for non-standard operating conditions, and wake models that capture the effect of complex flow and terrain on wakes.

Many different wake models exist and many have been validated for use in simple terrain. However, it is not clear how well these models perform in complex hilly or mountainous terrain or in complex weather situations. Validated wake models would allow increased confidence in energy yield analysis carried out in complex hilly or mountainous terrain locations. Wake models could be validated through field measurements, for example combining data from from met masts, wind lidars and wind turbines (**?**). This data would also allow the creation of new wake models. These improved wake models could be used to give better predictions of the wind resources available to downwind turbines.

4.3 Increased financial uncertainties

All of the previous factors lead to uncertainty in the potential income from a planned wind energy project.

Electricity from wind energy is usually sold through long-term energy supply contracts with a customer. If the contracts are too expensive, the wind farm owner risks being underbid by another supplier. Therefore, the developer is under pressure to drive the cost of energy as low as possible. However, if these contracts are too cheap (i.e. energy is sold at less than the cost to produce it), the owner risks losing money. To protect against such risks, the project financiers can increase the interest rates on any loans, which in turn increases the project cost and the LCOE.

Project developers typically mitigate these risks by carrying out extensive and detailed pre-construction studies. While these may be more expensive at complex sites than are required in simple terrain, they can reduce the uncertainty enough to reduce the overall project costs and thus justify the extra expense, especially if the site has a high capacity factor. However, there are no guidelines or standards for doing this.

In order to approach the challenge of planning and financing with uncertainties, a guideline for dealing with additional risk related to complex sites is recommended. This would allow project developers to mitigate the risks by carrying out extensive and detailed pre-construction studies in a standardised and agreed-upon way.

4.4 Increased conflict potential between stakeholders

Developing and operating wind energy projects involves a large number of stakeholders. As well as those directly involved with the development, they affect local residents, visitors, and people further away through visual impact, shadow flicker, sound, traffic, and other mechanisms.

The acceptance of wind farms by stakeholders is one of the major barriers to the adoption of wind energy. Acceptance must be considered for all wind farm developments, both on land and offshore. Experience suggests that wind farm acceptance can be increased through appropriate and sympathetic wind farm visual and acoustic design (**?**), coupled with positive stakeholder engagement (**?**). These challenges may become harder at complex sites because hilly or mountainous regions may be important for tourism or recreation, wildlife, or other uses, leading to potential conflict between stakeholders ~~(see e.g., ?)~~(see e.g., **?**).

Also, it is possible that the physical processes linked to social acceptance may be harder to predict in ~~complex terrain or at complex sites~~hilly or mountainous terrain. Sound propagation from wind turbines is fairly well understood over flat and uniform terrain in uniform wind conditions and can be modelled with some accuracy. In contrast the physical effects of ~~complex~~ terrain or patchy landcover on sound propagation are less well understood and sound reflection by terrain or damping by forestry have only recently started to be explored (see review in **?**).

Securing public acceptance is thus one of main challenges the development of wind energy has to face in the next decades. This is part of the growing need to obtain public acceptance – and even more important support – for the far-reaching technological changes connected to the transformation to a carbon-neutral energy generation and the associated social and economic impact. Developing wind energy in ~~complex~~ hilly or mountainous terrain is just one focus point where, e.g. the prominent and highly visible siting of wind turbines on peaks and ridges in mountainous regions, may evoke concerns about landscape conservation and touristic and recreational uses. Technical measures such as reducing and managing of the wind turbine's sound and light emissions or changes in turbine design and wind park layout may contribute to a certain degree to the alleviation of these concerns. However, social acceptance of wind energy in ~~complex~~ hilly or mountainous terrain might also grow from ongoing social transformations through policy making, fostering of the public understanding of the need for renewables, and the personal participation and benefit from renewable energy projects. One of the initiatives on this interface between technology and social research is the IEA ~~UsersTCP~~Users TCP, which also has a big focus on the social acceptance of clean energy technologies.

5 Wind turbine design

~~Complex sites pose challenges for wind turbine design due to the complex flow conditions. This includes (1) Increased importance of quantifying the operating conditions at complex sites; (2) Higher complexity of input conditions for wind turbine modelling; (3) Identifying the freestream wind speed for power performance measurements; (4) Identifying the freestream wind speed for mechanical loads testing; (5) Taking into account icing in the design.~~ After a wind resource assessment has been completed, a suitable wind turbine needs to be selected. Wind turbines are designed to operate safely and predictably on the basis of expected operating conditions at a site. The complex flows and cold climates associated with hilly or mountainous terrain create a range of challenges for this process. These challenges and the resulting R&D needs are discussed in ~~the next sections.~~ this section and summarised in Table **??**.

5.1 ~~Quantification of operating conditions at complex sites~~

~~Operating conditions at sites in complex terrain often fall outside "typical" values.~~

5.1 Lack of understanding of operating conditions at complex sites

Historically wind energy standards ~~focus~~focused on the operating conditions found in early development areas such as ~~those found in~~ northern Europe or the American mid west, giving rise to a few standard operating envelopes that are captured in turbine classes. Small deviations from the ~~operating conditions in such sites are captured using~~ standard operating conditions – such as those found in in hilly or mountainous terrain or cold climates – are given special classes. The design conditions for each special class usually have to be determined on a case-by-case basis~~, requiring extra measurements or modeling of the site and extra effort by the turbine OEM, and thus raising costs. And, the lack of understanding of the operating conditions at complex sites results in a combination of mechanically conservative designs (i. e. with larger safety factors), but may also result in unexpected component failures.~~ .

~~Since then there~~ Hilly and mountainous regions may also experience other challenging weather and climate phenomena. These may include events associated with convective (thunder) storms, for example heavy rain, hail (**?**), or lightning. All of these can lead to blade damage or affect electrical systems, or prevent people from moving around on site. Standards exist for lightning protection (?), but information about the geographical spread or frequency of potentially damaging events is limited (see e.g., ?).

There have been efforts to develop guidelines or standards for wind energy developments in cold climates [1] (?), but in general the trend has been to ~~consider complex terrain to be unique sites and~~ require local measurements of operating conditions as well as extrapolation to the plant life cycle. ~~This is problematic as it add costs for the developer and turbine supplier, and slows down~~

Extra measurements or modeling at a potential wind farm development location raises costs and slows the development process~~.~~, compared to a simple site in temperate climate. And, the lack of understanding of the operating conditions at complex locations results in a combination of mechanically conservative designs (i.e. with larger safety factors), but may also result in unexpected component failures.

Research is therefore needed to develop tools that can cheaply, accurately, and quickly define the operating conditions over ~~complex~~ hilly or mountainous terrain. These tools also need to account for the effect of forestry and be capable of predicting ~~complex~~ the complex flows and weather associated with the site. This could include realistic time series or spectra of wind resources and ~~complex~~ weather, akin to the standard operating conditions defined in the IEC 61400 family of standards.

5.2 ~~Wind~~ Obtaining inflow data to validate wind turbine ~~modelling~~aeroelastic models

~~Wind turbine design is carried out in the wind energy industry according to the IEC 61400-1 standard (?). In this standard, so-called "load cases" are defined. These refer to particular combinations of external conditions and wind turbineoperational status, which have to be considered when simulating wind turbine performance in the design phase.~~

Validating wind turbine aeroelastic modelling for the design process requires accurate, high-resolution information about the inflow to a test turbine, coupled with data from loads and electrical sensors. These simulations are particularly challenging to set up and carry out for turbines at complex sites due to ~~the higher~~ non-standard turbulence intensity, shear, veer, temporally varying temperature gradients, and extreme changes in wind speed and wind direction.

~~Validating wind turbine aeroelastic modelling requires accurate, high-resolution information about the inflow to a test turbine , coupled with data from loads and electrical sensors. Meteorological~~ In the absence of standards, a wind turbine manufacturer could try to use site measurements. However, meteorological towers that are tall enough to measure the wind conditions across the turbine rotor disk are hard to build and operate, while assumptions need to be made about the structure of atmospheric turbulence. Ground-based wind lidar can be used ~~in some cases, but are not ideal in complex terrain situations~~to provide wind data, but their ability to provide turbulence data that can be used in turbine design is a subject of ongoing research (???, e.g.,).

[1] ~~Task 19 document~~

5.3 ~~Power~~ No standards for power performance testing

Power performance testing ~~according to IEC 61400-12 (?)~~ relates the power produced by a wind turbine to the free-stream wind conditions. Power performance testing is done as part of the certification process of a new wind turbine type. ~~Power performance testing relates the power produced by a wind turbine to the free-stream wind conditions.~~

Power performance testing in simple, flat terrain using upwind masts or vertically-profiling remote sensing devices is covered by the IEC 61400-12-1 standard (**?**). This standard specifically excludes winds from directions where there are steep slopes or obstacles from the power performance database. This is because ~~in these conditions it is~~ these conditions make it extremely challenging to identify an appropriate free-stream wind speed, as there may be terrain-induced speed-up or slow-down effects on the flow. As a result, there is no widely-recognised way to perform a power performance test in ~~complex~~ hilly or mountainous terrain.

Investigations suggest that it may be possible to fit wind speed measurements made by a nacelle- or spinner-mounted wind lidar looking forward into the turbine's induction zone to a model of the induction, and use this model to estimate the free-stream wind speed (**?**). This approach would allow a power curve of power versus free-stream wind speed but has not been widely tested, or standardised.

The recently published IEC 61400-50-3 standard (**?**) for the use of nacelle-mounted lidar for power performance testing describes the use of wind lidar to measure the turbine inflow wind speed. The wind is required to be measured at more than ~~2D~~ 2 diameters (D) upwind of the turbine. Modern wind turbines can have rotors with ~~diameter D of~~ diameters more than 150 m and so this could require wind measurements at well over 300 m upwind. However, complex flow conditions could introduce significant flow variation between the measurement point and the turbine~~(Figure **??**),~~, and so it is not clear that the method can be reliably used in ~~complex~~ hilly or mountainous terrain.

~~Complex terrain can introduce significant flow variation upwind of wind turbines. The 2D arrow indicates the distance two rotor diameters (D) upwind of the turbines.~~

5.4 ~~Mechanical~~ Challenging conditions for mechanical loads testing

The certification process of a new wind turbine type requires mechanical load measurements. These are carried out according to to IEC 61400-13 (**?**). The wind measurements required for this testing are covered by the IEC 61400-12 standard discussed above, and therefore the same challenges apply. Additional challenges to mechanical loads testing at complex sites relate to the complex behaviour of the loads on the rotor blades due to effects such as shear and veer.

In order to help solve the challenges related to power performance testing and mechanical loads testing at complex sites, field measurements on large wind turbines situated at complex sites are required. This would allow an improved understanding of the actual behaviour of operating wind turbines in the field, enabling OEMs and researchers to improve their design tools and thus optimise design.

5.5 ~~Design~~ Designing turbines for icing conditions

Icing impacts the turbine in several ways and these effects should also be taken into account in turbine design. ~~IEC-61400-1~~ IEC 61400-1:2019 (**?**) outlines a number of issues caused by icing that need to be taken into account in turbine design. These include reduced turbine performance due to blade icing, unequal ice distribution on wind turbine blades leading to unequal loads and increased vibrations, ice shedding from blades, icing effects on wind measurements increased sound levels and prolonged standstills.

These conditions cause issues for turbine control due to ice accretion altering the blade aerodynamics. Turbine control during icing events can have different and competing goals, depending on operator objectives and local regulations~~. The priority can be chosen~~ ; for example, the priority might be to maximise production, to ~~be minimise risks~~minimise risks, or to minimise additional loads on ~~the~~ turbine components. Additionally, icing conditions might require extra instrumentation or changes in materials. Active icing mitigation systems such as blade heating will often require changes in turbine design.

An important requirement when designing a turbine to operate in icing conditions is to understand and quantify how ice builds up on the turbine blades, and how this will affect the turbine aerodynamics. This would need to be taken into account when doing simulations during turbine design.

There are existing solutions for these issues. For example, icing on the blades can be mitigated by a blade heating system, anemometers are available on the market that function better in icing conditions, and the risks caused by ice shedding and the issues with increased noise levels can be taken into account when planning the site~~. The~~ ; see **?** for an overview of solutions. A 2019 IEA Wind TCP Task 19 ~~report "Available technologies for wind power in cold climates" lists the state-of-the-art solutions that exist in the market (?). In 2019 Task 19 did a~~ survey on experiences with blade heating and other cold climate solutions ~~and~~ found that many people working in the field still feel that there is room for improvement in the maturity and reliability of these solutions (**?**). ~~This need for continued testing is part of the reasoning behind establishing the Nergica test centre in Canada, and the RISE cold climate test centre in Sweden.~~

Many of the solutions for icing need to be designed in to wind turbines and wind plants. For example, safe operation in icing conditions, and optimal blade heating control, will require reliable ice detection. Any ice detection method should be able to react quickly to icing conditions and also be able to tell when icing conditions and active ice accretion end in order to optimise turbine and blade heating control. In addition, if ice detection is done for safety reasons it's important to be able to tell when blades are ice free.

More detailed icing models are being constantly developed. These models are mainly being validated against wind tunnel measurements (**?**). Measurements of water droplets during icing events would be very useful. Actual measurements of ice shapes from an operating turbine are required to validate these models.

There is a large uncertainty related to icing conditions and the icing of turbine air foils. The year-over-year variation of icing conditions can be large and will introduce a large uncertainty in operations. The impact of icing on turbine production also has a large variation that further introduces uncertainty in any estimates on production in an icing climate site. More research is needed to reduce the margin of error in forecasting and modelling production losses (**?**).

In order to determine the need for icing mitigation, the existence of icing conditions at the site needs to be determined early during site prospecting. The methods for converting these pre-construction measurements into estimates on production losses still have room for improvement. Also, icing conditions need to be known before construction starts in order to determine the need for a blade heating system and the specific operating envelope of a blade heating system (?).

While some of this research and development can be done by wind turbine OEMs or by specialist service providers, there is still a need for independent validation on full-scale turbines. This is part of the rationale behind founding and operating the Nergica test centre in Canada (see e.g., ?), and the Research Institutes of Sweden (RISE) cold climate test centre in Sweden (?).

6 Operational wind plants

There are a number of challenges associated with operating wind turbines at complex sites, including (1) Lack of standards for performance verification tests; (2) Accurate site-specific power prediction; (3) Forecasting for operational wind farms; (4) Downscaling forecasts to individual turbines ; and (5) Predicting icing effects. These Once a wind energy facility has been built, it is essential that the turbines operate as expected and in a predictable, safe fashion. The related challenges and the resulting R&D needs are discussed in the next sectionsthis section and summarised in Table ??.

6.1 Lack of standards for performance verification tests at complex sites

Power performance measurements (see §5.3) are also frequently carried out on newly-commissioned wind turbines or on wind turbines that have been operating for a long period of time. These performance verification tests can reveal problems with the turbine yaw alignment or the turbine control system that can result in several percentage points of lost energy, compared to the optimal setup. However, as with power performance testing during the turbine design phase, the lack of standards for doing this at complex sites makes it very difficult to interpret the results from such tests.

A coordinated research effort and parametric studies on the effect of complex sites on power performance is required. This could involve carrying out a coordinated set of parametric studies using a combination of wind tunnel tests, CFD simulations and field tests at a range of sites with varying complexity and exposed to a range of different complex flow conditions.

6.2 Accurate site-specific power prediction

Accurate wind turbine power curves are important for wind farm operation. They can be used for performance monitoring, calculating compensation for forced curtailment, and for making short-term power forecasts for optimising revenues.

There is therefore a need for site-specific power curves that predict power based on the atmospheric conditions expected at a turbine's location, such as shear, veer, and turbulence intensity. The challenges and needs associated with this are discussed in detail in §??4.1.

6.3 Forecasting ~~for~~ weather and power at operational plants

Weather and power forecasting can both increase the income from a wind plant and reduce expenses. ~~They can~~ Income can be increased by scheduling maintenance to ensure turbine operation during forecast high wind-speed periods or by supporting energy trading, while expenses can be reduced by scheduling maintenance for good weather periods and avoiding market penalties. Forecasts can also enable the integration of wind energy into a regional or national electricity system. As such, effective forecasting is an essential capability for operational wind farms at complex sites.

The ability to forecast conditions at a wind farm several days ahead is essential for forecasting power production, safe operations, and scheduling maintenance. Wind forecasts over shorter horizons can also be used to support plant control decisions, and in future such insights will be essential for the effective operation of hybrid plants where wind, solar energy, and storage are co-located.

These plant-scale forecasts rely upon understanding the weather in a region up to 1,000 km around the point of interest - i.e., the mesoscale - and predicting it scales of around 1 km or less (the microscale) around the wind farm. These data can then be used directly or further processed, leveraging site observations.

Current generations of mesoscale models are routinely used by commercial and national weather forecasting services at complex sites. However, crucial for a forecast is the model and the initial state or analysis. The analysis is made by a complicated data assimilation process combining short range forecasts and observations. In mountainous terrains the analysis is more difficult because of greater differences in the height of the model orography and the real terrain. Then, simple questions like the observation height become complicated: Should an observation be assimilated at the same height above ground or at the same height above mean sea level as in nature? Probably, there is no clear answer, and it must be tested for the assimilation system.

Additional forecast errors stem from the ~~inherent uncertainty of the~~ non-linear basic equations of the models. This uncertainty is estimated calculating an ensemble of forecasts. ~~Complex~~ Hilly or mountainous terrain can increase or decrease the uncertainty of wind forecasts by channelling the wind in ~~two preferred directions~~ a few preferred directions (see e.g., **?**). This makes the forecast more stable for a wider range of weather regimes. However, near the tipping point from one regime to the other, errors can strongly increase.

Another problem of numerical weather prediction models can be conflicting interests for model improvement. For example, **?** showed that reducing turbulent mixing in the ECMWF's IFS model would improve ~~hub~~ hub- height wind speeds, but ~~deteriorate near surface~~ worsen near-surface temperature and the large scale circulation.

There are many ways to forecast the amount and timing of energy produced by a wind turbine or wind plant with order (1 minute) resolution up to a week ahead ~~(for a review of approaches, see e.g., ?)~~(see **?**, for a review of approaches). However, every wind plant operator has to go through an evaluation process for their own site when selecting a provider. Although evaluation criteria exist (**???**), this process is time consuming, requires specialist skills, and the cost of the selection process could be high compared to the savings from the improved forecast.

Simplified and even standardised evaluation processes would help the assessment and adoption of operational forecasts. Further, sharing anonymised results would help the community and service providers understand where model improvements are required. The challenge is to overcome the wind energy industry's traditional reluctance to share such information. And, objective characterising metrics are also required so that experience can be exchanged (see §~~??~~??).

6.4 Downscaling forecasts to individual turbines

Some applications require weather data at individual turbines' locations. This downscaling process can take place using physical models or by leveraging site observations and applying model output statistics, machine learning, or other methods. Model-based approaches require an understanding of the physics and descriptive equations, while statistical and machine learning tools can be trained on historical data sets. Therefore, the model-based approaches can work better in unusual weather events, but machine learning solutions tend to be faster, and more precise if well trained. However, major changes of the weather prediction model require new training of the statistical model. Otherwise an improvement of the weather prediction model can result in a degradation of the forecast for the site.

~~There are many studies about downscaling mesoscale data to e.g., automated weather station locations. But, it is not clear how well such downscaling processes work for wind energy applications, and what the major contributors to uncertainty are.~~ Downscaling - whether by physical models or using statistical approaches - is harder in ~~complex~~ hilly or mountainous terrain as there is usually more subgrid scale variation in ~~complex~~ this terrain. As all subgrid scale has to be parameterized this introduces greater uncertainty to the predicted flow. Also, the wind variation is more sensitive to the exact location in ~~complex terrain.~~ hilly or mountainous terrain. Although there are many studies about downscaling mesoscale data to e.g., automated weather station locations, it is not clear how well such downscaling processes work for wind energy applications, and what the major contributors to uncertainty are. Because of the scale of the work involved, this may suit a collaborative assessment similar to the comparison of yield and energy prediction for wind energy carried out regularly since 2011 (known as 'CREYAP' and described in **?**).

6.5 Predicting the likelihood and impact of icing conditions

In icing conditions an icing forecast can also be required in addition to wind forecasts. This icing forecast can be made by combining a weather forecast model with a wind turbine model to predict ice accretion on the wind turbine blades, or on the monitoring instruments.

An operational icing forecast can have several different use cases. The more common one is to improve production forecasts. Icing can cause sudden reduction in wind farm energy production. In some electricity markets this will force the wind farm operator to pay a penalty for missed production. These financial penalties can be avoided if icing is included in the normal production forecast. Some operators might be concerned about operational safety and ice throw risk and forecasts can help identify times when there is an elevated ice throw risk.

An operational icing forecast model usually consists of three components: the numerical weather model, a model for blade ice growth, and an iced turbine model (see examples in **??**). The icing model needs to take into account not only how the ice builds on the blade, but also how and when ice is removed from the blade.

The ice accretion rate will depend on temperature, wind speed, and droplet size of water droplets in airand turbine specifics such as blade shape and , and information about the turbine, such as the blade shape, and the turbine's size. Accurate prediction of the appropriate meteorological parameters and modelling ice accretion continues to be problematic, but improving them would benefit many different activities in ice-prone regions (**?**).

Wind turbine behaviour in icing conditions is specific to a turbine model. Many current models of ice accretion or ice shedding require detailed information about the turbine, such as the controller design or airfoil shape. Wind turbine OEMs are often unwilling to share this intellectual property, which in turn prevents the development of operational models. Therefore, operation models are required that use less sensitive information.

Wind farm operators are typically concerned about the magnitude and duration of icing events. An icing forecast therefore requires not only an assessment of the meteorological conditions when ice builds on the blades, but also an estimate of how long ice will remain on the blades and impact turbine performance. The latter is much harder problem to solve as ice can be removed from turbine blades via mechanical shedding, or by melting, or combination of both. The ice shedding will have implications on the production forecasts and also on safety around the wind turbines (**?**).

As with other issues discussed in this paper, new or improved models of cloud formation, ice accretion, and shedding would in turn require validation from lab or field tests. It is possible that making multi-scale test data open would allow multiple different models to be tested and thus accelerate innovation in this field.

7 General challenges

The general challenges of complex sites for wind energy applications are those that affect every step of the project life-cycle, and include: (1) No agreed-upon definition of 'complex terrain '; (2) Interrelated physical processes.

In preparing this review, we have identified several challenges that arise repeatedly during the life cycle of a wind plant in hilly or mountainous terrain, or are linked to the ability of the wind energy community to collaborate effectively. These are described below. The challenges and the resulting R&D needs are discussed in this section and summarised in Table **??**.

7.1 No agreed-upon definition of 'complex terrain'

As discussed in the introduction of this paper, the existing unclear, varying and binary definitions of 'complex terrain' pose a challenge to all parts of the wind farm project life-cycle because it makes it difficult, if not impossible, to quantify the risks associated with project planning and operation as well as to effectively choose optimal measurement instruments, wind models and analysis methods. In this section, therefore, we examine the existing definitions and the important aspects contributing to this challenge.

~~Modern commercial wind turbines were initially deployed on sites in flat, uniform terrain. This is often described as 'simple terrain' in the wind energy industry. It is easy to recognise by eye; it is characterised by long, flat plains or low-angle slopes, consistent land cover, and a lack of buildings. These conditions allow a deep, uniform wind field to develop. There are several important characteristics of flow over 'simple' terrain:~~

1. ~~The wind speed profile follows a monotonically increasing, logarithmic profile throughout the atmospheric boundary layer.~~

2. ~~On the scales typical to a wind farm, any spatial differences in the wind profile are due to pressure gradients. Differences in Coriolis effects can be neglected over such scales.~~

3. ~~As pressure gradients are low, there are only small differences in wind profiles across a wind farm.~~

~~One of the implications of these characteristics is that the wind speed profile across the wind turbine rotor disk (i.e., up to 250 m above ground) can be determined with confidence from measurements made using met masts that might not even reach the hub-height of a future wind turbine.~~

~~However, not all flow is 'simple'. Factors including variation in surface conditions, local meteorology, and terrain can all cause wind conditions that deviate from the 'simple flow' case. Following the language used in the wind energy industry , this is implicitly 'complex flow'. However, it is also often called 'complex terrain', leading to difficulties in comparing or exchanging experience. Currently,~~ As discussed in the introduction of this paper, the wind energy industry often uses the catch-all phrase, 'complex terrain', ~~is often used to describe this type of site, although no clear, agreed-upon definition exists. And, the same term~~ to describe hilly or mountainous sites and other locations where the terrain modifies flow such that it is outside of the body of standards. But, 'complex terrain' is used interchangeably for different applications. For example:

– The software package WAsP is often used in the wind energy industry to model winds at a potential site. ~~The WAsPRiX value (?) -~~ WAsP's RIX value is a measure of the slope angle around a location ~~-~~ and has some predictive value for the uncertainty of the linear wind model used in WAsP (**?**). Experience shows that WAsP cannot be used confidently when ~~$|RiX| > 0$, which is then frequently referred to as "complex terrain" in literature. As a result, the~~ $|RIX| > 0$. The widespread availability of WAsP and the simplicity of the ~~RiX~~ RIX metric means that ~~$|RiX| > 0$~~ $|RIX| > 0$ has become the *de facto* definition for "complex terrain".

– Similarly, terrain slope angles are used to assess complexity for power performance testing according to the International Electrotechnical Committee (IEC) 61400-12-1 standard (**?**). Terrain that exceeds certain angles is said to be "complex".

– The IEC 61400-1 standard (**?**) contains a somewhat different scheme that evaluates slope angles and terrain variance and ~~yields a categorisation in~~ categorises locations into low, medium, and high terrain complexity.

WAsP and the IEC 61400 standards ~~therefore refer to 'complex terrain', but~~ use different definitions for ~~it~~complex terrain. And, terrain complexity impacts different aspects of the development and operation of wind energy facilities in different ways. ~~Therefore the criteria used to assess complexity for flow modelling using WAsP or power performance testing are not interchangeable, and should not be used for other applications.~~

~~Furthermore, many~~ Furthermore, studies have shown that ~~other modelling tools do not have the same limitations as WAsP~~ different flow modelling tools have varying sensitivity to terrain (e.g., **?**). As a result, it only makes sense to use an absolute value of ~~RiX~~ RIX as a division between "complex" and "not complex" terrain when using WAsP, but not as a general metric for all ~~modelling tools.~~ flow modelling tools or for other applications. So, the criteria used to assess complexity for flow modelling using WAsP or power performance testing are not interchangeable, and should not be used for other applications.

~~A~~ Also, a binary definition of "complex" or "not complex" terrain is difficult to translate into project uncertainties ~~or risks,~~ (which are usually assessed on an continuous scale~~from 0-100% (uncertainties) or at least in~~) or risks (typically at least 3-4 different categories~~(risks). This~~). The binary definition is ~~in turn~~ also difficult to translate into "go" or "no-go" decisions, or to use for deciding which tool or workflow to use for a particular project.

~~As an illustration of these challenges, imagine three wind farm development sites in complex terrain. One is a sparsely wooded and moderately uniform slope, another is a mountain ridge, while another is in a mountain pass (Figure **??**).~~

~~Examples of three different types of complex terrain. Images are exemplary only and do not represent potential wind energy development sites. Photo credits:) Delaney Turner,) Adrian Jakob, and) Tomoe Steineck. All photos are from Unsplash.com and used under the Unsplash license.~~

~~Experience suggests that each site will have different pre- and post-construction challenges related to the interaction of the terrain and weather:~~

- ~~A uniform slope is subjectively relatively simple terrain, but is likely to experience a diurnal cycle of up- and down-slope winds, driven by surface heating and cooling. As a result, wind flow models are required that can generate such buoyancy-driven flows.~~

- ~~A mountain ridge has more apparent complexity because of the marked three-dimensional relief. Accurately predicting the wind resource means accurately predicting the effect of the ridge terrain and landcover on the local wind fields, which in turn requires the hilltop geometry to be resolved in the models that are used.~~

- ~~Winds in a mountain pass are driven by a combination of thermal effects and regional pressure gradients (**?**). Accurately resolving the wind resource requires very high resolution modelling that also includes buoyancy.~~

~~These examples illustrate that any scheme for assessing site complexity should be able to quantify the different aspects that can lead to the characterisation of a site as a "complex terrain" site. Moreover complexity might not be the same for all applications, methods, and devices.~~

~~We therefore consider the lack of a clear and transferable definition (or definitions) of site complexity to be an important challenge for the development of~~ Research effort is therefore needed to develop definitions of terrain complexity that have meaning for some or all of the processes involved in developing a wind ~~energy at complex sites~~plant. This would simplify information exchange between stakeholders, make it easier to transfer experience from one site to another, and allow an informed choice of optimal measurement instruments, wind models, and analysis methods.

7.2 Interrelated physical processes

The wind energy industry leverages knowledge from many different scientific disciplines to design, build, and operate a wind farm. Knowledge is transferred between wind energy projects in the form of computer models that approximate the many different physical processes taking place, and their interaction.

This is particularly challenging for complex sites due to the additional complexity of the flow and its interaction with the wind turbines. For example, predicting the energy that might be produced over the course of a year requires information about the wind resource, the ability of the wind turbine to capture that energy, and losses due to icing, soiling, wakes, and other effects. This might be implemented as a complex computer model. The performance of each individual model in the this system can be verified by conducting experiments that isolate specific effects (e.g., the effect of atmospheric stability on wakes, described in **?**). The performance of the whole modelling system can be verified against field experiments that simultaneously resolve physical processes acting at different scales and in different parts of the system and their effects on wind turbines(e. g., . Some experiments have already been carried out, for example the US Wind Forecasting Improvement Projects WFIP 1WFIP1, (**?**) and WFIP2 (**?**), and the New European Wind Atlas (**?**)). However, these are extremely . These complex and expensive studies to carry out, and , field studies have all required significant inter-organisation cooperation and many years of preparation. Although they have provided much useful information, further research is needed to extract more understanding from the data sets they generated. And, as wind turbines' dimensions increase and their rated power increases, these experiments or wind plants increase in size and wake effects become more important, these field studies may need to be repeated.

This is particularly challenging for complex sites due to the additional complexity of the flow and its interaction with the wind turbines.

These challenges could be solved in the following ways:

7.3 Few frameworks for sharing data

New frameworks for sharing data: There are a number of desktop tools available for supporting wind energy site development, which can be used to estimate resources, carry out coarse energy yield assessments, and identify other challenges in advance of significant effort on site. Some tools additionally allow resource estimates based on downscaled mesoscale weather models or reanalysis data that can then be coupled with simple turbine production models. However

At this time, there is no framework we know of for bringing together data to rapidly analyse the opportunities and challenges of a potential wind energy development site. This data exchange may be enabled by the ongoing digitalisation of the wind energy industry. For example, in 2021 IEA Wind Task 43 (Digitalisation) produced a data structure to allow simplified data sharing for wind resource assessments (**?**)., and there are many other proposals for ways to share turbine design information (**?**) and other data. Further research is needed into ways to collect, combine, and act upon these myriad data.

A network of test facilities in complex terrain, weather and climate locations:

7.4 A lack of test facilities in complex locations

Technological progress requires that potential solutions to the challenges faced by wind energy in complex locations be tested on real turbines. To date several wind turbines have been erected in part or entirely for research purposes in ~~complex~~ hilly or mountainous terrain, including the Gütsch site in Switzerland and the CENER Alaiz experimental wind farm in Spain, or in complex flow conditions such as those found at times at the US National Wind Technology Center (NWTC) near Boulder, Colorado, or in the complex weather and climate found at the Nergica facility in the Gaspe region of Canada. A further wind energy research facility is in development by the southern German wind energy research cluster WindForS in the Swabian Alb. These facilities individually cover different parts of the spectrum of terrain, flow, and weather complexity and include a range of turbines, from 600 kW machines at Gütsch to multi-megawatt turbines at Alaiz and the NWTC.

Despite the ongoing trend towards taller wind turbines with larger rotors and higher rated power, so far there are no research turbines of greater than 100 m hub height or more than 5 MW rated power in ~~complex~~ hilly or mountainous terrain that also ~~experience complex weather and climate~~periodically experience cold temperatures or icing. This lack of available research turbines makes it difficult for the international wind energy community to identify and test solutions to the issues identified in this paper. A turbine of this scale would potentially cost ~~well over €20M~~ €10-20M to procure and construct ~~(but~~ – although operations could be self-funding through the income from power sales ~~),~~ – and so might require an international consortium to realise it.

8 Conclusions

Wind turbines have been successfully deployed ~~in all kinds of operating conditions~~ from the Arctic to Antarctic and at up to 4,000 m above sea level. ~~However, wind energy developments in the so-called "complex terrain" found in hilly or mountainous regions are still viewed negatively despite potentially increased wind resources and the potential of such sites to support the global transition to low-carbon energy.~~

~~The ongoing development of wind energy in complex flow, terrain, weather and climates has shown that wind farms can be productive and economic, and can contribute to the ongoing energy revolution. Complex sites can~~ Many of these turbines are in the hilly and mountainous regions that cover almost one third of the earth's land surface. These locations can have markedly increased wind resources compared to other locations, making them potentially significant contributions to energy supplies in many regions.

However, deploying wind turbines ~~at complex sites~~ in these locations is not easy. The interaction between ~~winds,~~ terrain, weather and climate leads to bigger turbine- and wind farm-scale variability than are usually found at traditional deployment locations. Conditions – particularly in cold climates that experience low temperatures or icing – can be more extreme than at ~~"typical" locations, and~~ lowland locations, thus reducing energy production and raising costs, but it can be hard to obtain realistic or representative data about the conditions from measurements or models. Together these lead to costly uncertainty that can make it difficult to finance a new wind energy project. Operating wind farms in such conditions is not easy, either; weather conditions may make it hard to work, forecasts are often less precise than in flat terrain, and there may be conflicts with other stakeholders.

Focused R&D is therefore required to maintain the competitiveness of wind energy at complex ~~sites~~locations. While some of the outcomes of this R&D will be able to be applied to existing wind farms, larger benefits can be obtained by designing new wind farms from the outset with the site's complexity in mind. The development of appropriate metrics to characterise terrain and flow, as well as the performance of the tools and processes used in such terrain will be a key enabler for this R&D. It will allow the exchange of experience across developments, and help investors understand the applicability of different tools. ~~Finally, platforms and~~ Then, frameworks are required to ~~bring together the complex terrain wind energy community, where stakeholders can~~ allow stakeholders to collect and share their ~~experiences.~~ data. And, dedicated test facilities are required so that new technologies can be tested at scale, helping the process of technology transfer and adoption.

In this article we have shown how sites at ~~complex sites~~ hilly or mountainous sites – a type of complex terrain – may have different challenges compared to simple~~sites. However, there are~~ , lowland sites. Many of the challenges to deploying wind energy at ~~complex sites that~~ these sites can occur in simple terrain, such as complex flow, ~~weather and~~ or cold climate conditions. As a result, research and development for wind energy at complex sites can benefit the entire wind energy industry.

Appendix A: Definition of mountainous terrain

Figure 1 shows regions of low and high mountains. This map is created from GIS data downloaded from the United States Geological Survey (USGS). This data includes a pre-processsed data layer that characterises each grid point as belonging to one of the K3 mountain classes (**?**), where the K3 data set is a 250-m spatial resolution digital elevation model (**?**).

The K3 mountain characterization uses 3 parameters to characterise the terrain in a 3-km moving neighborhood analysis window (NAW). These are slope, relative relief (the absolute value of the difference between the maximum and minimum elevations in a NAW), and the profile parameter, which is the percentage of area of high slope ($\geq$8%) in a 6-km NAW. This is further divided into upland pixels (higher than the midpoint of the elevation range in the NAW) or lowland pixels (lower than the midpoint of the elevation range in the NAW). The classes are described in Table **??**.

These data are available through the USGS Global Mountain Explorer at https://rmgsc.cr.usgs.gov/gme/gme.shtml.

Author contributions. This paper was initiated and led by AC. AS, HF, and TK contributed materials on resource assessment, forecasting, and icing respectively.

Competing interests. AC, AS, and TK provide consultancy on the deployment of wind energy in complex terrain. All authors except HF receive grant funding for research into aspects of wind energy in complex locations.

Acknowledgements. AC was funded by the Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg during the writing of this paper.

Table 2. Challenges and R&D needs for wind resource assessment in complex locations. The table follows the format of Table 1.

Challenge	R&D need	Impact on project risk	Impact on LCOE	Relevance
Lack of guidelines and planning tools (§3.1)	Standards for wind resource assessment in complex terrain	Medium	Medium	Most sites
	Software for planning measurement campaigns built on this guidance	Medium	Low	Some sites
Unknown instrument uncertainty and bias (§3.2)	Tools to predict uncertainty and bias in different flow conditions	Medium	Low	Some sites
The difficulty of using remote sensing devices to supplement or replace met masts (§3.3)	Tools for processing wind lidar data collected in complex flow	Medium	Medium	Some sites
Barriers to the adoption of scanning lidar (§3.4)	Simplify the use of scanning lidar	Low	Low	Some sites
	Develop modular lidar processes to enable custom data processing toolchains	Low	Low	Some sites
Integrating airborne measurement systems (§3.5)	Improved vehicles	Medium	Low	Some sites
	Swarm operation	Medium	Low	Some sites
	Sensor fusion and data assimilation	Medium	Low	Some sites
Choosing the right sensor (§3.6)	Guidelines or tools for instrument selection	Medium	Low	Some sites
Demands on wind field modelling tools (§3.7)	Improved atmospheric models	High	Medium	All sites
	Decision tool for optimum choice of wind modeling tool	Medium	Low	Some sites
	Repeatable, auditable, experience-based processes	Low	Low	Some sites

Table 3. Challenges and R&D needs for project planning in complex locations. The table follows the format of Table 1.

Challenge	R&D need	Impact on project risk	Impact on LCOE	Relevance
Increased uncertainty of wind turbine performance models (§4.1)	Data sets for verification of multi-variate power performance models	Medium	Low	Some sites
	Acceptance of black-box approaches	Medium	Low	Some sites
Additional information required for wind farm design (§4.2)	Data needed for multi-variate power performance models	Medium	Low	Some sites
	Wake models for complex terrain	Medium	Medium	Some sites
Increased financial uncertainties (§4.3)	Guidelines for dealing with additional risk at complex sites	Medium	Medium	Most sites
Increased conflict potential between stakeholders (§4.4)	Better understanding of the sources of stakeholder conflict	Medium	Medium	Some sites
	Better understanding of the physics of sound in complex terrain	Medium	Low	Some sites

Table 4. Challenges and R&D needs for the design of turbines for use in complex locations. The table follows the format of Table 1.

Challenge	R&D need	Impact on project risk	Impact on LCOE	Relevance
Lack of understanding of operating conditions at complex sites (§5.1)	Standardised operating conditions for complex sites	High	High	All new sites
	Tools to cheaply and accurately estimate operating conditions	High	High	All sites
Obtaining inflow data to validate wind turbine aeroelastic models (§5.2)	Quick desktop tools	Medium	Medium	Most sites
	high-resolution data for model validation	Medium	Medium	Most sites
No standards for power performance testing (§5.3)	Standards for using nacelle-mounted lidar in complex terrain	Medium	High	Most sites
Challenging conditions for mechanical loads testing (§5.4)	Field testing on large turbines in complex terrain	Medium	Medium	Most sites
Designing turbines for icing conditions (§5.5)	Improved icing models	Medium	Low	Most sites
	Improved solutions for blade and instrument icing	Medium	Medium	Some sites
	Improved AEP estimation accounting for icing	Low	Medium	Some sites

Table 5. Challenges and R&D needs for operational wind plants in complex locations. The table follows the format of Table 1.

Challenge	R&D need	Impact on project risk	Impact on LCOE	Relevance
Lack of standards for performance verification tests at complex sites (§6.1)	Standards for using nacelle-mounted lidar in complex terrain	High	High	All sites
Accurate site-specific power prediction (§6.2)	Multi-parameter power prediction tools	High	High	All sites
	Use and acceptance of machine learning	Medium	Medium	Most sites
Forecasting weather and power at operational plants (§??)	Simplified or standardised model evaluation processes	Medium	Medium	All sites
Downscaling forecasts to individual turbines (§??)	Collaborative exercise on downscaling wind forecasts	Medium	Medium	Most sites
Predicting the likelihood and impact of icing conditions (§??)	Improved weather models	Medium	Medium	Some sites
	Improved ice accretion models	Medium	Medium	Some sites
	Improved turbine performance models	Medium	Medium	Some sites
	Climate-controlled test facilities	High	High	-
	Test facilities in icing locations	High	High	All sites

Table 6. General challenges and R&D needs for wind energy plants in complex locations. The table follows the format of Table 1.

Challenge	R&D need	Risk impact	LCOE impact	Relevance
No agreed-upon definition of "complex terrain" (§??)	Clear, transferable definition(s) of complexity that are relevant to the different processes happening there	High	High	All sites
Interrelated physical processes (§??)	New frameworks for sharing data	High	High	All sites
	Test facilities in complex locations	High	High	-
Few frameworks for sharing data (§??)	Ways to combine data from multiple sources following many different and changing conventions	High	High	All sites
Lack of test facilities in complex locations (§??)	Establishment of accessible full-scale test facilities in complex locations	High	High	-

Table A1. The K3 Mountain Classes according to **?**

~~Stage in life cycle~~ Class	~~Challenge~~ Slope class	~~R&D need~~ ~~Site prospecting (§2)~~ Relative relief	~~Low accuracy of wind atlases~~ Profile	~~Inclusion of local and seasonal weather effects; time series databases; increased spatial resolution~~ Area	~~Low availability of local GIS data~~ ~~Data marketplaces; digital tools for easier data discovery and integration; data sharing frameworks~~ Area as percent of global land surface
High mountains	~~Lack of information about icing risk~~ 81-100%	~~Simple tools to assess icing risk; tools to estimate ice throw risk~~ ~~Resource assessment (§3)~~ >900 m	~~Lack of guidelines and planning tools~~ Not used	~~Standards for resource assessment in complex terrain; software for planning measurement campaigns built on this guidance~~ 12,579,032 km^2	~~Unknown instrument uncertainty and bias~~ ~~Tools to predict uncertainty and bias in different flow conditions~~ 9.4%
	~~The difficulty of using remote sensing devices to replace met masts~~ 51-80%	~~Tools for processing wind lidar data collected in very complex situations; simplify the use of scanning lidar;~~	~~Integrating airborne measurement systems~~ >50% of all cells in the NAW are high (≥8% slope)	~~Improved vehicles; swarm operation; sensor fusion and data assimilation~~	~~Choosing the right sensor~~ ~~Guidelines or tools for instrument selection~~