Wind Resources and Wakes

Vindforsk projects, a survey of the development and research needs.

Elforsk report 12:38

Lars Landberg

June 2012

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Preface

Vindforsk III is a Swedish research program that is running in the period 2009-2012. The programme is divided into five activity areas:

1. The wind resource and external conditions.

2. Cost-effective plants

3. Operation and maintenance

4. Wind power in the power system

5. Standardization

In the preparation final report at the end of the program work with survey reports for different research areas is being carried out. One such research area is "Wind Resources and Wakes".

The report is used as one basis for preparing the next period of Vindforsk.

Work with a survey report for this area is carried out by Lars Landberg from GL Garrad Hassan.

Conclusions and opinions in the report are those of the author.

Vindforsk-III is funded by ABB, Arise windpower, AQ System, E.ON Elnät, E.ON Vind Sverige, EnergiNorge, Falkenberg Energi, Fortum, Fred. Olsen Renewables, Gothia Vind, Göteborg Energi, HS Kraft, Jämtkraft, Karlstads Energi, Luleå Energi, Mälarenergi, o2 Vindkompaniet, Rabbalshede Kraft, Skellefteå Kraft, Statkraft, Sena Renewable, Svenska kraftnät, Tekniska Verken i Linköping, Triventus, Wallenstam, Varberg Energi, Vattenfall Vindkraft, Vestas Northern Europe, Öresundskraft and the Swedish Energy Agency.

Stockholm june 2011

Anders Björck

Programme manager Vindforsk-III

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Summary

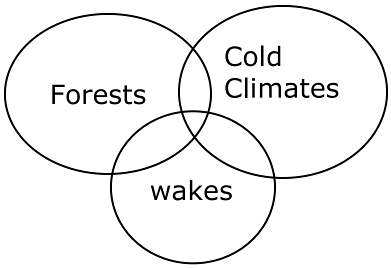
This survey contains the following: a description of the ongoing Vindforsk projects within the research areas of wind resources and wake modelling; a description of the current trends and developments within the two areas; and finally an analysis of future research needs.

The current trends identified were:

- Uncertainty: quantifying the accuracy of the estimation
- Atmospheric stability: understanding and modelling the effects
- Forestry issues: understanding how the atmospheric boundary layer is affected by forestry
- Long-term variability: getting accurate climatological values of the estimates of wind speed and power production
- Wind profiles: understanding how the wind varies with height, especially above the so-called surface layer.
- Offshore winds: most of the issues on this list have a set of special characteristics when offshore
- Remote sensing (Lidars/Sodars): finding accurate and potentially cheaper ways of measuring the wind resource, especially high aloft
- Meso-scale modelling: understating the variation of the wind over larger areas
- Satellite inferred data: seeing how these data sets can be used for topography inference and in some cases wind speed measurements
- CFD (computational fluid dynamics): modelling flow in complex terrain
- Meso-scale/CFD coupling: combining the meso-scale models with very high resolution models, to get detailed results over larger areas

In the chapter discussing future research needs, it is concluded that *winds in forests* is one of the areas that needs further research. Since knowledge and competence is critical to have in Sweden within this area, research is highly motivated. Similarly, Sweden has a strong need for knowledge within and a capability to address the areas of *wind in cold climates* and the study of *wakes*.

It is suggested to develop centres of excellence, which should also address the overlap between research in the three areas for Forests, Cold climates and wakes as illustrated below:



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1 Projects within Vindforsk III

1.1 About the Vindforsk programme 2009-2012

Vindforsk III is a co-financed research programme that provides funding for basic and applied wind energy research. The Swedish Energy Agency is financing 50 percent of the costs within the programme, and the other half is financed by energy companies and other companies with connection to wind power. The programme total budget is 80 million SEK over a four-year period.

The overall objective of Vindforsk is to strengthen the conditions for building and operating wind power by:

- producing generalizable results concerning wind energy characteristics and opportunities
- conducting research at the international forefront within a number of technology areas to preserve and strengthen the skills of existing research groups at universities and engineering consultants.
- strengthening the recruitment base for Swedish wind power industry
- making wind energy research visible and disseminate its results

The programme is divided into five activity areas:

1. The wind resource and external conditions.
2. Cost-effective plants
3. Operation and maintenance
4. Wind power in the power system
5. Standardization

1.2 Vindforsk projects within the research area of Wind Resources and Wakes

Table 1 and 2 show the Vindforsk III projects in the field the wind resource and wakes. Chapter 1.3 summarizes the projects and the results obtained so far.

Project	Project title	Project leader	Financing
V-312	Wind in forests	Hans Bergström, Uppsala University	10 000 kSEK in cash funding and 3 500 kSEK as in kind
V-352	State of the art of wind remote sensing.	Lasse Johansson, Vattenfall Power Consultant	200 kSEK in cash funding

V-356	Knowledge inventory of methods used for wind mapping at different scales	Mikael Magnusson SMHI	305 kSEK in cash funding and 50 kSEK as in kind
V-366	Instant Wind	Klaus-Ole Vogstad, Agder Energi	1020 kSEK in cash funding and 700 kSEK as in kind
V-333	Nordic consortium for optimization and control of windpowerfarms	Dan Henningsson (and Stefan Ivanell), KTH	5500 kSEK in cash funding and 1260 kSEK as in kind
V-355	Partcipation in IEA task 31 Wakebench, Benchmarking Wind Farm Flow Models	Stefan Ivanell, Gotland University	400 kSEK in cash
V-370	FarmFarm, Wind Farm interaction	Stefan Ivanell, Gotland University	1150 kSEK in cash funding

Table 1 Expected results from Vindforsk projects within the area, Generators and internal electrical system.

Project number	Project title	Important international cooperation	Planned Concrete use of results of the project
V-312	Wind in forests	The project is a co-operation between partners in Sweden and researchers at Risø-DTU in Denmark.	Will make it possible to better estimates of wind power production and wind turbine load in forested areas.
V-352	State of the art of wind remote sensing.	Only a survey project.	The report will serve as a good guide to users of remote sensing equipment in Sweden, however, it must be noted that this field is under very rapid development, so knowledge outdates quickly.
V-356	Knowledge inventory of methods used for wind mapping at different scales	Only a survey project.	N/A

V-366	Instant Wind	Collaboration between parties in the UK, Norway, the US and Sweden	Development of coupled and reduced models in optimisation algorithms
V-333	Nordic consortium for optimization and control of windpowerfarms	Cooperation with several Nordic and international partners	improved knowledge of how to optimise large wind farms to maximize production and minimize loads
V-355	Partcipation in IEA task 31 Wakebench, Benchmarking Wind Farm Flow Models	Cooperation with an international group,	improved knowledge of how to optimise large wind farms to maximize production and minimize loads
V-370	FarmFarm, Wind Farm interaction	Connected to the cooperation in V-333 and V-355	improved knowledge of how to optimise large wind farms to maximize production and minimize loads

Table 2 Expected results from the Vindforsk projects.

1.3 Summary of ongoing VindForsk projects

In the following each of the seven Vindforsk research and development projects within the area of wind resources and wake modelling will be described. The description varies with the stage of completion of each project.

1.3.1 V-312: Wind in forests

Project duration, from September 2009 to December 2012

The goal of the project is to create knowledge allowing better judgement of the output of a wind power plant in a forest environment and to study the resulting loads. Models describing the properties of the wind will be developed allowing better design and site specific choice of wind turbines. The project is a cooperation between Uppsala University, WeatherTech Scandinavia, the Royal Institute of Technology (KTH), Risø-DTU in Denmark and Teknikgruppen.

There are three parts to the project: Atmospheric Measurements, Measurements in a Wind Tunnel, and Modelling of a Wind Turbine in a forested area. The purpose of the two measuring parts is to get a deeper understanding of the turbulent winds above the forest canopy. The wind turbine modelling part aims at modelling the loads and output of a wind turbine in a forested region.

The Atmospheric Measurements have been carried out by Risø DTU (now DTU Wind) at two sites: Skogaryd and Ryningsnäs. The Skogaryd campaign was completed in October of 2011; and the Ryningsnäs campaign is expected to have been completed in May of 2012.

The 38 m tall mast at Skogaryd was instrumented with 6 sonic anemometers and temperature measurements ranging from 1 m to 38 m above ground level. The height of the forest was about 26 m.

The 140 m tall mast at Ryningsnäs mast was instrumented with sonic anemometers at 6 heights from 40 m to 138 m above ground, furthermore, thermometers and surface energy balance instrumentation was also mounted.

The focus at Skogaryd has been on the within and just-above canopy flow, while at Ryningsnäs focus has been on the deeper boundary layer up to turbine hub heights. A ZephIR prototype Lidar was also used at Skogaryd, and a standard ZephIR at Ryningsnäs. A valuable database of atmospheric measurements over forests is being build.

The Wind Tunnel Measurements were done at KTH in their MTL (Minimum Turbulence Level) wind tunnel and were completed in November 2010. To simulate the effect of the forest canopy a new physical canopy model was designed with small cylindrical elements that should simulate the effect of the trees generating a known momentum sink able to affect the flow.

A first comparison between the Ryningsnäs data and the measured wind tunnel data has shown reasonable agreement in the surface layer. However, there is a difference at the outer edge of the boundary layer, where the flow is still affected by the method used to generate the thick boundary layer.

A detailed analysis of the wind tunnel statistics with no clearings was also performed. The distribution of the velocity statistics shared much of the typical experimental observations in real forest canopies, showing that the replicated wind tunnel canopy model mimics the phenomena occurring in a real forest. A new set of wind tunnel measurements using the PIV (particle image velocimetry) technique was prepared and made.

The third part, Modelling of a Wind Turbine, investigated the effect of the high turbulence levels and large wind shear found over forestry canopies. In order to facilitate representation of coherent structures in simulated wind time series, a state of the art tool for wind field simulation was modified to include one predefined event per simulation. The main idea is to compare results from aeroelastic simulations around rated wind speed with similar measurement campaigns where characteristic gusts are present.

The extensive data set from Ryningsnäs was initially scanned, in order to try to identify situations where wind and turbine simultaneously behave in a way that is usually not observed in flat terrain. A limited number of campaigns were then selected for further investigation.

Open information describing the Nordex N90 (reports, brochures, articles, web sites) was then used to build a simulation model for the aeroelastic code Vidyn. A standard controller was modified for the actual rotor and some initial simulations were performed near rated wind speed. The wind input was here given in simplified form, and based on some measured wind data.

The main targets of the modelling work are transient control events that induce large load cycles in several components due to significant variation in rotor thrust. If such events can be modelled in a realistic way with aeroelastic simulation tools, then this would mean an important advantage when developing control algorithms suitable for wind turbines operating in forests.

A number of scientific papers will be produced to disseminate the findings.

1.3.2 V-352: State of the art of wind remote sensing

Project duration, from November 2010 to May 2011

This project is finished and the final report can be found here: http://www.elforsk.se/Rapporter/?rid=11_20_.

The report consists of three parts: the first part is a Literature Survey with a very thorough survey of available literature (focus has been on publication not older than 10 years), the survey has focused mainly on Sodars. Major findings are that the theoretical treatment of Sodars is more challenging than for Lidars (due to the much longer wavelength), the list of available literature in the report is in itself a valuable source of information.

The second part describes the State of the Art and includes a list of the available types of Sodars and Lidars, and also a detailed and very useful section on "advantages and drawbacks" aimed at hands-on operation.

The final, third, part reports from a Remote Sensing workshop which was organised as part of the project. At the workshop a wide range of remote sensing users exchanged experiences of mainly practical nature (maintenance, snow, ice etc). The difficulties getting information about the type of processing applied to the data was also highlighted as a major issue facing the users.

The report has identified some major issues for measurements with remote sensing, one is that it is clear that there are no usable standards or norms for carrying out measurements with remote sensing equipment, which of course is a real challenge to the industry.

Overall the benefits from the project include a number of very useful insights into the theory and use of remote sensing devices (mainly Sodars). A list of available remote sensing devices, including their advantages and drawbacks. And finally the project managed to gather a group of remote sensing device users for the workshop.

V-356: Knowledge inventory of methods used for wind mapping at different scales

Project duration, from November 2011 to august 2012

The project is an inventory of the state of the art in methods used for wind mapping. The project is ongoing and has not yet produced its final report.

1.3.3 V-366: Instant Wind

Project duration, from November 2011 to October 2012

The goal of the project is to make CFD simulations of wind farms practically usable by use of so-called model reduction and coupling techniques. Reduction techniques, such as proper orthogonal decomposition is used to post-process CFD simulations into reduced models of both wakes and the terrain flow. The reduced models will then be coupled to obtain solutions for the entire wind farm flow. The aim is to develop such techniques to allow for fast, almost instant simulations at the cost of some minor reduced accuracy and hasve been successfully applied in the field of computer graphics by Wicke and Treuille amongst others.

Initial simulations on off-shore wind farms with reduction of CFD-calculations and coupling of smaller parts of the reduced models to obtain the flow for a whole park has started. It shown that this can be used to obtain fast solutions of the flow when moving individual turbines in the farm. The project is ongoing and the aim is to present comparisons with the simplified results and full CFD-calculations and to further investigate the models applicability to more complex terrain..

1.3.4 V-333, V-355, V-370: Wake related projects.

The three projects:

- V-333: *Nordic consortium for optimization and control of windpowerfarms*
- V-355: *Participation in IEA task 31 Wakebench, Benchmarking Wind Farm Flow Models*
- V-370: *FarmFarm, Wind Farm interaction*

Are all related to modelling and other investigations relating to wakes.

The three Vindforsk projects are part of the activities of a KTH mechanics group and the Gotland University in what is called a Nordic consortium. This consortium includes universities in Sweden and Denmark and companies in those countries plus Norway. The projects are to a large extent carried out as PhD-projects but contains co-operation with both software industry, consultants such as Kjeller Vindteknik and Teknikgruppen and wind farm operators. In total the consortium includes six PhD-students. Two, directly funded by Energimyndigheten are employed by KTH, two financed through Vindforsk are employed at the Gotland University. Additionally one student financed through the Nordic Energy project IceWind is employed at the Gotland University. The sixth PhD-students is employed at DTU in Denmark.

The expected outcome from this project cluster is improved knowledge about the behaviour of wakes and discovery of possibilities of how to optimize large wind farms to maximize production and minimize loads and thereby decrease the cost of energy for wind energy. The work in the project cluster covers simulations as well as wind tunnel investigations of wake instability and interaction in order to enhance the knowledge of wake flow.

The Vindforsk project V-333 is aimed at investigating the advantages of wind turbine control in wind farms. The control is made considering the effect of one turbine on the other turbines in the park. The aim is to investigate how such control can increase the total farm production but even more important to reduce fatigue loads.

Studies are made using data from several wind farms. Specifically new studies are being made on the Lillgrund wind farm in Öresund. This farm is interesting for the studies since turbines are very dense placed and data for different spacing are available using different wind directions. The CFD-calculations show very good resemblance to measured power data. Full Aeroelastic calculations using the far less time consuming Blade Element Momentum method together with wake models is also being used. Initial calculations show good agreement with measured data and CFD-calculations. The full Aeroelastic calculations is now carried out with different modes of turbine control. The results of these studies expected during the end of 2012.

In the Vinforsk project V-370 the effects of a wind farm on the overall flow picture is studied. The aim is to contribute to methods of calculating the effects of one farm´s influence on other farms in the neighbourhood.

One important part of the work in the projects is knowledge transfer and international cooperation. The Vindforsk supports of the participation in IEA task 31 Wakebench is one example.

Ten papers have currently been published and more will be so at the end of the project.

2 Trends and development

2.1 Introduction

This survey covers the trends and developments within two technical areas:

- wind resource estimation/assessment and
- wake modelling.

Due to the different nature of the two areas they will be treated separately in the following. It should be noted, however, that wake modelling traditionally has been a part of wind resource estimation, but due to the sophistication of the subject, it is more and more treated as a separate area in its own right.

In order to set the survey into a Swedish context it is important to start out by trying to define – and keep in mind during the whole survey - what the special Swedish challenges are within these two areas (much more about this in Section 3.2), and it is clear that the main issues are

- wind farms in forested areas
- wind farms in cold climates

a third, more common issue for the wind energy industry as a whole is that of complex terrain. Overlaid this, are the challenges related to wakes in the wind farms located in the above areas, combined with the fact that as wind farms get larger and larger, the industry knowledge of the wakes within and behind these wind farms starts to be less and less certain, both with respect to the theoretical aspects but also the empirical ones, since the availability of solid data sets is currently quite limited.

2.2 Wind resource estimation

There are currently the following trends and developments within the field of wind resource estimation[1]:

- Uncertainty: estimating the accuracy of the estimation
- Atmospheric stability: understanding and modelling the effects
- Forestry issues: understanding how the atmospheric boundary layer is affected by forestry
- Long-term variability: getting accurate climatological values of the estimates of wind speed and power production

[1] Please note, that the field of *wind power short-term forecasting* has not been included in this survey, since it outside the current scope. There is no doubt in the authors mind, though, that this will become more and more important in Sweden, and that the knowledge in Sweden of this field is quite limited at present.

- Wind profiles: understanding how the wind varies with height, especially above the so-called surface layer.
- Offshore winds: most of the issues on this list have a set of special characteristics when offshore
- Remote sensing (Lidars/Sodars): finding accurate and potentially cheaper ways of measuring the wind resource, especially high aloft
- Meso-scale modelling: understating the variation of the wind over larger areas
- Satellite inferred data: seeing how these data sets can be used for topography inference and in some cases wind speed measurements
- CFD (computational fluid dynamics): modelling flow in complex terrain
- Meso-scale/CFD coupling: combining the meso-scale models with very high resolution models, to get detailed results over larger areas

Prioritising the importance of these trends and developments is not obvious from a general point of view, but the above range of trends has been confirmed by the recently held European Wind Energy Association's Annual Event, EWEA 2012 in Copenhagen, where all of these trends were discussed. It is interesting to note, that Forestry is found on the list but in the greater context, Icing is not. Taking the special Swedish drivers into account (see Section 3.2) will make this an obvious priority area in the Swedish context.

In the following sections, each of these areas will be discussed in some detail.

2.2.1 Uncertainty

Calculating the expected production of a wind farm over its lifetime (ie typically around 20 years or more) involves a great number of steps, and at each step a certain amount of uncertainty is introduced. Current research includes both an attempt to identify these uncertainties and also to quantify them. The identification has currently taken the form of itemising the various sources, so the research part of this is quite limited, bordering on non-existent, however, the quantification of these uncertainties is still a ripe field of investigation and research into separating and modelling them is still taking place. Hot topics include partial dependencies and accurate context-dependent quantification of the uncertainties of the individual steps (see eg AWEA Wind Resource & Project Energy Assessment Workshop, 2011, Seattle).

2.2.2 Atmospheric stability

As the models and measurements get more and more sophisticated an understanding of the atmospheric stability has been seen to be more and more important. For a very long time, neutral stability (ie no heat flux at the ground) was assumed; this has had the convenience of greatly simplifying the governing equations. However, as the turbines grow in size and as more and more challenging sites are being developed, it is no longer possible to ignore the stability dependence of the governing equations. Current trends include: stability-dependence of CFD codes (mainly stable stratification modelling), stability-dependence of the vertical wind and direction profiles, and stability-dependence of meso-scale models applied to wind energy (see eg the session on this at EWEA11, Brussels).

2.2.3 Forestry issues

Basically the issues related to mean wind and turbulence profiles in forestry are split into two lines of inquiry: linearised and CFD models. For the linearised models the areas of study are: roughness, ie estimation of the roughness of a forest with one tree species, a forest with various types of tree species within the forest and forests with clearings; these will all have different roughnesses and in many cases the roughness also varies with season; displacement height (again given the above issues); forest edge slope, ie determining how quickly the influence of the forestry dies away as one goes away from the forest edge. The main issue in CFD modelling is to find appropriate formulations for canopy models (ie how to represent the forest in the model). The purpose of both lines of inquiry is to model (and in the first place understand) the surface layer above the forest: vertical and horizontal variation of wind speed, turbulence, and temperature (see eg Dellwik et al, 2011). A further challenge which will in turn emerge and should be considered is how to reliably survey forests and the various parameters required, once a suitable modelling approach has been established (ie how practical is it to survey tree leaf density, tree heights etc over large areas).

2.2.4 Long-term variability

The specific issues related to estimating the long-term variability are not the most scientific, but they have been on the research agenda for a long time anyhow – they include: choice of reference source (eg MERRA, NCEP/NCAR, ground station, virtual time series based on combinations of above, etc), duration of reference (ie how many years to use to get a climatologically stable and representative time series), the reference period itself (ie which years to chose, eg the latest years or the "best" years (in some kind of definition of "best")), and finally which correlation techniques to use (how many sectors, which mathematical function to use in the fitting (eg linear), which data windows to use etc). The subject of longer-term climate cycles, trends and the impact of climate change are also frequently debated although firm conclusions have not emerged.

2.2.5 Wind profiles

As wind turbines grow in height, most or all of the rotor disc will at many times during the day be outside of the so-called surface layer (typical height of this layer is 50-200 m). Traditional boundary-layer meteorology has – due partly to the limitation of available measurements – not studied this part of the atmosphere to the same extent as the surface layer. This has the consequence that the theoretical understanding of the variation of the wind speed, wind direction and temperature high aloft, has been and still is quite limited. New theoretical formulations are required and these need to be based on and verified by high-quality measurements. The main theoretical issues are stability dependence and non-similarity theory aspects (see eg Pena et al, 2010).

2.2.6 Remote sensing

The field of remote sensing covers mainly two areas: firstly, practical issues about how to install and run Lidars and Sodars; secondly, how to analyse and validate the measurements. On the first issue (usage), the benefits and the application of the findings are very great indeed seen from a practical standpoint, however, the scientific content is, given the nature of the subject quite limited. The second area (analysis/validation), on the other hand, has seen a lot of scientific investigation being applied to it, numerous validation experiments have been carried out (for Sodars, see eg the EU-funded WISE project, and for Lidars numerous test sites have been used, eg ECN and Risø) and the theory behind Lidars as well as Sodars has seen rapid development as well (see eg Sanz Rodrigo, 2012). The ultimate aim of remote sensing is *bankability*, ie an approval by the banks and their advisors of the use of remote sensing equipment to produce wind resource measurements for direct and sole use in calculations of the energy yield of a wind farm project, which a bank is willing to use as a basis for finance of the project. For historical reasons, Sweden has seen - in an international perspective – a relatively large fraction of Sodar devices being used. Remote sensing devices have the potential to provide additional information and data about the wider flow field and characteristics which currently is not the focus of research effort although this is likely to change.

2.2.7 Meso-scale modelling

Meso-scale models are being used both on- and offshore for determining the wind resource of a larger area (eg a region or a whole country). Current developments include: increasing the spatial resolution of the models (including the coupling of meso-models with finer resolution linear or CFD models), understanding better how to model stability effects and also in the wind energy context, tailor-making the models to be able to model the wind speeds (as opposed to the many other quantities that are modelled by these models) as accurately as possible. Another particular line of development is putting together whole systems which can produce climatologically representative wind speed and direction distributions, and in some cases extreme winds as well, the so-called wind atlas methods.

2.2.8 Satellite inferred data

Two main applications of data obtained from satellites are seen: inference of topographical data (orography and roughness) and offshore wind speeds. The first application has not and does not see a lot of scientific investigation, which is probably appropriate given the nature of the subject. Elements of scientific investigation can be found in meso-scale modelling where finding the appropriate data source and resolution is a concern. Offshore wind speeds are a field of some investigation since very few measurements exist offshore (see eg Badger et al, 2012), but significant opportunities remain to conduct additional wind resource research on the existing and expanding body of data.

2.2.9 CFD/Complex terrain

Complex terrain (i.e. terrain with very steep slopes) has been a challenge for the wind energy industry ever since the early beginning. Until recently, due to limitations of computational power, only relatively simple, i.e. linearised, models have been used to model the effects of terrain slopes. However, the accuracy of linear models decreases as the steepness of slopes increases. Within the past 5 years or so, the more advanced CFD models have been increasingly applied on complex terrain sites where linear models fail. In order to exploit their full potential, CFD models require, to a much greater extent than linearised models, a high level of user expertise as well as computational capacity exceeding that available from typical personal computers. The recent general advances in computational power have brought down the cost of such computational resources, thus making possible a wider application of CFD models. The most active fields of research in CFD include: forest canopy modelling, modelling of atmospheric stability effects, and coupling to mesoscale models. More practical issues include convergence criteria, and optimal resolutions. The majority of CFD modelling is currently undertaken by solving the Reynolds-Averaged Navier Stokes (RANS) equations to force the flow solution to be in a steady-state. Increasingly, transient approaches such as Detached Eddy Simulations (DES) which allow computations to take into account the transient nature of the flow features caused by the larger turbulent eddies that circulate above the terrain are being investiagted. However, the computational power required is several orders of magnitude greater than for traditional RANS modelling and these transient simulations will become more widely used only as the computation power becomes more readily available.

2.2.10 Meso-scale/CFD coupling

In order to produce wind resource maps for large areas, the abovementioned meso-scale models are required. If one also wishes to make these maps detailed, it is necessary, due to the limitations of the meso-scale models, to "nest" flow models which can cover a smaller area but at a higher resolution, the so-called micro-scale models. The field of investigation has been ongoing for a while (see Frank and Landberg, 1997), however and as mentioned above, it is now possible to apply CFD codes to the micro-scale part of the calculation. Developing the right match between the two models is an area of intense investigation currently (see eg Ely, 2012).

2.2.11 Offshore winds

Due to the increasing interest in erecting wind turbines offshore, wind resource estimation offshore has seen a tremendous increase in interest. Seen from a theoretical point of view, however, there is nothing different as such about an offshore location, but given the industry interest, a discipline in its own right seems to be developing. The issues are to a great extent the same as those seen by the general industry and they include in particular: atmospheric stability, ambient turbulence, wind-wave interaction, long-term variability, wind profiles, remote sensing (including satellites), and meso-scale modelling.

2.2.12 Geographical distribution of research and current status[2]

There are a few institutions globally who stand out in the field of wind resource estimation research, these will be listed below. There are of course numerous other places where individuals or groups also have made significant contributions to the field, due to the scope of the present survey these are, however, not listed below[3].

a) Europe

- Risø[4] (now DTU Wind Energy), Denmark: a very strong boundary-layer meteorology group with focus on all aspects of wind energy meteorology. Also several test sites.
- University of Oldenburg/ForWind, Germany: strong boundary-layer meteorology group, emphasis on offshore
- ISET (now Frauenhofer IWES), Germany: cover most aspects of wind power meteorology also with some emphasis on offshore
- CENER, Spain: some aspects of wind power meteorology and a test site
- University of Porto, Portugal: focus on flow modelling (CFD)
- University of Loughborough, UK: some aspects of wind power meteorology
- ECMWF (European Centre for Medium-range Weather Forecasting), UK: development of global weather prediction models, some applications to wind energy.

b) North America

- NCAR, US: in many ways the centre of global boundary-layer meteorology research; they have, however, never focused directly on wind energy applications, but many of the generic and general results (especially meso-scale model development and global databases of reanalysis data) they produce are directly applicable to wind resource estimation.
- NREL, US: wind mapping
- Environment Canada: meso-scale modelling

c) Australia

- CSIRO, Australia: strong boundary-layer meteorology group: in wind resource estimation mainly known for forest measurements and modelling.

d) Commercial players

Some commercial players are also active in the study of flow modelling, notably ANSYS (UK), CD Adapco (UK), WindSim (NO), Meteodyn (FR), and Wind Lab Systems (AU).

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[2] The views expressed in the following are those of the author, not necessarly those of GL Garrad Hassan

[3] In Sweden these would include University of Uppsala, and in the US the likes of Texas Tech.

[4] It should be noted that the author has been leading this group from 1997-2007

2.3 Wake modelling

The easiest way to give an overview of wake modelling is to give an overview of which models are currently in use or under development. In the following sections this overview will be given starting out with a description of the models currently in use and then continuing on to describe the state of the art in wake modelling.

2.3.1 Wake models

The tables below list the various models currently used in the wind energy industry. Three different overall types of models are described:

1. Actuator disc with linear expansion of wake
2. Analytical wake representation – non-linear expansion
3. Axis-symmetrical RANS solver

Wake models with linear expansion of wake:

Name	Developer	"Method"
WAsP	Risø	Park
WindPro	EMD	Jensen 83
WindPro	EMD	Jensen 05
WindFarm	ReSoft	Park
WindSim	WindSim	Jensen 83
MeteoDyn	Meteodyn	Actuator Disc
OpenWind	AWS Truepower	Park
WindFarmer	GL Garrad Hassan	Modified Park
FLAP	Forwind	Park

The different "methods" are briefly described below.

All models in this group use the concept of a so called actuator disc.

The Actuator Disc is a disc inserted in the flow and accelerates the flow in a so-called stream tube. The mantle of this stream tube is formed by the path of particles moving through the circumference of the disc. The stream tube serves as a control volume for applying the conservation laws, and the actuator disc serves as a representation of the wind turbine. It reduces the wind speed homogenously over the rotor area.

Park is a simple, two dimensional model which uses momentum theory and the turbine thrust coefficient. The model developed in Jensen (1983) and Katic (1986) and was first implemented as stand-alone programme PARK distributed with early versions of WAsP. It is currently in use as *Jensen 83* in WindPro.

A later version of Park as implemented in the Risø WAsP code (Mortensen et al, 2007), in WindFarm, OpenWind and FLAP as *Park* and in WindPro as *Jensen 2005* also models wind turbines with different hub heights.

The *Modified Park* model (WindFarmer, 2011) incorporates further expansions to the Park model. It adjusts the wake to (for example in topography induced) changes in the ambient flow conditions in the wind farm area and uses an alternative wake superposition model.

Analyical representation of wake expansion:

Name	Developer	"Method"
WindPro	EMD	Larsen
WindSim	WindSim	Ishihara
OpenWind	AWS Truepower	Anderson
N/A	Aero-vironment	Lissaman
Milly	ECN	Vermeulen

Lissaman is based on Lissaman (1979) which is one of the first analytical wake representations and *Vermeulen* based on Vermeulen (1981), which is a modification of the analytical model in Vermeulen (1981). This method divides the wake into sections, each described by a particular linear expansion and wind speed profile.

The methods *Larsen, Ishihara and Anderson* are models based on the work in Larsen (1988), Ishihara (2004) and Anderson (2009), respectively, all simplify the self-similar profile to be of Gaussian shape. Each of these methods uses a particular analytical expression for the wake expansion

The final type of wake model is the Axis-symmetrical RANS (Reynolds Averaged Navier Stokes) solvers, and an overview is given below:

Name	Developer	"Method"
WindPRO	EMD	Ainslie
WindFarm	RESoft	Ainslie
OpenWind	AWS Truepower	Eddy Visc
WindFarmer	GL GH	Eddy Visc
N/A	Risø/DTU	Fuga
FLAP	ForWind	Ainslie
FyndFarm	ECN	FyndFarm

The methods are: *Ainslie* an axis-symmetrical RANS solver of a single wake using the parameterisation of Ainslie (1988). *Eddy Visc,* short for Eddy Viscosity, are models based on the Navier-Stokes equations. The model equations ensure that momentum and mass conservation are observed simultaneously, see Ainslie (1985). *Fuga* is based on the work in Ott (2011) and is a linerised model in a mixed-spectral formulation. *FyndFarm* is based on the work in Bulder (1997).

2.3.2 Wake modelling state of the art

The use of a 2D CFD RANS solver (see above), with empirical adjustments for known problem areas, currently represents the state of the art for both onshore and offshore wind farm wake calculation. The number of commercial wind farm design software packages offering such state of the art solutions is quite small. Over the next 5-10 years it is expected that more comprehensive 3D models may become a viable option. It should be noted that there is a neighbouring field of investigation concerned with estimating the loads and turbulence of wakes (as opposed to the energy yield only), and that there are many possibilities to combine these two fields.

2.3.3 Geographical distribution of research and current status

The geographical distribution below will give an overview of where research and model development take place. As noted above, very few publicly available data sets exist, so research is mainly focused on model development, validated against the few data sets available. It is interesting to note that both academic and commercial players are to be found in this field.

a) Europe

- Risø[5] (now DTU Wind Energy), Denmark: deep research into 3D CFD DES modelling and exploration of a multitude of innovative concepts. Maintain database of validation data.
- University of Oldenburg/ForWind, Germany: experienced wake modelling group, current emphasis on experimental validation of models using Lidar
- CENER, Spain: Research of 3D CFD wake models based on Ansys and OpenFoam some aspects of wind power meteorology and a test site, currently coordinating the WAKEBENCH project.
- CRES/National technical university of Athens, Greece: Experienced wake modelling group, research of 3D CFD wake models.
- ECN, Netherlands: experienced wake modelling group, operate a full range of wake models. Experimental validation through own linear test wind farm and scaled wind farm.
- GL Garrad Hassan, UK and Germany, commercial research for development of WindFarmer
- Ansys, UK, commercial research for 3D CFD wake models based on Ansys

A steady level of activity in the field is observed in Sweden distributed over a number of universities. A recent focal point has been the University of

[5] It should be noted that the author has been leading parts of this group from 1997-2007

Gotland, but has not yet made the international ”leagues tables”, but this will happen soon.

b) North America

Recently renewed and increased interest and activity at University of Indiana, and at NREL.

c) Rest of the world
Little activity

3 Future research needs

3.1 Introduction

In this section the future research needs of the Swedish Vindforsk programme will be suggested. The suggestion will be based on an analysis of the main drivers seen in a Swedish context. This analysis is of course in many respects subjective, since different angles of view will inevitably result in different conclusions. The perspective that has been taken here is trying to take a *global* view of the Swedish research and development scene in the context of wind resource and wakes, whilst at the same time trying to identify unique Swedish issues. In order to give value-for-money from a Swedish funding perspective these unique Swedish issues will carry the most weight.

3.2 Drivers in the Swedish context

The analysis of the drivers will again in the following be treated separately for wind resource modelling and wakes.

3.2.1 Wind resource

From a wind resource point of view the wind industry in Sweden sees many of the same drivers as the rest of the world when developing new sites (listed in Section 2.2 and 2.3, above). So from a global point of view Vindforsk could choose to set up a funding strategy where the best projects (defined by a strictly international scientific standard) in any of the topics identified above would be funded on a competitive basis. In this way, Sweden would contribute to the global pool of knowledge within both wind resource estimation and wake modelling. A call would then only give very general descriptions of the focus areas of interest, and the call would also underline that selection will be to strict international scientific standards, and not prioritising any particular fields.

It is the author's point of view, however, that wind energy in Sweden has some unique issues facing the industry, which could nicely serve as drivers for a Swedish research agenda. In particular two issues spring to mind:

1) Forests
2) Cold climates[6]

Almost 80% of Sweden is covered by forest and woodland and a very large fraction of wind farms are build in forested areas, so this gives Sweden a unique position to experience, observe and model very large forested areas. Similarly, around 15% of the land mass is above the Arctic Circle and in general many parts of the country sees below-zero temperatures for parts of

[6] The author is aware of the fact that other Vindforsk projects and project surveys also address this issue (Icing of wind turbines by René Cattin Meteo Swiss) and it will be discussed only briefly here

the year, which again gives rise to issues in constructing wind farms and a unique opportunity to study the effects of cold climates first hand.

Whereas there is some international interest in studying flow over forests (also within other areas of interest, like CO_2 modelling), also within the wind energy context, very little is taking place concerning the study of the effect of cold climates on wind energy. So here Sweden has an even more unique position - it is no coincidence that the annual meeting on wind energy in cold climates, Winterwind, is arranged by Swedes, and takes place in Sweden[7].

Although not as high on the list as the two main drivers identified above it is worth mentioning that many sites in Sweden are also located in complex terrain, ie terrain with steep slopes. Sweden has also seen some offshore projects coming on-line and being planned, it is not, however, the author's opinion that this is or will be in the near future a significant driver. Finally, it should be noted that due to the fact that wind farm development in forests inevitably results in turbine hub heights being increased, it is also worth studying winds at higher heights.

3.2.2 Wakes

The issues with modelling wakes in very big wind farms are definitely also issues in Sweden, but that research field is already rather crowded. If it is felt necessary that Vindforsk has activities within the area of wake modelling, then the current line of investigation could and should be continued, with the development of more and more advanced and accurate models. The wake modelleing research in Sweden has not been ongiong for such a long time, which means that from an international perspective, it is harder to see any unique areas where Swedish research can make a big contribution. However, the international cooperation that has taken and is taking place in projects V-333, V-355 and V-370 is the right way to go in order to firstly stay informed about what goes on elsewhere, secondly, to build the knowledge base in Sweden and thridly, to – through active two-way cooperation – contribute to the field.

3.3 Research needs

The identification of research needs will be based on an analysis of current projects and in particular to which extend they already address the issues raised by the drivers identified above. The research needs will then be discussed and a proposal will be made.

3.3.1 Current projects

The table below gives an overview of the areas within wind resource estimation and wake modelling (described in Sections 2.2 and 2.3) addressed by the current set of Vindforsk R&D projects.

[7] Note, that similar agencies in Canada have also recently re-started an interest in cold climate issues related to wind energy

	V312	V352	V356	V366	V333	V355	V370
Uncertainty							
Atmospheric Stability	√						
Forestry	√						
Long-Term variability							
Wind Profiles	√	√					
Offshore Wind				√	√	√	√
Remote sensing	√	√					
Meso-scale modelling	√		?				
Satellite data							
CFD	√			√	√	√	√
Meso/CFD coupling			?				√
Wakes				√	√	√	√

As can be seen from the matrix above, especially within wind resource estimation, the areas currently addressed by Vindforsk cover most of the topics currently under investigation by the wider wind energy research community; however, possibly not very deeply. They do, however, cover Forestry which should remain high on the R&D agenda. One could also claim that a characteristic of the projects, again especially within wind resource estimation, is that they attempt to cover a rather large number of topics, possibly at the risk of losing scientific focus.

3.3.2 Identification of research needs, wind resource

Following the above analysis of the unique drivers for the Swedish wind industry it is proposed that Vindforsk focuses on two areas:

1. Forestry
2. Cold climates[8]

This can be done in a number of ways:

1. Continue as now, with activities based on individual calls, covering a fairly broad range of areas.

[8] Dealt with in much more detail in the abovementioned survey report on Icing

2. Set up two *centres of excellence* focusing on the two above areas. These two centres should not be physical, but rather be coordination units, for the two areas, to make sure that Vindforsk benefits optimally from the money spent. Each centre of excellence should have a steering group consisting of both Swedish and international experts, ensuring that the focus remains Swedish, whilst at the same time work is carried out to international standards.

Independent of the organisational form topics should include:

Forestry

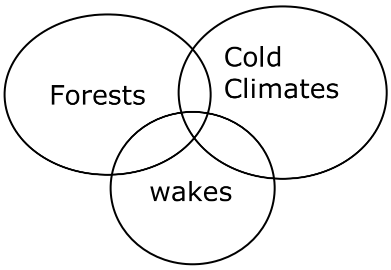
- Forest characteristics: how to practically obtain usable information about roughness, displacement height, leaf area index etc for large varied forests; estimate the uncertainty related to this; development of new methods to do the same.
- Measurements: the parameters of interest are: wind speed and direction, various turbulence quantities, temperature, temperature differences and heat fluxes. The parameters can be obtained by use of traditional masts and remote sensing devices. Given the prevalence of Sodars in Sweden a specific topic could be how well Sodars measure in forested areas of all the above quantities.
- Modelling, simple models: develop methods for accurately modelling flow over forested terrain for linear models.
- Modelling, CFD: develop canopy models
- Modelling: tall wind profiles.
- Overlap areas: forestry in cold climates, forestry in complex terrain, wakes in wind farms in forested areas.

3.3.3 Identification of research needs, wakes

Due to the lack of unique drivers within the field of wake modelling, three possible strategies could be followed:

1. Discontinue the funding of all wake modelling projects
2. Continue at the current level
3. In line with the wind resource approach set up a "centre of excellence" to coordinate and continue the wake modelling work that is already ongoing (mainly PhD-projects and participation in international working groups). The potentially most rewarding line of investigation could be to measure and model wakes in large wind farms in the two typical kinds of Swedish challenging areas, ie forests and cold climates. This would allow the research within wake and wind resource modelling to cross-fertilise each other, thereby improving both.

3.3.4 Summary, research needs



To summarise the proposed research needs the figure above lists the three proposed research and development centres of excellence within wind resource estimation and wake modelling. It should be noted that these three areas (especially Forests and Cold Climates) have a unique Swedish context, and as such will not only solve global scientific issues, but also be of particular benefit to the Swedish wind energy industry. As also indicated by the figure, further benefit can be obtained for exploring the overlap regions of the three areas of investigation.

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