

Trends and challenges for wind energy harvesting : workshop, March 30-31, 2015, Coimbra, Portugal

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WORKSHOP

Trends and Challenges for Wind Energy Harvesting

March 30-31, 2015
Coimbra, Portugal

WORKSHOP

Trends and Challenges for Wind Energy Harvesting

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March 30-31, 2015
Coimbra, Portugal

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COST ACTION TU1304

WINERCOST

TU1304 WINERCOST ACTION

WIND ENERGY TECHNOLOGY RECONSIDERATION TO ENHANCE THE CONCEPT OF SMART CITIES

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Abstract: The Strategic Workshop on the trends and challenges for wind energy harvesting is the first open forum organised within the framework of the activities of the TU1304 WINERCOST Action “Wind energy technology reconsideration to enhance the concept of smart future cities”. The state-of-the-art of the wind characteristics in disturbed and non-disturbed environment, the state-of-the-art of the wind energy structures and emerging applications as well as the society acceptance of wind energy technology and related topics are issues that were presented in details and discussed during the two days of the present Strategic Workshop.

1. Introduction to the WINERCOST COST TU1304 Action

1.1 Aims and objectives

The WINERCOST Action (TU1304) aims to merge the efforts of the European research groups working on the wind energy technology and find the pathways to introduce it by means of robust applications to the urban and suburban built environment, and thus to enhance the concept of smart future cities.

WINERCOST Action shall revisit safe, cost-effective and societally accepted wind energy technology for consideration in the design and development of the future urban and suburban habitat.

The principal objectives of the WINERCOST activity are:

- to collect the existing expertise on the built environment wind energy technology recently developed as a follow-up of the onshore and offshore wind energy technology and
- to investigate effective adoption methods for enabling the concept of smart future cities.

In addition, the utmost important issue of the social acceptance strategy will be scrutinized in close collaboration with municipality authorities, industry, manufacturers as well as the international wind energy organisations and platforms.

1.2 Background

The objective of future smart cities of EU HORIZON 2020 aims at 20% of renewable energy in terms of produced electricity by renewable sources. Nowadays, the major contributors to locally produced renewable energy are photovoltaic systems, solar panels and combined heat power systems, whereas there is also a significant potential from small and medium scale (15kW-100kW) wind turbines to complement them. The upper limit of 100kW is the maximum power that can be connected directly to the low voltage grid in most European countries, where, during the last years, a significant growth in the sector of small and medium turbines has been observed and a further increase is expected in the next years. According to the Kyoto Protocol and Rio+20 Declaration wind energy technology provides a robust and mature technology to meet the increasing energy demand without compromising the environment. As Europe is currently the worldwide leader in on- and offshore wind energy technology with respect to size, expansion trends and innovation applications like the BWT, it becomes mandatory for all COST countries stakeholders:

- 1) to intensively collaborate in order to exchange expertise,
- 2) to discuss any open problem (like noise, integrity, societal acceptance, etc.),
- 3) to disseminate the respective outcomes to engineers/designers/researchers (in particular early stage researchers) by means of Training Schools, Seminars and Conference educational material in digital and hard copy versions.

It is noteworthy that municipal authorities and decision-makers have been already attracted to the discussion on the societal acceptance of wind energy technology applications in built environment. This Action builds upon previous successful COST Actions such as COST C14: Impact of wind and storm on city life and built environment, COST 732: Quality assurance and improvement of micro-scale meteorological models and ES1002 WIRE: Weather intelligence for renewable energies. This way WINERCOST will strongly contribute to the benefit of the future smart cities concept:

- a) by identifying prerequisites and conditions for the adoption of wind energy technology into the urban and suburban habitat constructions,
- b) by supporting relevant measures and actions,
- c) by promoting its capability and trying to motivate city and municipal authorities, decision-making groups and in particular local society itself about the assets of the application of the built environment wind energy technology exploitation in Smart Cities.

Besides the obvious positive issues of wind energy technology (CO₂ zero emission, job creation, etc), the respective heavy economic social load, the social acceptance with reference to the aesthetics, the noise etc. of the built environment wind energy technology there are still open problems which started been systematically collected, discussed and thoroughly analysed within the WINERCOST framework.

1.3 Current state of knowledge

Nowadays three types of integration of wind energy generation systems into urban environments are used: a) sitting stand-alone wind turbines in urban locations; b) retrofitting wind turbines onto existing buildings and c) wind turbines fully incorporated into the architecture. They are either Horizontal Axis Wind Turbines (HAWT) or Vertical Axis Wind Turbine (VAWT) mounted on the top of masts in fairly open areas. The performance of these systems has been reported to be very site-specific and in many cases the proximity to buildings has decreased the performance; they take advantage of augmented airflow around buildings, addressing both the two later categories applications, the former including traditional or newly

developed wind turbines fitted onto either existing buildings or new buildings without modifying the building form. The last category consists of modified building forms for full integration of wind turbines. Well-known examples of high-rise buildings designed having integrated large-scale wind turbines are the Bahrain World Trade Centre, the Strata Tower in London and the Pearl River Tower in Guangzhou. Computational and laboratory investigations on the last category applications were focused on “twin-tower” configurations where the HAWTs are placed in between the two towers. These efforts performed in the framework of the European project WEB (“Wind Energy for the Built environment”), found “kidney” or “boomerang” shapes to be the best shapes. Substantial power enhancement was found for effective angles of wind incidence up to 60°, and satisfactory power output (i.e. > 50%) when the wind is effectively coming at right angles to the building/turbine. It is noteworthy that recently the first principles for the effective design of built environment wind energy technology systems have been proposed. Although several valuable earlier research efforts have focused on BWT and its application in urban areas, these efforts have so far been fragmented and often not combined with social acceptance strategies. The latter issues are addressed by WINERCOST and constitute and strengthen its innovative character.

During this first period the existing expertise on onshore, offshore and any other application of wind energy structures, as well as relevant non-technical and society acceptance issues started been scrutinized, where a vivid exchange of the accumulated scientific and technological knowledge among the partners started aiming to lead to the cross-fertilisation of the involved research group efforts.

In this way, following the discussions of the possible negative impacts/effects (e.g. noise, production/installation costs, logistics, reliability, integrity, system robustness, aesthetic and societal acceptance problems), the forthcoming WINERCOST years will mainly focus on developing a strategy to enhance the smart city concept by extensively introducing BWT applications to the urban/suburban environment. In this framework, a wealth of expertise on the previous wind energy technology topics started been collected, critically analysed and worked out by the WINERCOST partners.

2. Scientific programme and work plan

2.1 Scientific programme

Having as ultimate objective the implementation of the concept of Smart Future Cities, WINERCOST Action started motivating wind energy research groups to put all their efforts into the advancement of the wind energy technology at the urban and suburban built environment. The rich existing expertise on the well-established onshore and offshore wind energy technology started been collected and used as a robust background towards a safe, cost-effective and socially accepted built environment wind energy technology for consideration in the planning, design and development of the future urban and suburban habitat.

To this purpose, the principal research tasks of the WINERCOST Action have been established:

- To collect any available data of existing small, medium and large wind turbines and wind turbine supporting structures for urban and suburban areas. In a first step, existing data on installed capacities of Small and Medium Wind Technology (SMWT) in the urban environment are to be collected and evaluated with reference to different turbines types and sizes, installation capacities, wind conditions and grid integration (central or de-central). Aim of this task is to collect actual knowledge, assess relevant wind energy technology applications and evaluate assets and weaknesses.
- To transfer of knowledge from on- and offshore wind energy projects. A review of the

installation process of on- and offshore wind energy technology applications since the decade of '80s will show the development of well-established wind energy markets. It is necessary to check, if gained experiences and knowledge of the "large scale" wind energy could be effectively downscaled to SMWT.

- To evaluate regional differences including energy policies, design requirements and building rules for SMWT in urban areas. Due to the differences in installation capacities of SMWT in urban areas, a review of policy-based factors like energy harvesting is to be discussed. Political-based installation and design requirements will reveal local needs for possible improvements in actual design guidelines. Furthermore, differences in fixed price purchase will also be taken into account.
- To assess wind conditions in urban and suburban environment, wind maps/roses quality and wind comfort problems in neighbouring areas. Compared to large ON- and OFF-SHORE wind turbines, SMWT are comparably small, a fact that can be traced back to wind conditions and site-specific wind fields. A review on existing wind data for urban areas will show the opportunities for SMWT in the built environment.
- To determine societal acceptance criteria: in fact, the installation of SMWT in urban areas is influenced significantly by the acceptance by the local communities. A European criteria catalogue on social acceptance does not yet exist, although some preliminary effort has been done recently in international renewable energy fora. This results from a different understanding and acceptance of the SMWT. Nevertheless, to seek for required research needs, a thorough investigation of the social acceptance criteria is to be performed. By this, necessary research in the different countries of the participants and also for Europe can be used for future research needs and activities.
- To discuss European energy policies and strategy for advancement of the BWT with consumers, municipalities, industry (turbine manufacturers) and network providers. As a result, a new research field for the investigation of optimized central or de-central grid-integration may be implemented.

2.2 Work plan

TU1304 Action consists of several work packages in order to cover all the important aspects of the WINERCOST Action.

During the first half of the WINERCOST Action, the existing expertise on onshore/offshore wind energy structures, Aeolian parks and any other application like Building-Integrated Wind-Energy Technology applications started been studied and the relevant scientific and technological knowledge achieved among the partners started been exchanged, aiming to lead to the cross-fertilization of the research activities.

During the second half of the Action, the activities will be focused on the development of a strategy to enhance the Smart Cities Concept by effectively introducing BWT projects into the built fabric. The Action will also work on the technological implementation difficulties, possible non-technical negative effects as are e.g. noise, production and installation costs, logistics, reliability, integrity, system robustness, aesthetic and societal acceptance problems, as well as the European energy policy as well as societal acceptance issues.

In this sense, the WINERCOST network that includes all relevant built environment wind energy technology stakeholders will soon develop an overall view on the research needs and the respective necessary actions for the future. In this way, incorporating all partners' relevant expertise, WINERCOST Action will develop an extensive database of the existing knowledge showing the opportunities for the built environment wind energy technology in urban and suburban environment. Note that for the time being research groups from 26 countries (Belgium,

Bosnia and Herzegovina, Croatia, Cyprus, Czech Republic, Finland, FYR of Macedonia, Norway, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Serbia, Slovakia, Spain, Sweden, Switzerland, Turkey and United Kingdom) collaborate and contribute towards the successful completion of the WINERCOST aims and objectives.

3. The Strategic Workshop “Trends and Challenges for Wind Energy Harvesting”

WINERCOST has the following scopes:

- i) to open dialogue with and incorporate decision making administrative structures like municipalities, technical chambers, urban design bodies or offices and International organization or European level and government policy makers to the WINERCOST activities,
- ii) to coordinate relevant activities of the academia and research centres working with wind energy technology, built environment wind energy technology and future smart cities (both participating and outside WINERCOST groups),
- iii) to convince industry (WET manufacturers and WET/BWT service providers) to invest in this sector by communicating to them all the wealth of findings and outcomes of WINERCOST and
- iv) to motivate general public in the sense of city/municipality citizens to enthusiastically support the implementation of built environment wind energy technology for future smart cities.

To this purpose, key-persons in appropriate decision making positions have been approached and gained to the activities of the project (Strategic Workshop and International Conferences). The perception of the importance to integrate wind energy infrastructures into the fabric of the urban networks in the future started been studied; decision-makers started discussing first-hand the relevant technologies if they are mature enough and ready to hit the market and if they can make a real difference. Academia, i.e. research groups in universities and research centres, has been already joined WINERCOST. This has been easily achieved as the channels of information dissemination (scientific journals, proceedings, relevant websites) are already in place. The International Conferences, as well as the WINERCOST website www.wincercost.com, are of utmost importance for the success of the Action. In the meantime, strong efforts were invested to attract industry and convince it for investing in an emerging field being traditionally considered as a high risk venture. However, putting people from industry in touch with their potential clients (decision making authorities) and the human capital with the know-how (academia) will generate potential for positive steps. Last but not least: the general public started been communicated the assets of using built environment wind energy technology as a factor of the smart future cities concept and CO₂ zero emission policy via the collaborating municipality authorities with the WINERCOST members working with the hot issue of societal acceptance.

As described in details in the Memorandum of Understanding of WINERCOST, the research outcome will be disseminated by means of a robust and meticulously designed dissemination strategy.

The Strategic Workshop on the trends and challenges for wind energy harvesting that took place in Coimbra, 30-31 March 2015 is the first open forum within the lines of the previously described dissemination framework. In order to investigate future synergies and possible collaborations the chairpersons of 2 “neighbouring” COST Actions (namely the one entitled “Smart energy regions” and the one entitled “Building integrated solar thermal systems”) have

been invited to contribute to this Workshop by presenting the activities of their Actions and exchange ideas on the possibility of further collaboration with the WINERCOST members.

Within these two days, three cycles of discussions corresponding to the activities of the three WINERCOST Working Groups were organised.

The first one concerns the state-of-the-art of the wind characteristics in disturbed and undisturbed environment. In particular, several topics on the wind flow in built environment, the urban electricity networks for smart cities and the wind fields and dispersion patterns were presented and in depth discussed. The second cycle of presentations refers to the state-of-the-art of the wind energy structures and the emerging applications. Among others, topics on on-shore and offshore wind energy structures and monitoring of their response were discussed. The last part of the Strategic Workshop considers the importance of the society acceptance of the wind energy technology and related non-technical issues as is e.g. the relevant strategies in municipality level. The previous topics correspond to the presentations delivered by 23 scientists collaborating within the WINERCOST Action and the respective papers have been included to the present proceedings.

4. Future steps

After the Strategic Workshop, at the end of the 1st year of the WINERCOST Action an utmost important activity has been planned within the TU1304 activities: the 1st WINERCOST Training School that will take place in Malta end of May 2015 aiming to train Early Stage Researchers on the advances of wind energy technology.

According to the Action general schedule, three more Training Schools have been also planned for the next three years of WINERCOST aiming to train as many Early Stage Researchers as possible on relevant built environment wind energy topics. In the selection of the trainees and trainers a gender balance policy will be in all cases adopted.

Eventually, in spring 2016 the 1st WINERCOST International Conference will be organised in the Centre for Wind Energy of the Middle East Technical University in Ankara to provide a broad international forum for the presentation and discussion of different aspects of wind energy and wind energy technologies in urban and suburban built environment in order to enhance the concept of smart future cities.

Acknowledgements

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Workshop Part 1

State of the Art of the Wind Characteristics
in Disturbed and Non-Disturbed Environment

FOREWORD TO WG1 PROCEEDINGS: WIND SIMULATION AND CHARACTERIZATION

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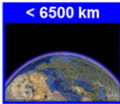
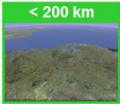


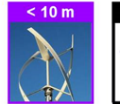
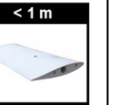
Spatial scale	Global	Mesoscale	Microscale	Building	Turbine	Blade
Distance	< 6500 km 	< 200 km 	< 2 km 	< 100 m 	< 10 m 	< 1 m 
Model cat.	NWP	NWP / MMM	CFD/WT/OS	CFD/WT/OS	CFD/WT/OS	CFD/WT

Fig. 1: Schematic representation of the spatial scales in wind energy resource assessment, their typical maximum horizontal length scales and associated assessment methods. NWP = Numerical Weather Prediction; MMM = Mesoscale Meteorological Model; CFD = Computational Fluid Dynamics; WT = Atmospheric Boundary Layer Wind Tunnel; OS = On-Site Measurement.

It is well known that the continued emission of greenhouse gases is likely to cause severe, pervasive and irreversible impacts for the world's population and ecosystem [1]. A reduction in these emissions could dramatically decrease the climate risks for the 21st century and beyond. Aiming to reduce the global greenhouse gas emissions has led to increased efforts to generate a growing proportion of our energy via clean, renewable technologies. That was the main reason for the European Union (EU) Commission to issue the 2009/28/EC1 Directive on the promotion of the use of energy from renewable sources (the "Renewable Energy Directive") and to establish mandatory targets to be achieved by 2020 for a 20% overall share of renewable energy in the EU and a 10% share for renewable energy in the transport sector. One of the promising sources of clean and renewable energy is the wind. Currently, the majority of the wind energy production is from large wind farms, which are built away from the built environment. These can be on-shore or off-shore wind farms and are normally located in a flat terrain, in which the atmospheric boundary layer (ABL) is usually undisturbed. The characteristics of

the undisturbed ABL are well defined and its turbulence intensity is usually lower than that of its disturbed counterpart, which usually occurs over complex terrain and built environment. Since the world's population has been rapidly urbanising for at least the last 5 decades and currently about 54% of the world's population live in urban areas, and this number is expected to continue to increase [2], there is a large increase in demand for medium and small size wind turbines to operate in the urban environment. This has the potential to reduce the load on the existing transmission networks, assuming the energy would have otherwise been generated rurally. Additionally it can help to significantly reduce energy losses due to reduced transmission lengths. Given the above information, urban wind generation has become a particular interest for many researchers around the world, and could one day become a significant contributor to solving the global energy crisis. Often policy makers talk about the balance of finding secure, clean and cheap energy; otherwise known as the 'Energy Trilemma'. However, generating wind energy in built environment comes with significant challenges that need to be resolved in order to promote this technology. One of these is the low mean wind speed and the high turbulence intensity in built environment.

In the first Working Group (WG1) of the COST Action TU1304 we aim to provide improved understanding of the wind characteristics of both the disturbed and undisturbed atmospheric boundary layer with a special emphasis on flow in the built environment. This will be achieved through two parts of the working group: WG1A and WG1B. WG1A focuses on wind simulation, characterization and related issues, with reference to theoretical, experimental and numerical research approaches. Particular attention is devoted to on-site measurements, wind-tunnel measurements and especially numerical simulation by Computational Fluid Dynamics (CFD). Afterwards, WG1B will more specifically focus on Built Environment Wind Energy Technology (BWT) advances.

Figure 1 provides a schematic representation of the methods for wind energy resource assessment. At the macroscale or the synoptic scale and at the mesoscale, the numerical integration of the approximate forms of the governing equations for atmospheric dynamics subject to specified initial conditions is termed Numerical Weather Prediction (NWP). More specifically, models at the mesoscale are also called Mesoscale Meteorological Models (MMM). At the meteorological microscale, the numerical alternative is termed CFD, while also reduced-scale wind-tunnel testing in atmospheric boundary layer wind tunnels and on-site measurements are key assessment tools. At this microscale, deciding which approach is most appropriate for a given problem is not always straightforward, as each approach has specific advantages and disadvantages. The main advantage of field measurements is that they are able to capture the real complexity of the problem under study. Important disadvantages however are that they are not fully controllable due to – among others – the inherently variable meteorological conditions, that they are not possible in the design stage of a building or urban area and that usually only point measurements are performed. The main advantages of wind-tunnel measurements are the large degree of control over the boundary conditions and test conditions and the fact that buildings, urban areas and their components can be evaluated in the design stage. However, as in field measurements, also in wind-tunnel measurements, generally only point measurements are performed. Techniques such as Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF) in principle allow planar or even full 3D data to be obtained, but the cost is considerably higher and application for complicated geometries can be hampered by laser-light shielding by the obstructions constituting the model, e.g. in case of an urban model consisting of many buildings. Another potential disadvantage of wind-tunnel testing is the required adherence to similarity criteria when testing at reduced scale.

Numerical modeling with CFD can be a powerful alternative because it can avoid some of these limitations. It can provide detailed information on the relevant flow variables in the

whole calculation domain ("whole-flow field data"), under well-controlled conditions and without similarity constraints. However, the accuracy of CFD is an important matter of concern. Care is required in the geometrical implementation of the model, in grid generation, in selection of proper solution strategies and in interpretation of the results. Selection of proper solution strategies includes choices between the steady Reynolds-averaged Navier-Stokes (RANS) approach, the unsteady RANS (URANS) approach, Large Eddy Simulation (LES) or hybrid URANS/LES, choices between different turbulence models, discretization schemes, etc. In addition, numerical and physical modeling errors need to be assessed by solution verification and validation studies. CFD validation in turn requires high-quality experimental data to be compared with the simulation results.

At the scale of individual wind turbine and its blades, also CFD, reduced-scale wind-tunnel testing and on-site measurements are the main categories.

The current proceedings present an interesting variety of studies from WG1A, and we hope you will enjoy reading them.

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WIND FLOW IN THE URBAN ENVIRONMENT

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Abstract: The viability of wind turbines in urban areas is crucially dependent on an accurate understanding of urban wind-flow. General characteristics of urban wind climate are that the high roughness of the buildings causes low wind-speed and high turbulence intensity. Turbulent fluctuations are sensitive to height, proximity to buildings, and vary diurnally according to surface heating. Work to generalise urban turbulence levels and impact on generation is needed. Simple models of mean wind-speeds can be improved by including better estimates of roughness parameters based on building morphology data. Sites should be targeted in locations with low roughness and good exposure – rivers, parks, coastal sites, tall buildings.

1. Introduction

The viability of wind turbines in urban areas is crucially dependent on an accurate understanding of the wind-flow and turbulence patterns. This applies to both selecting the right turbine design and a suitable site, and to predicting potential yield in an economic analysis. This paper briefly highlights characteristics of urban wind-flow relevant to wind energy considerations.

2. General characteristics of wind-flow in urban areas

In this section, a brief overview of urban wind characteristics is given, as well as how surface aerodynamic roughness can be described and quantified. For more detail, please see reviews by Barlow (2014) [1], and Ishugah et al. (2014) [2].

2.1 Overview

The urban boundary layer can be defined as being the depth of atmosphere influenced by urban surface heating and drag. Its depth determines the size of the largest turbulent eddies that can influence a wind turbine mounted at the surface. A typical framework for describing the urban boundary layer can be understood in terms of the following characteristics:

1) Three horizontal scales can be defined: street $O(10-100\text{ m})$, neighbourhood $O(100-1000\text{ m})$ and city $O(1-10\text{ km})$. These can be interpreted as scales on which the urban morphology becomes homogeneous (i.e. a single house or street; a collection of buildings of similar height and shape in a neighbourhood; a town or city which is rougher than the surrounding rural area).

2) Urban surfaces are heterogeneous and thus advection is a key characteristic at both city and neighbourhood scale. At city scale an Internal Boundary Layer (IBL) forms at the interface between the smoother rural and rougher urban surfaces. If the city is large enough, the urban IBL fully replaces the rural boundary layer upstream (i.e. attains the upstream boundary layer depth). On a neighbourhood scale, flow is continually adjusting to changes in roughness (i.e. from parks to suburbs to city centre), producing local IBLs where wind profiles are locally in equilibrium with the underlying surface drag. The IBL depth to fetch ratio is approximately 1:100, whereas the equilibrium layer to fetch ratio is approximately 1:1000. Equilibrium layer is here defined as being where the mean flow and momentum flux profiles are consistent with the downstream surface roughness and occupies c. 10% of IBL depth – the remaining 90% of the IBL is a transition layer where profiles and fluxes adjust gradually back to the upstream surface values.

3) Roughness elements are large, and thus an urban roughness sub-layer (RSL) can be defined of depth between $2-5 H$, where H is the mean building height. Within this layer, flow is highly spatially dependent (see Fig. 1a); turbulence can dominate the mean flow; turbulence has different characteristics from the flow in the inertial sub-layer above (e.g. the gust distribution in the RSL is non-Gaussian). For an extensive review of urban turbulence above roof height, see Roth (2000) [3], and for the RSL, see Barlow and Coceal (2009) [4].

4) A helpful concept is to define the “urban canopy”: spatial averaging of the flow between the roughness elements gives an exponential profile up to roof height, and logarithmic profile above (see Fig. 1b) which can then be related to general morphological characteristics of the canopy.

5) A typical two-dimensional “unit” of urban roughness that has been much studied is the street canyon, consisting of two parallel rows of buildings of similar heights with a length generally $L \sim 5-10 H$. An equivalent three-dimensional idealization is the cube or cuboid.

6) Descriptions of urban morphology across a neighbourhood, or defined “lot area” are generally simplified and expressed in terms of packing density. Two parameters in particular are defined: the frontal area index λ_f which is the ratio of total frontal area of roughness elements divided by lot area; and the plan area index λ_p which is the ratio of total plan area of roughness elements divided by lot area.

The heating and cooling characteristics of an urban surface are different to a rural surface: atmospheric stability is closer to being neutral due to the larger aerodynamic roughness. As an urban surface is generally drier and made of materials with higher heat capacity, an “urban heat island” can occur where the city is warmer than the countryside at night; more information on this can be found in the review of Arnfield (2003) [5].

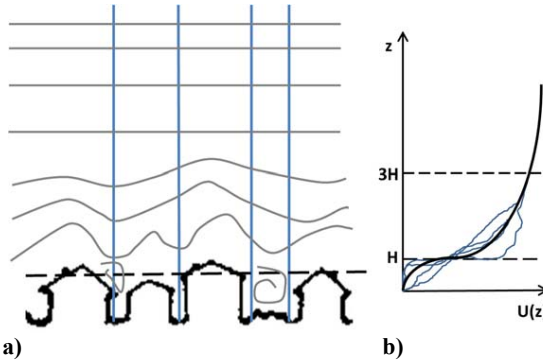


Fig. 1: Schematic of urban flow near to buildings. a) Streamlines (in grey) are perturbed directly by the buildings on a length-scale associated with their mean height, H . Blue vertical lines indicate locations of vertical wind profiles, $U(z)$, where z is height, as shown in b). Black solid line indicates the spatial average of the four wind profiles. The profiles are spatially dependent in the roughness sublayer up to $z \sim 3H$, and are identical above this layer.

2.2 Urban roughness parameter estimation

Given a neighbourhood of relatively homogeneous buildings, large enough to develop an equilibrium layer and subsequent logarithmic wind profile in response to the surface aerodynamic roughness, the wind-speed at a particular height $U(z)$ can be estimated. It is important to determine suitable values of the relevant roughness parameters and how they relate to different types of urban surface (e.g. residential low-rise, central urban, skyscrapers, etc). Whilst roughness length z_0 is clearly required, the zero-plane displacement height z_d also needs to be determined as defined by the log law

$$U(z) = \frac{u_*}{k} \ln \left(\frac{z - z_d}{z_0} \right) \quad (1)$$

where u_* is the friction velocity and k is the von Kármán constant (usually taken to equal 0.4). In common with other canopies of roughness elements of medium to high density, the drag is distributed over a finite depth and the logarithmic layer is displaced upwards. A rule of thumb for a dense urban surface is that $z_d/H \sim 0.75$, i.e. that the displacement height is approximately three-quarters of the mean height of the buildings. When z_d is not taken into account, wind-speeds estimated near roof-tops can have large errors.

There is a large literature on determining look-up tables of roughness parameters for different land surface types (e.g. the Davenport classification). This paper will focus on the methods used in urban climate studies, which are more quantitative, to determine whether the increased sophistication adds value to determining wind energy resource. Grimmond and Oke (1999) [6] reviewed the methods whereby the roughness parameters z_0 and z_d are determined. They defined two categories of method: a) morphological, whereby the parameters are related to mean height and packing density of the buildings, and b) micrometeorological, whereby the parameters are estimated from measurements. Morphological algorithms relating roughness parameters to packing density were invariably drawn from wind-tunnel or other scale model studies, often for cubes.

Fig. 2 shows a schematic of how roughness parameters generally depend on packing density taken from [6]. Roughness length peaks ($z_0 \approx 0.05$ to $0.15 H$) for low to moderate values of the packing density (plan area density $\lambda_p \approx 0.2$ to 0.4 ; frontal area density $\lambda_f \approx 0.1$ to 0.3). The displacement height increases monotonically and non-linearly with packing density, more

rapidly for lower packing densities. It can be seen that not all urban surfaces are the same – [6] quote typical ranges for cities as $\lambda_p \approx 0.1$ to 0.6, and $\lambda_f \approx 0.05$ to 0.45. The relationship between the two parameters depends on predominant aspect ratio of the buildings, for example [7] investigated the relationship for London packing densities estimated on a 1 km² grid across the city. The relationship $\lambda_f: \lambda_p$ is less than 1:1 due to the predominantly low-rise, cuboid nature of the buildings, thus showing the short-comings of assuming a cubic geometry when deriving a morphological algorithm. Other work has shown that when identical cubes were replaced by varying height cuboids of the same total volume, roughness was increased [8], showing another factor not included in such parametrizations.

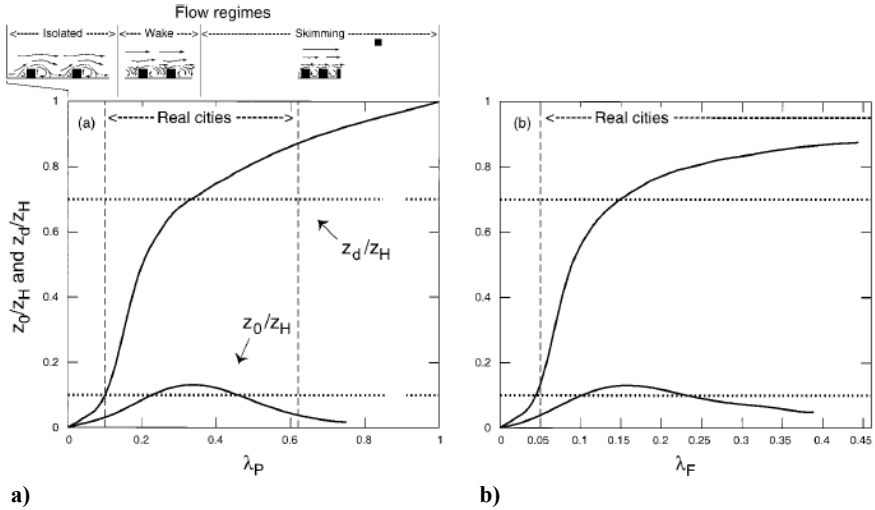


Fig. 2: Schematic showing dependence of roughness parameters on a) plan area index, λ_p and b) frontal area index, λ_f . Roughness length z_0 and zero plane displacement height z_d are normalized by mean building height, given in figure as z_H . Figure taken from [6].

[6] concluded that there are few high quality micrometeorological observations of roughness parameters that can be used to test the algorithms and recommend three of the morphological algorithms. One of these, due to MacDonald et al. (1998) [9], was highlighted as being promising. This has become one of the most widely used algorithms for predicting roughness parameters over urban areas.

3. Methods of estimating wind resource in urban areas

In this section a brief review is given of some work on improving wind resource assessment tools for the UK.

3.1 Existing methods for estimating urban wind resource in the UK

A number of studies have developed techniques for estimating resource in urban areas ([10], [11], [12], [13]). Despite this, local authorities currently rely on the predictions of low resolution wind speed databases. In the UK, the DECC wind speed database has been widely used by installers and planners for a number of years to evaluate the wind resource at potential sites

for a micro-wind turbine ([14], [15]). It provides estimates of the mean wind speed at a 1 km resolution at 10, 25 and 45 m above ground level. The database was produced by a mass consistent flow model, NOABL (Numerical Objective Analysis of the Boundary Layer), which interpolated wind speed data from 56 weather stations across the UK ([16]). UK field trials carried out by Energy Saving Trust and Encraft demonstrated that the DECC database (hereafter NOABL) tended to overestimate the wind speed, particularly at locations in close proximity to buildings ([17]). In 2009 the Carbon Trust in collaboration with the UK Meteorological Office launched an online wind speed estimator. However, this tool is no longer available and consumers are now recommended to use the Energy Saving Trust Wind Speed Prediction Tool (EST tool). The EST tool is freely available online and provides an estimate of the annual mean wind speed at a height of 10 m based on the site's postcode and land use type (either urban, suburban or rural). However, little information of the calculation process is provided.

The wind speed predictions of the two tools were compared with data measured at 91 weather stations across the UK by [18]. In general, NOABL tended to overestimate the wind resource (73 out of 91 sites). The magnitude of the overestimate was relatively large; there was a mean error of 23% over the 73 sites and it was in excess of 20% at 35 sites. In comparison, for the 18 sites at which the resource was underestimated there was a mean error of 10%. The majority of the underestimates tended to occur at higher wind speed sites (15 occurred at sites with a mean wind speed in excess of 5 ms^{-1}). These results are in agreement with the findings of previous research. The predictions of the Energy Saving Trust tool showed similar results however the magnitude of the error was generally lower. The model underestimated the wind speed at 64 sites, with a mean error of 18%.

The Micro-generation Installation Standard (MIS 3003) applies correction factors to the NOABL wind speed based on turbine height and urbanization of the site, termed NOABL-MCS ([19]). While this approach considers the impact of the surface on the flow in the roughness sublayer, it does not consider the impact which occurs on larger scales. Consequently, [14] showed that despite the adjustment, the NOABL-MCS still generally overestimates the wind resource in urban areas.

2.2 Adjustment of wind profiles to the urban canopy

[20] and [10] considered the growth of an internal boundary layer (IBL) at the boundary between a rural and urban surface to estimate the wind speed in an urban area from a reference rural wind speed. However both studies assumed a uniform roughness length for the whole urban area. In reality, while urban surfaces are very different from the surrounding rural surfaces, they are not internally uniform. Typically, because of common use, neighbourhoods (up to 1 or 2 km) tend to exhibit reasonably uniform surface characteristics (e.g. residential, industry, commercial, parkland). However variability of the surface on this scale has not been considered when estimating the wind speed in urban areas, therefore there is a clear need to develop a method of estimating the variability of the wind resource across an urban area on a neighbourhood scale.

[11] adapted the method of [20] to take into account varying roughness across an urban area. Using the MacDonald model to estimate roughness parameters on a 1 km grid across London, coupled with a simple model for IBL growth rate with distance, the wind profile for each grid-box was adjusted to take into account the impact of gridbox roughness on the incident upstream wind profile. Validating the model against 10 years of data available at two sites, the prediction of the annual mean wind speed lay within one standard deviation of the measured value. At one site the model overestimated the measured annual mean wind speed by only 3%. In comparison, the NOABL database gave an overestimate of 27% and the Carbon Trust tool an underestimate of 16%. A similar result was shown at the Heathrow airport site, with the model overestimating

the annual mean wind speed by only 1% in comparison to an 18% overestimate by NOABL and 31% underestimate by the Carbon Trust tool. This work showed the importance of allowing for intra-urban roughness variations when estimating wind resource.

[11] then applied the newly derived wind map for London to calculate capacity factors for a range of 34 commercially available small wind turbines. Fig. 3 shows the range of capacity factors across London, normalized by the rural capacity factor upstream.

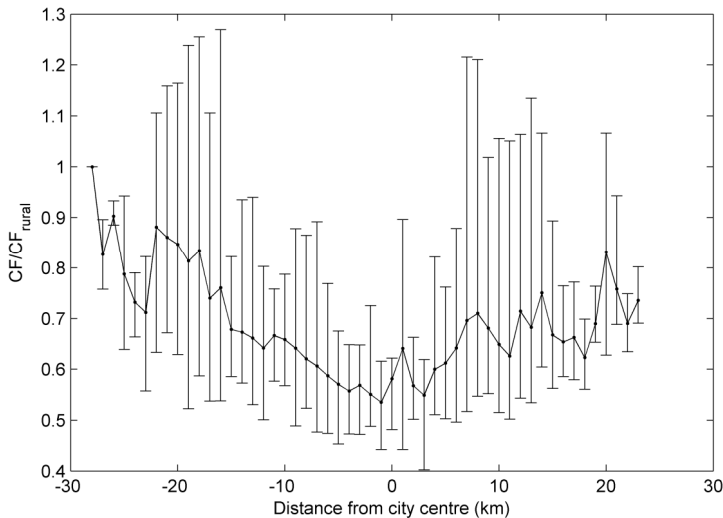


Fig 3: Capacity factor CF for 34 commercially available small wind turbines normalized by upwind rural capacity factor CF_{rural} for London, error bars show standard deviation. Data are plotted as a function of distance from the city centre by taking the mean of 15 transects across London. Taken from [11]

Fig. 3 shows that the wind resource decreases towards the centre of the city, as expected – but the standard deviation shows that individual sites can perform even better than rural sites upstream. For cities which fit a concentric growth spatial model, distance from city centre can be a useful parameter when deciding on whether to install wind turbines. Generally these sites are of lower roughness (parks, riverside locations, some industrial areas) and the work suggests that urban wind installations could be targeted at lower roughness areas. [21] also performed an analysis suggesting that sub-urban and coastal urban sites were the only economically viable options.

Recent work is starting to include assessment of wind resource for taller buildings which are better exposed and experience considerably higher mean wind-speeds ([12]). Newer designs of turbine can be optimized to perform well in such locations, especially when integrated into the design of the building: for instance, an augmented vertical axis wind turbine was tested using unsteady computational simulation ([22]) given the higher turbulence intensity and range of wind-speeds expected at the top of a typical high-rise building. A prototype version of this particular design has been integrated into a high-rise building in London, of height around 200 m – performance results are not yet available due to commercial confidentiality.

4. Case study: the wind climate of London

Over more than a decade and several research projects, much has been learnt about urban wind climates from a series of projects in London. The DAPPLE project (Dispersion of Air Pollution and its Penetration into the Local Environment, 2002-2009) focused on dispersion processes but included extensive investigations of wind-flow both below and above roof height and established long term measurement sites in the centre of London ([23], [24]). Combining full-scale measurements, wind tunnel modelling and numerical simulation, much was learnt about how street scale flows relate to the larger scale city wind environment. Investigations have continued from 2009 to the present, introducing ground-based remote sensing of wind profiles using Doppler lidar ([25]) during the Advanced Climate Technology Urban Atmospheric Laboratory (ACTUAL, www.actual.ac.uk). These and numerous other observations sites in London are reviewed by [26], showing that improved urban meteorological measurements can play a significant role in the sustainable development of cities.

3.1 Relating building level flows to city scale

[27] characterized the direction-dependent flow characteristics of two roof-top sites at 3 m above roof height, and located within 10 m of each other during the DAPPLE campaign. Due to wake flows behind adjacent buildings, strong differences between the sites emerged, demonstrating the extreme spatial dependence of wind-flow within the roughness sublayer. Turbulence intensity levels ranged from 50 to 100%. However, when compared with a well-exposed reference site at a height of 190 m on top of the nearby BT Tower, it emerged that both wind-speed and direction at one of the roof-top sites were well correlated with the undisturbed flow aloft. This demonstrates that whilst never perfect, reasonable locations for roof-top installations can be found.

In this spirit, [28] performed an extensive wind-tunnel study to consider flow around a range of different building designs and configurations in the roughness sublayer (i.e. on the street scale). Scale factors were derived that could be used to relate local wind-speeds to a well-exposed reference wind-speed, such as is measured at e.g. a local airport or telecommunications tower. [20] and [29] performed a similar analysis using CFD simulations. The approach of [28] can perhaps avoid having to do costly Computational Fluid Dynamics (CFD) simulations for specific building configurations as long as the geometry of building layout is generic enough.

A real lesson from DAPPLE was the importance of including atmospheric stability changes when considering urban wind environments. The dispersion simulations of [30] were greatly improved with the inclusion of convectively-driven, low frequency fluctuations in wind direction, as measured at the BT Tower reference site, as boundary conditions for the inlet flow. Wind-speed magnitude is also affected: the diurnal cycle of heating and cooling of the urban surface can cause large increases in windspeed during the day by downward mixing of higher momentum air by convection. During the ACTUAL project, [31] observed wind-speed increases from approximately 3.5 to 5 ms⁻¹ during sunny conditions. At higher altitude locations, such as the BT Tower (190 m), wind-speeds could even increase at night due to nocturnal jets ([32]), whilst roof-top wind-speeds were simultaneously decreased. Such sub-diurnal fluctuations should be considered in a fuller appraisal of urban wind climates.

3.2 Wind profiles over city – model evaluation

[33] tested various mathematical formulations for urban wind profiles often used in the wind engineering community, testing the results against several months of wind data (May 2011 – Jan 2012) from the ACTUAL Doppler lidar database of wind profiles ([24]). The mean wind

speed profile for the whole observation period was shown to fit well to a logarithmic relationship below 1000 m. The Deaves and Harris (1978) ([34]) model for equilibrium flows was re-derived for multiple roughness changes ([35]). It was then adapted for the UK, Australian and New Zealand wind loading codes and the ESDU Data Item. The ESDU (2006) version of the non-equilibrium model was also used and compared with data.

The analysis showed that when used in conjunction with surface roughness parameters derived from an urban morphology database, as used by [11], the model outlined in the ESDU data item provided a good representation of the urban wind speed profile. For heights below 500 m, the predicted wind speed profile showed a good fit with the measured data, remaining within the 95% confidence interval. Above 500 m, the model tended to overestimate the wind speed. This relationship was shown for a range of wind speed conditions.

However, if the magnitude of the surface parameters was estimated using land use as a proxy, the predictions of the model were not as accurate. The model tended to overestimate the wind speed, particularly for very high wind speed periods. These results highlight the importance of a detailed assessment of the nature of the urban surface. In contrast, the equilibrium internal boundary layer model tended to underestimate the urban wind speed at all heights.

5. Conclusions

This paper has given a framework for describing general characteristics of the urban surface and the flows arising as the wind adjusts to its enhanced friction. Key results on the way to estimating urban wind resource have been highlighted. The main conclusions are:

1. Improved knowledge of the layout and morphology of buildings can be exploited to produce a considerable improvement in roughness parameter estimation, and thus mean wind resource estimation.
2. General models of urban turbulence are still lacking, as are models of the impact of turbulence on wind turbine power curves. Given the generally high turbulence intensity of urban flows, this should be a focus for future work.
3. Wind turbines in urban areas are generally only economically viable in certain sites with good exposure to the wind: parks, rivers, coastal urban areas, sub-urban sites, tall buildings.
4. Any new "urban wind turbine" designs should be carefully specified for urban flow characteristics, particularly if building-integrated.

Acknowledgments

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EXPERIMENTAL INVESTIGATION OF WIND FLOW ABOVE THE ROOF OF A HIGH-RISE BUILDING

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Abstract: This paper reports on the velocity measurements of the wind above a flat roof of a high-rise building. The experiments have been carried out in the atmospheric wind tunnel of Ruhr-University Bochum as a part of a Short-Term Scientific Mission sponsored by the COST Action TU1304. The air velocity was measured using hot-wire anemometer at seven roof locations of a 1:300 scale model. The tests were performed at four different wind angles; 0°, 15°, 30° and 45°. Both the mean velocity and turbulence intensity were analysed and the time history of the velocity was used to calculate the different frequencies of the flow.

1. Introduction

Demand for energy is on a meteoric rise. The U.S. Energy Information Administration (EIA) predicts that by 2040, world energy consumption will increase by 56% [1]. If no action is taken while depending only on the same source of energy production (fossil fuel) then there will be a continuous increase in emissions of greenhouse gases and in this will dramatically impact on the climate change. It is well known that the continued emission of greenhouse gases is likely to cause severe, pervasive and irreversible impacts for the world's population and ecosystem [2]. However, a reduction in said emissions could dramatically decrease the climate risks for the 21st century and beyond. Aiming to reduce the global greenhouse gas emissions has led to increased efforts to generate a growing proportion of our energy via clean, renewable technologies. That was the main reason for the European Union (EU) Commission to issue the 2009/28/EC Directive [3] on the promotion of the use of energy from renewable sources (the "Renewable Energy Directive") and to establish mandatory targets to be achieved by 2020 for a 20% overall share of renewable energy in the EU and a 10% share for renewable energy in the transport sector.

One of the promising sources of clean and renewable energy is the wind. Currently, the majority of the wind energy production is from large wind farms, which are built away from the built

environment. These can be on-shore or off-shore wind farms and are normally located in a flat terrain, in which the atmospheric boundary layer (ABL) is usually undisturbed. The characteristics of undisturbed ABL are well defined and its turbulence intensity is usually lower than that of a disturbed one.

Since the world's population has been rapidly urbanising for at least the last 5 decades and currently about 54% of the world's population live in urban areas [4], there is a large increase in demand for medium and small size wind turbine to operate in urban environment.

The generation of energy in urban areas can reduce the load on the existing transmission networks, assuming the energy would have otherwise been generated rurally. Additionally it can help to significantly reduce energy losses due to reduced transmission lengths. Given the above information, urban wind generation has become a particular interest for many researchers around the world, and could one day become a significant contributor to solving the global energy crisis. Often policy makers talk about the balance of finding secure, clean and cheap energy; otherwise known as the 'Energy Trilemma'. However, generating wind energy in built environment comes with significant challenges that need to be resolved in order to promote this technology. One of these is the low mean wind speed and the high turbulence intensity.

In this paper, the wind characteristics around a scale model of a single high-rise building in turbulent ABL are presented. This work is part of the wind tunnel experiments that have been carried out in the ABL wind tunnel in the Ruhr-University Bochum as part of a Short Term Scientific Mission (STSM) sponsored by the COST-Action TU1304.

2. Wind tunnel and the building model

A 1:300 scale model of a high-rise building has been used for the experiment. As shown in Figure 1(a), the height of the building is denoted by H (400 mm) and the width by B (133.3 mm). The height to width ratio of the building is $H:B=3:1$.

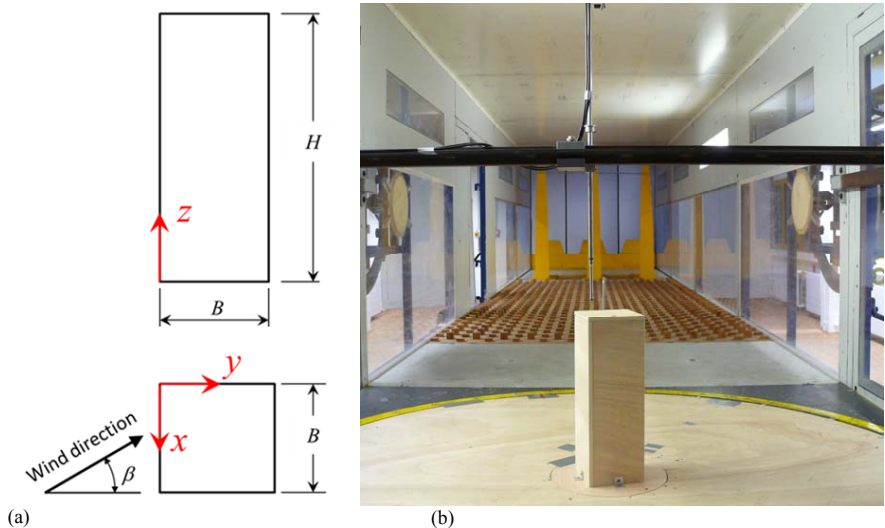


Figure 1 High-rise building model used in the investigation. (a) dimensions, notations and coordinate system and (b) photo of the wind tunnel with the model mounted in a turning table.

The experiments have been conducted in the atmospheric boundary-layer wind tunnel of the Ruhr-University Bochum, Germany. The wind tunnel has a cross section of 1.6 m x 1.8 m and a test section length of 9.4 m. Figure 1(b) shows the wooden model mounted on a rotating table in the wind tunnel. A two velocity components hot wire anemometer has been used to measure the velocity components in the stream-wise and vertical directions. No attempt has been made to measure the span-wise velocity component. The sampling frequency of the hot wire used was 2000 Hz. The anemometer has been calibrated in a laminar flow in a calibration tunnel. The atmospheric boundary layer has been simulated using a castellated barrier, turbulence generators and the roughness elements (cascaded small cubes of edge length 3.6 cm and 1.6 cm, respectively) as shown in wind tunnel schematic in Figure 2. In addition to the velocity measurements, the surface pressure has been obtained at different locations to give extra data for the CFD validation. The pressure sensors are connected to the bores in the wooden model by optimized pressure tubes with a length of about 0.9 m. Reference velocity was measured using Prandtl tube placed 1m in front of the model at the height corresponding to the height of the model.

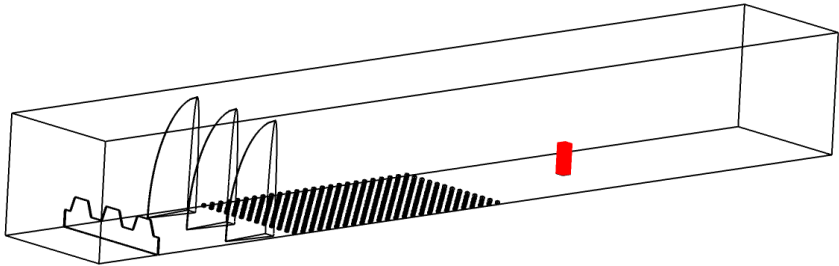


Figure 2 Schematic of the wind tunnel showing the castellated barrier, turbulence generators and roughness elements.

The wind tunnel time-averaged streamwise velocity profile ahead of the model and after the roughness elements is shown in Figure 3, which fits well with the standard power law of urban ABL.

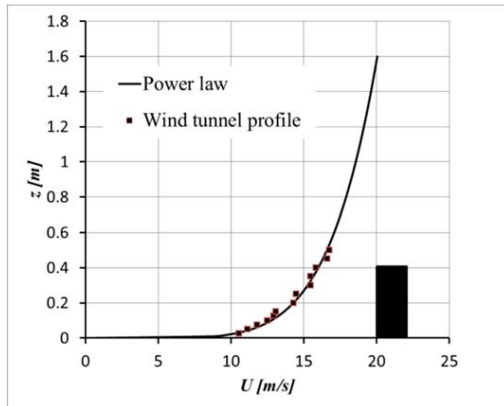


Figure 3 Wind-tunnel velocity profile ahead of the model.

3. Measurement techniques

The techniques used to measure the surface pressure and the wind velocity above the building are described in the following sub-sections.

3.1 Pressure measurement

The surface pressure was measured through ninety pressure taps distributed on the roof (64 taps) and sides (26 taps) as shown in Figure 4. The spacing between the different taps is also shown in Figure 4. The results of the surface pressure measurements are not shown in this paper.

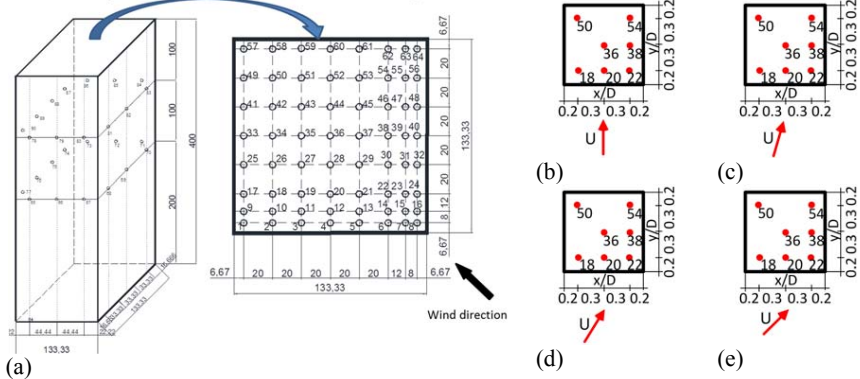


Figure 4 Distribution of pressure taps on the surface of the building (a) and positions of velocity measurements (a), (c), (d) and (e) for 0° , 15° , 30° and 45° , respectively.

3.2 Velocity measurement

Hot wire anemometry and measurements of mean dynamic pressure were used to measure velocity. A Prandtl tube mounted one meter upstream of the model was used to set the reference wind tunnel velocity for each test. Using the measured dynamic pressure the mean wind speed is obtained applying Bernoulli equation.

The velocities above the roof of the building have been measured at different heights. For these measurements the necessary equipment consists of a hot wire anemometer, amplifier and analog/digital (A/D) converter. Anemometer consists of two cross wires with $5\ \mu\text{m}$ in diameter and 1.2mm long that are suspended between two needle-shaped prongs (refer to Figure 7 (a)). These cross wires allow to measure two wind components. For these experiments, the velocity components in the stream-wise and vertical directions are chosen. No attempt has been made to measure the span-wise velocity component. Even though it is possible to place more hot-wire probes in the wind tunnel, in order to minimize the impact on the flow field, only one is used for all tests. The used sampling frequency was 2000 Hz.

The anemometer has been calibrated in a laminar flow in a calibration tunnel. The calibration establishes a relation between the output (in voltages) and the flow velocity. It is performed by exposing the probe to a set of known velocities (U) and corresponding voltages (E) are recorded. A fitting curve is estimated through the points (U, E) representing a transfer function, for each wire, that is used when converting data signal from voltages into velocities. The fitting curve

which is adopted is a polynomial curve of 3rd order. The coefficients are calculated by fitting the data in the least-squares sense. Calibration curves used in this case are reported in Figure 8. As an amplifier Multichannel CTA 54N80 by Dantec is used and all analog signals are converted to digital ones, using analog/digital (A/D) converter.

4. Time-averaged velocity

In order to investigate the sensitivity of the hot-wire and to estimate the percentage error of the velocity measurements, the measurements of the velocity distribution above the building at the centre of the roof (point 36 in Figure 4) have been repeated three times. The velocity components in the y and z directions, u and w , respectively were measured at 10 heights as shown in Figure 5. The time history of each signal was used to obtain the mean value and the turbulence intensity of each velocity component. The length window of each velocity signal was 131 sec. It can be seen that the turbulence intensity, in the streamwise velocity component and the vertical velocity components (I_u and I_w), are higher than 20% up to about $z/D=0.3$ and reaches about 60% less than about $z/D=0.1$. Since flow separation is expected to occur in this region and hot-wire anemometer is not suitable to measure a reverse flow then the measurements of the streamwise velocity component in this region are not reliable. However, the measurements of the turbulence intensity and vertical component of the velocity are valid. The reference velocity used to calculate the percentage increase in velocity is the upstream wind velocity at the height of the building.

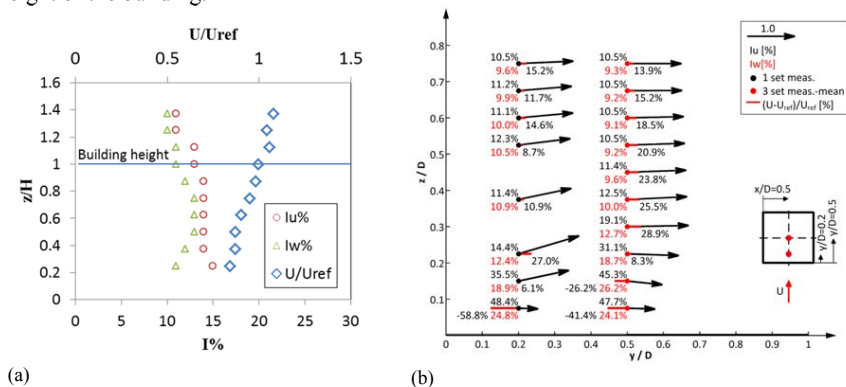


Figure 5 (a) Wind tunnel velocity and turbulence intensity profiles. (b) Velocity vectors, I_u and I_w above the building measured at P20 and P36 ($x/D=0.5$) at 0° wind angle.

Above $z/D \approx 0.3$, turbulence intensity declines to about 10% in both u and w . This is comparable to the turbulence intensity of the upstream flow generated by the roughness elements and turbulence generators at the inlet of the wind tunnel. This suggests that the effect of the building on the turbulence intensity in the above roof flow is limited to a height of about one third of the building width above the roof. Figure 5 shows also a maximum increase in the wind velocity above the center of the building (point P36) at about $z/D \approx 0.3$. This is just above the shear layer between the separation region and the core flow. This is in agreement with the study of Hemida [5]. Closer to the upstream edge (Point P18), the maximum wind velocity occurs at lower height meaning that the maximum height of the separation region occurs downstream of Point P20.

4.1 Velocity distribution above the roof

The wind velocities above the roof of the building have been measured at three different heights and at selected points at four different wind direction; 0° , 15° , 30° and 45° . Figure 6 shows the mean velocity vector, turbulence intensity and percentage increase in the wind speed at points P18 and P50 at the different wind angles. These two points are in the upstream half of the roof in case of large wind angles and for small wind angles point P18 is in the upstream half and point P50 is in the downstream half.

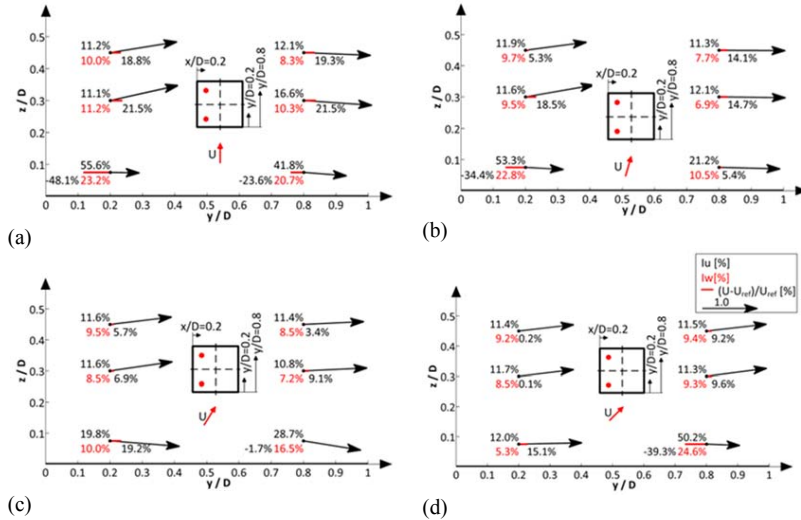


Figure 6 Velocity vectors, Iu (black number) and Iw (red number) measured at Points P18 and P50 ($x/D=0.2$) at wind angles: 0° (a), 15° (b), 30° (c), 45° (d).

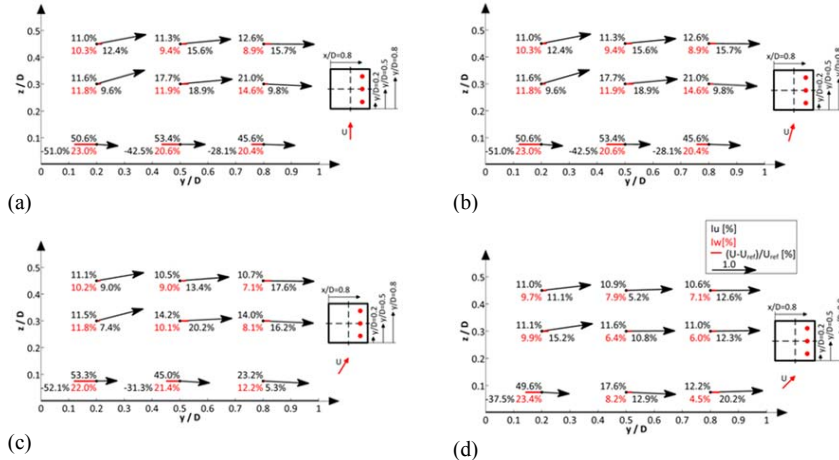


Figure 7 Velocity vectors, Iu (black number) and Iw (red number) measured at Points P22, P38 and P54 ($x/D=0.2$) at wind angles: 0° (a), 15° (b), 30° (c), 45° (d)

For 0° wind, the wind accelerates upward at point P18 and downward at point P50, meaning that the flow reattaches to the roof of the building after a region of separation. The turbulence intensity and percentage increase in velocity at point P18 are comparable to those at point P20

in Figure 5. For 15° wind the velocity profile above the upstream point is similar to that for 0° wind. However, the velocity vectors above point P50 are no longer pointing downward, meaning that the separation region is shifted away from this position and the flow behaves like that upstream of a separation bubble. Increasing the wind angle to 30° generates a small separation cone forms along the upstream side edge of the building starting at the upstream corner. The downward velocity vectors at the lower measuring points suggest that both points P18 and P50 are located at the tail of the separation cone where the flow tends to attach to the roof. There is also a significant reduction in turbulence intensity of the flow above point P18 and slightly in the flow above point P50. For 45° wind angle, the wind flow is steady above point P18 and highly turbulent close to the roof above point 50 suggesting that a large separation cone occurs at the upstream edge and increases in size along the length of the building side. The lower measurement position above point P50 is entirely in the separation zone as the turbulence intensity I_u and I_w are larger than 50% and 25%, respectively.

Figure 7 shows the velocity vectors and turbulence intensities above the building at 3 points; P22, P38 and P54. At 0° wind angle, the flow separates at the windward edge and reattaches around the last point. This is supported by the downward direction of the velocity vector at the last point. The flow turbulence intensities at 45° yaw angles are much lower than those at 0° angle suggesting that these points might not be inside a separation region and the flow structure is rather complicated at 45° yaw angle.

4.2 Effect of wind angle

The magnitude of the wind velocity component in the direction of the upstream wind and the turbulence intensities for different wind angles above points P22 and P36 are shown in Figure 8 and 9, respectively.

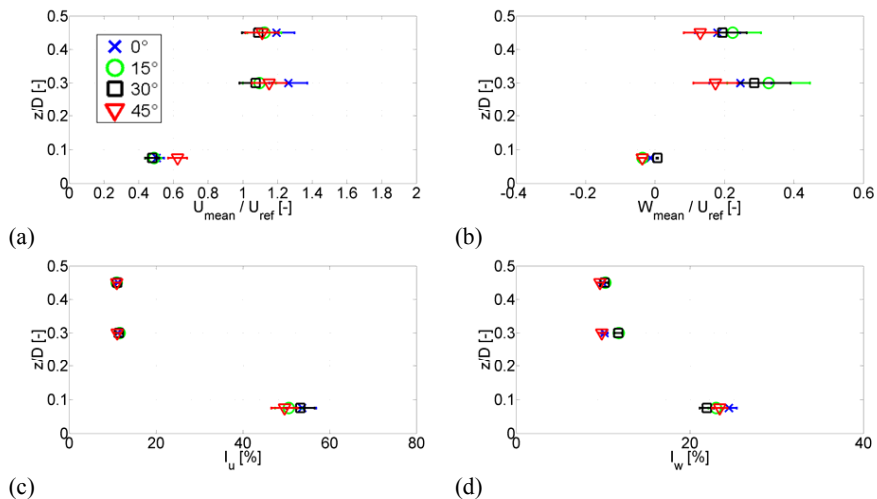


Figure 8 Height profile of U_{mean} (a), W_{mean} (b), I_u (c) and I_w (d) measured at position P22 on the roof top of the single high-rise building for different approaching flow angles 0° , 15° , 30° and 45° .

The most increase in the wind velocity above point P22 occurs at about $z/D \approx 0.3$. Above this particular point, there is no much difference in turbulence intensity. This is because the loca-

tion above P22 is the streamwise half of the roof in which the flow is not affected significantly by the roof separation. However, there is a significant effect of the wind angle in the vertical component of the velocity. This is a result of the cone shape vortices formed at the front corner for wind angles larger than 0° . The largest velocity component in the direction of the upstream wind was measured at wind angle 0° . Increasing the wind angle more than 30° has little effect on the U_{mean} . However, the lowest W_{mean} component was measured at 45° wind angle.

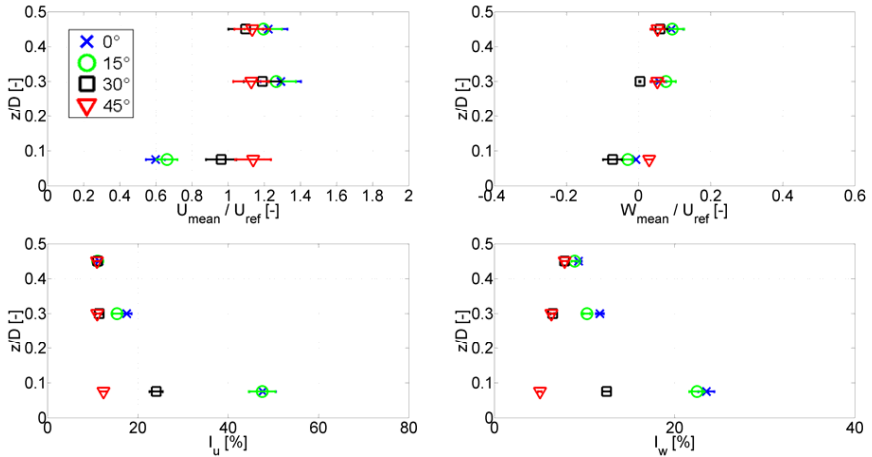


Figure 9 Height profile of U_{mean} (a), W_{mean} (b), I_u (c) and I_w (d) measured at position P36 on the roof top of the single high-rise building for different approaching flow angles 0° , 15° , 30° and 45° .

Figure 9 shows the velocity components and turbulence intensities in both the upstream wind and vertical directions, respectively of the wind flow above the roof at point P36. As this point is at the centre of the roof, it experience separation close to the roof at lower wind angles. For 45° wind angle, the wind separates at the two sides of the building forming two separation cones and the flow at the middle of the roof might be fully attached. This is demonstrated in Figure 9 by relatively low turbulence intensity at 45° yaw angle.

5. Instantaneous flow

The time history of the velocity measurements were used to calculate the different frequencies of the flow at the different measurement points by the mean of velocity power spectra. Figures 10 and 11 represent the velocity energy spectra of the different locations at $z/D \approx 0.3$ for wind angles 0° and 45° , respectively. The upstream points P18, P20 and P22 show similar spectra for 0° wind angle. The bottom right plot in Figure 10 represents the velocity energy spectra for the upstream flow at the reference point. The dominating energy of the upstream flow occurs at $nD/U_{\text{ref}} \approx 0.03$. The dominating frequencies at points P18, P20 and P22 are similar to that at the reference point suggesting that these are the frequencies of the large scale wind tunnel vortices and thus these points are not in the roof separation region. The spectra at the downstream locations P38, P54, P36 and P50 show that there are dominating energies at high frequencies. These frequencies are related to the generation of relatively large vortices in the separation region above the roof. These energy spectra shown in Figure 10 demonstrate that the flow is highly

turbulent at $z/D \approx 0.3$ and this suggests that this height lies in the separation region or at least in the shear layer between the circulation region and the core flow.

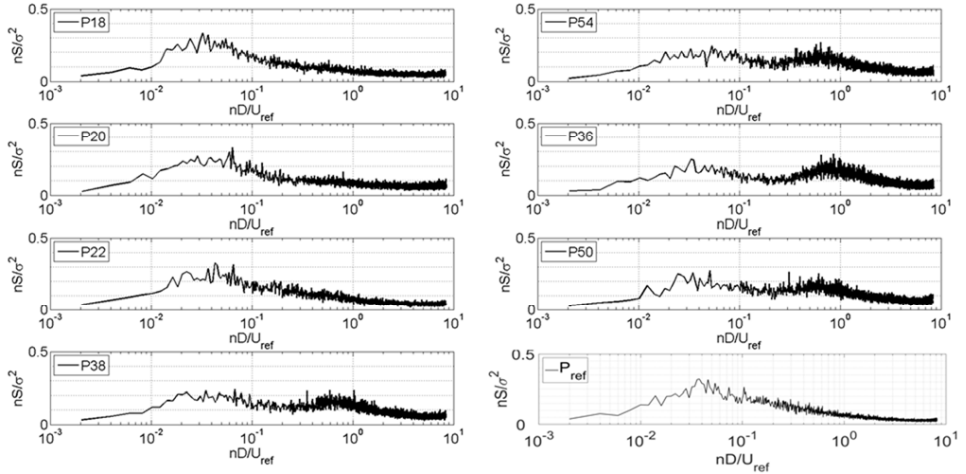


Figure 10 Energy spectra of the velocity at 0.3 z/D height above different positions above the roof top of the single high-rise building for an approaching flow angle of 0° .

Figure 11 shows that at wind angle of 45° the energy spectra at all the locations above the roof and at the same height of $z/D \approx 0.3$ are similar. Many there are dominant low frequency modes, associated with the large-scale vortices in the wind tunnel flow generated by the upstream roughness elements and vortex generators. This suggested that this height is above the separation regions.

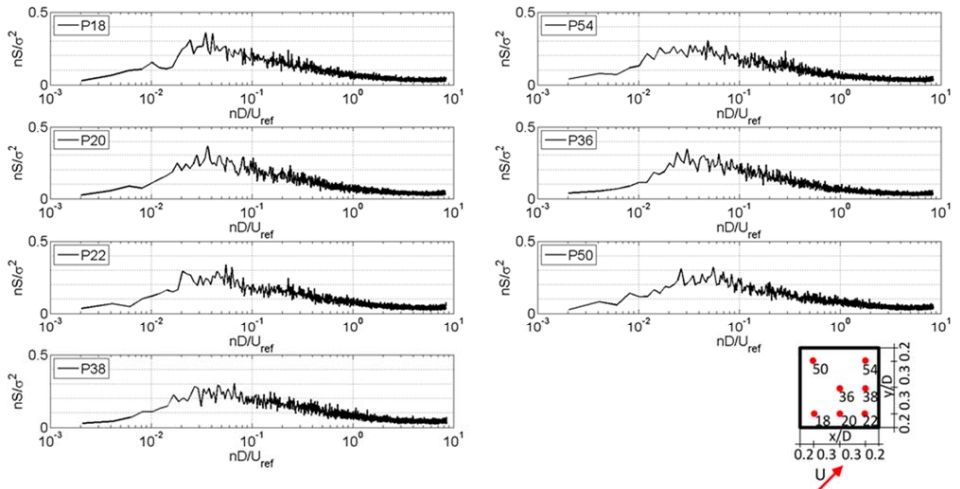


Figure 11 Energy spectra of the velocity at 0.3 z/D height at different positions above the roof top of the single high-rise building for an approaching flow angle of 45° .

6. Conclusions

The wind velocities above the roof of a 1:300 model of a high-rise building have been measured using hot-wire anemometer at different locations and heights in the environmental wind tunnel of the Ruhr-University Bochum. The time histories of the velocity have been used to calculate the mean velocities and turbulence intensities in both the streamwise and vertical directions and to reveal the different frequencies of the flow above the roof. The following conclusions can be made from the current study:

1. The flow separates and reattaches to the roof of the building to form a separation bubble. The height of the separation is about one third the width of the building.
2. The wind is highly turbulent inside the separation and in the shear layer between the separation region and the core flow.
3. Above about one third of the building width the turbulence intensity is similar to that of the upstream wind.
4. There is an average increase of the wind speed of about 1.2 of the reference velocity just above the shear layer at height of 0.3 the building width and the maximum amplification occurs at the middle of the building at zero wind angle relative to the building sides.
5. The turbulence intensity is a minimum at the middle of the building for wind angles from 30° to 45°. At these angles the wind separates at the windward corner to form two separation cones. The size and height of these cones are smaller than the separation zone for the zero wind angle case.

The results of this study will be used to validate future CFD simulations to detail the flow structures in the above roof flow at different wind conditions and angles.

Acknowledgments

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BEHAVIOUR OF A HORIZONTAL AND VERTICAL AXIS SMALL WIND TURBINE UNDER LOW AND HIGH TURBULENCE REGIME

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Abstract: This paper presents an experimental study over two small size wind turbines integrated with a solar photovoltaic generating unit. The two turbines have different technology, but are characterized by the same rated power. The behaviour of the two typologies is investigated under two different wind regimes of high turbulence (wind coming from the sea) and low turbulence (wind coming from the land) pointing out strengths and shortcomings of these technologies.

1. Introduction

The size of commercial wind turbines has increased dramatically in the last 25 years. The growing interest attracted by large wind turbines [1] has brought into being a well consolidated technology and an extensive scientific literature. Common commercial machines are rated 2 MW; 8 MW turbines are now available and the tendency is to up scaling.

Small size wind turbines [2] play generally a marginal role in the overall energy production. Indeed, they are attractive from many points of view: the environmental impact is low, they do not cause instabilities in the power network distribution and they do not need large power storage capabilities. They can be connected directly to the local distribution or micro grid and are therefore particularly suitable in isolated contexts, like small islands. They represent an appropriate technology to develop the strategic aim of small-scale distributed generation energy systems, as either complements or alternatives to centralized operations [3].

Small wind turbines can be realized according to two typologies. Horizontal axis wind turbines (HAWTs) follow the most common technology in use for large wind turbines (that has received a lot of attention from research and commercial sectors). Vertical axis wind turbines (VAWTs, [4]) are less efficient, in principle, but can be more attractive for small size applications, especially in complex contexts like urban areas. VAWTs do not require any yaw mechanism, pitch regulation or gearbox; they have few movable parts and, therefore, lower maintenance costs.

Unfortunately, two main shortcomings can be found at this regard: construction and operating costs are often high, due these small size machines require sophisticated technology and maintenance. Moreover, the definition of the technical data is usually obtained from wind tunnel tests carried out in smooth flow that does not allow reproducing the actual behaviour of the

turbines during the operating conditions [5]. Therefore there is the need, from the one hand, to improve and to develop this specific technology, and, from the other hand, to carry out sound and reliable characterizations based on full-scale investigations considering different typologies and real wind conditions [6] - [9]

The present paper describes the experimental facility for the power production at the Savona Harbour (Northern Italy) which houses commercial ships, cruise ships and a marina. The energy requirement is partially satisfied by a power plant which integrates two 20kW small size wind turbines with a 121kW solar energy generating unit. Wind turbines were installed in 2012. In the subsequent years, they suffered some damage and were repaired. They also underwent to some improvements to the control apparatus and the safety system. Section 2 describes the wind turbines and the monitoring system; Section 3 describes the wind field; Section 4 gives some details of the power production during the first year of activity and during the following years; Section 5 concludes the paper. The full description of the results is reported in an extended paper [10].

2. Experimental facility

The Savona Harbour (Fig. 1) avails of a photovoltaic generating unit (Fig. 2 a) integrated with wind power production (Fig. 2 b) and of procedures in waste management that allow to make use of renewable resources in an environmental and economical sustainable way.



Fig. 1: Savona Harbour with the location of the solar photovoltaic system (circle), the wind turbines (stars), the sonic anemometer (triangle)

The two wind turbines have the same rated power and different technology, i.e. horizontal and vertical axis. They are equipped with a real time monitoring system, which allows a constant check of the power production. The analyses carried out during the first year of activity in 2012 allowed to investigate their behaviour, pointing out some drawbacks and the best conditions for a satisfactory production. The following year of activity was overshadowed by a series of problems. The HAWT had to be secured by reducing the slowing-down wind velocity threshold and the cut-off wind speed. Later, it experienced severe damage due to the external conditions. The VAWT proved to be less exposed to gust effects but, unfortunately, it suffered damage due to a lightning and it also went out of use. Besides repairing the machines, thanks to the experience gained during the first year of monitoring, the control and inverter systems of both turbines had been redesigned in 2014.



a) 121 kW solar PV system

b) VAWT and HAWT

Fig. 2: Power production facility at the Savona Harbour.

The vertical axis wind turbine (VAWT), shown on the left side of Fig. 2 b) and in Fig. 3 a), has a 8m rotor diameter, its height is 5.8 m. It is provided with 5 aluminium, steel and fiberglass blades. It is supported by a 10.5 m high steel pole. The horizontal axis wind turbine (HAWT), shown on the right side in Figure 2 b) and Fig. 3 b), has a rotor diameter of 10 m and consists of three fiberglass blades. It is supported by a 18 m high steel pole, which is more than 1.5 the VAWT's one. Besides, it is worth noting that the swept area of the HAWT is almost twice the area swept by the VAWT. Both turbines stand upon the 5 m high dam of the harbour. They are equipped by a breaking system consisting of both a hydraulic and electrical brake and are slowed down and stopped under strong winds. The VAWT control system also provides a regenerative braking. Table I summarizes the main features given by the producers.



a) VAWT



b)HAWT

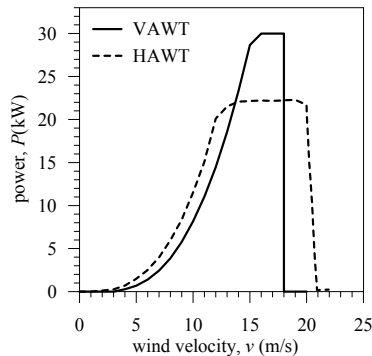
Fig. 3: Wind turbines at the Savona harbour.

A monitoring system records and collects the power production, rotational speed of the rotor and wind velocity with a sampling rate of 10 seconds. Wind data are recorded by means of two cup anemometers measuring at 12 m above the ground on a mast close to the VAWT and at 23.5 m on top of the HAWT's hub. The theoretical power curves of the wind turbines provided by the manufacturers are shown in Fig. 4. The rated power is 20 kW; the VAWT may go further but it is limited to this target. Both turbines are equipped with a suitable power control system exerted by the inverter and are slowed down and stopped under strong winds.

The wind turbine monitoring system is integrated with a sonic anemometer installed in the Harbour, nearby the turbines (see Fig. 1) at 12.5 m above the ground, that registers continuously the wind velocities with a frequency rate of 10 Hz. It is part of a large monitoring network, realized in the framework of the European Project “Wind and Ports” (www.ventoeporti.net, [10])

Table 1: Technical sheets

Type	HAWT	VAWT
nominal power	20kW	20kW
maximum power	22 kW	30 kW
turbine diameter	10m	8m (height=5.8m)
swept area	78.5m ²	46.5m ²
generator	synchronous, permanent magnets	synchronous, permanent magnets
Reducer	not present	not present
power regulation	active yaw	power curve
over speed control	electrical, hydraulic brake, active yaw	electrical, hydraulic brake
max. rotation speed	90 rpm	90 rpm
cut-in wind speed	2.5m/s	3-4 m/s
nominal wind speed	12 m/s	12.5 m/s
cut-out wind speed	20 m/s	18 m/s
noisiness	60dB	45dB

**Fig. 4:** Manufacturer power curves of the vertical- and horizontal-axis wind turbine.

3. Wind statistics

The three datasets of wind speed records registered by the two cup anemometers and by the sonic anemometer are preliminary checked leading up to a corrected and synchronous data base following the procedure in [12]. In this way, from the row data of the wind speed and of the power production records, a new dataset is created consisting of the 10-minute average wind speed and direction, peak value, turbulence intensity, and the 10-minute average power produced by each turbine.

The two cup anemometers suffer a series of shortcomings, due to the low sampling rate and to the partially sheltered positions. The description of the wind statistics and turbulence field

is, consequently, accomplished by the sonic anemometer dataset, which also allows the evaluation of turbulence intensities and spectra. The non-directional probability density function of the 10-minute mean wind velocities is represented by the Weibull model; the shape and scale parameters, k and c , are regressed by the moment method, as we are mainly interested in a limited range of moderate and frequent values. Fig. 5 a) shows the frequency distribution (a) of this dataset, as well as the regressed Weibull function. Fig. 5 b) shows the wind rose, which reveals a prevalent direction from North-West and some frequent sectors around South-East, while the wind coming from the third quadrant is very rare.

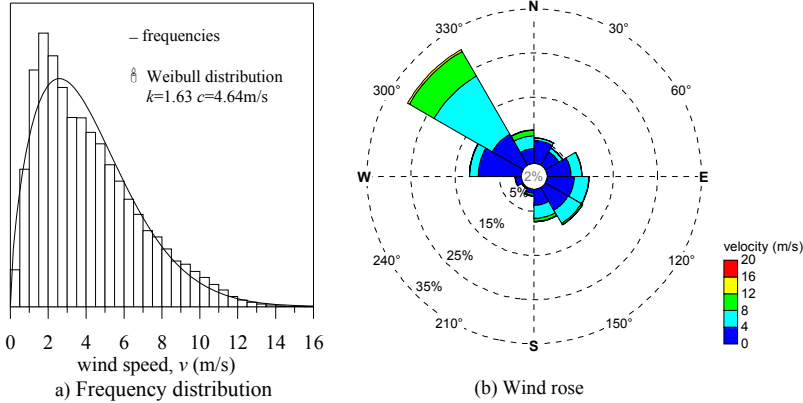


Fig. 5: Description of the dataset recorded by the sonic anemometer.

The sonic anemometer dataset is been adopted as the reference time series for all the analyses, after the following further corrections. Firstly, the missing periods are reconstructed by the correlation between these measures and the measures recorded by the cup anemometer at the HAWT hub and at the VAWT. The new dataset is herein referred to as V_S . Then, the V_S time series is transferred to the turbines hub heights through a suitable scaling factor, according to the following formula:

$$V_H(\alpha) = k_{SH}(\alpha) \times V_S(\alpha); \quad V_V(\alpha) = k_{SV}(\alpha) \times V_S(\alpha) \quad (1)$$

where V_H and V_V indicate, respectively, the wind data transferred to the position of the turbine rotor centre of the HAWT, which is at 23 m above the ground, and to the rotor centre of the VAWT, which is 18 m above the ground. The transfer coefficients k_{SH} and k_{SV} depend on the wind direction α and take into account the different levels and roughness values between the location of the sonic anemometer and the rotor position. The transfer coefficients are calculated following the procedures introduced by the Engineering Sciences Data Unit [13]. Fig. 6 a) shows the roughness map used for the simulations; Fig. 6 b) shows the transferring coefficients for the different directions. The new datasets of the wind velocity at the HAWT hub height (23 m) and at the VAWT height of the rotor centre (18 m) can be considered representative of the incoming wind field at the turbine locations.

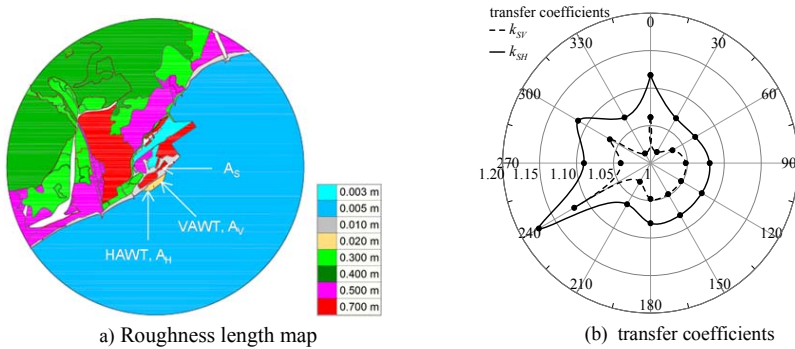


Fig. 6: Transferring coefficients to the turbine rotor using ESDU [13].

The area surrounding the turbines is very heterogeneous, as shown in Fig. 6 a). In particular, the turbines lie just in front of the sea, so that the coastal line separates two main directional sectors, corresponding to sea (approximately from 30° to 235°) and land sectors (approximately from 235° to 360° and from 0° to 30°), respectively. The wind blowing from the land sectors is more frequent but it suffers the effects of high roughness and complex orography behind the city of Savona; on the contrary, the wind blowing from the sea sectors is less frequent but it is characterized by lower roughness and flat surface. These aspects have important consequences on the turbulence at the site.

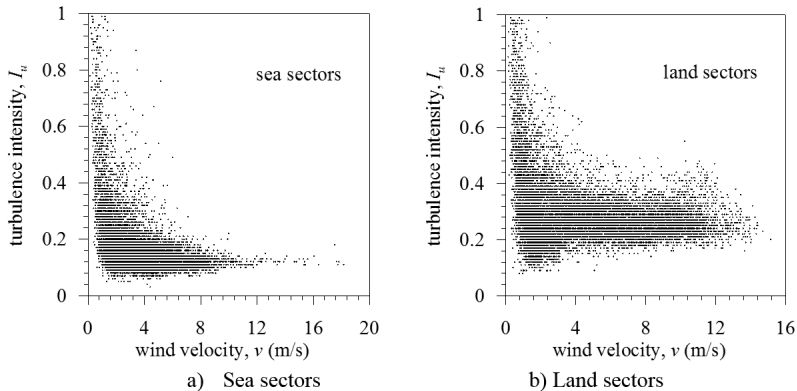


Fig. 7 shows the longitudinal (i.e. along- wind) turbulence intensity, I_u , as a function of the mean wind speed of the flow blowing from sea sectors (

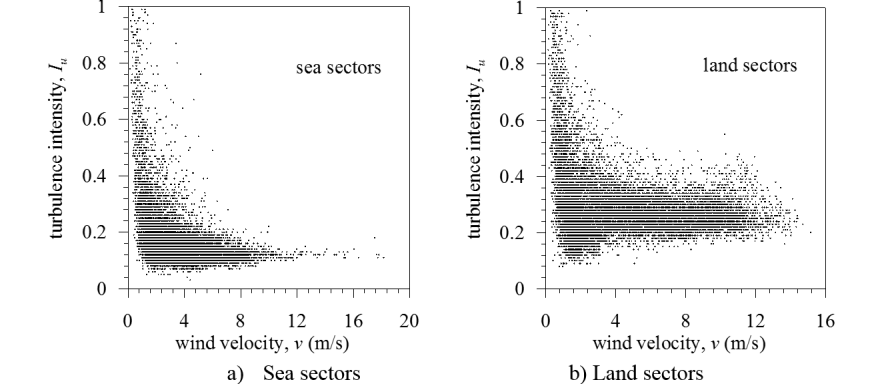
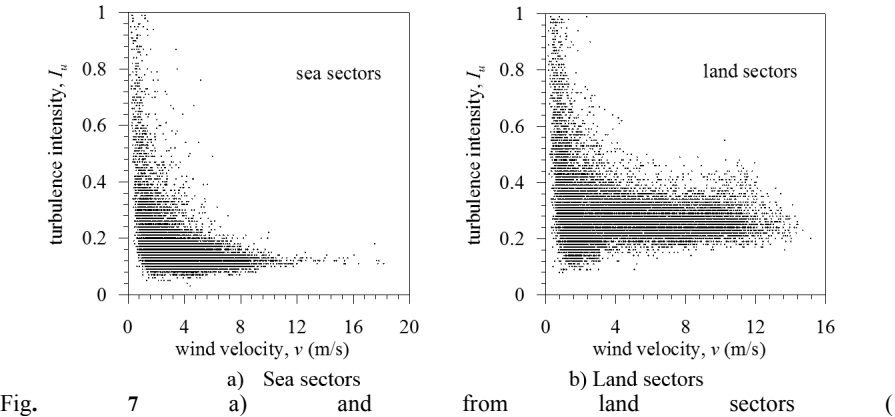


Fig. 7 b). As expected, the turbulence intensity is generally higher for the land sectors, due to the higher roughness and orographic effects.

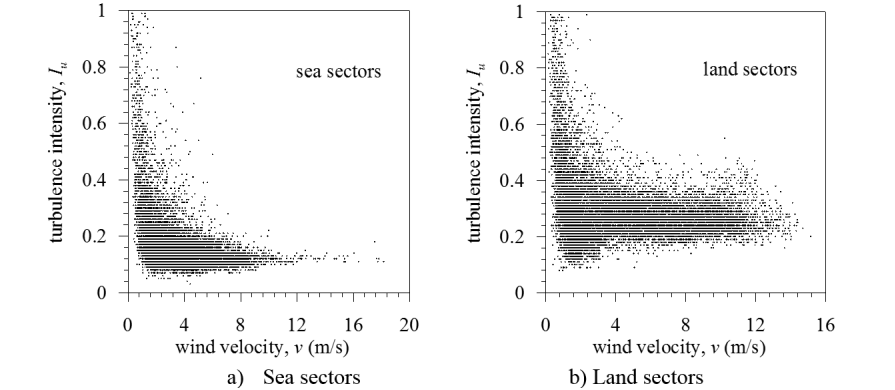


Fig. 7: Longitudinal turbulence intensity of the flow as a function of the mean wind speed.

4. Power production

Fig. 8 and Fig. 10 show some results obtained during 2012. Fig. 8 represents a record of the 10-minute average power and wind speed during a couple of day of moderate windiness. It is interesting to note that the HAWT power production lies beneath the VAWT production at smaller turbulence conditions, that are related to the wind coming from the sea, but the VAWT production turn out to be larger at turbulent winds, which are related to the land un-coming wind. The slight decrease of the wind speed was due to a sudden change of the incoming wind direction (from sea at first, from land later), followed by the increase of the wind turbulence and gusts which has caused the fall of the power production.

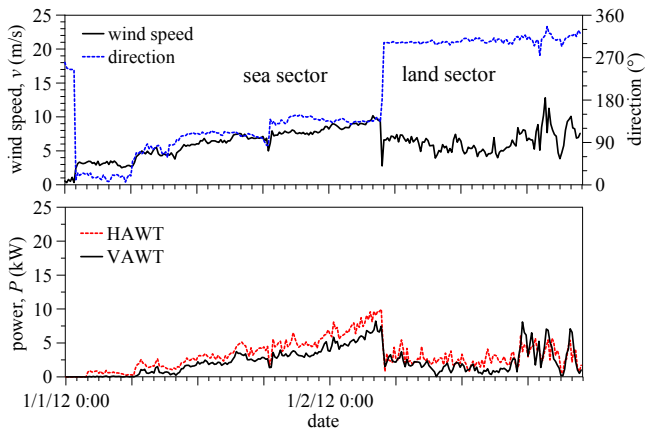


Fig. 8: 10-min averaged values of power and wind speed collected on January, the 1 - 2 2012.

Fig. 9 shows a record during a couple of day characterized by quite high, intermittent wind. This time, the HAWT is slowed by the safety system and cannot exploit this situation as long as the wind speed v is higher than about 10-15 m/s; on the contrary, the VAWT almost reaches the rated power. The HAWT power production becomes higher than the VAWT's one when v decreases to about 10 m/s.

Fig. 10 a) and b) reports the power curves, obtained by the bin method given by ref. [14] for the measures during year 2012 as 10-minute average values for VAWT (Fig. 10 a) and the HAWT (Fig. 10 b), respectively, together with the power curves given by the manufacturer. It is apparent that both the measured curves lie very out underneath the target power for wind velocities higher than 6-7 m/s. The HAWT seems to produce more in the range of the low wind velocities, which are frequent, and has a lower cut in speed. It reaches the maximum power production at about 10 m/s. The VAWT, which almost follows the same trend in the range 0-12 m/s, has an upturn after about 15 m/s and reaches a higher power production, still much lower than the target one.

It is also apparent that large turbulence has a detrimental effect on the turbine efficiency since the power curve is higher limiting the analysis to the (less frequent) sea sectors. This feature is stressed for the VAWT because for this sector the wind speed is usually higher and the HAWT turns out to be slowed or often stopped by the safety control system due to wind gusts.

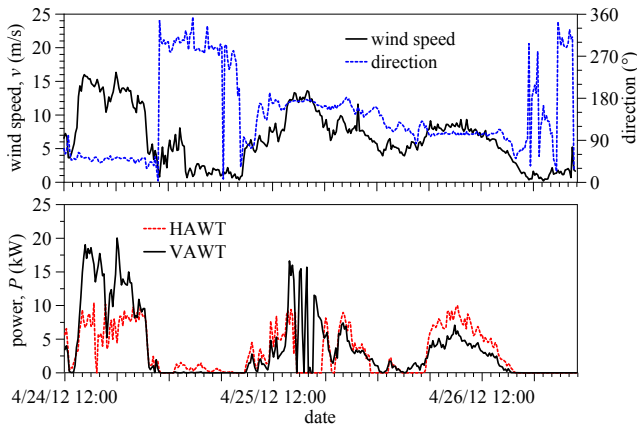


Fig. 9: 10-min averaged values of power and wind speed collected on April, 24-25 2012.

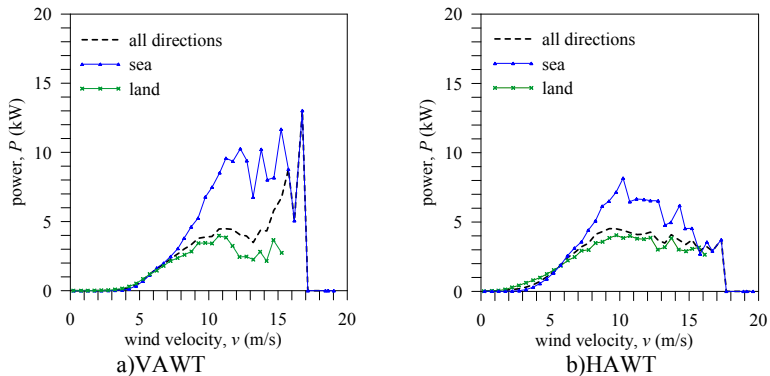


Fig. 10: Experimental power curves of the turbines accounting for the ambient turbulence according the different directions of the un-coming wind

Fig. 11 shows the records of the 10 minute average power and mean wind speed during a couple of day characterized by high wind in 2014, *i.e.* after the turbine were renovated. As in the records of Fig. 8, the passage from land to sea sectors to land sectors produce an overall decrease of the wind velocity and an increase of turbulence (

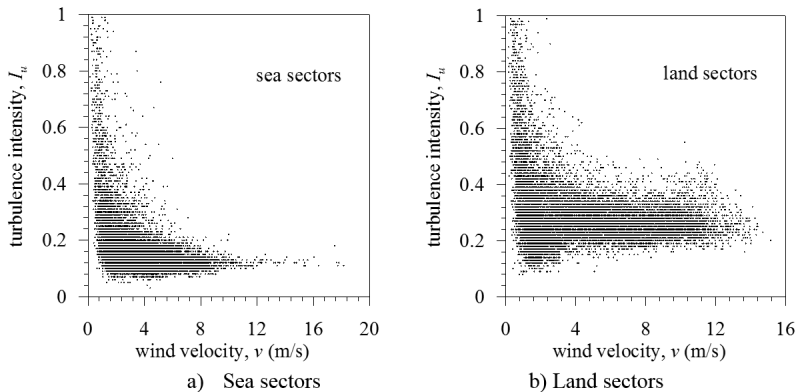


Fig. 7). This record shows that the HAWT production is quite ever higher than the VAWT as far as the wind is moderate. When the wind speed increases, i.e. up to 10-15 m/s, the HAWT is slowed and stopped by the control system while the VAWT keep on working reaching the rated power. Fig. 12 a) shows the power curve evaluated for the VAWT during this period of particularly favourable conditions, which appears to be very satisfactory with respect to the curve given by the manufacturer. The power curve of the HAWT evaluated for other records taken under some other very favourable wind conditions, Fig. 12 b), shows that this turbine also can work properly, under low turbulence, steady, moderate high windiness. Unfortunately these conditions are occurring very rarely in this site, such as in most urban sites.

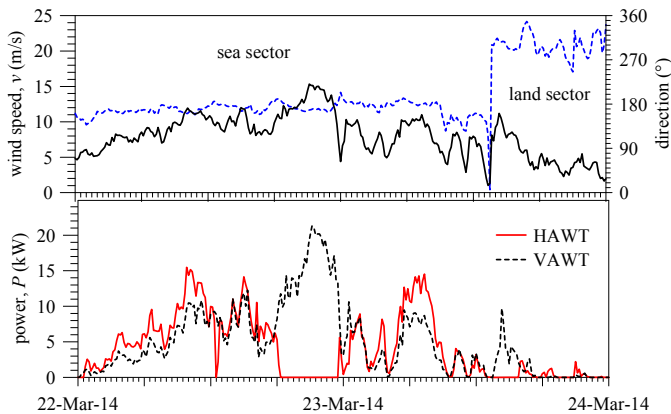


Fig. 11: 10-min average values of power and wind speed collected on March, 22-23 2014.

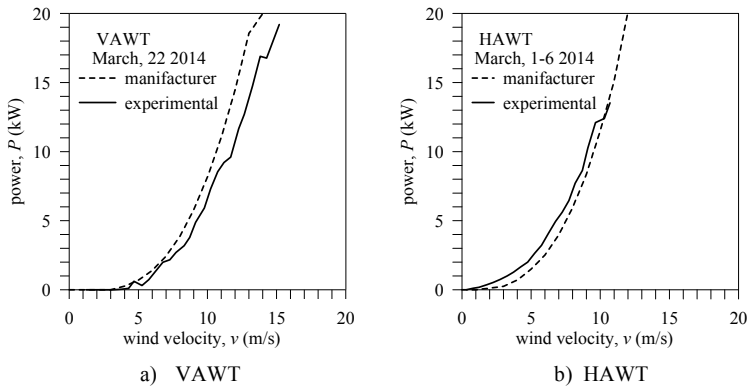


Fig. 12: experimental power curves recorded during some days under favourable conditions.

5. Conclusions

The power production facility of combined PV solar and mini wind turbines in the Savona harbour has many aspects of interests concerning both the integration among the different renewable sources and the specific study of the wind turbine behaviour. The monitoring equipment which records, in real time, the wind velocity and the power production of the turbines, is integrated in a network of sonic anemometers, realized in the framework of a European Project, which allows an extensive investigation of the windiness of the site.

Focusing on the two wind turbines with horizontal and vertical axis, this paper presents the experimental facility and describes the wind field conditions. Some sketches of the results in terms of power productions are also given, highlighting the need of a sound characterization of the wind turbines' behaviour under real wind conditions.

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AN EXAMINATION OF THE POTENTIAL FOR DISTRIBUTED WIND GENERATION (DwG) IN URBAN DISTRIBUTION NETWORKS

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Abstract: In a *sustainable* economy, *smarter* cities need energy networks that can deliver consistent electricity while maximising the use of intermittent renewables. Therefore an understanding of the available resource and a means for viable integration of distributed generation (DG) is required. In this research, energy harvesting of the wind climate is considered in the context of distributed wind generation (DwG) as an integral component of a smarter electricity network. The approach combines wind climate modeling of the resource at the urban scale with enhanced electricity network simulation. The former considers energy harvesting potential while the latter investigates the opportunities for this form of renewable electricity.

1. Introduction

Cities are responsible for between 71% and 76% of CO₂ emissions from global final energy use [1], much of it derived from fossil-fuel based electricity generation. The connection of small and micro-generation at consumer level could contribute positively towards national renewable energy targets; particularly in a smart grid context. This kind of evolution requires a more integrated, distributed and bi-directional energy supply chain, which is representing a tough challenge for distribution network operators. Electricity networks were originally designed for a vertically integrated power system with several large power plants and a mainly passive grid. The presence of generation units in distribution networks leads to the need for detailed modeling and for smarter energy networks, a particular focus on the low voltage (LV) grid is required. These networks are generally asymmetrical with unbalanced loading conditions on the three phases.

Wind turbines, as integral components of a renewable energy mix, are most efficient when air flow is strong and steady, that is high mean wind speeds with little variability in speed or direction. Urban areas disturb the airflow and produce lower wind speeds (relatively) and sub-optimal environments for turbines. A major (technical) barrier to the effective deployment of wind turbines in these areas is due to a lack of accurate methods for estimating wind speeds and

energy yields at potential urban sites [2]. This is because cities are aerodynamically *rough*, heterogeneous and have a highly localised and complex wind environment. Furthermore, there is general acknowledgement that rougher landscape characteristics in cities will also result in an increased level of turbulence that will further degrade wind turbine output.

This paper summarises ongoing research that studies how best to integrate the wind resource into a smarter urban energy networks.

2. The urban wind resource and energy harvesting

The focus of this research is the application of an enhanced urban wind climatology appreciation for an energy harvesting context that involves micro/small wind energy connections at consumer level within distribution networks. This is considered here in two parts: 1) urban wind speed complexity and 2) electrical engineering modeling, which is further separated into how turbulence affects wind energy systems and how distribution networks, in the context of LV consumers, can engage with micro/small wind energy systems.

2.1 Urban wind complexities

The wind resource close to the urban 'surface' (that is, near rooftop height) is highly variable in space and time. Turbines located at or near rooftops experience a highly localised wind environment that has proved difficult to predict from measurements made elsewhere. Some researchers have used computational fluid dynamic modeling to ascertain the potential of building mounted turbines [3]. That work has shown the sensitivity of energy output to turbine position and mounting height with regard to the building, such that small changes in location can have dramatic impacts on performance. However, this approach is of limited value if a *routine* approach to site evaluation of the available wind resource is to be developed.

Empirical tools employ the acquired knowledge of the atmospheric boundary layer to estimate the properties of near surface airflow from standard observations adjusted for local considerations (e.g. variations in the roughness of surface cover and terrain). These schemes derive vertical profiles of the horizontal wind to characterise the wind potential for turbines [4]. There are also wind atlases that employ air flow models that account for the effects of topography [5]; mean wind speed over an area of 1km² is estimated as a function of height by employing both the regional wind climate and the roughness characteristics of the surface [6]. For example, the small scale wind resource study [7], was later developed into a freely available tool by the Carbon Trust [2] as was a wind speed estimation tool, as suggested by Drew *et al* in [8]. These types of wind speed profiling tools/databases generally employ transfer functions to transfer the properties of regional scale wind climates to an area of interest.

The empirical techniques have proved useful in evaluating locations for wind farms where turbines are located in an exposed setting at a considerable height above extensive surfaces that are relatively homogenous (grass, crops or shrub). However, they are of limited use for micro-generation in cities where buildings generate considerable turbulence and the urban terrain is heterogeneous. Researchers such as Millward-Hopkins *et al* [9] are improving urban wind modeling capability, but there remains a need for observations of wind speed close to urban rooftops to provide validation for model results [10].

Depending on the period of examination, we can decompose the wind field into a mean and fluctuating component.

$$V_{(i)} = \bar{V} + dV_{(i)} \quad (1)$$

where \bar{V} is the mean wind speed and dV is a fluctuating or turbulent wind speed component.

A commonly employed means of assessing the *mean* wind speed available at an urban site is to use the log wind profile (2) to describe the vertical profile of horizontal airflow,

$$u(z) = \frac{u_*}{\kappa} \ln \left(\frac{z - z_d}{z_0} \right) \quad (2)$$

Where κ is the von Karman's constant (0.4), z is height above the ground, z_0 is the roughness length and z_d is the displacement height (below which there is no mean flow) and u_* is the frictional velocity. This relationship describes wind-speed in the direction of airflow within a boundary layer where airflow has adjusted to the underlying surface. Observations made at standard meteorological stations fit this description and may be used to evaluate the background wind resource, within which the urban effect occurs. By modifying the parameters of eq. (2), wind-speed over an urban surface may be extrapolated from observations made at these ideal sites, with an important caveat. The considerable variation among roughness elements (buildings and trees) means that the turbulence generated extends well above the heights of buildings. The depth of this roughness sub-layer (RSL) in cities extends from the ground to between two and four times the heights of buildings (z_{Hm}). In other words, the log profile can be used to describe the wind profile *above* the RSL. Below this height the profile is more complex and eq. (2) does not apply.

From a turbulent wind flow perspective, turbulence intensity (*TI*) is the most common metric to explain the turbulent effect [11]. In this regard, *TI* is the standard deviation of the wind speed σ_u normalised with the mean wind speed \bar{u} (3).

$$T.I. = \frac{\sigma_u}{\bar{u}} \quad (3)$$

The link between both the reduced wind resource and the manifestation of turbulence (in a neutral climate such as Ireland's), is the *surface roughness* length (z_0). This highly directionally sensitive parameter refers to how homogeneous or heterogeneous the surface characteristics that define a particular area. These areas can consist of grassland, high-rise buildings and even water sources. Furthermore, urban surface elements (i.e. buildings and trees) are often arranged into patterns that may generate organised motions both between and above buildings. The complex morphology experienced in an urban environment results in a modified flow and turbulence structure in the urban atmosphere in contrast to the flow over 'ideal or homogenous' surfaces [12]. However, depending upon the scale one considers, all surface roughness characteristics are analogous to blades of grass in a field. In other words, heterogeneity in landscape can be considered as homogeneity if the height above the surface is sufficient. In this way, surface roughness characteristics (z_0) can be grouped into classifications or *lengths* describing how fractious or rough a particular landscape might be [13]. So notwithstanding the previously suggested limitations of log law application, some work, such as that by Cheng and Castro [14] has shown that a single log-law spatially averaged mean velocity in the roughness sub layer is achievable, provided an appropriate frictional velocity for the surface is known. Consistent with [14], the analyses in [15] also concluded that the friction velocity (u_*) is an intrinsic parameter in a rural/urban wind profile extrapolation.

The urban wind resource research reported on here is based on observations made at three sites in Dublin, one of which (Dublin Airport) represents a reference station that provides information on the 'background' wind climate. The two urban sites as described in [15], are further employed in the modeling of how turbine performance is affected by turbulence [16].

2.2 Energy harvesting concerns and distribution network issues

Wind turbines extract kinetic energy from moving air, converting it into mechanical energy via the turbine rotor and then into electrical energy as described in eq. (4),

$$P = \frac{C_p \cdot \rho \cdot A \cdot u^3}{2} \quad (4)$$

where the mechanical output power (P) is a function of the performance coefficient of the turbine (C_p), the density of air (ρ), the area swept by the turbine projected in the direction of the wind (A) and wind-speed (u). The two factors that regulate power then are the turbine technology and the wind resource. The aerodynamic conversion losses are significant and according to Betz's law, only 59.25% of the kinetic wind energy can be converted into mechanical power (P_{mech}). This is a guideline figure and is generally much lower (due to blade roughness, hub loss, wake rotation and tip losses) and could be as low as 36.2 % for large scale wind turbine systems [17]. A flow of power conversion in a wind turbine system is presented in context in Fig.1.

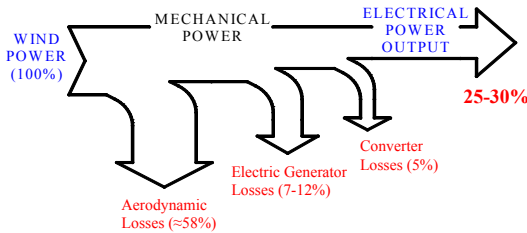


Fig. 1: Flow of Power Conversion in a Wind Turbine System

Most commercially available wind turbines have overall efficiencies typically around 30% [18]. The cumulative energy output of a generator is often presented as a capacity factor: the ratio of the measured turbine yield to the maximum output over a given time period. Establishing the capacity factor *a priori* is essential for calculating the economic return on investment in wind turbine technology. As discussed in section 2.1, an urban environment will have a lower mean wind speed relative to a rural environment. Clearly, as the power generated is proportional to the cube of the wind-speed, small variations in wind speed will have a significant impact on the wind turbines productivity. Moreover, as reported in this paper, eq. (4) is also applicable in describing the affects of turbulence on the productivity of a wind turbine, except in that regard, the affect on the turbine power curve modelled.

Turbulence has been shown to have an effect on the wind turbine power characteristic. Field trials by Lubitz [19] as well as correlation techniques by Langreder [20] have illustrated this point. The research undertaken by both Lubitz and Langreder concluded that turbulence has positive effects at low wind speeds and negative effects at higher wind speeds. Albers [21] provides a means and justification of normalising the turbine characteristic for site specific measurements of TI. Albers hypothesis is that if the wind speed within an observation period (10 min) is Gaussian distributed, it is fully determinable by the average wind speed and by the turbulence intensity (or standard deviation of wind speeds within the observation period, $\sigma = T.I. \times \bar{u}$, based on eq. (3)). This method if slightly amended has the ability to generate a power curve for a given turbine at any given TI value. Furthermore, this approach can be extended to other distribution characteristics, such as the Weibull distribution.

An improved understanding of the urban wind resource, coupled with the affects of turbulence, facilitates an enhanced distribution network engagement context for wind energy. This context is only possible however, if a distribution network model, capable of accurately representing the network's configuration, safety aspects and load/generation capacity at LV consumer level, is available. Such a model, which is the starting position for a smart network, needs to be able to reflect that at LV consumer load is not distributed in a balanced manner. Such load

distribution may cause voltage unbalance across the network. Furthermore, if increased penetrations of distributed generation are to be facilitated, the network needs to be able to accommodate bi-directional power flow. Historically, distribution networks accommodated electrical energy in a hierarchical top-down manner, so bi-directional energy flows could cause difficulties for the associated protection regimes.

The power flow calculation is used to compute the steady state operating condition of a power system and its solution should be fast, require low storage requirements and be reliable and versatile through an inherent simplicity [22, 23]. The algorithms generally adopted are *Gauss-Seidel* or *Newton-Raphson* (and its decoupled versions [24]), which are sufficiently robust and fast even for large networks but don't allow a very easy extension to a multi-phase system.

This paper utilizes an n -phase power flow approach, as described in [25] which is based on a *complex admittance matrix* methodology [26] to consider a representative urban distribution network [27, 28]. The main feature of this method is the inherent flexibility in how multi-conductor network models and their associated effects are considered. Mutual coupling influences between phases, are computed through a method that was originally developed for calculating electromagnetic coupling of complex conductor geometries [28]. The model developed allows for the system earthing, the primary customer safety provision from a network perspective, to be modeled. The algorithm presented here has been applied to a 4-wire representation of a sub-urban distribution network within Dublin city, which incorporates consumer connections at single-phase (230V-N).

3. Methodology

3.1 Wind observations

The reference site is located at the Airport (A), which is located on the margins of the city, 10 km from the city centre. The site conforms to the WMO standards for synoptic weather stations and is managed by Met Eireann, the Irish Meteorological Service. From an urban wind modeling perspective, the wind records are used to represent the wind climate that would be present across the Dublin area in the absence of the city itself.

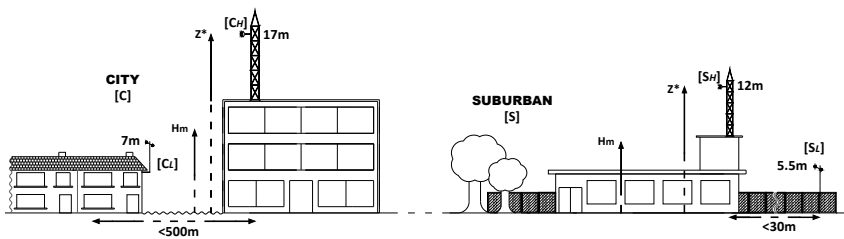


Fig. 2: Relative context of wind observation locations illustrating the relative position of the observation platforms and a z^* estimation for both the urban (C) and suburban (S) locations [15].

The two other observation sites represent two distinct urban landscapes. One is located close to the city centre (C) in an area that has mixed residential, industrial and commercial uses. The buildings vary considerably in dimensions and there is comparatively little green space. Site (S) is located in a mature, vegetated suburb, where the dimensions of the buildings are nearly uniform and the land use is residential in character. At each site there are two measurement platforms at different heights with regard to the urban surface. The high platform (C_H and S_H at

the urban and suburban locations respectively) is at least 1.5 times the average height of buildings (Fig. 2). Both high-platforms are facilitated by a Campbell Scientific CSAT3 three-dimensional sonic anemometer (10Hz). Each of the stations is positioned within a broadly defined 'homogenous' landscape in the sense that the character of the surrounding urban morphology is similar in all directions. This is especially true of the suburban site.

3.2 Urban wind modeling

Hourly airport data for the period November 2010-2011 was used for the urban wind resource consideration. The observations at the airport site are used to derive estimates of the wind resource at both urban sites. The primary focus of the work presented here is on wind at the top of the RSL ($u(z^*)$) where turbine losses due to unsteady winds are minimized. Initially, the background wind conditions for both observation sites is established by extrapolating (using eq. (1)) from the airport site upwards to a height well above the surface roughness elements (z_r), which here is set at 200 m. The wind at this level ($u(z_r)$) is then used to estimate the wind resource at the top of the RSL ($u(z^*)$), which is situated close to observations at both high-platform positions.

This paper, for brevity, prioritises a *log-fitting* approach to both estimate $u(z^*)$. The log-fitting approach is achieved by numerically fitting z_0 and u^* estimates, for each urban site, to the observed data at both high-platforms, using the established values for u at the reference height of 200 m as an upper boundary condition. This fitting is done by varying z_0 and u^* in eq. (1) so as to minimise the error between estimated and measured wind at each site.

3.3 Turbulence modeling

At the two sites described in section 3.1, 10Hz wind measurements were taken over a 40 day period from 4/4/2012 to 15/5/2012. A 10 minute sampling period bench mark was employed; this period is used on a moving window basis with each window consisting of 6000 samples (10 minutes at 10Hz).

Two models have been developed. The first is based on an approximation to the methodology presented in [21], with the second based on the Weibull distribution. The methodology, as described in detail in [16], uses a manufacturer's wind turbine power curve that is modified on the basis of varying TI and wind speed so that the turbine power output for each 10 minute summary of observed TI and mean wind speed, through a 'look-up table', can be obtained.

The specific turbine power curve, a *Skystream 3.7*, 2.4kW, is decomposed within MATLAB into a polynomial equation that can be applied to any set or subset of wind speeds; subject to limiting the power curve in terms of both cut-in wind speed and for wind speeds in excess of the power curve's maximum specified wind speed.

3.4 Distribution network consideration

The network considered in this work is depicted in Fig. 3. It consists of a section of LV (urban) distribution network incorporating 74 households facilitated by 10 mini-pillar connections (along the LV feeder) and supplied by a 10/0.4 kV supply.

The network is radial in structure with the sub-distribution branch section (pillar) accommodates single-phase consumer connections (domestic installations). The supply voltage at the 10/0.4 kV transformer operates in accordance with the assumed maximum voltage drop limits as defined in the EN50160 voltage standard [29]. Essentially, the DNO is prescribed to deliver electricity in a voltage range of 207V to 253V ($\pm 10\%$ V_{Nominal} of 230V). In the analysis presented here, the sending voltage at the feeder bus is +5% with respect to the nominal voltage.

The passive network model parameters and associated data were supplied by the Irish DNO, *ESB Networks* [27].

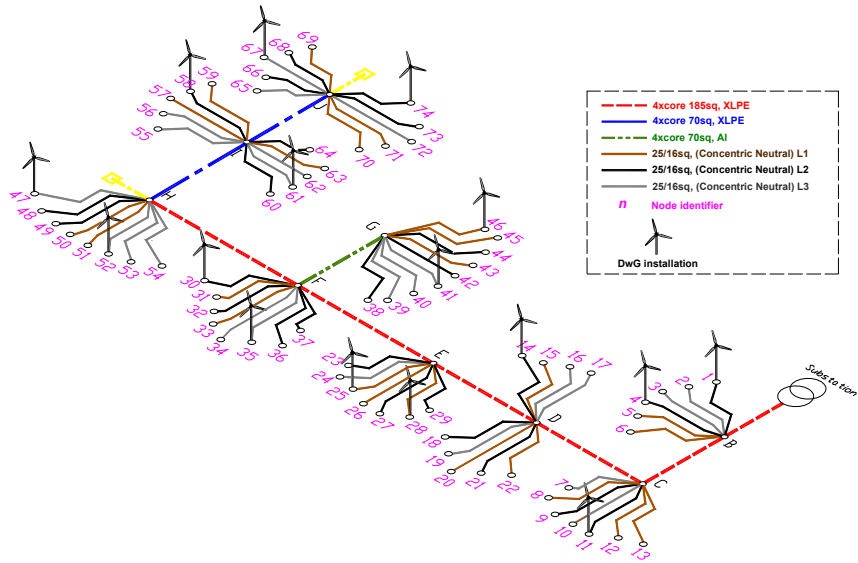


Fig. 3: Section of (Irish) urban distribution network mini-pillar/consumer interconnections illustrating load profile variation and domestic (micro) generation connections.

4. Results

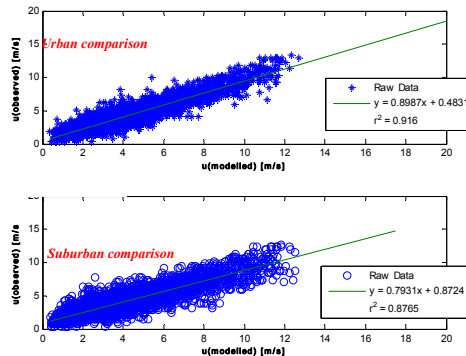


Fig. 4: Scatter-grams comparing the (high-platform) observed and modelled wind

The estimated z_0 at the city and suburb sites is 0.87 and 0.52 m respectively. Both of these values are within the range of roughness associated with each landscape [13], but are on the low end (especially for the city site). These z_0 values represent an average for the urban landscape, weighted by the frequency of wind from a given direction. The resulting model describes the observations closely. Fig. 4 plots the observed against the estimated wind-speed at both the

urban and suburban sites – the coefficients of determination (r^2) are 0.92 and 0.88, respectively. Note that the scatter of points is consistent across the range of observations.

The log-fitting model is subsequently considered to establish the network voltage profile over 8760 hours, or a typical mean year. In this regard, a first order Markov chain is employed to ‘extend’ the model to facilitate statistical consistency [25]. In this regard the Skystream 3.7 and representative consumer load are applied [25].

The network voltage profiles, for a typical year for the urban location are illustrated Fig. 5. Voltage breaches are incurred on L₂ and L₃ only. With respect to L₂, there are on average upper voltage breaches (>1.1 pu) on 0.051% of the year at the urban sites, with the urban wind speed causing the maximum breach of 1.102pu. For a similar comparison of the voltage breaches incurred on L₃, there are on average upper voltage breaches on 0.715% of the year. In consideration of an unbalance range between 0.15% and 0.3%, the pillar voltage unbalance was within said range on 13.42% at the urban location. The maximum voltage unbalance at pillar J was 0.296%

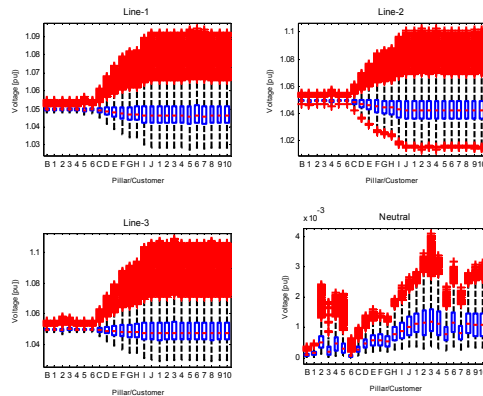


Fig.5: Network Pillar/Consumer Profiles for a mean typical year (100% consumer generation integration)

Table 1 presents a capacity factor consideration for both urban/suburban locations in respect of the *Skystream 3.7* wind turbine. The capacity are comparable to those observed by Drew *et al.* in their analysis of micro wind generators across the greater London area [8].

Table 1: Generation capacity (typical mean year) in terms of the *Skystream 3.7* wind turbine

	Cumulative Energy [kWh]	Capacity Factor [%]
Urban (C _H)	3250.1	15.46
Suburban (S _H)	2727.0	12.97

Finally, an investigation into how the distribution network voltage profile as a consequence of turbulence affected wind turbine, is considered. The results from [16] are utilised to acquire a perspective on how the modelled distribution network reacts to a turbulently described wind input. In this regard, the output of the *Skystream 3.7* is considered three ways. An observation aggregated average power, is compared to an average power based on the average wind speed over the observation window. Both averages are compared to the models developed in [16].

Fig. 6 illustrates the maximum/average voltage profiles ((a) and (b) respectively) for the suburban location (S). It suggests that at the higher wind speeds, the Albers and Weibull ap-

proximations [16] over estimate turbine power output leading to a higher network voltage profile. Furthermore, the dynamics of the turbine are not incorporated in the models. The dynamics of a wind turbine will affect the power output of a wind turbine, particularly in urban environments and are likely to reduce overall turbine productivity. In this regard, the overall system voltage profile would be somewhat depleted and over voltages would be less likely.

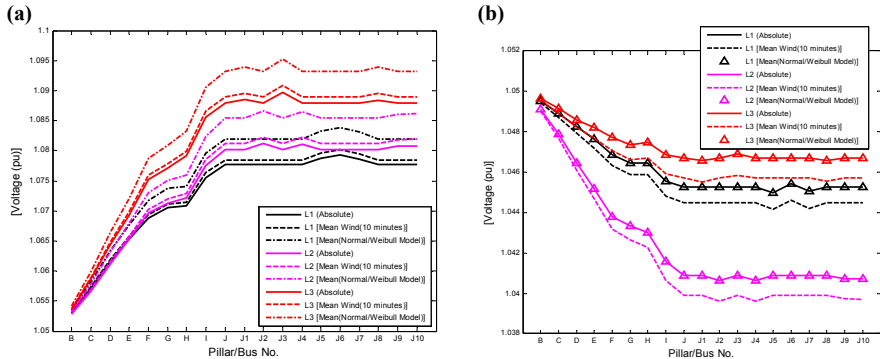


Fig.6: Turbulence considered Maximum and Mean Voltage profiles

5. Conclusion

The paper summarises a power flow analysis of a representative city distribution network that was based on an *urban* wind resource consideration. Initially a mean wind resource was considered with subsequent emphasis on the affect of turbulence on a wind energy system. For a scenario with generation connected at all consumers some over voltage breaches across the network will occur, but said breaches were relatively rare (<1% of 8760 hours). The results suggest that wind generation systems within urban environments should not inhibit the operational concerns of DNOs from a consumer voltage and network voltage balance perspective. The research presented here demonstrates a methodology applicable for Dublin. Further work will investigate if the method developed for these two sites could be extrapolated to other urban sites. In the manner in which the distribution network model was developed and how it is configured, other network structures and forms of renewable energies could easily be integrated to investigate alternative energy scenarios that can include photo voltaic systems, electric vehicles and storage considerations.

Future work will also consider the dynamic response modeling of the input resource (wind turbine) is required as this may have further implications on the voltage volatility that may be experienced across the network.

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EXPERIMENTAL INVESTIGATION OF INTERFERENCE EFFECT OF HIGH-RISE BUILDINGS FOR WIND ENERGY EXTRACTION

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Abstract: In order to increase wind energy harvesting from urban environment, the wind behavior and the effect of the surrounding buildings needs to be fully understood. In this paper, wind tunnel experiments of the flow around a high-rise building with a height to width ratio of 3:1 surrounded by four high-rise buildings of the same geometry were performed to investigate the interference effect on the above roof flow. The buildings were mounted in an environmental boundary layer resembling that of a built environment and velocity measurements over the top of the principal building were performed. Four different wind angles, with respect to the side of the high-rise building, were investigated experimentally; 0°, 15°, 30°, and 45°.

1. Introduction

Worldwide, existing buildings consume about 40% of the world's energy and are responsible for approximately the same percentage of global carbon emissions [1]. With the increase in energy needs in general, there is a strong need to reduce the carbon foot print of houses through the use of green source of energy. One of the available options is to move towards the renewable green energy and to lower down the CO₂ emissions. Such an example could be a building that uses renewable energy and does not contribute to any CO₂ emissions. It is well known that wind carries considerable amount of energy that could produce enough electricity for the entire human needs. However, nowadays only less than 0.1% of this energy is in use [2].

Urban environment is characterized by low wind speed compared to the rural areas as a consequence of the large roughness size. In order to maximize the wind extraction from the urban environment, the wind turbine is recommended to be installed on the roof. However, the wind velocity is not the same above the roof of a building alone and when it is surrounded by similar buildings, which is usually the case in urban areas.

Many researchers have been attracted to study the flow around buildings, using wind tunnel experiments [3] and [4] and computational techniques [5] and [6]. Still, large percentage of the

studies of the flow around buildings has been carried out for the purpose of wind loading and only smaller is dealing with the wind energy harvesting. Also the interference effect has been studied by researchers for the purpose of wind loading. An example of this is the work of Kim et. al., [3] in 2010. The authors investigated the interference effect related to two close buildings on local peak pressures. Detailed wind tunnel experiments included investigation of the change of heights and various locations of the interfering building, as well as the wind directions with the purpose of accessing the interference effects for local peak pressures.

In this paper, the interference effect related to the high-rise building surrounded by four buildings is presented. This work reports on the wind tunnel experiments that have been carried out in the ABL wind tunnel in the Ruhr-University Bochum as part of a Short Term Scientific Mission (STSM) sponsored by the COST-Action TU1304.

2. Wind tunnel and the building model

The interference effect of the surrounding buildings was investigated in case of the high-rise building with the flat roof in the wind tunnel. Wind tunnel experiments were carried out in the Atmospheric Boundary Layer Wind Tunnel of the Ruhr-University Bochum, Germany. The wind tunnel has a cross section of 1.6 m x 1.8 m and a test section length of 9.4 m.

The experiments included the main (principal) building surrounded with four interfering buildings. The principal model of the high-rise building with the flat roof in a scale 1:300 has been used. As shown in Fig. 1a), the height of the building is denoted by H (400 mm) and the width by D (133.3 mm). The height to width ratio of the building is $H:D=3:1$. Interfering buildings are represented as a copy of the main building with exactly same dimensions. The used geometrical arrangement for the interference configuration is presented in Fig. 1b) and the models mounted in the wind tunnel are presented in Fig. 1c). Four different wind directions (angles), with respect to the side of the building, have been considered; 0° , 15° , 30° and 45° .

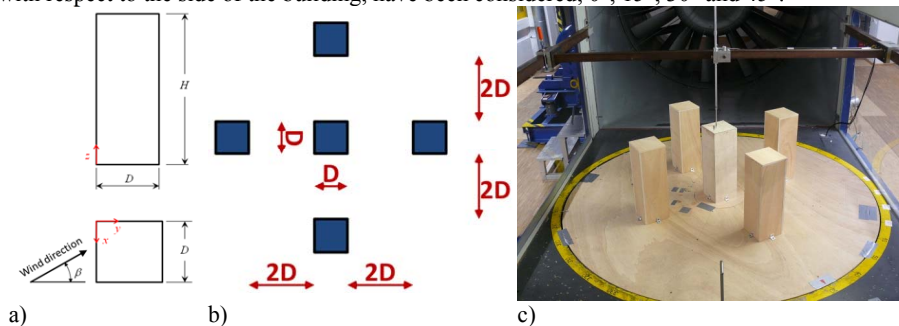


Fig. 1: a) Principle model of the high-rise building, b) arrangement of the buildings in interference configuration of the high-rise building, c) interference configuration of the high-rise building mounted in the wind tunnel.

3. Measurement technique – velocity measurements

Hot wire anemometry and measurements of mean dynamic pressure were used to measure velocity. A Prandtl tube mounted one meter upstream of the model was used to set the reference wind tunnel velocity for each test. Using the measured dynamic pressure, the mean wind speed is obtained applying Bernoulli equation.

The velocities above the roof of the principal building in interfering configuration at different heights have been measured. For these measurements the necessary equipment consists of a hot wire anemometer, amplifier and analog/digital (A/D) converter. Anemometer consists of two cross wires with 5 μm in diameter and 1.2mm long that are suspended between two needle-shaped prongs (refer to Fig. 2a)). These cross wires allow to measure two wind components. For these experiments, the velocity components in the stream-wise and vertical directions are chosen. No attempt has been made to measure the span-wise velocity component. Even though it is possible to place more hot-wire probes in the wind tunnel, in order to minimize the impact on the flow field, only one is used for all tests. The used sampling frequency was 2000 Hz. The length window of each velocity signal was around 131s. Velocities are measured above the roof of the principal building above the measurement points shown in Fig. 2c) at three different heights $z/D = 0.075, 0.3$ and 0.45 .

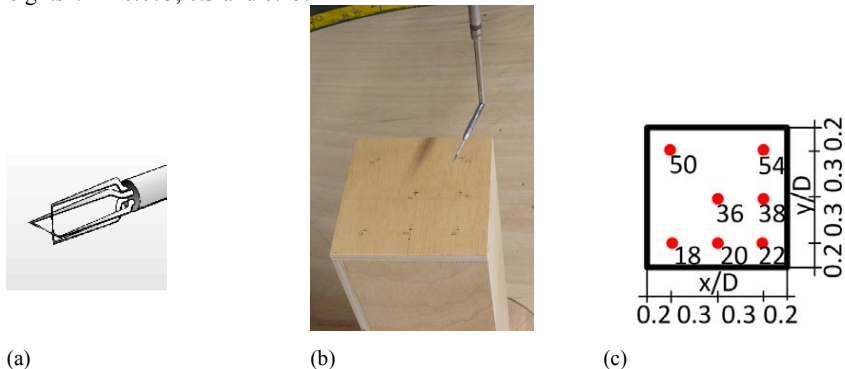


Fig.2: a) Zoom at miniature wires (X array), b) hot-wire during the measurements, c) positions of measurement points

The anemometer has been calibrated in a laminar flow in a calibration tunnel. The calibration establishes a relation between the output (in voltages) and the flow velocity. It is performed by exposing the probe to a set of known velocities (U) and corresponding voltages (E) are recorded. A fitting curve is estimated through the points (U, E) representing a transfer function, for each wire, that is used when converting data signal from voltages into velocities. The fitting curve which is adopted is a polynomial curve of 3rd order. The coefficients are calculated by fitting the data in the least-squares sense. Calibration curves used in this case are reported in Fig. 3. As an amplifier Multichannel CTA 54N80 by Dantec is used and all analog signals are converted to digital ones, using analog/digital (A/D) converter.

Uncertainties related to the velocity measurements are calculated following the procedure presented in [7]. The uncertainty is determined taking into account used calibration equipment, linearization, experimental conditions (such as temperature and pressure), etc. Still positioning of the probe remains as one of the main uncertainty contributors. Since it would be very time consuming to repeat all the measurements several times, this uncertainty is evaluated based on the three sets of measurements at 8 heights above the single high rise building and added to the total uncertainty.

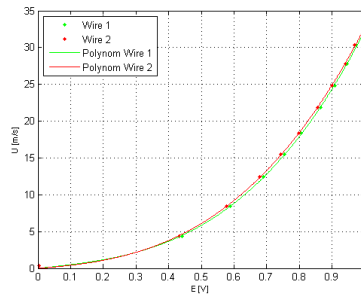
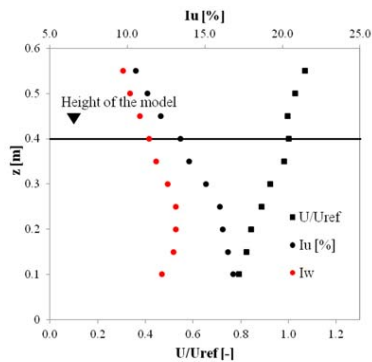


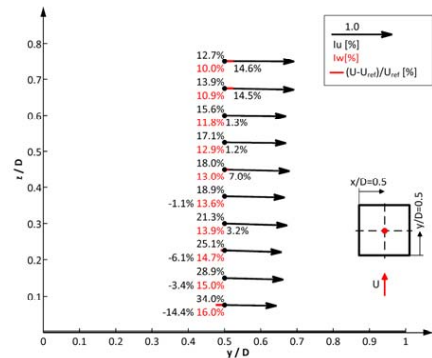
Fig.3: Calibration curves – wires 1 and 2 of used probe

4. Time-averaged velocity

4.1 Velocity distribution above the roof



(a)



(b)

Fig. 4: (a) Wind tunnel velocity and turbulence intensity profiles, (b) Profiles of velocity vectors, I_u (black number - marked next to the measurement points), I_w (red number - marked next to the measurement points) and percentage increase in the wind speed (black number - marked aside of a vertical line defined by measurement points) over a single high-rise building under the influence of 4 surrounding high-rise buildings measured at P36 ($x/D=0.5$) at angles: 0° (a), 45° (b)

The approaching flow in the wind tunnel representing an urban wind exposure is generated using the spire-roughness technique and its streamwise U/U_{ref} , I_u and I_w profiles are presented in Fig. 4a). The profiles presented in Fig. 4a) are obtained averaging three sets of measurement. The reference velocity is defined as the upstream wind velocity at the height of the building.

Fig. 4b) shows velocity distribution measured at 10 heights above the building at the centre of the roof (point P36 from Fig. 2c)) for the 0° angel of flow attack. The velocity components in the y and z directions from Fig. 1a), u and w , respectively were measured as shown in Fig. 4b). It can be observed that nearly parallel flow to the roof top is obtained, experiencing no significant increase in the streamwise wind velocity up to the height of $z/D=0.675$, where the magnitude of streamwise velocity suddenly increases to 14.5%. In addition, from this location also smaller turbulence intensities I_u and I_w are measured then in the region closer to the roof

top. Namely observed turbulence intensities are becoming more comparable to the turbulence intensity of the upstream flow generated by the roughness elements and turbulence generators at the inlet of the wind tunnel. This suggests that the effect of this configuration, namely upstream building and the principal building downstream, on the turbulence intensity in the above roof flow is limited to a height of about two thirds of the building width.

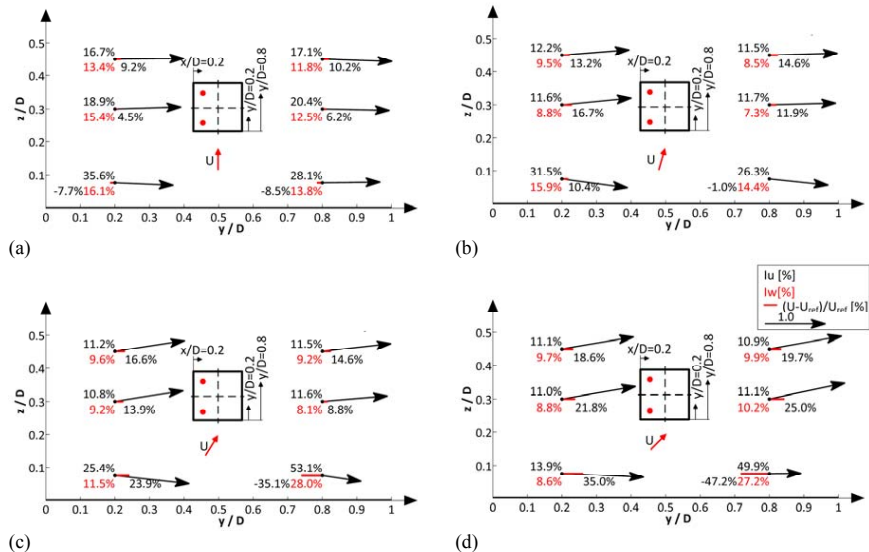


Fig. 5: Profiles of velocity vectors, I_u (black number- marked next to the measurement points) and I_w (red number- marked next to the measurement points) over a high-rise building under the influence of 4 surrounding high-rise buildings measured at P18 and P50 ($x/D=0.2$) at angles: 0° (a), 15° (b), 30° (c), 45° (d)

The wind velocities above the roof of the building have been measured at three different heights presented in Fig. 5 at four different angles of flow attack: 0° , 15° , 30° and 45° . Fig. 5 shows the mean velocity vector, I_u and I_w turbulence intensities and percentage increase in the wind speed for points P18 and P50. Considering different wind angles, these two points are in upstream half of the roof in case of larger wind angles and for smaller ones point P18 is in the upstream half and P50 in the downstream half. It can be seen that the streamwise and vertical turbulence intensities (I_u and I_w), especially at points closest to the roof top are sometimes higher than 30%. In those regions, flow separation is expected to occur. Since hot-wire anemometer is not suitable to measure a reverse flow then the measurements of the streamwise velocity component in this region cannot be treated as reliable [7]. However, the measurements of the turbulence intensity and the direction of the vertical component still can be taken into account. For 0° wind angle, the lower measurement position above point P18 is slightly pointing downwards as well as the middle measurement position upwards, suggesting a possible small separation at the upstream corner. However, all other velocity vectors are almost lacking with vertical component, still showing higher turbulence intensities than for other approaching angles of the flow. This is comparable to turbulence intensities over the point P36 presented in Fig. 4b). The explanation could be that the incoming flow separates from the top of the upstream building and generates a shear flow that affects, as well, the flow over the principal building. From Fig. 4b) can be observed that the height $z/D=0.675$ is just above the shear layer between

the separation region and the core flow. For 15° wind angle, the velocity profile is different. Namely, a small separation cone is formed along the upstream side edge of the building starting at the upstream corner. The velocity vectors at lower measuring points are pointing downwards suggesting that the both points P18 and P50 are located at the tail of the separation cone where the flow tends to attach to the roof. Increasing the wind angle to 30° , the velocity profile is similar to 15° flow angle. Jet, velocity vectors above the the point P50 are pointing upwards, suggesting larger separation cone compared to wind angle of 15° . For 45° wind angle, the velocity vector close to the roof above the point P18 is slightly pointing downward and it is highly turbulent above the point P50 suggesting that a large separation cone occurs and increases in size along the upstream edge. Due to the fact that the turbulence intensities I_u and I_w are considerably high (around 50% and 30%, respectively) at lower measurement position above the point P50, the location of the measurement point is entirely in the separation zone.

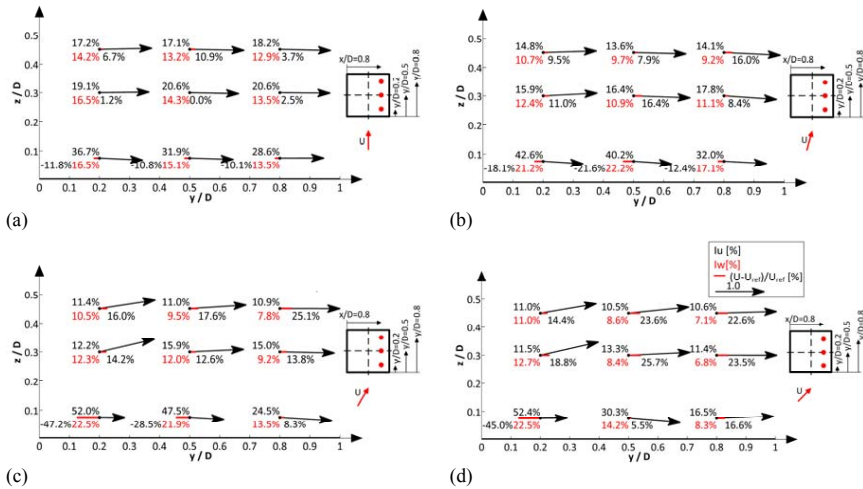


Fig. 6: Profiles of velocity vectors, I_u (black number- marked next to the measurement points) and I_w (red number- marked next to the measurement points) over a single high-rise building under the influence of 4 surrounding high-rise buildings measured at P22, P38 and P50 ($x/D=0.8$) at angles: 0° (a), 15° (b), 30° (c), 45° (d)

Similar to previous figure, Fig. 6 presents the wind velocities above the roof of the building above the points P22, P38 and P54. Considering different wind angles, point P22 is in the upstream half of the roof in case of small wind angles and for larger ones is in the downstream half. Points P38 and P54 are in downstream part of the roof for all angles of approaching flow. Similarly as observed in Fig. 5, due to symmetrical positions of the measurement points, high turbulence intensities are observed with velocity vectors parallel to the roof top in case of 0° of angle of flow attack. Increasing the wind angle to 15° , the wind slightly accelerates upward at point P22 and downward at point P54. This suggests that the flow reattaches the roof of the building after a region of separation. However, compared to the case of wind angle of 15° for points P18 and P50, higher turbulence intensities are observed. Possibly the shear flow generated from the upstream building is affecting the flow over the principal building in this region. For wind angle of 30° , a separation cone is formed along the upstream side of the building, affecting the flow above points P22 and P38. However, the flow over the point P54 seems to be getting out of the influence of the separation cone. The lower measurement positions above

the points P22 and P38 are entirely in the separation zone as the turbulence intensities I_u are around 50%. Similar flow pattern is observed for the case of 45° .

4.2 Effect of wind angle

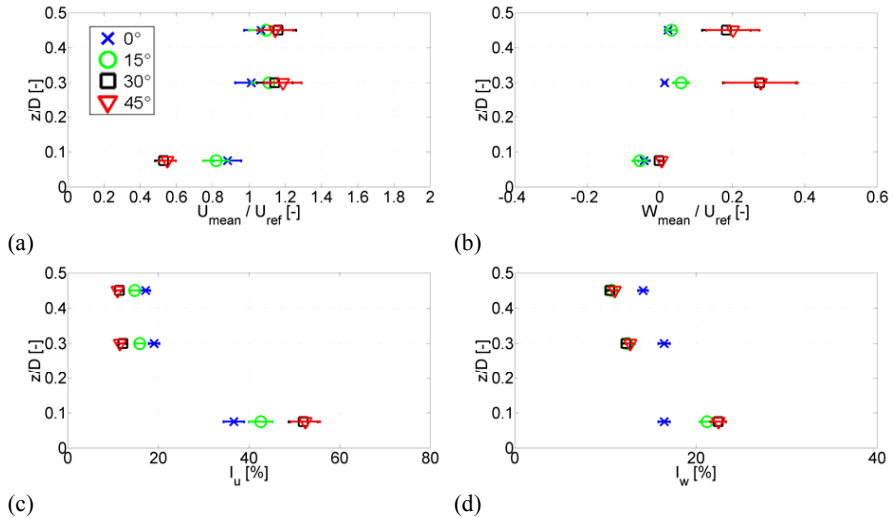


Fig. 7: Height profile of $U_{\text{mean}}/U_{\text{ref}}$ (a), $W_{\text{mean}}/U_{\text{ref}}$ (b), I_u (c) and I_w (d) measured at position P22 on the roof top of the high-rise building under the influence of 4 surrounding high-rise buildings for different approaching flow angles 0° , 15° , 30° and 45° . Uncertainty estimates correspond to 95% confidence intervals.

Height profiles of mean streamwise and vertical velocity over the reference velocity, as well as I_u and I_w turbulence intensities over measurement position P22 are presented in Fig. 7 for different approaching flow angles. Highest increase of the streamwise wind speed is obtained at the height $z/D=0.3$ for approaching flow angle of 45° , which is followed by the highest vertical component as well. This corresponds to the flow over separation cone shown in Fig. 6. Similar streamwise velocity profile, with highest increase at the middle level is observed for wind angle of 15° . For wind angle of 0° continuous decreasing profile is obtained almost parallel to the roof top, jet with considerably higher I_u and I_w turbulence intensities. Wind angle of 15° shows also higher I_u turbulence intensity as previously observed in Fig. 6.

Similarly Fig. 8 presents height profiles over the measurement point P36 for different flow angles. Again, highest increase in streamwise wind speed is obtained for approaching wind angle of 45° . However, increase seems to be constant at presented positions and followed by slight increase of vertical component over the height. This could be attributed to large mass of air which has to overcome upwind interfering buildings and large separation cones at the upwind side of the principal building. Interesting is to observe that subsequent increase in magnitude of streamwise velocity is obtained for approaching angle of 15° , while angles 30° and 0° have more comparable results. Again turbulence intensities I_u and I_w in case of 0° angle of flow attack has higher values compared to other angles.

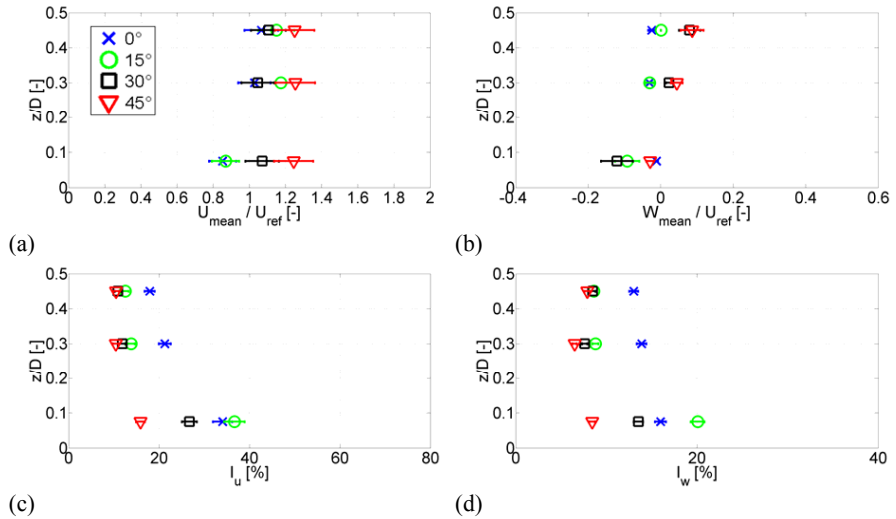


Fig. 8: Height profile of $U_{\text{mean}}/U_{\text{ref}}$ (a), $W_{\text{mean}}/U_{\text{ref}}$ (b), I_u (c) and I_w (d) measured at position P36 on the roof top of the high-rise building under the influence of 4 surrounding high-rise buildings for different approaching flow angles 0° , 15° , 30° and 45° . Uncertainty estimates correspond to 95% confidence intervals.

5. Instantaneous flow - velocity spectra

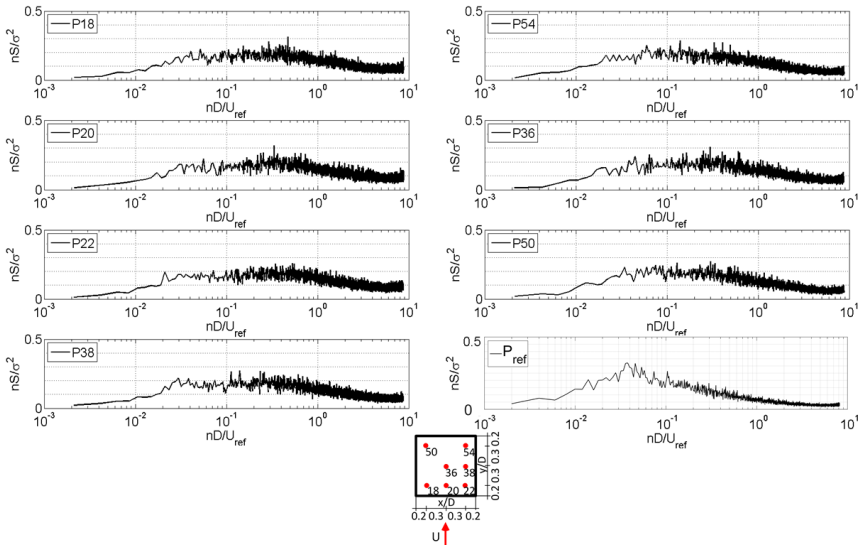


Fig. 9: Energy spectra of the velocity in 0.3 z/D height above different positions on the roof top of the high-rise building under the influence of 4 surrounding high-rise buildings for an approaching flow angle of 0° and of the reference point.

Power spectra density (PSD) plots for the streamwise velocity component of all measurement points at height $z/D=0.3$ for an approaching flow angle of 0° are shown in Fig. 9. Each figure demonstrates how the energy is redistributed among scales above the roof top. In addition, in Fig. 9 power spectra density plot for streamwise velocity component of the reference point is also included for the comparison with the free stream flow. Even though there are no significant differences between the PSD plots related to the measurement points, still compared to the PSD of the reference point differences exists. These energy spectra related to the measurement points are showing higher broad band energy levels. Again, explanation can be related to the interfering effect from the upwind building that generates a shear flow affecting the flow over the principal building, as already observed in Section 4.1.

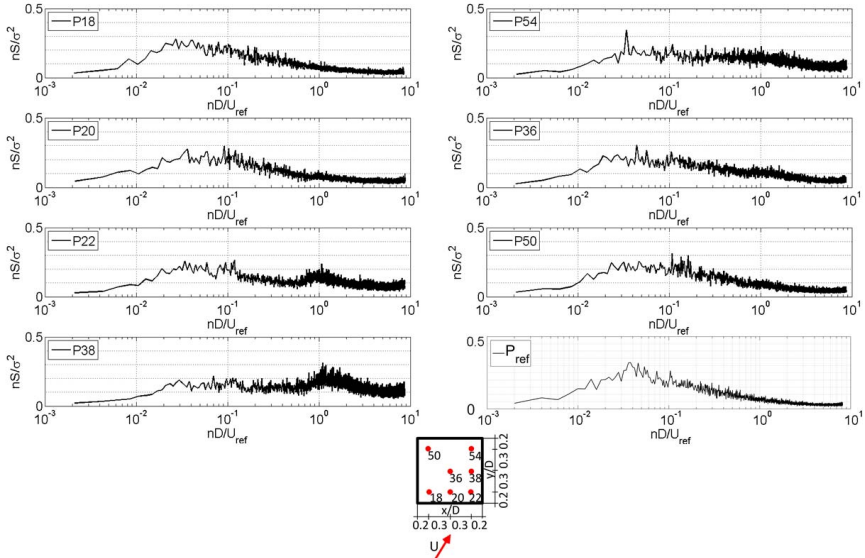


Fig. 10: Energy spectra of the velocity in $0.3 z/D$ height above different positions on the roof top of the single high-rise building under the influence of 4 surrounding high-rise buildings for an approaching flow angle of 30° and of the reference point.

Power spectra density plots for the streamwise velocity component of all measurement points at height $z/D=0.3$ for an approaching flow angle of 30° are shown in Fig. 10. The upstream points P18 and P20 are showing similar spectra as the reference point velocity spectra. The peak occurs around $nD/U_{ref} \approx 0.03$. Larger differences are observed in case of points P22 and P38 where distinctive broad peak can be observed and it is related to high frequencies around $nD/U_{ref} \approx 1$. Possible explanation is that these points lie either in separation region or in the shear layer between the circulation region and the core flow the separation zone where higher frequencies are dominant. This can be supported by observing the flow field in Fig. 6. Similar pattern is observed as well in separation region in case of approaching angles of 15° and 45° .

6. Conclusions

This paper reports on the velocity measurements performed in the wind tunnel above the roof of a high-rise building surrounded by four identical buildings. Velocity measurements are done

using the hot-wire anemometer at seven locations at three different heights above the roof for four different approaching wind angles: 0°, 15°, 30°, and 45°. Some of the conclusions can be summarized as:

1. At 0° of approaching flow, the interference effect is related to the shear layer generated above the upstream building that governs the flow above the principal building as well. This is supported by observed high levels of turbulence intensity, lack of increase in wind speed and similar patterns of PSD above the roof of the principal building.
2. At 0° of approaching flow, increase of streamwise velocity component, as well as decrease of the turbulence intensity to the level similar to the free stream occurs at about two thirds of the building width above the roof.
3. By increasing the angle of approaching flow, separation cones are generated at the upstream sides of the building. In particular they are pronounced for approaching wind angles above 30°.
4. It has been found that the maximum increase of wind speed (about 24% increase over the reference velocity) is observed at 45° angle of flow attack.

CFD analysis will be performed in the future in order to support these results and to investigate features in more detail.

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CFD SIMULATION OF WIND ENVIRONMENTAL CONDITIONS OVER NATURAL COMPLEX TERRAIN

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Abstract: Accurate and reliable Computational Fluid Dynamics (CFD) simulations of wind flow over natural complex terrain are very important for wind energy resource assessment. There is a lack of CFD studies including validation by field measurements for natural complex terrain beyond the case of isolated hills. Therefore, this paper presents a CFD study with field measurement validation for natural complex terrain that consists of an irregular succession of hills and valleys surrounding a narrow entrance channel. The simulations are performed with 3D steady RANS and the realizable k- ϵ model. The study shows that for the present application, the 3D steady RANS approach with the realizable k- ϵ model can provide an accurate assessment of the complex mean wind-flow patterns and the funnelling effect by the natural complex topography on the wind.

1. Introduction

The study of wind flow over hills, valleys and other types of complex topography is crucial for wind energy resource assessment (e.g. [1-4]). In the past 50 years, Computational Fluid Dynamics (CFD) has been increasingly developed and applied as a powerful assessment tool in wind engineering (e.g. [5]). CFD has some important advantages compared to field measurements and reduced-scale wind-tunnel testing. The main advantage of field measurements is that they are able to capture the real complexity of the problem under study. Important disadvantages however are that they are not fully controllable due to – among others – the inherently variable meteorological conditions and that usually only point measurements are performed. Also wind-tunnel measurements are generally only performed at a few selected points in the model area, and do not provide a whole image of the flow field. CFD on the other hand provides whole-flow field data, i.e. data on the relevant parameters in all points of the computational

domain. Unlike reduced-scale wind-tunnel testing, CFD does not suffer from potential violation of similarity requirements because simulations can be conducted at full scale. This is particularly important for studies involving very extensive topographic areas, which is the topic of this paper. Main disadvantages of CFD however are its large sensitivity to the wide range of computational parameters involved – and to the user of the CFD software – and the associated concerns for accuracy and reliability of CFD results.

In the past 50 years, a very large number of valuable CFD studies of wind flow over hills have been performed. Initially these studies were based on linearization of the equations of motion. This type of linear CFD models is less computationally demanding and can show good performance for wind flow in absence of flow separation, i.e. for low slopes (e.g. slopes below 10°). However, later approaches were based on the nonlinear equations of motion (e.g. [6]), which are more suitable for cases with flow separation, as flow separation is a process that involves dominant non-linear mechanisms. Most of these nonlinear studies, published in the past 30 years, focused on 2D or 3D generic/idealized isolated hills or sometimes on successions of idealized hills, often with validation by reduced-scale wind-tunnel measurements. Several others were nonlinear CFD studies without specific validation efforts.

As opposed to these studies, the present paper focuses on nonlinear 3D CFD studies for natural complex terrain including validation with field measurements. It presents a CFD study with field measurement validation for a natural complex terrain that consists of an irregular succession of hills and valleys surrounding a narrow entrance channel, i.e. the Ria de Ferrol in Galicia, Spain.

2. Case study problem statement and topography

The case under study is Ria de Ferrol in Galicia, Spain. It is an entrance channel that connects the LNG terminal of Reganosa in Mugarodos with the sea (Fig. 1). It roughly extends from UTM (29 T 553955 E – 4811241.48 N) to (29 T 563337 E – 4813138 N). The immediate surroundings consist of irregular hilly terrain with peak altitudes up to about 250 m both north and south of the Ria. The hilly character is illustrated in Figures 1b and 1c, which are perspective views from west and from east, and in Figures 2a and 2b, which are perspective views from south.

The distance between the entrance of the Ria and the LNG terminal is about 10 km. In aerodynamic studies, typically an upstream fetch of 5 to 10 km needs to be taken into account, because this is the distance over which the vertical atmospheric boundary layer (ABL) profiles of mean velocity and turbulence properties develop due to their interaction with the aerodynamic roughness length of the terrain [7]. The study area is therefore larger than the extent of the Ria and is illustrated by the yellow rectangle in Figure 3. The landscape topography in this area is described by Geographic Information System (GIS) data (Cartographia-Fotografía Aérea - S.A. Desenvolvimento Comarcal de Galiza) with a horizontal resolution of 10 m.

The present CFD study focuses on high wind speed conditions, for which the atmospheric boundary layer exhibits neutral stratification. The reason is that high wind speeds are most relevant for wind energy applications.



Fig. 1: (a) Top view of Ria de Ferrol and surroundings, with indication of LNG terminal and Ferrol city centre. (b) Perspective view from west. (c) Perspective view from east.



Fig. 2: (a) Perspective view of Ria de Ferrol with LNG carrier assisted by tug boats (© Pedrotop); (b) Perspective view with cruise ship (CC-BY 3.0, datuopinion.com 2011). View positions and directions are given in plan view subfigures in top right corners.

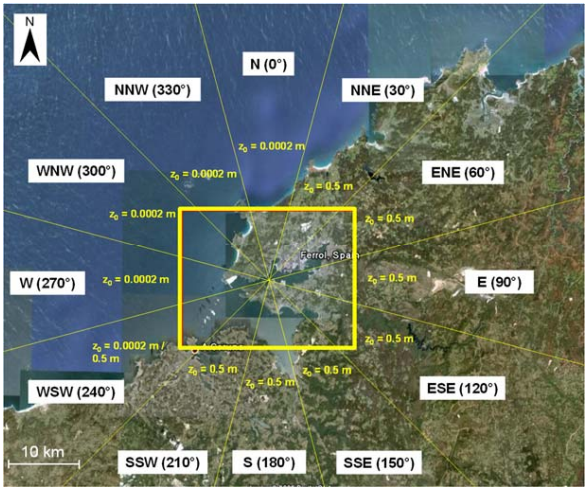


Fig. 3: Indication of the study area (yellow rectangle) and aerodynamic roughness lengths z_0 for the terrain surrounding the study area.

3. Field measurements

Field measurements of wind speed with two-dimensional ultrasonic anemometers have been made at five different positions A-E (Fig. 4a) for a period of four weeks. The UTM coordinates of the five positions are given in Table 1. Position A is the reference position, located on top of a crane at the Port Exterior, at a height of about 65 m above mean sea level (MSL) (Fig. 4b). The four other positions are different locations along the channel, at a height of about 10 m above the local terrain surface. Selecting good measurement positions was a difficult task. The criteria for selection were: (1) avoiding local disturbance effects by small-scale terrain features that are not included in detail in the numerical model, such as individual buildings and trees; and (2) safety and theft protection of the equipment. Position A provides a good reference measurement position, because it is not significantly influenced by the surrounding terrain for most wind directions (Fig. 4b). Position B is situated at Cabo Prioriño, at a height of about 50 m above MSL, and is also a suitable measurement location (Fig. 4c). Position C is at the top of the beacon tower at Punta de San Martin, at a height of 2.1 m above the tower, and about 14 m above MSL (Fig. 4d). For this position, the presence of the beacon tower might have some influence on the measurements. Position D is at Castillo de La Palma, at a height of about 6.7 m above the surrounding balustrade, and about 12.7 m above MSL (Fig. 4e). For this position, a nearby building strongly influences the measurements, except for wind directions NW en SE. Only data from these wind directions will therefore be used for validation at this point. Finally, position E is placed at the outer northwest mooring dolphin of the terminal, at a height of about 11.7 m above MSL (Fig. 4f). This is a relatively unobstructed measurement position.

Table 1: UTM coordinates of the five measurement positions.

Measurement position	Easting (m)	Northing (m)
A	554079.02	4812301.73
B	553552.59	4812881.73
C	558020.02	4812351.09
D	558911.69	4812765.31
E	561381.98	4812773.79

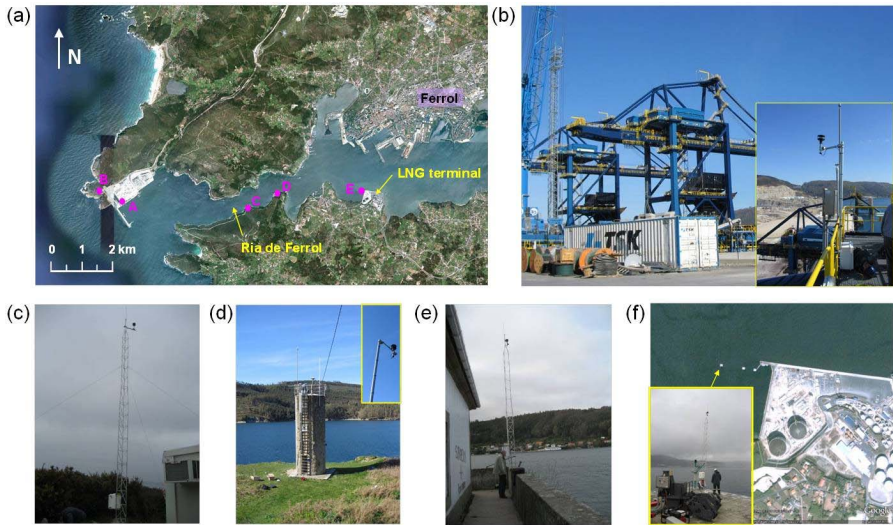


Fig. 4: (a) Indication of the five measurement positions A-E; (b) Measurement position A on top of the crane at Port Exterior; (c) Measurement position B at Cabo Prioriño; (d) Measurement position C at the top of the beacon tower at Punta de San Martin; (e) Measurement position D on balustrade of Castillo de La Palma; (f) Measurement position E at outer northwest mooring dolphin of the terminal.

The gathered field measurements were 1-minute data, which were converted (averaged) into 10-minute data to more strongly position them in the spectral gap of the wind speed power spectrum [8]. The comparison between CFD results and experimental data was only made for those wind directions for which sufficient data satisfying two criteria were available. The first criterion was that the reference wind speed at point A has to be higher than 7 m/s. This is important to exclude thermal effects from the comparison. As mentioned before, the CFD simulations are performed for neutral atmospheric conditions, and thermal effects are ignored. Note that the manoeuvring simulations that will be based on the wind-velocity patterns – but that are not reported in this paper – are typically carried out for a reference wind speed $U_{10} = 10$ m/s. The second criterion concerned wind direction selection. Around every of the 12 wind directions for which CFD simulations were made ($0^\circ - 30^\circ - \dots - 330^\circ$), a relatively narrow 10° wind direction sector was defined. All experimental 10-minute data values that had 10-minute wind directions at point A within this sector, were averaged and standard deviations were obtained. This was only performed for those wind direction sectors with more than twenty 10-minute data points. These averages will be compared with the corresponding CFD results in section 6. Note

that because of the above-mentioned two criteria, data for wind directions 90° and 120° were not available for comparison.

4. CFD simulations: computational settings and parameters

4.1 Computational geometry, domain and grid

The computational geometry is based on the GIS data with a horizontal resolution of 10 m. Only the data in the yellow rectangle in Figure 4 are used, which bounds the horizontal area of the computational domain of $25 \times 20.5 \text{ km}^2$. The height of the domain is 1 km. As mentioned earlier, the choice of the horizontal extent of the domain is based on the fact that a distance of about 5–10 km from the region of interest, being the entrance channel, is sufficient to numerically model the development of the approaching ABL due to the aerodynamic roughness length of the terrain. The GIS data are implemented as points, and surfaces are fit through these data points. Next, the surfaces are discretised with quadrilateral and triangular cells that provide the basis for the generation of 3D cells for application of the control volume method.

The computational grid (Fig. 5) is generated using the surface-grid extrusion technique [9]. This technique allows a large degree of control over the size and shape of the computational cells. This grid technique only uses hexahedral and prismatic cells, and no tetrahedral and pyramid cells. In this case, all cell faces are either vertical, or parallel to the underlying terrain surface. This reduces the numerical discretisation error and allows the use of second-order discretisation schemes without compromising convergence. The grid resolution in the vertical direction is 2.5 m for the first 10 m, and increases gradually with height. The resulting grid contains 3,984,984 control volumes and is based on a grid-sensitivity analysis focused on mean wind speed in the entrance channel.

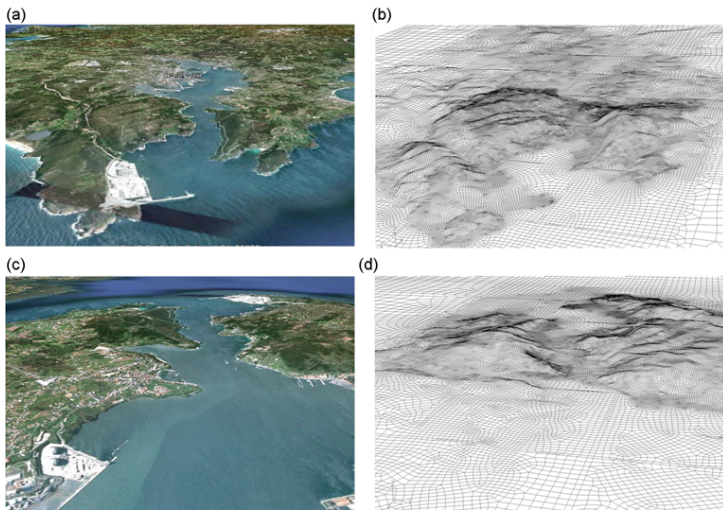


Fig. 5: (a-b) Perspective view from west of topography and computational grid on terrain surface; (c-d) Perspective view from east of topography and computational grid on terrain surface.

Total number of cells is 3,984,984.

4.2 Boundary conditions and solver settings

A distinction is made between two types of roughness [10]: (1) the roughness of the terrain that is included in the computational domain and (2) the roughness of the terrain that is not included in the computational domain. The knowledge of the roughness of the terrain that is situated outside the computational domain is important because it determines the shape of the inlet profiles of mean wind speed and turbulence properties. These profiles are generally expressed as a function of the aerodynamic roughness length z_0 [7]. This parameter can be determined based on a roughness estimation of the terrain that extends from the inlet of the computational domain up to about 5-10 km upstream of this inlet. This is done using the roughness classification of Davenport, updated by Wieringa [7]. Figure 4 graphically represents the 12 wind direction sectors surrounding the computational domain and their z_0 values.

On the other hand, the roughness of the terrain inside the computational domain is important because it determines to a large extent the local flow conditions and the development of internal boundary layers in the domain. For CFD codes that use wall functions with a roughness modification based on the equivalent sand-grain roughness height k_s and the roughness constant C_s , such as the code ANSYS/Fluent 6.3 used in this study, three steps are required:

- (1) subdivision of the terrain into patches with similar roughness (see Fig. 6);
- (2) estimation of the local z_0 using the roughness classification [7]; and
- (3) conversion of z_0 into the corresponding wall function parameters k_s and C_s [10]. These parameters can be calculated from z_0 using the appropriate conversion equation, which, for Fluent 6.3, was derived by Blocken et al. [10]:

$$k_{s,ABL} = \frac{9.793 z_0}{C_s} \quad (1)$$



Type	Nr.	z_0 (m)	k_s (m)	C_s
Sea/estuary	I	0.0002 m	0.0039	0.5
Concrete/bare land	II	0.005 m	0.10	0.5
Grass land	III	0.03 m	0.59	0.5
Spread-out built environment	VI	0.5 m	1.25	3.92
Clumps of forest	VII	1 m	1.25	7.83
Ferrol centre	VII	1 m	1.25	7.83

Fig. 6: Subdivision of local terrain into patches based on roughness classification and corresponding roughness categories and parameters z_0 , k_s and C_s .

Figure 6 also lists the resulting roughness categories and the roughness parameters. Based on the first type of roughness (z_0 from Fig. 4), at the inlet of the domain, the inlet profiles of mean wind speed U , turbulent kinetic energy k and turbulence dissipation rate ε are imposed, using the equations by Richards and Hoxey [11]:

$$U(z) = \frac{u_{ABL}^*}{\kappa} \ln \left(\frac{z + z_0}{z_0} \right) \quad (2)$$

$$k(z) = \frac{u_{ABL}^{*2}}{\sqrt{C_\mu}} \quad (3)$$

$$\varepsilon(z) = \frac{u_{ABL}^{*3}}{\kappa (z + z_0)} \quad (4)$$

where u_{ABL}^* is the ABL friction velocity, κ the von Karman constant (0.42) and C_μ a constant equal to 0.09.

Based on the second type of roughness (z_0 from Fig. 4), for the ground surface, the standard wall functions by Launder and Spalding [12] with roughness modification by Cebeci and Bradshaw [13] and the appropriate parameters k_s and C_s are applied. The sides and top of the domain are modelled as a slip walls (zero normal velocity and zero normal gradients of all variables). At the outlet, zero static pressure is set.

The 3D steady Reynolds-Averaged Navier-Stokes (RANS) equations are solved with the commercial CFD code ANSYS/Fluent 6.3 [14] using the control volume method. The realizable k - ε model [15] is used to provide closure. Second-order discretisation schemes are used for both the convective and viscous terms of the governing equations. The SIMPLE algorithm is used for pressure-velocity coupling and standard pressure interpolation is used. Calculations are performed for 12 wind directions: 0° - 30° - ... - 330° . Convergence is assumed to be obtained when all the scaled residuals [14] have levelled off.

5. CFD simulations: results

The values that are compared are the wind speed ratio and the wind direction. Two sets of wind speed ratios are distinguished:

- (1) The wind speed ratios K at the measurement positions, which are related to the crane position A. This means that K is the wind speed at a measurement position divided by the wind speed at position A.
- (2) The wind speed ratios K_{10} at a height of 10 m above MSL, which are related to the reference wind speed over open sea at 10 m above MSL. This means that K_{10} is the local horizontal wind speed at 10 m divided by the horizontal reference wind speed over open sea at the same height. Note that the wind speed over open sea corresponds to the logarithmic law for the neutral atmospheric boundary layer with an aerodynamic roughness length $z_0 = 0.0002$ m.

The numerically simulated values at the measurement positions have been obtained from the CFD results by 3D interpolation from the neighbouring cell centre values. Figures 7 and 8 illustrate the colour contours of simulated wind speed ratio K_{10} at 10 m height above MSL, together with the simulated and measured wind speed ratio vectors K at the five measurement positions, for reference (i.e. inlet) wind directions 60° and 210° . The tables in the top left corner of the figures provide the mean and standard deviations of the measured values of K and Φ , as well as the simulated (numerical) values. For all positions except position D, a good to very good agreement is obtained. The numerically simulated wind speed ratios and wind directions are generally situated within the standard deviations of the measurements. As mentioned earlier, at position D, the presence of a nearby building affects the measurement accuracy there.

Figure 9a compares the simulated and measured wind speed ratio K for all five measurement positions and for ten different wind directions, illustrating the good agreement for each of these directions. The numerical values are generally within 10-20% of the corresponding measurements. Figure 9b provides the same information for simulated and measured wind directions. The numerical values show deviations from the measurement values that are generally less than 30°.

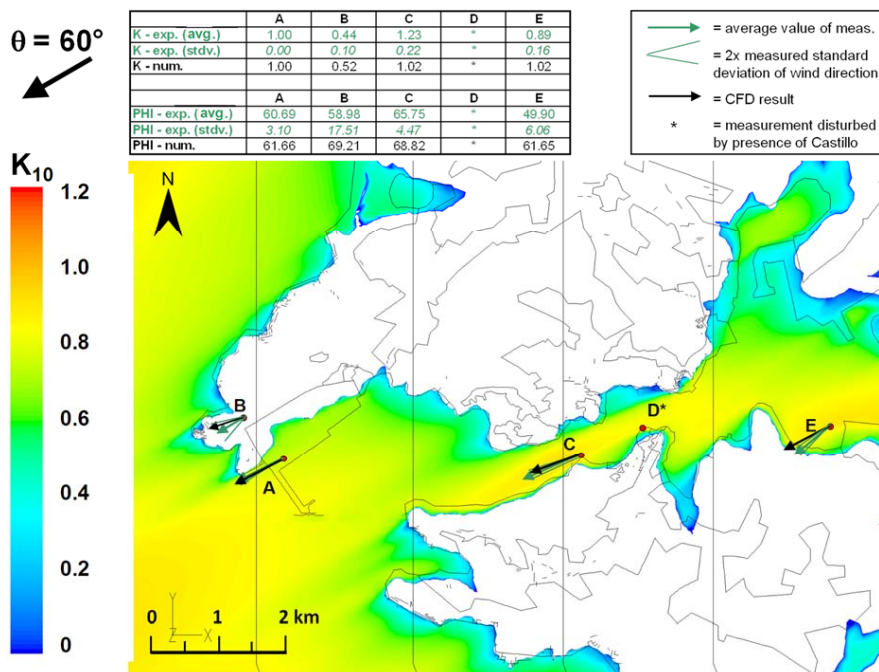


Fig. 7: Colour contours of simulated wind speed ratio K_{10} in a horizontal plane at 10 m height above mean sea level for reference wind direction $\theta = 60^\circ$. Wind speed ratio vectors K at measurement positions: simulated (black) versus measured (green), with indication of standard deviation (green). Average values and standard deviations are given in the table in the upper left corner. Note: K_{10} and K are defined in a different way, related to different reference wind speed values.

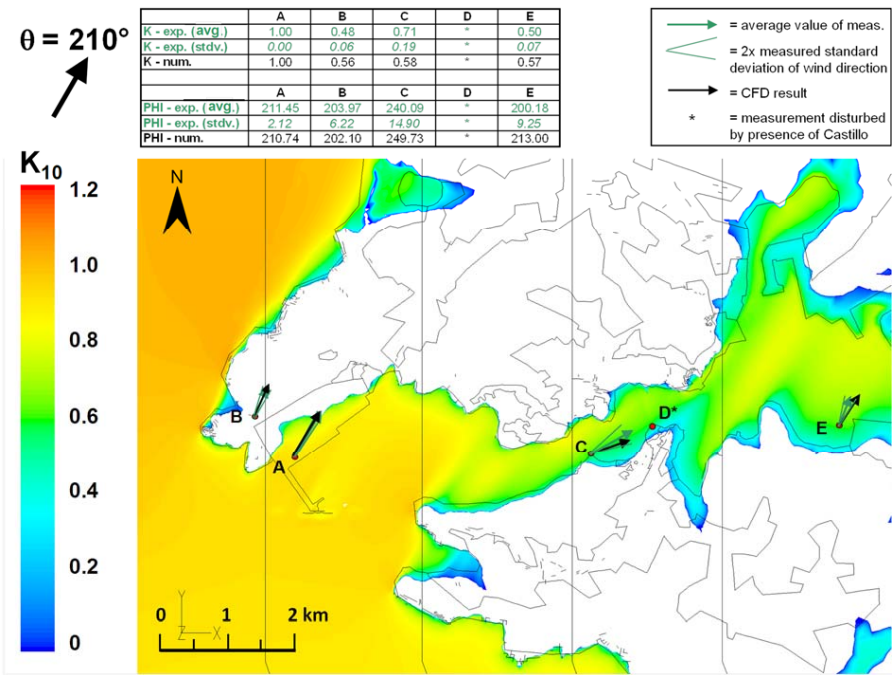


Fig. 8: Colour contours of simulated wind speed ratio K_{10} in a horizontal plane at 10 m height above mean sea level for reference wind direction $\theta = 210^\circ$. Wind speed ratio vectors K at measurement positions: simulated (black) versus measured (green), with indication of standard deviation (green). Average values and standard deviations are given in the table in the upper left corner. Note: K_{10} and K are defined in a different way, related to different reference wind speed values.

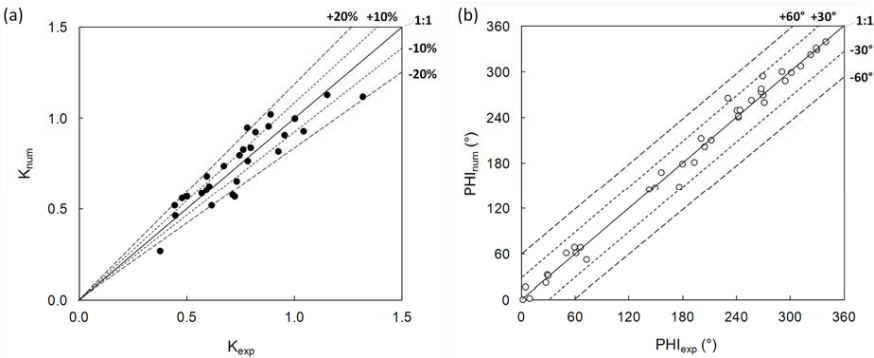


Fig. 9: (a) Comparison of numerically simulated and experimentally measured wind speed ratio K at the five measurement positions for ten different reference wind directions. (b) Same, for local wind direction PHI ($^\circ$ from north).

6. Conclusions

Accurate and reliable Computational Fluid Dynamics (CFD) simulations of wind flow over natural complex terrain are crucial for wind energy resource assessment. A detailed review of the literature shows a clear lack of CFD studies including validation by field measurements for natural complex terrain beyond the case of isolated hills. Therefore, this paper presents a CFD study with field measurement validation for natural complex terrain that consists of an irregular succession of hills and valleys surrounding a narrow entrance channel, i.e. Ria de Ferrol in Galicia, Spain. The 400-500 m wide channel connects the LNG terminal of Reganosa in Murgardos with the sea. It is enclosed by irregular hilly terrain up to about 250 m above sea level, which was expected to yield complex wind-flow patterns.

The case study is performed using 3D steady RANS simulations with the realizable $k-\epsilon$ model to provide mean wind velocity in and around the narrow entrance channel. The study focused on high wind speed conditions, for which the atmospheric boundary layer exhibits neutral stratification. The comparison of the results of the CFD simulations with the measurements shows a good to very good agreement, with deviations that are generally within 10%-20%. Both the numerical and the measured results illustrate the complexity of the mean wind-flow pattern and the funnelling effect by the topography on the wind for some specific wind directions. The study shows that for the present application, the 3D steady RANS approach with the realizable $k-\epsilon$ model can provide an accurate assessment of the complex mean wind-flow patterns and the funnelling effect by the topography on the wind.

Acknowledgments

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AN EXPERIMENTAL AND NUMERICAL STUDY OF THE AIRFLOW AROUND UNIVERSITY BUILDINGS IN TUBINGEN

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Abstract: This paper presents a project running in the University of Tübingen, a university town located south west of Germany. The project aims to look at the potential for renewable energies in University and Hospital buildings of Tübingen. Among the different kind of renewable energy, the wind energy is studied in order to evaluate the potential from small wind turbine and identify optimal locations for turbine installation. This investigation combines a full-scale experiment and a numerical study using computational fluid dynamic CFD. Comparisons between the measurements and the simulation allow validation of the modelling.

1. Introduction

The environmental aspects as a public concern have increased in politics within last years. The University of Tübingen is a pioneer in sustainability and environmental management in the region. The University of Tübingen and its Hospitals are currently using around 20 percent of their electricity from renewable sources. The aim is to increase it to 35 percent by 2020. A large and efficient photovoltaic system is already in service but no wind energy resources are there to complement them.

The usual way to assess wind energy potential in urban environments is technically limited. A met tower installed at a single location is not a good indicator of the overall resources within the all area. CFD tools offer considerable advantages: they can provide detailed information of the flow in the whole calculation domain. The application of CFD tools for wind resource prediction is growing. Such studies [1] have showed that CFD combined with meteorological data directly measured at the sites can be integrated in resource assessment procedure.

In order to perform the study of the wind energy resources in the university site, this project is combining an on-site experimentation with a large eddy simulation LES. This paper presents the tools used to conclude this study and some of the preliminary results.

2. Methodology

2.1 Site selection

According to a pre-investigation, this project will focus on one area where the average wind speed is estimated to be the highest among university buildings of Tübingen. The chosen investigation site is located in outlying districts of the city, at the top of a hill. A majority of the buildings is higher than 20 meters with 3 of them around 50 meters as shown in Fig. 1.

Calculated from a 500x500m gridcell simulation, based on the mesoscale model METRAS-PC [2] the prevailing wind direction is south-west.

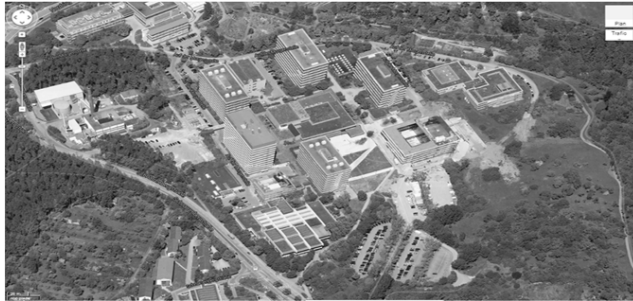


Fig. 1: Aerial view from Google Maps (GeoBasis-DE/BKG)

2.2 Experimental design

A common technique to calculate the energy potential includes wind measurements at least for an annual cycle. Thereby, six anemometers were installed (Fig. 2) in April 2014 and should stay in the site until end of 2015. These stations are installed mainly on the roofs but also on a balcony or on a ground.

This study was conducted with three-dimensional ultrasonic anemometers providing wind speed, direction and temperature with a high temporal resolution (10 Hz). These anemometers were mounted on a 3 meter high mast except for the balcony station. Around the sensor itself complementary equipment e.g. masts and mounting equipment, power supply and data acquisition systems were needed. Due to different conditions at the chosen measurement locations, on the one hand one data logger operating on an external battery is used. On the other hand five grid powered systems driven by a microcomputer (Raspberry Pi) were developed.

These stations are providing a huge amount of data: around 300MB of data is received per day. A database management of these data is necessary. A Structured Query Language (SQL) database has been build using a programming language designed for managing data. A public dynamic website is under construction.

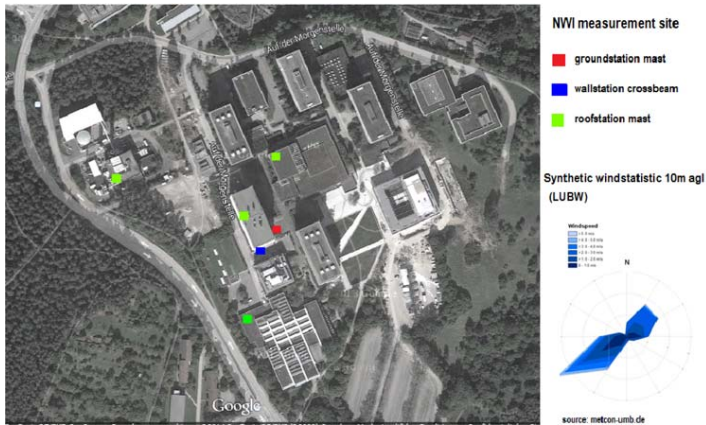


Fig. 2: An overview of the 6 stations (left) and the wind rose (right)

The topography of the site shows a valley upstream of the site as seen in Fig. 3. This valley changes the wind profile at the site. Therefore, for future simulations we need to 'adjust' the velocity profile for the inlet to also consider the vertical profile. In September 2014, we got flight permission for the area upstream of the university buildings. This permission allowed us to fly up to 300m height in the area corresponding to our numerical inlet.



Fig. 3: A photo of the valley upstream of the site.

2.3 Numerical modelling

This study uses the open source C++ code OpenFOAM. An LES with a subgrid-scale model is applied to examine the wind conditions around the site. The Smagorinsky eddy-viscosity formulation model is used. Several earlier studies [3,4,5] have shown that large eddy simulation LES and detached eddy simulation DES are methods that perform in general better than Reynolds averaged Navier Stokes RANS and Unsteady RANS methods (see [6] for a brief review). The quality of CFD simulations are still marginally used in computational wind engineering CWE [7] particularly for LES.

LES has indeed some disadvantages not easy to overcome like the computational resources requirements or the appropriate inlet. The inlet prescription is of crucial importance for LES. Different methodologies for producing inlet conditions exist. This study is conducted with a

synthetic inlet: an inflow field is generated by adding a random component to a reference (mean) field. This method requires neither simulation nor an extra domain length. The turbulent generator of [8] has been implemented by the Rostock University on OpenFOAM. This method has been performed well in terms of both mean velocity and RMS velocities. As a first approach, we run the simulation with a log-law velocity profile [9] at the inlet using the OpenFOAM libraries and adding the synthetic turbulence. The inlet profile of horizontal velocity is assumed with a representative velocity of 5m/s at a reference height of 10m.

The size of the entire computational domain in the vertical, lateral and flow directions is not limited to the region of interest but should include the surroundings. Indeed some recommendations on how to place the inlet, lateral and the top boundary exist [7,5]. Considering these recommendations, the dimensions of the computational domain are around 700m*1100m*300m. The mesh has been created with SnappyHexMesh (the OpenFOAM mesh generator). The mesh size is around 14 millions cells with a resolution of 1m near the area of interest. A mesh independence study with different grid resolution would require a highly consuming simulation time. Hence we decided to evaluate the quality of the results based on experimental data and if time allows us, we will perform it on a second mesh.

3. First results

3.1 Experimental results

A flight campaign using a small Unmanned Aircraft (UAV) developed by our group [10] have been conducted. The research UAV MASC (Multi-purpose Airborne Sensor Carrier) can resolve turbulence fluctuation of wind and temperature up to 20 Hz. Unfortunately, this flight campaign was carried out during 2 days of weak wind. Fig. 4 shows a vertical wind profile with a wind velocity of around 2m/s. These data are not useful because the wind was too weak but we plan another flight campaign during more windy days in April 2015. These measurement data will provide realistic inlet conditions combined with the synthetic turbulence.

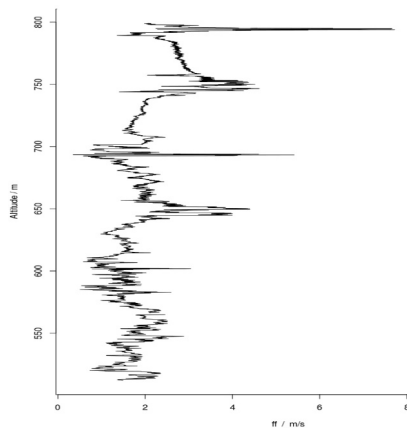


Fig. 4: Vertical profile of velocity obtained during the first flight campaign

A processing and filtering analysis of anemometer data is underway, mainly filtering data for typical measurement error sources such as sensor malfunction, icing. Some expected

outcomes can already been seen. For example, the station mounted between buildings shows the highest value due to the wind tunnel effect generated by the two tall buildings.

The days with a wind direction of south-west and strong wind have also been extracted for a direct comparison with the simulation.

3.2 Numerical results

The present study should take 30 days of wall-clock time using 512 processors. But the total CPU time is in reality several months because simulations can be only run 1 day continuous period after which they should be restarted by sending them back in the queue. The simulations can stay several days in the queue. Only 200 s of physical time have been simulated up to today. Fig. 5 and Fig. 6 show these first results. As seen through the colour scale, the simulated flow records strong turbulence inside the site (large perturbation in wind speed).

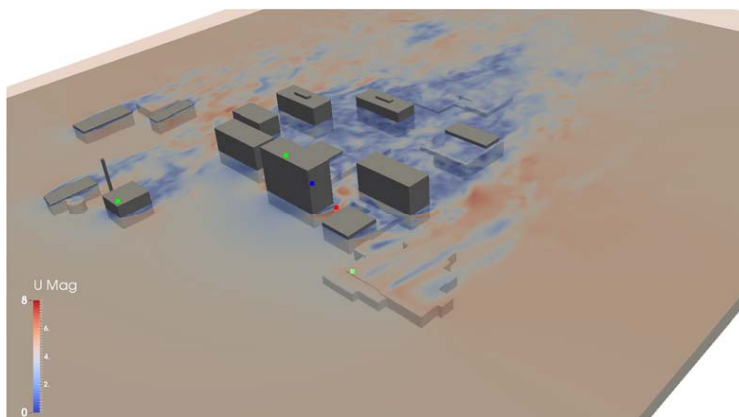


Fig. 5: Velocity contour plot at 10 m height

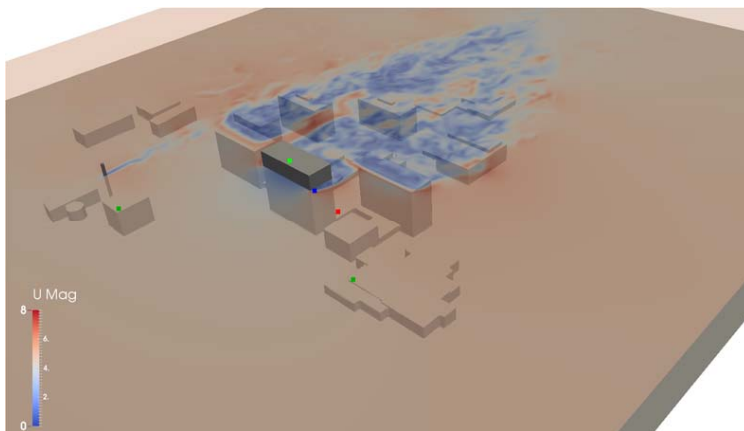


Fig. 5: Velocity contour plot at 40 m height

4. Conclusions

This project should end up with the locations where wind energy resources are possible. It should also show how CFD model combined with on-site experimentation can be integrated into the wind resource assessment.

1. The analysis of one annual year will provide an improved understanding of the wind resources of the University of Tübingen but also for verification calculations.
2. The LES should be improved by including a realistic inlet. This inlet will be provided by the UAV MASC during the next flight campaign.
3. Some restrictions may be encountered on this site: one important restriction will be the vibration and the resonance. A concrete roof is not a problem since its mass is high and its resonance frequency is low but our site has some metallic roofs where the occurring resonance frequencies is complicated to calculate.

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PRELIMINARY CFD SIMULATIONS FOR THE TORQUE WIND TURBINE

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Abstract: A Computational Fluid Dynamics (CFD) study has been conducted to analyze the efficiency of the newly designed drag-driven Torque Wind Turbine (TWT). Specific objectives of this study are the analysis of the flow field around one blade of the turbine fixed in a static position, and the generation of the power and torque coefficient curves for a single rotating blade. The commercial software Ansys Fluent was used to perform the simulations adopting the SST $k-\omega$ turbulence model. A single blade of the turbine offers a maximum power coefficient around 0.065 at a tip speed ratio ranging from 0.45 to 0.55 depending on the wind speed.

1. Introduction

As part of the current interest in renewable energy sources, driven by environmental awareness and the wish to meet the European Union 20-20-20 targets, many research activities are addressing the development of innovative solutions for wind energy harvesting. The Torque Wind Turbine (TWT) has been designed in this context of innovation.

Wind turbines can be classified into two essential categories, based on the orientation of the rotation axis: Horizontal-Axis Wind Turbines and Vertical-Axis Wind Turbines [1]. A further classification distinguishes wind turbines that operate by means of drag force from those driven by lift force [1].

The TWT is a Vertical-Axis drag-driven Wind Turbine. Compared to other drag-driven designs, a reduction of air resistance is achieved for blades moving upwind. This is accomplished by folding the blade to create a more aerodynamic body, reducing the drag and increasing the overall performance of the turbine. Fig. 1 shows the folded and unfolded configurations of the blade and Fig. 2 highlights their deployment as a function of the angular position of the blade. This innovative design is analyzed in this document by means of preliminary CFD simulations.

The study was initiated by evaluating the minimum mesh resolution required to perform accurate simulations and to assess the feasibility of analyzing only half the geometry, taking advantage of the symmetry of the blade. Then, CFD simulations were performed for a single blade both in static and rotating conditions. Specifically, by fixing the blade at several angular positions, it is possible to have a rough idea of self-start capabilities. At the same time, simulations of the rotating blade offered the possibility to generate power and torque coefficient curves.

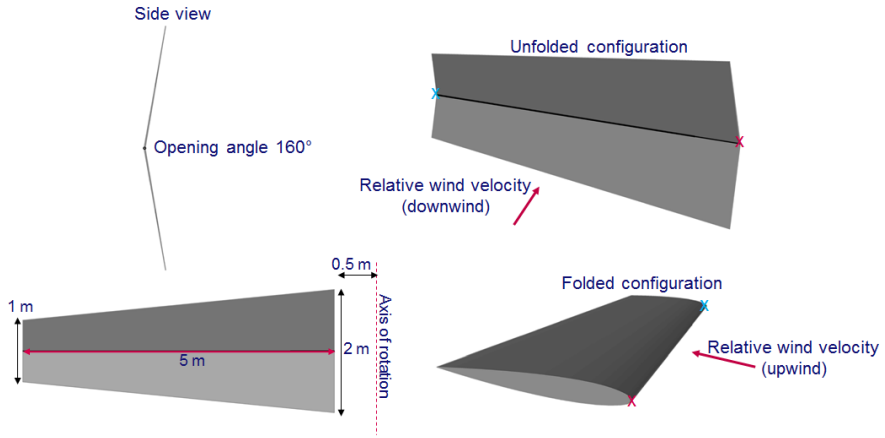


Fig. 1: Drawing of the blade of the TWT. The figure shows both the folded and the unfolded configurations

2. Numerical setup

The CFD simulations reported in this document were performed using Ansys Fluent 15.0 following best-practice guidelines [2]. Steady-state and unsteady Reynolds-Averaged Navier-Stokes (RANS) calculations were employed to analyze the static and rotating blades, respectively. The $k-\omega$ SST model was adopted for turbulence modelling in combination with low-Reynolds number modelling [3]. In previous studies this model was found to perform very well for the simulation of drag-driven turbines [4-6].

An incompressible solver was used given that the velocity typical of this study allows the neglect of compressibility effects. The partial differential equations were discretized using second order discretization schemes along with the SIMPLE algorithm to couple pressure and velocity. Calculations were run until all scaled residuals had dropped below 10^{-6} . In addition, the drag coefficient was required to be constant to within 0.01%.

In this study all calculations were performed for the blade in the unfolded configuration. Consequently, the results offered in this document are related only to the angular positions in which the blade is effectively unfolded (i.e. between 30° and 150°).

The following definitions are used in this study (notations at the end of this document):

$$C_p = M \omega / P_{ref} \quad (1)$$

$$P_{ref} = 0.5 \rho V_w^3 S \quad (2)$$

$$\lambda = \omega R / V_w \quad (3)$$

$$C_m = 0.5 \rho V_w^2 S L \quad (4)$$

3. Preliminary study

The preliminary investigation consisted of two steps: a grid convergence analysis and a feasibility study on the use of a symmetry boundary condition. These steps are explained in the following sections.

3.1 The physical setup

In order to carry out the preliminary investigation, CFD simulations of the blade, fixed at an angular position of 90° on the rotor disk (see Fig. 2), were performed. The drag coefficient has been monitored as the main indicator of mesh convergence, comparing the values obtained with different grids. The wind speed was set to 10 m/s.

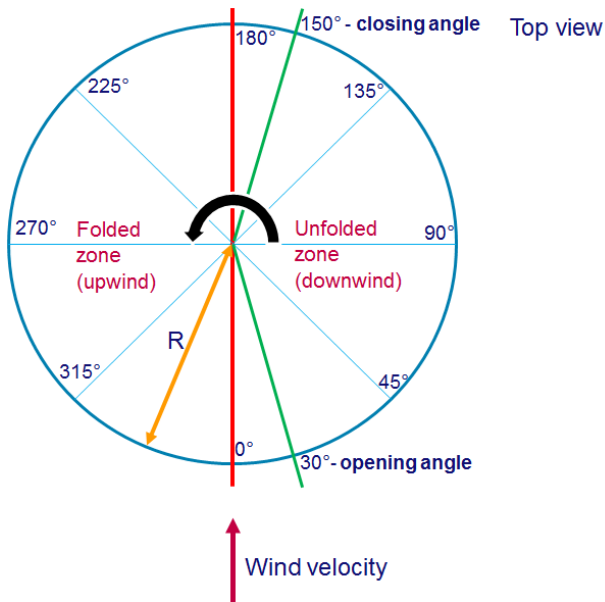


Fig. 2: Rotor disk for the TWT (top view). From 30° to 150° the blade is unfolded

3.2 Grids and boundary conditions

In this preliminary investigation four different grids have been employed. An example is shown in Fig. 3. The meshes were generated using Gambit 2.4.6. The cell stretching ratio was limited to a maximum of 1.3. The boundaries of the domain must be located far enough from the blade in order not to affect the CFD results [4-8].

Defining L as the blade length, for this analysis, a middle way was adopted: the inlet face is taken at $8L$ from the blade, the outlet at $15L$ and the top of the domain at $4L$. In Fig. 3 a detail of the mesh on the blade is shown as well as the boundary conditions adopted.

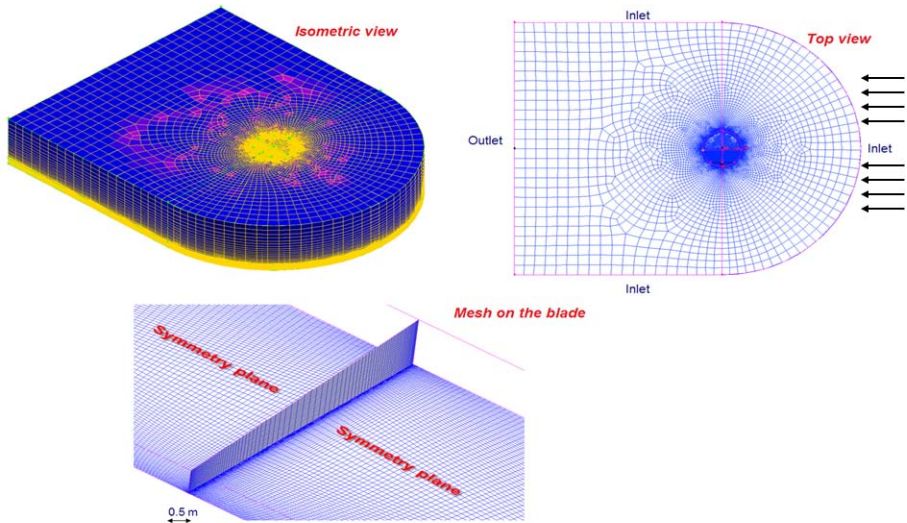


Fig. 3: Mesh used for the grid convergence analysis

3.3 Grid convergence analysis

The grid convergence study is useful to evaluate the minimum mesh resolution needed to obtain accurate results. This analysis consists in testing several mesh resolutions and in monitoring the changes of a physical property as a function of the mesh refinement grade. For the TWT, only half the blade was analysed, taking advantage of the symmetry of the geometry (feasible as shown in the next section). Table 1 shows the drag coefficient acting on the blade, calculated on 4 different meshes.

Table 1: Results from the grid convergence analysis. C_D is the drag coefficient

Mesh	Number of cells	First cell height [m]	C_D
Coarsest	680,000	0.05	1.41
Coarse	1,050,000	0.01	1.32
Medium	2,500,000	0.001	1.28
Fine	9,500,000	0.0005	1.30

For “Coarse”, “Medium” and “Fine Mesh” the mutual differences between the computed drag coefficients are within a range of the 3.1%. Therefore, the “Coarse” refinement level seems to be acceptable and was used for all successive simulations.

3.4 Feasibility study on the use of a symmetry condition

The TWT blade has a horizontal symmetry plane as shown in Fig. 3. To reduce the computational efforts, it might be feasible to simulate half the geometry. However, this assumption also requires the symmetry of the flow field, which can be verified with CFD simulations. Therefore, CFD analyses were performed to evaluate the drag coefficient for half and full geometries. The results of this analysis are displayed in Table 2, showing that there is no significant difference in simulating half the blade or the whole one.

Table 2: Results of feasibility study on the use of a symmetry condition

Simulation	Mesh	Number of cells	C_D
Steady, half geometry	Coarse	1,050,000	1.32
Unsteady, full geometry	Coarse	2,100,000	1.31

3.5 Conclusion of the preliminary study

1. Adopting a symmetry condition is allowed;
2. A mesh counting about 1 million cells is able to produce accurate results.

Thus, for all the successive simulations, the symmetry condition is employed with a mesh that counts roughly 1 million cells.

4. Results

Two studies have been performed: an analysis of the drag coefficient for the blade in a fixed position and a study of the rotating blade for the generation of torque and power curves.

4.1 CFD analysis of the static blade

Several CFD simulations have been performed to analyze the drag coefficient of the blade fixed at several angular positions.

4.1.1 Physical setup

The following angular positions were analyzed: 50°, 60°, 90°, 120° and 130° (Fig. 4). Two different wind speeds were considered: 5 and 10 m/s.

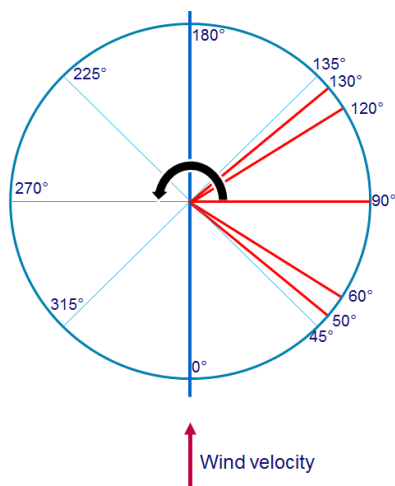


Fig. 4: Rotor disk for the TWT. The red lines identify the angular positions analyzed.

4.1.2 Results

Table 3 shows the drag coefficient of the blade in a static condition, at several angular positions.

Table 3: Drag coefficient for the blade in a static position

Angular position	C_D , wind speed 5 m/s	C_D , wind speed 10 m/s
50°	1.30	1.31
60°	1.12	1.12
90°	1.32	1.31
120°	1.13	1.12
130°	1.31	1.32

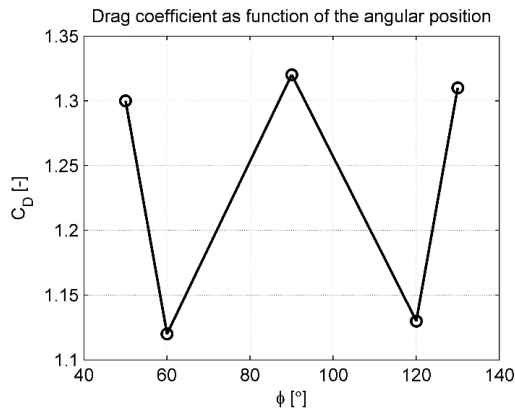


Fig. 5: Drag coefficient expressed as function of the angular position for two different wind speeds: 5 m/s and 10 m/s. ϕ defines the angular position on the rotor disk (see Figure 4)

The drag coefficient does not depend significantly on the wind speed. The values for 45° and 135° and those for 60° and 120° are quite similar.

4.2 CFD simulations of the rotating blade

Several power and torque curves were generated by performing unsteady CFD simulations of the rotating blade using the moving mesh technique.

4.2.1 Physical setup

Several wind speeds were analyzed, ranging from 2 m/s to 10 m/s. The power coefficient has been expressed as a function of the tip speed ratio.

4.2.2 Power coefficient curves

Several power coefficient curves were generated by imposing different wind speeds. These curves are shown in Fig.6. They express the power coefficient as a function of the tip speed ratio.

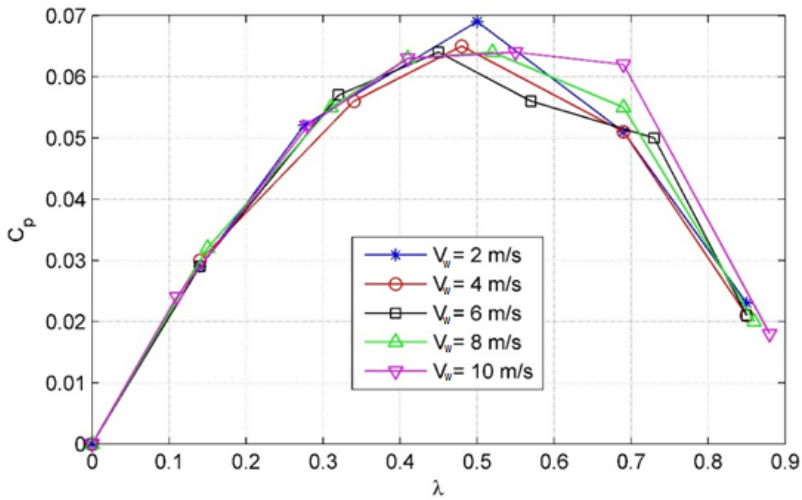


Fig. 6: Power coefficient as a function of tip speed ratio for one blade of the TWT

The maximum power coefficient is around 0.065 for all the wind speeds except at a wind speed of 2 m/s. In this case, the maximum power coefficient is around 0.07.

4.2.3 Torque coefficient curves

Several torque coefficient curves were generated as a function of the angular position (Fig. 7-11). Each curve is obtained by fixing the wind speed and the tip speed ratio and shows a maximum value at an angular position below 90°.

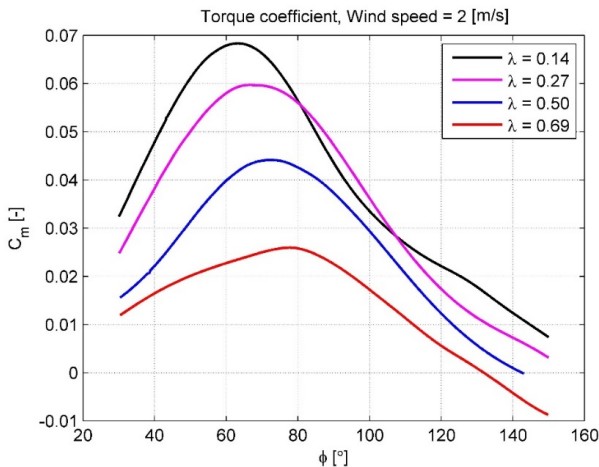


Fig. 7: Torque coefficient as function of the angular position at a wind speed of 2 m/s

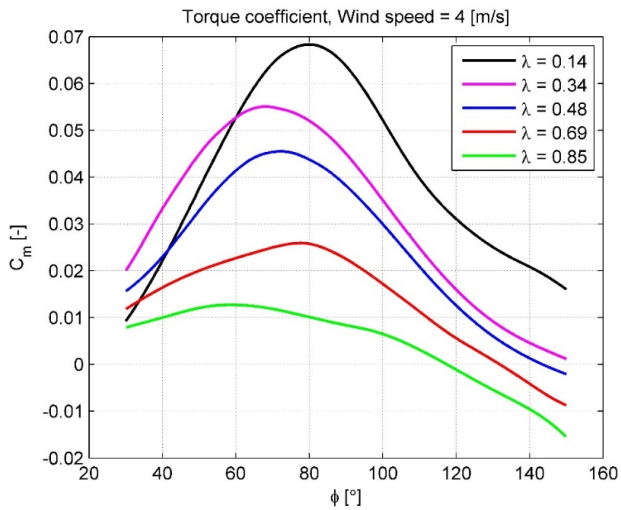


Fig. 8: Torque coefficient as function of the angular position at a wind speed of 4 m/s

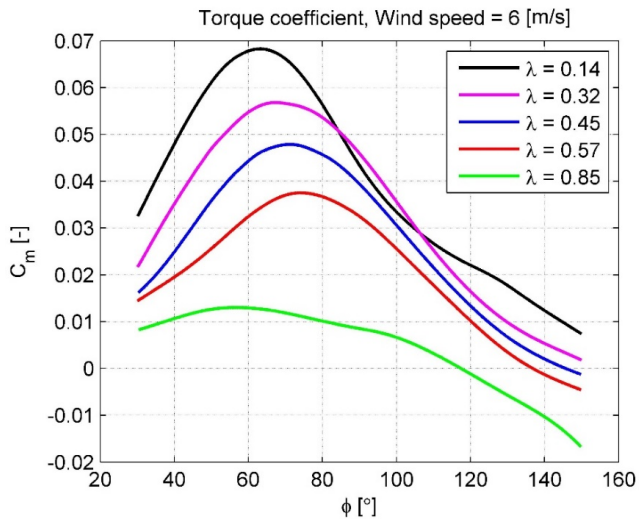


Fig. 9: Torque coefficient as function of the angular position at a wind speed of 6 m/s

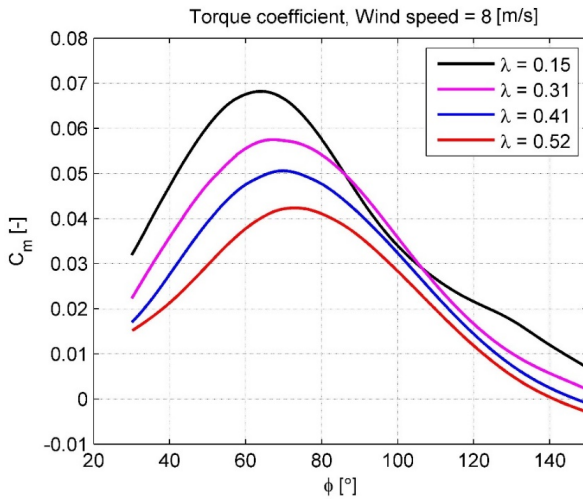


Fig. 10: Torque coefficient as function of the angular position at a wind speed of 8 m/s

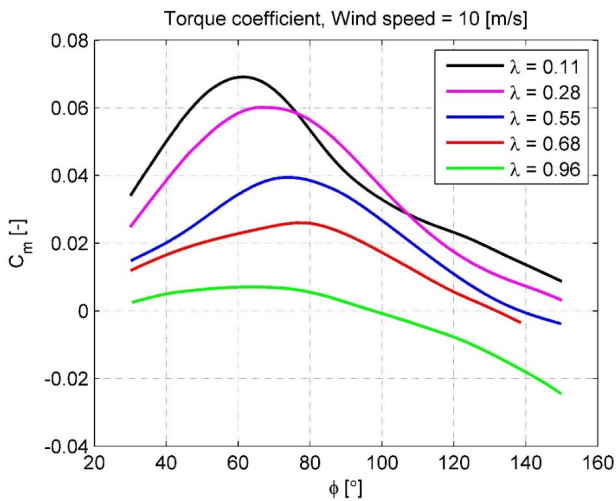


Fig. 11: Torque coefficient as function of the angular position at a wind speed of 10 m/s

5. Conclusions

The CFD study carried out on the TWT leads to the following conclusions:

1. the TWT works at low tip speed ratios: the maximum power coefficient for a single blade occurs at a tip speed ratio of about 0.5;
2. the exact tip speed ratio at which the maximum power coefficient occurs ranges between 0.45 and 0.55 depending on the wind speed;
3. at all analyzed wind speeds, a single blade of the TWT offers a maximum power coefficient around 0.065;

4. if the aerodynamic interference between the blades is negligible, the power coefficient of the full TWT can be obtained by multiplying that of a single blade by the number of blades. However, simulations should be performed to evaluate the aerodynamic interference;
5. the torque coefficient curves show a maximum value at angular positions below 90° ;
6. judging from the torque coefficient curves at the TWT opening angle its performance might possibly be increased by decreasing the opening angle, which is now set to 30° ;

Moreover, the TWT is at its first design stage, thus, an aerodynamic optimization study should be carried out to evaluate the optimal geometry and opening angle.

Notation

C_D	Drag coefficient
ρ	Air density
V_w	Wind speed
C_p	Power coefficient
M	Torque acting on the turbine
ω	Turbine rotational speed
P_{ref}	Reference power (wind power)
S	Frontal area of the turbine
λ	Tip speed ratio
R	Radius of the turbine
C_m	Torque coefficient
L	Reference length, set to 1 m
ϕ	Angular position

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INVESTIGATION OF WIND CHARACTERISTICS AT URBAN SCALE THROUGH SCALED MODEL WIND TUNNEL TESTS

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Abstract: This paper presents the possibilities that can be exploited performing wind tunnel testing for wind assessment in urban areas. The availability of experimental data measured in laboratory environment provides valuable material for data analysis and for numerical code validation. Often measurement techniques perturb the flow characteristics, therefore a wide range of flow speed measurement techniques are presented in order to have an overview of the data that can be extracted during wind tunnel testing.

1. Introduction

Next generation cities will have a sharp look at energy management. The possible solution for smart energy management is to exploit technologies that enhance green energy production, strategies for energy saving or connect different application fields that may be integrated (i.e. use waste incinerator for thermal energy as hot water or house heating). Wind energy is increasing its interest in many fields, since it has many applications on different application and on several scales. Wind energy can be intended as large scale energy production, where the typical solution is big plants with large wind turbines, typically horizontal axis wind turbines (HAWT): this installation is very challenging since an extraordinary technology is necessary to guarantee the energy harvesting and the survival of the machine in all wind conditions. Moreover large plant are suitable not only for onshore but also for offshore installation: here the issues are even more difficult, since the marine environment presents additional difficulty. HAWT exist also at smaller scale (100 kW), but they are not really present for widespread applications. Small scale HAWT (up to 1 kW) are present for small applications e.g. remote installations, sailing boat applications, rural areas. An alternative to the advanced HAWT are vertical axis wind turbines (VAWT) that use a much simpler technology and require very little maintenance compared to HAWT. Vertical axis turbines can be furtherly divided in Darrieus type wind turbines and Savonius turbines. Darrieus VAWT present quite high power extraction features, but one of the most critical points is the inability to start the rotation of the turbine. The need to provide energy to

start the turbine rotation is one of the most critical points since it requires to design a system that has a strong feedback on the wind condition. Savonius turbines on the other hand has good self-starting capabilities, requires negligible maintenance but on the other hand the very simple concept allows very poor energy harvesting features.

Flow characteristics play an important role on the energy harvesting capabilities of each wind turbine typology. Wind incoming direction, mean wind speed and its turbulence characteristics highly influence the energy that may be extracted from incoming flow. It is important therefore to define in the correct way the wind resource in the area where the installation of a wind turbine is taken into account. Several methods can be used for the wind assessment of the area. A wide literature can be found for site assessment in open spaces with negligible interference of human constructions on the wind. A more limited amount of studies has been performed on wind characterization at urban scale for wind energy harvesting purposes.

In general wind characterization in urban areas is generally studied for wind comfort, pollutant dispersion and urban heat island issues.

Urban area installation of wind turbine may lead to the installation of many turbines closely spaced, therefore the interaction between several rotors may be important for assessing the power extraction feature of distributed plants.

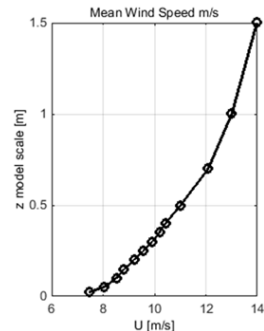
2. Wind Tunnel tests in urban environment

The Boundary Layer Wind Tunnel of Politecnico di Milano with its large test section size allows testing large models. The test section is 14m wide and 4m high and is equipped with a 13m diameter turntable, allowing to install large models with a small scaling. Typically urban models in Polimi Wind Tunnel are realized reproducing scaling ratios between 1:20 to 1:100: this allows to reproduce with a reasonable detail the characteristics of the urban models and therefore with more accuracy the urban flow.

This facility allows to test neutral flow conditions, since it is not possible to take into account stability in the reproduction of the Atmospheric Boundary Layer (ABL).



a) Polimi wind tunnel with spires and floor roughness



b) Vertical wind profile

Fig. 1: ABL profile in Polimi Wind Tunnel

Several research has been carried out analysing ABL flows in the wind tunnel: the reproduction of the ABL is performed using passive devices as spires and roughness elements [1] as can be seen in Fig.1. Using different combinations of spires at the beginning of the test section and roughness elements on the floor it is possible to change the flow characteristics, such as mean flow vertical profile, turbulence intensity vertical profile and turbulence length scale profile,

depending on the characteristics of the terrain that surrounds the area of interest. It is important to note that the roughness plays an important role on the flow field that arrives on the structure to be studied, since the lower part of the profile is driven by the roughness and positioning the roughness elements too far away from the model changes the lower part of the incoming wind. The total length of the BL test section is about 20m before the turntable. Despite the low length to height ratio it is possible to obtain vertical mean wind profiles that comply with Eurocode standard [2] requirements.

2.1 Wind tunnel measurements of air speed

The measurement of wind in complex environment presents several issues in wind tunnel tests. If full description of the wind speed is required in experimental tests, it is necessary to measure the wind speed in each single point: this requires the use of an airspeed sensor to be positioned in the chosen position and the acquisition of data for a suitable sampling time. Moreover the sensor itself should not perturb the flow, but this is often difficult, since most probes have a large influence on the measured flow. When performing wind assessment it is important to define the magnitude and the direction of the flow; wind statistics are also important, therefore high frequency response sensors are needed. Possible sensors are hot wire anemometers and cobra probes. If many positions must be sampled it is important to have an automatic probe positioning system. Cobra probes have been used extensively in wind tunnel tests at Politecnico di Milano: in Fig. 2 it is possible to see the size and the positioning system of the cobra probes around a corner of Amore Pacific building. Of course wind assessment requires the analysis of the flow in the same position for a wind incidence angle that covers all possible wind directions: this implies that the air speed sensor must be placed correctly for all wind directions.

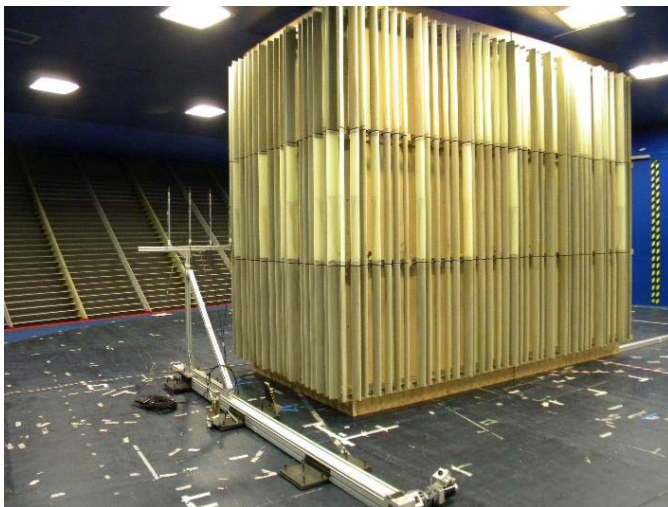


Fig. 2: Wind measurement using cobra probes around a 1:4 building corner

Other possibilities for wind assessment close to solid surfaces is the installation of omnidirectional Irwin probes [3]. This instrumentation has been used for assessing wind comfort and wind speed up on the Bosco Verticale building [4] shown in Fig. 3 and Fig. 4. These wind speed sensors allow to measure the wind speed (not the direction) measuring the pressure on the top

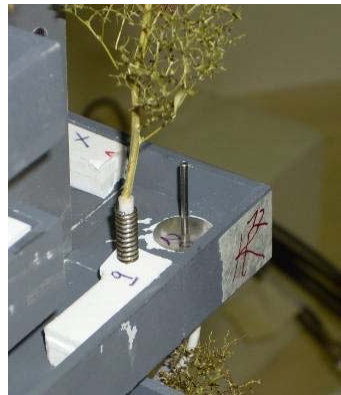
and on the bottom of the probe. This sensor is very easy to install, has low influence on the incoming flow but has no fast response and is limited to almost planar flows.



Fig. 3: Bosco Verticale buildings placed in the wind tunnel around the surrounding



a) Bosco Verticale building scaled model



b) Irwin probe installation

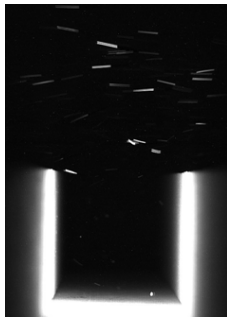
Fig. 4: Bosco Verticale building model and installation of Irwin probe on balcony

Additional methods for the evaluation of air speed in urban environment are related to the visualization of the flow. Possible solution is the smoke visualization reported in Fig. 5, where it is possible to have a qualitative overview of the flow around an object, while using particles tracing it is possible to have also a quantitative overview. In figure is reported the flow around an urban canyon: the wind is blowing perpendicular to an array of building blocks separated by streets. The interest in the visualization is the characteristics of the flow between the two blocks, to provide data for the Urban Heat Island phenomenon assessment.

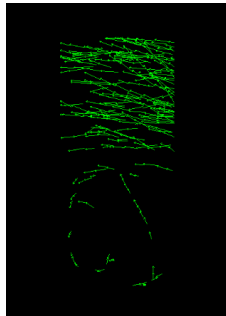


Fig. 5: Smoke visualization over an array of blocks to simulate an urban canyon.

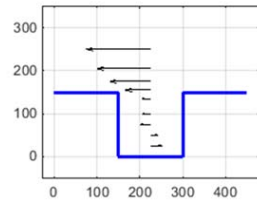
Smoke visualization technique allows to visualize the three-dimensional flow structures, in order to achieve the detail of the flow that is developing around a structure. It is very useful to get the overview of the flow and explain phenomena that may not be explained without having an insight in the flow; the lack of information on the air speed makes useless smoke visualization for wind resource assessment.



a) Frame of the flow in-
seminated with helium bub-
bles



b) Digital reconstruction
of particle tracing



c) Reconstruction of the vertical
wind profile in the urban canyon

Fig. 6: Analysis of the flow in the urban canyon using helium bubbles PIV technique

The same analysis on the urban canyon has been conducted using helium bubbles PIV technique as shown in Fig. 6, where it is possible to see the tracer particles on the last canyon of the row. PIV relies on the reconstruction of the flow pattern and velocity fields using video recording of the helium bubbles illuminated by a light source. In this case the light source is planar: it is fundamental that the flow is planar using this approach since the method is not able to recognize the flow in the third dimension. This method uses the helium gas since it is important that the particles have very small inertial features compared to the main flow characteristics; it is very complex also to set up this kind of measurement for complex scenarios. On the other hand the results are very important, since the only perturbation of the flow field is done by the bubble machine and the bubbles themselves.



Fig. 7: Flow visualization in urban area with sewing threads.

Another qualitative way for the visualization of flow characteristics is represented by sewing threads as shown in Fig. 7. This method allows to see the direction of the flow since the threads are aligned with the local wind direction, but no information is given on the wind magnitude or on the local turbulence. From image processing it may be possible to have information on the turbulence related to the local direction change in the threads, but the air speed cannot be obtained.

2.2 Wind tunnel measurements for the validation of numerical tools

Wind tunnel testing of complex environments offers also a different perspective to wind engineers: wind tunnel data can on the other side be used to validate numerical tools. Experimental wind tunnel approach is not able to give the information at the same time in all locations within an urban area. This limitation can be used to validate numerical codes against experimental data available in limited but valuable locations. In this case experimental test are devoted to the definition of reference data for the validation of numerical codes.

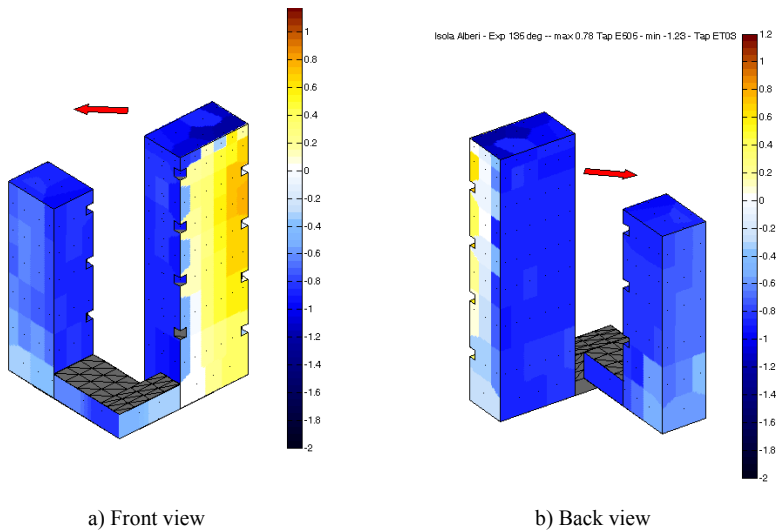


Fig. 8: Mean pressure coefficient distribution on Bosco Verticale building

The validation can be performed not only by comparing wind speed, turbulence quantities, but also other fluid dynamic quantities such as wind loads and pressure distribution on buildings (as can be seen in Fig. 8): the measurement of pressure distribution is moreover a non-invasive measurement, since it does not perturb the flow field. Moreover it is common to use pressure scanners able to perform pressure measurements on many pressure taps, therefore it is a convenient method to achieve many measurements on the scenario. Pressure measurements are typically performed installing the instrumentation inside the models, and it creates no disturbance the rotation of the scenario or the surrounding.

3. Wind Tunnel testing opportunities

The Boundary Layer Wind Tunnel testing is very useful for wind resource assessment in urban area when related to the study of a single configuration, especially if used to validate the outcome of a numerical code. The application of wind tunnel study for a specific site is very useful for the verification of the planned installations and therefore to guarantee a fruitful exploitation of the wind resource in the specific case.

On the other hand wind tunnel tests may be planned for the definition of urban arrangements that may enhance the wind energy exploitation: the definition of a typical urban scenario and the measurement of data useful for numerical code validation may be useful for the development of future smart neighbourhoods and guidelines for district construction. Closely spaced buildings arranged properly may enhance the flow speed-up in certain zones that may be suitable for HAWT or VAWT.

Concerning the tests on scaled models of wind turbines, wind tunnels are not fully reliable for the definition of aerodynamic performances: HAWT and VAWT are very sensible to Reynolds number effects on the power production, since their aerodynamic features may be significantly sensible with respect to their scale or the operating speed. In general it is very difficult to test small scale turbines, since the measurable quantities are negligible and can be easily of the same order of magnitude of measurement uncertainties or affected by large errors due to internal friction.

Despite these cons wind tunnel testing of wind turbines is very useful to gather experimental data in controlled environment for the validation of numerical codes: a numerical code able to reproduce the scaled model wind turbine features will be reasonably able to calculate the real scale wind turbine behaviour. This assumption is valid for HAWT, where the Reynolds effect largely affects the performance of the scaled model with respect to the real model: here the scale is often very large due to the big size of HAWTs. On VAWT the scale is generally lower, it is not so common to find large sizes turbines, and their operation itself is often affected by Reynolds number effects.

As a conclusion it is possible to say that for wind resource assessment and wind energy exploitation during wind tunnel tests it is necessary to perform different analysis: wind tunnel analysis of wind resource and wind tunnel test of wind turbine performance.

4. Conclusions

In this paper several features of wind tunnel testing activities have been presented to support wind resource assessment in urban areas. Several measurement techniques are presented in order to support wind resource assessment in urban areas.

Probes for the definition of punctual information on local flow characteristics (such as hot wires and cobra probes) give a more precise information on selected points, but if the characterization of a large area is required the experimental campaign becomes expensive and time demanding.

Probes that give only information on air speed (like Irwin probes) give less information on the flow, but their simplicity allows for multiple installation and a more detailed description of the flow field, nevertheless the information on the direction of the flow is not provided.

Sewing threads on the other hand provide information on flow direction but are not able to estimate wind speed, but can give a good overview of the flow direction.

Flow visualization with tracers such as smoke allow to see the flow structures to understand phenomena that happen in the flow field, but are not able to give any quantitative information on the flow field. Flow visualization with tracer on a plane (such as helium bubbles) allow to have also a quantitative analysis of the flow, describing the wind speed and direction.

Wind tunnel may be used also for the validation of numerical codes, using as benchmark wind speed data on some points, but also using pressure distributions on structures for the assessment of the numerical tools performances. The validation of numerical tools may be extended also to the analysis of the performance of wind turbines: scaled models of wind turbines may not behave as full scale turbines, but numerical codes are able to reproduce the features of both scaled and real machines and can be therefore validated against laboratory wind tunnel data.

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INFLOW UNCERTAINTY QUANTIFICATION WITHIN URBAN ENVIRONMENTS: WIND FIELDS AND DISPERSION PATTERNS

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Abstract: Nowadays the high urban expansion rate is leading to an increased interest in the development of sustainable cities and the exploration of potential sources of urban renewable energy. Therefore, there is a demand for improved computational wind engineering tools to predict flow patterns within urban canopies. Since the flow patterns are strongly influenced by the large natural variability that is characteristic for wind engineering applications, it is important to quantify the resulting uncertainty in the predictions when using computational results to inform design decisions. In the present paper we summarize the application of an uncertainty quantification framework to the prediction of flow and dispersion in an urban canopy.

1. Introduction

The significant interest in the development of sustainable urban areas and renewable energy is driving engineers to develop improved computational methods to predict wind patterns in urban environments. The use of Reynolds-averaged Navier-Stokes (RANS) simulations is of particular interest from an engineering and industrial point of view because of their acceptable cost in terms of time and computer resources [1]. It is however important to acknowledge that a number of uncertainties can affect RANS predictions of wind patterns in the Atmospheric Boundary Layer (ABL). These uncertainties arise both because of a lack of knowledge (epistemic uncertainties) and because of the intrinsic variability of the atmospheric system (aleatory/stochastic uncertainty) [2]. Consequently, if an improvement of the computational accuracy is to be achieved, an adequate assessment of these uncertainties should be performed.

The approach presented here focusses on quantifying the inflow uncertainty, which is an irreducible stochastic uncertainty related to the inherently variable nature of ABL flows that results from the continuous changes in the atmosphere. The first section of this paper will present the uncertainty quantification approach used to define a confidence interval on the prediction of the wind field. The second part of this paper will focus on the use of the same approach to quantify the uncertainty in the prediction of dispersion patterns.

2. Uncertainty Quantification

Uncertainty quantification is generally focused on two main objectives:

1. The construction of a framework to estimate the error bars associated to given predictions.
2. The evaluation of the likelihood of a certain outcome.

When considering a stochastic uncertainty this process consists of defining probability density functions (PDF) of the uncertain parameters and propagating these through the system to obtain statistic quantities, such as the variance and expectation, of the outcome quantity of interest.

The UQ framework presented here uses a non-intrusive polynomial chaos expansion (PCE) method to propagate the inflow uncertainties.. In the studies presented here a tensor grid Clenshaw-Curtis stochastic collocation approach was used to compute the chaos expansion coefficients from 729 simulations. The non-intrusive code, RAY, developed at Stanford UQ lab was used to define the collocation points, queue the simulations and post-process the results in a parallel Linux environment [3-4].

There is a significant number of uncertainties present in simulations of the ABL. The work presented here focuses on the aleatory uncertainty related to the inflow conditions used in CFD simulations. The inflow uncertainty is expected to be of primary relevance because the inflow conditions determine flow and dispersion patterns within the urban canopy. For example, a small change in the inflow direction can have a large effect on the dispersion of a pollutant plume within a city, or the wind magnitude will strongly influence the predicted energy production of a wind farm.

3. Experiments: Joint Urban 2003

The validation of computational tools with experimental data is essential to evaluate the predictive capabilities. Both wind tunnel and field experiments can be performed to measure or reproduce flow phenomena in the atmospheric boundary layer. Laboratory measurements are characterized by a controlled environment, which can relatively easily be modeled in CFD. Field experiments are more challenging to reproduce because the flow conditions can not be controlled and usually only a limited number of measurement points is available to extract the boundary conditions required in the CFD simulations. In addition, it is impossible to represent the level of detail present in reality in any computational model. The number of full-scale experimental campaigns within urban environments is also scarce [5-8] due to the high cost and the complexity of the problem. However, considering the scope of this research, and the focus on quantifying the stochastic uncertainty related to inflow conditions in CFD simulations, validation with field experiments is essential, and the Joint Urban 2003 (JU2003) measurement campaign was selected as the test case for this study.

The JU2003 campaign was carried out in Oklahoma City during the full month of July, 2003. During that time, 10 Intensive Observation Periods (IOP) were carried out, where puff/continuous releases of SF₆ tracer took place. These periods covered different times of day and, therefore, diverse atmospheric stratification conditions. In this study we consider a 25 minute time

period to be reproduced by the UQ simulations, selected based on the amount and quality of data.

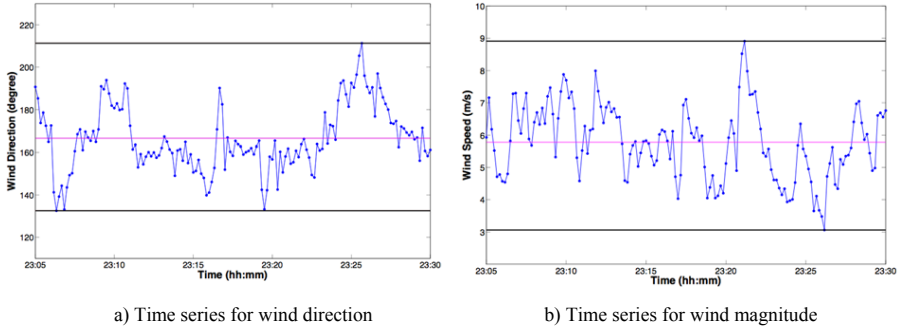


Fig. 1: Time series for the period of 23:05-23:00 of the 26th of July 2003 [5;9].

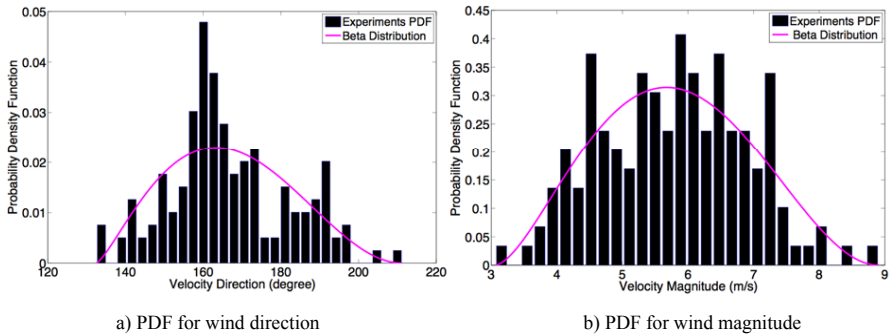


Fig. 2: PDFs for the period of 23:05-23:00 of the 26th of July 2003 [5;9].

The measurement stations used to compare the CFD results are the Portable Wind Display System (PWIDS and SuperWIDS). PWIDS stations are wind monitors which provide velocity magnitude and direction information sampling each second and averaged each 10 seconds; superWIDS stations are sonic anemometers capable of measuring three velocity components at a sampling frequency of 10Hz [10].

4. Uncertainty Quantification applied to wind fields

4.1 Uncertain Parameters

In order to improve the predictive capabilities of Computational Fluid Dynamics simulations (CFD) of the ABL, the intrinsic atmospheric variability should be represented in the computational framework. The approach presented here includes this variability in the inflow boundary conditions, and uses the field measurement data to define the ranges for the inflow variables. The simulations focus on the period of 23:05 to 23:30 during the night of the 26th of July. This

period was selected because the stability of the atmosphere was quasi neutral, and because it is close to one of the main releases of interest, IOP9.

Three uncertain variables are selected for the study: the velocity magnitude and direction, and the roughness length. The wind flow ranges are defined based on the measurements obtained at PWIDS 15, because the main wind flow direction during the campaign was south and PWIDS 15 is the southmost station. The roughness length ranges are based on the document published by Wieringa et al. [11]. The collocation points (729 simulations) that cover the resulting ranges for the UQ variables are shown in Fig.3.

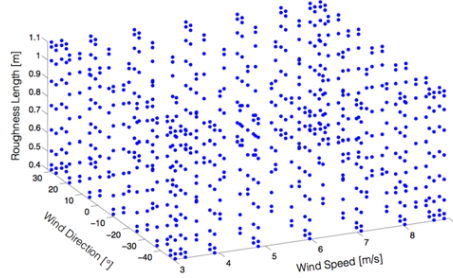


Fig. 3: Tensor grid Clenshaw-Curtis Stochastic Collocation points.

4.2 Governing equations and discretization schemes

The governing equations for neutral conditions are given by the steady, incompressible Reynolds-averaged Navier-Stokes equations:

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0 \quad (1)$$

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial \bar{u}_i' u_j'}{\partial x_j} \quad (2)$$

where \bar{u}_i are the time-averaged velocity components, ρ is the density, \bar{p} the pressure, ν the kinematic viscosity and $\bar{u}_i' u_j'$ the Reynolds stress tensor. The RANS equations need to be closed by a model for the Reynolds stress tensor. In the present simulations the standard k - ϵ turbulence model is used, which computes the Reynolds stresses based on the linear eddy viscosity hypothesis:

$$\overline{u_i' u_j'} = \frac{2}{3} k \delta_{ij} - 2 \nu_t S_{ij} \quad \rightarrow \quad \nu_t = C_\mu \frac{k^2}{\epsilon} \quad (3)$$

where k is the turbulence kinetic energy, δ_{ij} the Kronecker delta, S_{ij} the time-averaged shear stress tensor and ν_t the turbulent viscosity. C_μ is constant equal to 0.09, and the turbulence

kinetic energy k and turbulence dissipation rate ε obtained from solving their respective

$$u_i \frac{\partial k}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \varepsilon \quad (4)$$

$$u_i \frac{\partial \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \quad (5)$$

transport equations:

with P_k the turbulent production term and σ_k , σ_ε , $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ model constants, respectively equal to 1.0, 1.3, 1.44 and 1.92. The inflow boundary conditions specify a fully-developed neutral atmospheric boundary layer, using the classical Richards and Hoxey [12] profiles for velocity, turbulence kinetic energy and dissipation. The continuous equations are discretized using second order upwind schemes.

The pressure-velocity coupling is done with the SIMPLE algorithm, and the simulations were converged to residuals below 10^{-7} for velocity and turbulence kinetic energy, and below 5^{-6} for mass conservation and the turbulent dissipation.

4.3 Domain configuration and mesh generation

The domain is a rectangular box with length 2.4km and 2km, and 1km height. It contains the buildings in downtown Oklahoma City and its surroundings, as shown in fig. 4. The proposed domain satisfies the best practice guidelines introduced by COST 732 [13].

The mesh resolution is finest in the downtown area and close to the ground boundaries, and then the resolution is reduced gradually. In downtown, the maximum resolution under 10m is 2m in horizontal and 0.5m in vertical direction. The final mesh has approximately 5.5 million cells. Regarding the wall condition a modified wall function using the ABL roughness length is applied at the ground [14-15], while standard wall functions are used on the buildings. Further details of the set up of the simulations can be found in García-Sánchez et al. [9].

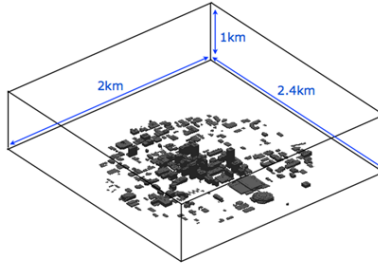


Fig. 4: Domain configuration.

4.4 Results for wind field predictions

As discussed in section 4.1, 729 RANS simulations were performed to cover the space defined by the three uncertain variables. Based on these results, PCE response surfaces can be reconstructed for the different quantities of interest. Subsequently the probability density functions that would be obtained for the quantities of interest given the beta distributions presented in fig. 2 were computed by drawing 10.000 samples from the PCE representation, according to these

distributions. Finally, the mean and confidence levels were determined from the probability density functions of the samples.

The results obtained for the UQ approach are presented in fig. 5, where the blue arrow represents the mean from the 10.000 samples drawn from the PCE according to the beta distributions in fig. 2, while the black arrow corresponds to the averaged velocity over the 25 minutes period for the different PWIDS stations. The arcs represent the 95% confidence interval for both the measured and the predicted velocities, being the angle the direction ranges, while the radius represents the velocity magnitude.

The plot demonstrates that the mean velocity magnitude from the experiment falls within the range predicted by the UQ study in all stations, while for the wind direction this is the case in 11 out of the 13 stations. Further analysis of the influence of the different uncertain variables on the results was performed, revealing that the wind direction and magnitude are the most important variables. Variations in their values can significantly modify the flow pattern within the city. On the other hand, the roughness length has a smaller impact on the results. We also note that a direct comparison between the 95% confidence intervals from the experiment and the CFD is not possible due to the fact that the RANS CFD simulations solve for the mean velocity, while the measurements ranges represent the instantaneous turbulent velocities.

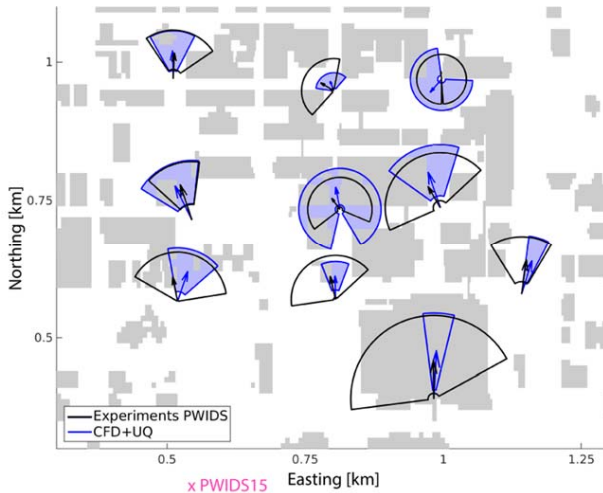


Fig. 5: Comparison of the measurements on July 26th from 23:05-23:30 with the uncertainty quantification study results [9].

5. Uncertainty Quantification applied to dispersion

The transport of the pollutants is also significantly influenced by wind flows that are affected by the large scale variability of the atmospheric boundary layer (ABL), and the UQ framework presented earlier can be used to represent the effect of the variability in the inflow boundary conditions on the prediction of pollutant concentrations. The simulations presented in this section focus on the Intensive Observation Period number 9, where a continuous release of SF₆

took place at Park Avenue. The turbulence model and discretization schemes are identical to those presented above. In the following subsections some small modifications in the domain and the mesh are discussed, the transport equation for the pollutant is presented, and some preliminary results are included.

5.1 Domain configuration and mesh generation

The lateral dimensions of the new computational domain are ~4km (west-east) and ~4.1km (south-north), and the height of the domain is 1.2km. These dimensions are selected based on the best practice guidelines COST 732 [13], and ensure that the computational resources for the UQ study remain acceptable. The mesh is designed with SnappyHexMesh, the parallel

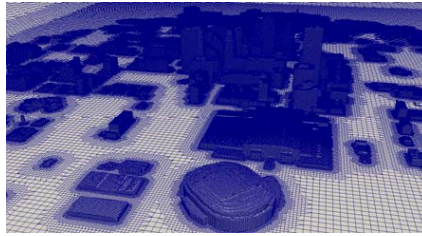


Fig. 6: Mesh design with SnappyHexMesh over Oklahoma City.

automatic mesh generator from OpenFOAM. The mesh is identical for all the simulations, and contains approximately 7.3 million cells, with a maximum resolution close to the wall in the downtown area of ~0.5m in vertical direction (first cell). A close view to the mesh is included in fig. 6. The lateral boundaries define two inlets and two outlets, which are selected depending on the inflow direction leading to different inflow cases. The selection of the flow inlets and outlets, and the definition of the values for the uncertain inflow variables values is done through a fully automated process.

5.1 Dispersion modelling

Dispersion is modeled using an Eulerian approach [16-18], solving the advection-diffusion equation for a passive scalar:

$$\frac{\partial \bar{C}}{\partial t} + \bar{u}_j \frac{\partial \bar{C}}{\partial x_j} + D_C \frac{\partial^2 \bar{C}}{\partial x_j^2} = Q_S \quad (6)$$

Where C is the passive scalar concentration, U is the fluid velocity, D_C the diffusion coefficient and Q_S is the release amount injected for the first continuous releases carried out during IOP9. Turbulent dispersion is using a standard gradient diffusion model, where the turbulent dispersion coefficient is defined as the ratio of turbulent viscosity and the turbulent Schmidt number (0.7).

5.3 Uncertainty Quantification applied to dispersion

The same 3 uncertain variables as in the previous section are considered. The ranges for the velocity magnitude and direction are again selected based on the 25 minute measurement period considered. The resulting ranges are presented in table 1.

A preliminary sensitivity study was carried out, considering 27 simulations. In fig. 7, results from 9 selected representative simulations are included. The first row presents the effects of changes of wind flow direction on the concentration, with the direction increasing from 74.8° on the left to -117.9° on the right, while the magnitude and roughness length are kept constant to 5.95 m/s and 0.25 m, respectively. The second row shows the influence of changing the velocity magnitude, with the velocity varying from 2.95m/s to 8.94m/s, while the angle and roughness are 96.35° and 0.25m. Lastly, the third row includes the changes with roughness length, from 0-0.5m, for the wind direction equal to 96.35° and the velocity magnitude to

Table 1: Uncertainty experimental ranges IOP9.

	U [m/s]	\square [$^\circ$]	z_0 [m]
Min.	2.95	74.8	~ 0.0001
Max.	8.94	117.9	0.5

5.95m/s. The dispersion results are presented on a non-dimensional logarithmic scale, with $K[-]$ is calculated as follows:

$$K = \frac{C}{C_s} \frac{\rho U_{inflow} H^2}{Q_s} \quad (7)$$

where C represents the local concentration, C_s is the source concentration, \square is the density, U_{inflow} is the velocity at the inflow location (PWIDS15 ~ 30 m height), H is the height of the highest building and Q_s is the flow rate injected.

The results are presented on logarithmic scale in Figure 7 to show more clearly how the dispersion pattern is modified by the varying uncertain parameters. It can be stated that the wind flow direction completely modifies the orientation of the pollution footprint depending on the inflow angle condition. The velocity magnitude affects mainly the dispersion length downstream, leading to longer patterns when the speed increases, and keeping pollution within the city when low velocities are imposed at the inflow. Lastly, regarding the roughness length, only slight changes can be observed when the values of z_0 are modified.

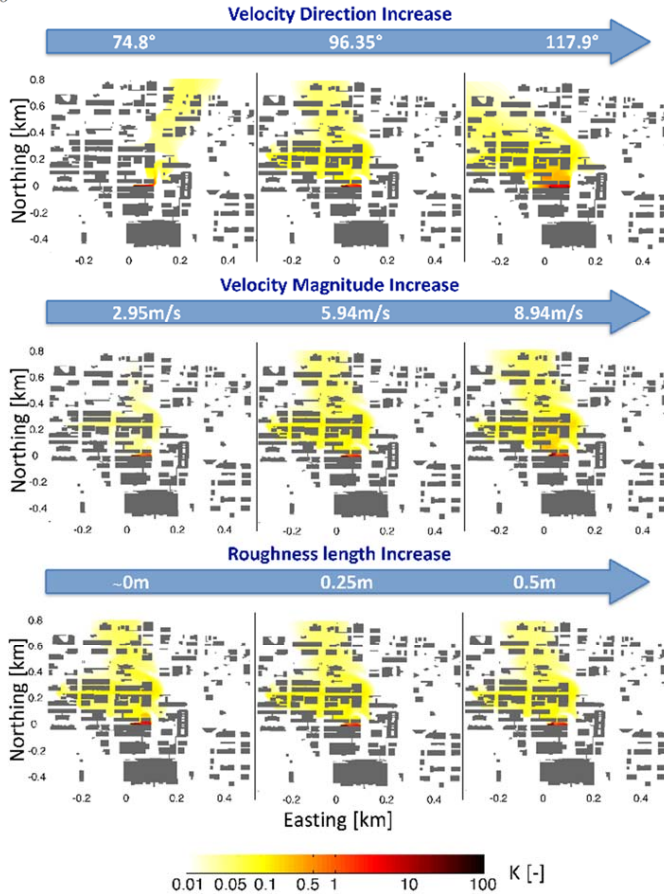


Fig. 7: IOP9 dispersion simulations over Oklahoma City.

6. Conclusions

The current increase in computational capabilities combined with the recent progress in uncertainty quantification methods applied to CFD simulations [19-20] creates an opportunity for developing improved simulation tools that can be applied to ABL simulations for different applications, such as pollutant dispersion or wind resource prediction. In this work, the approach has been applied to provide a prediction for the wind field in an urban environment with quantified confidence intervals that represent the uncertainty because of variability in the inflow conditions. In addition preliminary results for the prediction of pollutant dispersion were obtained. Several conclusions can be drawn based on the results:

1. It was shown that the inflow direction significantly affects both the velocity magnitude and direction in the domain, while the inflow velocity magnitude primarily affects the velocity

magnitudes at the locations of interest. The influence of the aerodynamic roughness was found to be relatively small in comparison to the other variables.

2. The results clearly identify locations in the flow that are particularly sensitive to the inflow conditions. This information is very valuable given the difficulty of defining accurate boundary conditions.
3. The UQ approach has potential applications to a wide range of problems, including pollutant dispersion, wind resource assessment, urban planning or pedestrian wind comfort.

Acknowledgments

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Workshop Part 2

State of the Art of the Wind Energy Structures
and Emerging Applications

FOREWORD TO WG2 PROCEEDINGS:

STATE OF THE ART OF WIND ENERGY TECHNOLOGIES AND UP- COMING APPLICATIONS FOR THE SMART-CITIES OF TOMOR- ROW

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In order to respond to the great challenge of societal needs and HORIZON 2020 (H2020) for the aeolian renewable contribution to the smart-cities, it is very important to scrutinize and systematically reconsider the accumulated expertise in on-shore, off-shore and built environment wind energy technologies. Recant research and development for the different needs and challenges of on-shore and off-shore projects produces a variety of innovations, new technologies and solutions, as it is illustrated in prepared papers collected in this publication. This allows wind energy to constantly increase competitiveness by reducing levelised cost of electricity (LCOE) in order to compete with fossil and nuclear energy mix and so ensuring the effectiveness of H2020 objectives [1]. Some of solution may be just modified for an appropriate scale, from on-shore and off-shore solutions, but majority of solutions will require its own approach for implementation for supporting structures of wind turbines in urban areas.

In urban and suburban sites of the smart-cities the atmospheric flows are found rather unsteady and turbulent, existing turbines are unlikely to be fitted for this unconventional wind source. In particular, a major component is in the large scale of eddies (0.015 Hz range), whose high energy content is well known, together with its harvesting challenges. E.g. variable speed operation of wind turbines is a technology that, through power electronics, allows for high performance in a wide range of wind speeds, while fixed speed operation only allows for maximum power extraction at the rated wind speed. High costs of the electronic components in large wind energy projects limited its application, while the relatively low costs in small size turbines for urban applications potentially favor its realization.

Another example of suitable knowledge transfer accumulated in previous research projects on wind turbine technologies executed at an open landscape is connection between steel and concrete components. This transition is rather complicated but may be used as inspiration for finding the most appropriate solution for anchoring of the steel components in the concrete.

It is therefore of great importance to review and analyze existing wind energy technologies as the base for a holistic design approach to innovative up-coming applications for the smart-cities of tomorrow, as e.g. in [2].

The final objective of WG2 will be provided at the end of TU1304 COST action, a deep insight on pilots, demonstration and good practice scale projects for Built environment Wind Energy projects.

- Onshore towers, basics of structural design
Veljkovic M., Rebelo, C., Pavlovic M. , Heistermann C.
- Design of offshore wind energy support structures
Schaumann P., Kelma S., Bechtel A.
- Monitoring techniques for the detection of fatigue damages at wind energy converters
Höffer R., Tewolde S., Haardt H. and Bogoevska S.
- Integrated analysis software for wind turbines
Thomassen P., Bruheim P.I.
- Nonlinear wave loads and dynamic response of wind turbine systems
Marino E., Lugni C., Borri C.
- Aerodynamic Losses Of Transport Systems As A New Wind Energy Market: Evaluation Of The Behaviour Of A Mini-VAWT
Morbiato T., Borri C., Bartoli G., Allori D.
- A review of Power Converters for Wind Energy Systems
Staines C. S., Caruana C., Licari J.

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ONSHORE WIND TOWERS, BASICS OF STRUCTURAL DESIGN

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Abstract: Tubular towers for wind turbines made in sections about 20-30 m for construction in site outside the city area of the total height around 80 m are considered. The state of art on major structural aspects is provided as well as the most recent development of in-situ connection. Basic references related to the loading aspects and structural safety checks of on-shore structures are addressed.

1. Introduction

Supporting structures for wind turbines are often tubular structures made of traditional structural materials: steel and concrete. There is a hybrid concrete/steel wind turbine tower in which combination of concrete and steel tubes are used in the lower and upper part respectively. Most commonly pre-fabricated concrete segments and steel tubes with maximum diameter of about 4 m are transported by the truck to the site. Increasing requirements in efficiency and competitiveness of wind turbines in generation of electrical energy lead to larger swept area, meaning the longer rotor blades, and higher hub height. Such developments, towers higher than 100 m were favourable for development of steel lattice towers.

2. Tower loading

2.1 Structural safety

Certification of following items are requested for by a certification company:

- Safety concept and control of loads
- Control of safety system and design of components (e.g. support structure)
- Testing requirements
- Control of manufacturing process
- Check of foundation design (optional)
- Characteristic measurement (optional)

Supporting structure has to comply with, IEC 61400-1 [1] and EN1990 [2]. Standard IEC 61400 outlines minimum design requirements and specifies essential design requirements to ensure the engineering integrity of onshore wind turbines. All subsystems of wind turbines such as

control and protection mechanisms, internal electrical systems, mechanical systems and support structures are considered. In addition, all necessary structural requirements defined in Euro-codes have to be properly checked and satisfied.

Two categories of external conditions for which the WT safety must be checked. Category 'Normal' includes the frequent situations during the service life of the WT. Category 'Extreme' represents rare external design situations. Category definition determines the load values, the safety factors and the load combinations to be used in the analysis and design.

Wind turbine classes are defined in terms of wind speed and turbulence parameters as shown in Table 1 where V_{ref} is the reference wind speed defined as the extreme 10 min average wind speed at the hub-height with a 50 year return period. I_{ref} is the reference turbulence intensity defined as expected value of hub-height turbulence intensity (coefficient of variation of wind speed) at a 10 min average wind speed of 15 m/s. Air density is 1.225 kg/m^3 .

Table 1: Wind Turbine Classes [3]

	I	II	III
V_{ref} (m/s)	50	42,5	37,5
I_{ref} for type A (high turbulence)		0,16	
I_{ref} for type B (medium turbulence)		0,14	
I_{ref} for type C (low turbulence)		0,12	

2.2 Load types

The loads include:

- Timely constant loads (e.g. dead weights, aerodynamic loads due to uniform, steady wind speed, and centrifugal forces, when the rotor is running at a constant speed) and
- Timely varying loads, which can be steady loads, such as cyclic loads due to tower interference or unbalanced weights in the rotor, or unsteady loads due to wind turbulence, cross winds or rapidly changing wind direction.

Following load types are defined for design according to [4]:

- Inertial and gravitational loads, both static and dynamic, acting on wind turbines, resulting from vibration, rotation, gravity and seismic activity;
- Aerodynamic loads, both static and dynamic which are caused by the airflow and its interaction with the stationary and moving parts of wind turbines. These loads are dependent upon the rotational speed of the rotor, the average wind speed across the rotor plane, the turbulence intensity, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including the aeroelastic effects.
- Operational loads, which result from the operation and control of wind turbines. They shall be assigned to several categories. These are the control of rotor speed and the torque control by pitching of blades or other aerodynamic devices. Other operational loads are the mechanical braking and transient loads arising during the starting and stopping of the rotor, connection and disconnection of the generator, and yaw movements.
- Other loads, such as wake loads, impact loads, ice loads may occur and shall be included where appropriate depending on the installation site.

2.3 Load cases

The combination of the design situations with pertinent safety factors is operationalized in IEC61400 using 22 Design Load Cases (DLC), 15 of them used for Ultimate Limit State (U) analyses and 7 LC for Fatigue Limit State (F) analyses.

The relevant load cases for tubular wind towers are those that cause maximum effects (e.g. cross-section forces) along the tower height. Along the tower height maximum effects can be achieved in different load cases. However, the load case causes maximum shear force at the top of the tower will be usually design driving for the bending moment along the tower. Possible exception is for the upper part of the tower where the load case causing the maximum bending moment will control the design. The load fatigue spectra for each section have to be provided based on the 7 load cases for fatigue design check. In seismic zones the mass of the tower may be decisive in inducing inertia forces due to earthquake accelerations. Concrete and hybrid steel-concrete towers are usually affected by this load situation, which is not considered in the standard wind turbine type certification.

2.1 Load tables

Strict rules provided by the certification body are defined for loading.

The results of the extreme load assessment (maxima and minima), including the partial safety factors, are presented in tabular form for a certain cross-section (e.g. tower cross section loads at different heights and at foundation bottom). This shall contain a brief description of the load case with statement on the partial safety factors applied. The extreme values of the corresponding load component are located on the diagonal of the load matrix and the simultaneous loads of the other load components are given in the rows.

The cross-section forces due to the fatigue loads are usually presented in a set of damage equivalent fatigue load tables for different tower section heights. The damage equivalent loads (DEL) given in the load tables can be considered as a static load case in combination with the reference number of cycles $N_{ref} = 2 \cdot 10^8$ and a constant Wöhler slope m . For a certain type of structural material only one slope is usually of interest (e.g. for steel structures $m = 4$ is relevant).

3. Resistance

Common assumption in the tower pre-design process is simplification of the tower as a cantilever with concentrated load at the top and a distributed load along the height. Bending moments in direction of wind are governing which leads to check of the tensile and compressive stresses in the tower shell. Following limit states are considered, acc. to GL Wind [4]:

- 1) Ultimate Limit State (ULS), taking into account rupture of critical parts due to fracture/exceedance of ultimate strength, loss of stability and fatigue, loss of static equilibrium.
- 2) Serviceability Limit State (SLS), taking into account deformations, vibration amplitudes and accelerations, crack widths, stresses and strains.

Relevant bending moments are used for the design check of the connection between two tubular segments.

3.1 Stability

Large thickness to diameter ratio of cylindrical shells in tubular tower and dominant bending moment leads to stability problem – the local shell buckling caused by meridional stresses. Stability of cylindrical shell structure is highly dependent on geometrical imperfections due to fabrication.

Design check of shell structures is defined by the Eurocode 3, Part 1-6 [5]. Several ultimate limit states are distinguished: plastic limit state (LS1), cyclic plasticity limit state (LS2), buckling limit state (LS3) and fatigue limit state (LS4).

There are three different approaches for verification of local buckling resistance: Stress limitation; materially nonlinear analysis (MNA) in conjunction with linear bifurcation analysis (LBA); and geometrically and materially nonlinear analysis with imperfections included (GMNIA). Generally stress limitation approach and MNA/LBA approach are suitable for verification of the shell, while the MNA/LBA and GMNIA approaches are suitable for verification of door openings.

Stress limitation approach is based on reduction of design resistance of membrane stress components in the tower shell. Meridional (longitudinal) σ_x , circumferential (tangential) σ_θ and in plane shear stresses $\tau_{x\theta}$, see Fig. 1, have to be used in the design check formulae (1)

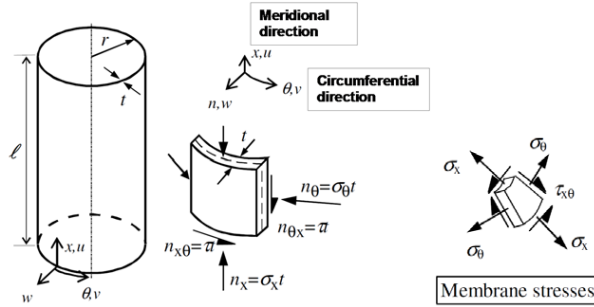


Fig. 1: Stress directions in a cylindrical shell [5].

The verification is made using individual stress components combined in interaction criteria:

$$\sigma_{x,Ed} \leq \sigma_{x,Rd}, \quad \sigma_{\theta,Ed} \leq \sigma_{\theta,Rd}, \quad \tau_{x\theta,Ed} \leq \tau_{x\theta,Rd}$$

$$\left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}} \right)^{k_x} - k_i \left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}} \right) \left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}} \right) + \left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}} \right)^{k_\theta} + \left(\frac{\tau_{x\theta,Ed}}{\tau_{x\theta,Rd}} \right)^{k_\tau} \leq 1 \quad (1)$$

Contribution of the circumferential and shear stress component is often negligible.

A design flowchart for calculation of reduced resistance to meridional stresses is shown in Fig. 2. Reduction factor χ is determined regarding the relative slenderness λ which is influenced by the elastic critical stress depending on boundary conditions and geometry, and geometry imperfections.

Boundary conditions and presence of stiffeners are important only in case of long cylinders, see Fig. 2. The case 3 from Fig. 3, with flexible stiffeners, most commonly apply. Influence of imperfections is introduced by meridional elastic imperfection reduction factor α_x which is dependent on fabrication tolerance quality class, see Table 2.

Table 2: Fabrication tolerance quality class [5]

Fabrication tolerance quality class	Description	Q
Class A	Excellent	40
Class B	High	25
Class C	Normal	16

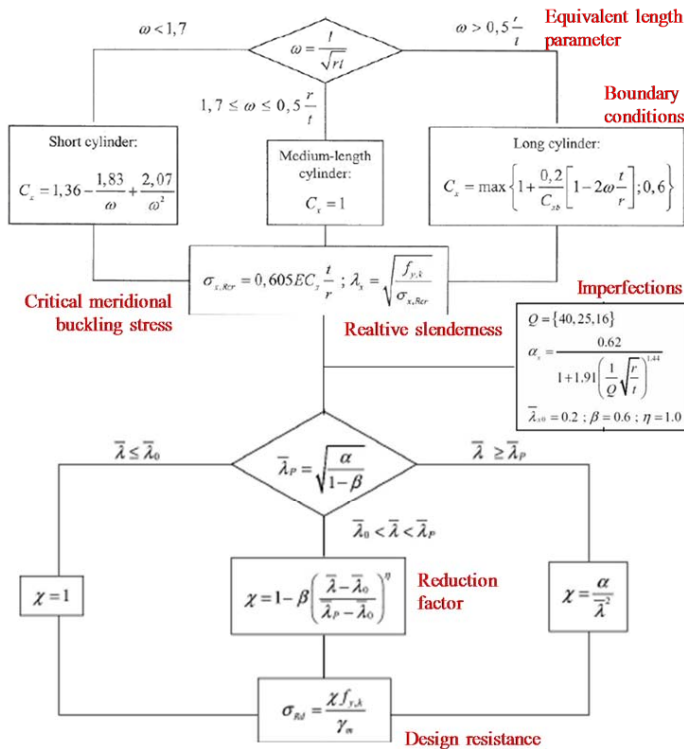


Fig. 2: Flowchart for design check using buckling stress limitation

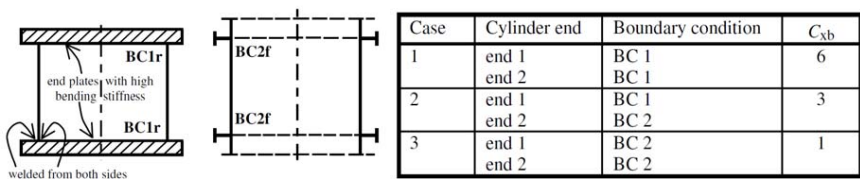


Fig. 3: Influence of boundary condition on local shell buckling parameters [5]

3.2 Door openings

Openings in the tower shell are made for two reasons: for the door at the lower segment of the tower which is used for maintenance, and for ventilation usually at the lower and top segment of the tower. A possible layout for a bottom door opening is shown in Fig. 4. Two possibilities exist for stiffening of the door opening, by adding a stiffener or by increasing the plate thickness in the area around the door opening.

Several failure modes in the ultimate limit state can develop in the area of the opening: buckling of the shell adjacent to the opening due to increased stresses and disturbed boundary conditions, compressive plastic yielding in the areas of stress concentration and tensile rupture due to occurrence of maximum principal stresses mostly above the opening. Resistance of the tower segment is reduced due to presence of the opening, see Fig. 5. The level of reduction depends on successfulness of the stiffening.

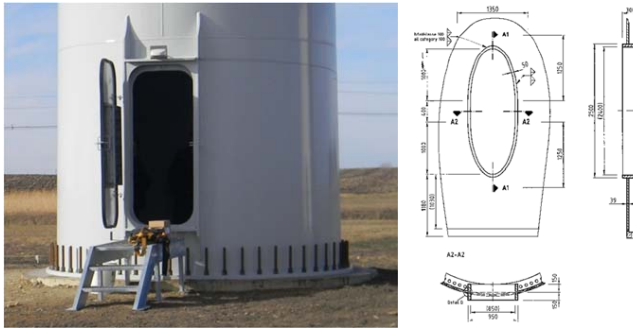


Fig. 4: Typical layout of the door opening in the lower segment of the tower shell.

Fatigue limit state is especially important because presence of the opening and stiffening around it imposes stress concentrations. It is supposed that stress concentrations are located around the narrow perimeter of the opening, see Fig. 5.

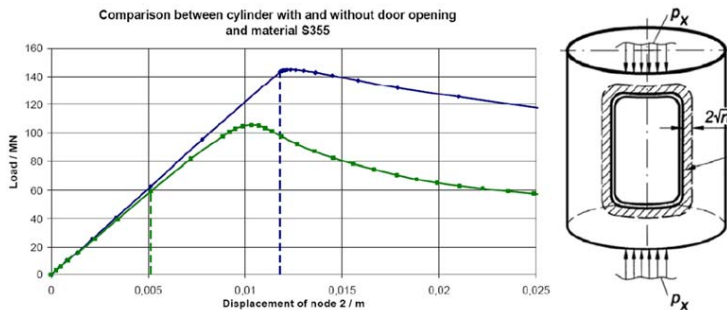


Fig. 5: Influence of the door opening on the bending moment resistance of the connection [6].

Stress limit approach for the buckling design of the door opening region is approximate and recommendations are limited only for few simple geometry cases. Tower manufacturers usually use complicated geometry of the opening and various stiffening approaches in order to optimise the buckling and fatigue performance. Therefore, design approaches relaying on Finite Element Analysis (FEA) are used for design check of the door opening region. Two approaches, described in EN 1993-1-6 [5], MNA/LBA and GMNIA are used.

MNA/LBA method is analogous to the basic general method in the Eurocode 3. Load amplification factors obtained from linear bifurcation analysis (LBA) r_{Lcr} and materially nonlinear analysis (MNA) r_{Rpl} are used to obtain the relative slenderness λ_{ov} of the structure zone around the opening:

$$\bar{\lambda}_{\text{ov}} = \sqrt{r_{\text{Rpl}} / r_{\text{Rcr}}} \quad (2)$$

Using MNA and LBA the boundary conditions, material properties and geometry of the structure are taken into account. The imperfections are adopted in the same manner as in the case of the stress limit approach and overall reduction factor χ_{ov} is determined following the appropriate part of the procedure shown in Fig. 2. Final verification for the MNA/LBA method is made by obtaining the buckling resistance ratio $r_{Rd} \geq 1.0$:

$$\begin{aligned} r_{\text{Rk}} &= \chi_{\text{ov}} r_{\text{Rpl}} \\ r_{\text{Rd}} &= r_{\text{Rk}} / \chi_{\text{Ml}} \end{aligned} \quad (3)$$

GMNIA approach comprises all issues in one analysis: boundary conditions, material properties, geometry and imperfections. Initial imperfections are applied to the geometry of the FE model in the most unfavourable manner which is defined by LBA in most cases.

3.3 Connections

Ring flange connections with preloaded high strength bolts are used for in-situ execution. Most commonly “L” model [7] is used although in exceptional cases of large towers and “T” model is used. The flange connection should be design so no opening under service loads appears. After the flanges separate two failure modes are possible: rupture in the bolts or the plastic joint in the tower shell.

To simplify the design, only one segment of the tower flange is considered, see Fig. 6, where the tension stresses acting in the tower shell are integrated into a concentrated load Z .

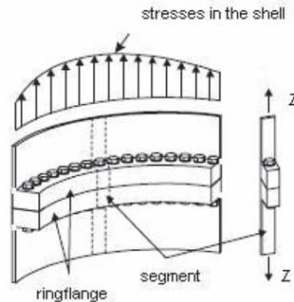


Fig. 6: Segment approach for flange connections [8]

Load carrying behaviour of the segment follows the nonlinear graph shown in Fig. 7. For small tension forces Z in the tower shell, as shown in Range 1, the inclination in bolt force F_s is low, keeping the force within the band of pretension force F_V . An increase in load Z relieves the pressure acting in the contact zone between the flanges. Thus, as soon as the flange starts to unclench, the bolt force rises (Range 2). The relation between the two forces in Range 3 keeps about linear until yielding of the bolt starts (Range 4) and final rupture occurs.

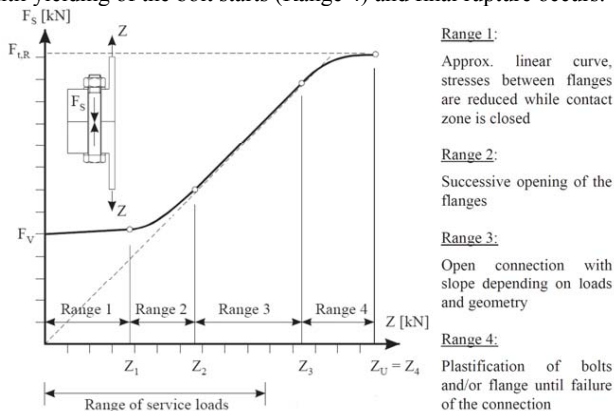


Fig. 7: Nonlinear relationship between bolt force and applied load in segment model for flange connections [8].

The ultimate limit state design follows an elasto-plastic approach by Petersen [7], which models the flange as a beam. The beam resistance has to be calculated according to plastic hinge theory. Petersen classified the failure of a flange connection into three different modes, see Fig. 8: failure of the bolt (A), failure of the bolt with simultaneous development of a plastic hinge in the shell (B) and failure of the connection due to formation of plastic hinges in the shell and in the flange (C). Limits and ultimate resistances for the application of failure modes (A) – (C) are given in Table 3.

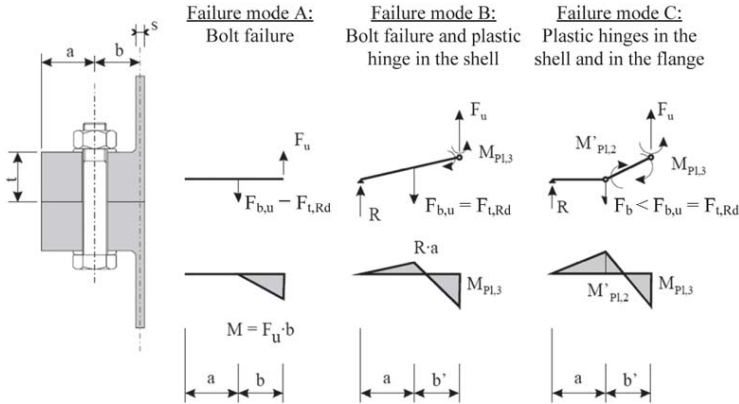


Fig. 8: Failure modes for flange connections according to Petersen [7]

The plastic moment resistance of the flange $M'_{pl,2}$ with consideration of reduction due to bolt hole can be calculated according to equation:

$$M'_{pl,2} = \frac{c' \cdot t^2}{4} \cdot f_y \quad (4)$$

Table 3: Limits and ultimate resistance for failure modes A, B and C [7]

Failure mode	A	B	C
Condition	$F_U \cdot b \leq M_{pl,3}$	$R \cdot a \leq M'_{pl,2}$	$F_s = Z \leq F_{t,R}$
Ultimate resistance	$F_U = F_{t,R}$	$F_U = \frac{F_{t,R} \cdot a + M_{pl,3}}{a + b'}$	$F_U = \frac{M'_{pl,2} + M_{pl,3}}{b'}$

The plastic moment resistance of the shell $M_{pl,3}$ with consideration of M/N interaction or plastic moment resistance of the flange with consideration of M/V-interaction, respectively, derived from equation:

$$M_{pl,3} = \min \left\{ \begin{aligned} M_{pl,N,sh} &= \left[1 - \left(\frac{N}{N_{pl,sh}} \right)^2 \right] \cdot M_{pl,sh} = \left[1 - \left(\frac{F_U}{c \cdot s \cdot f_{y,sh}} \right)^2 \right] \cdot \frac{c \cdot s^2}{4} \cdot f_{y,sh} \\ M_{pl,V,fl} &= \left[\sqrt{1 - \left(\frac{V}{V_{pl,fl}} \right)^2} \right] \cdot M_{pl,fl} = \left[\sqrt{1 - \left(\frac{F_U}{c \cdot t \cdot f_{y,fl}} \right)^2} \right] \cdot \frac{c \cdot t^2}{4} \cdot f_{y,fl} \end{aligned} \right. \quad (5)$$

Friction connections with normal clearance holes have been used in structural engineering for decades. Their behaviour has been extensively examined by various researchers and is comprehensively described by Kulak et al. [9]. Slip resistant joints rely on load transfer between the joined elements due to friction, which is ensured by a clamping force provided by preloaded high strength bolts, see Fig. 9a.

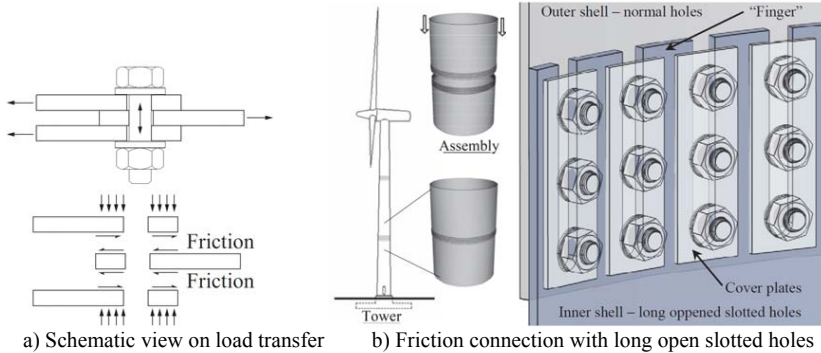


Fig. 9: Friction connection

Friction connections are rather efficient when movement in the connection with loads varying between tension and compression, as e.g. from wind, has to be prevented. Due to preloaded bolts and force transfer by friction, notch stresses do not appear. This structural detail belongs to fatigue class [7], which is much above fatigue detail of the L-flange which is between class 36 and 71. In many cases this fatigue criterion of the connection governs the design of the tower. Veljkovic et al. [10] suggest substituting normal clearance holes on the lower tower section with long open slotted holes with the covered plates, which are depicted in Fig. 9b. The remaining steel parts between the long open slotted holes are with respect to their visual appearance designated as “fingers”. The on top opened bolt hole shall ease the assembly process. On the inside of the tower, cover plates shall be mounted to ensure an equal distribution of pressure and to facilitate the assembly process.

The structural design of friction connections in general is regulated in various standards and guidelines [9], [11], [12]. As an example, the design procedure according to EN 1993-1-8 [12] is shown here. The calculation of design slip resistance $F_{s,Rd}$ depends on number of friction surfaces n , friction properties of joined surfaces: hole shape factor k_s and slip factor μ , and the preload in the engaged bolts $F_{p,C}$.

$$F_{s,Rd} = \frac{k_s \cdot n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} \quad (6)$$

The slip factor is experimentally established according to EN 1090-2, Annex G [13].

The friction connection with long open slotted holes is a single lap joint, thus providing one friction surface $n = 1$. Recent findings in the HISTWIN2 [14] project have shown that the second friction surface is activated after the ultimate limit state is reached.

4. Conclusions

Optimal design of towers is increasingly important competitiveness factor of wind turbines. Basics of design are provided indicating potential for structural innovations in tower designs.

Acknowledgments

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DESIGN OF OFFSHORE WIND ENERGY SUPPORT STRUCTURES

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Abstract: The importance of renewable energy is increasing significantly in Europe. Among the renewables, wind energy contributes the main part of the electricity supply. Major development is expected in the design of offshore wind energy. Several structural solutions for the support structures exist. In dependence of loads induced by site-specific environment conditions, design of the whole offshore wind turbine as well as of relevant structural components is carried out. Most recently, sustainability of support structures of offshore wind turbines is gaining in importance. This paper gives an overview of recent and ongoing research of the design of offshore wind turbines.

1. Introduction

CO₂-reduction is the response to climate change in most of the European countries. Furthermore, the Fukushima disaster led to phase-out of nuclear power production in many countries. To achieve these objectives, transformation of the electric energy production to renewable energy is needed. Among the alternatives like photovoltaics, biomass, and hydropower, wind energy seems to contribute the main part of the electricity supply by renewables.

The major future development may be expected in the design and technical challenges of offshore wind energy. By end of 2014, 2,488 turbines have been installed and grid connected with a total nominal power of roughly 8 GW [1]. During the last years, the annual offshore wind installations account for approximately 1.5 GW in Europe. Further in the future, EWEA has identified 26.4 GW of consented offshore wind farms in Europe and future plans for offshore wind farms amount to about 100 GW [1]. According to Roland Berger consultants [2] the life-time costs correspond to a total of about 180 Billion Euros, with 30% of the cost allocated to design, manufacturing and erection of the support structures. Assuming an average turbine size of 5 MW and an annual installation of 300 offshore units the annual quantity of steel for support structures amounts to half a million tons per year.



Fig. 1: Offshore wind turbines at the test site „alpha ventus” in the North Sea (Foto: DOTI)

Compared to typical steel constructions, support structures of offshore wind turbines are exposed to several types of external loadings, especially predominant wind and wave actions. In addition to the different types of loading, every offshore structure has to withstand almost 10^9 load cycles within an estimated life time of 20 years or longer. Due to the large number of load cycles in a short time, it is apparent that ultimate loads are of subordinate significance. Finally, only a sufficient fatigue design of the structural components and constructional details leads to a safe and reliable construction during its life time.

2. Support structures of offshore wind turbines

In Europe, the technical effort and the logistic and design challenge of the erection and operation of offshore wind parks are very much depending on the site conditions. For the reason of nature protection of the so called *Wadden Sea*, the development of offshore energy is focused on areas far from the coast and for that reason in water depth beyond 30 m of the North and Baltic Sea in Germany. Established technical solutions of coastal areas are only transferable to a limited extent because water depth and distance to the coast have a significant impact. Design, construction, and execution of the support structure being one of the major components of the offshore wind turbine are crucial. Offshore wind turbines in Germany have only been designed with steel support structures of different types; see Fig 2 and 3: Monopile, Jacket, Tripod and Tripile. In Europe to date 78.8% of substructures are monopiles, 10.4% are gravity foundations, 4.7% are jackets, 4.1% are tripods, and tripiles account for 1.9%. In addition, two full-scale grid-connected floating turbines have been installed [1].

Within the last decades, several types of support structures have been investigated. The support structure of an offshore wind turbine consists of the tower and the substructure. The substructure includes all structural components below the tower together with the foundation (see Fig. 2). Depending on the water depth, the size of the turbine and the local conditions different types of substructures have been developed. As mentioned above the great majority of the offshore wind parks in Europe are supported by Monopiles. The Monopile is a simple construction and extends effectively the turbine tower under water and into the seabed like illustrated in Figure 2. The Monopile consists of a steel pile with a diameter between 3.5 and 5.5 metres driven or drilled up to 40 metres into the seabed. This cylindrical tube is connected to the steel

tower by a transition piece. This transition piece connects the tower pile with the foundation pile. Within this unit, the foundation pile overlaps the tower pile and the annulus between the tubes is filled with high performance grout. This type of connection is called grouted joint and has been used in many monopiles. In recent time, the grouted connection is replaced by bolted connections with large preloaded bolts with diameter up to 72 mm. Monopiles are used extensively in the near- and offshore environment up to water depths of 25 metres. For the installation of Monopiles, only small preparations of the seabed are necessary. Heavy piling equipment drills the foundation into the seabed. Monopiles are not suitable for locations with many large boulders.

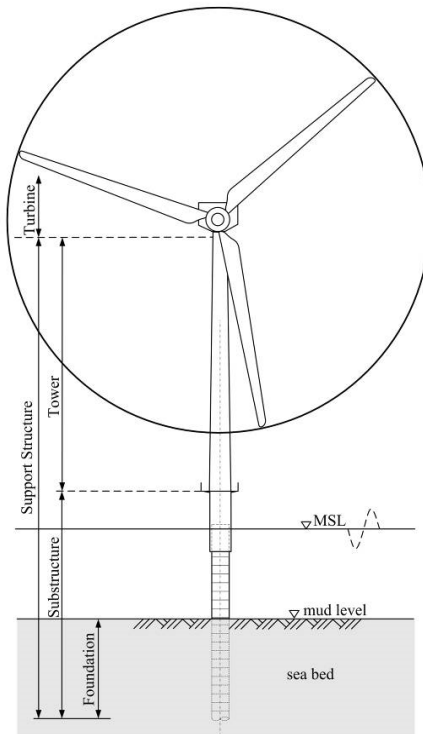


Fig 2: Components of an offshore wind turbine with Monopile substructure

For water depths larger than 25 m lattice steel structures are reasonable although Monopiles are under discussion beyond 25 m as well. The Jacket as a lattice substructure solution (see Figure 3, left) is suitable for offshore locations with water depths up to 50 metres.

On top of the Jacket, tower, turbine and blades are mounted subsequently. Jackets are multiple-pile constructions due to four-legged or three-legged foundations. The Jackets anchorage is formed by piles at all feet. Conveniently, the specific details are of comparatively small dimensions affording a production largely standardized. As a result of the spatial carcass the amount of steel and therefore the material costs experience a reduction. Compared to Monopile foundations a Jacket substructure consists of 40 % to 50 % less steel. Mentioned facts lead to marginally increasing project costs with significantly increasing water depth.

Compared to Jacket substructures the steel effort for Tripods is increased significantly. The three-legged Tripod (see Figure 3, middle) consists of a central steel cylinder connected with a steel lattice to three foundation piles symmetrically arranged around the central pile. The three upper and lower legs transfer the forces from the tower into the foundation piles. These piles are driven approximately 10 to 20 metres into the seabed depending on soil conditions. The installation needs marginal seabed prearrangement leading to an expeditious assembling. Though, the seabed needs to be free of boulders. Compared to the dimensions of the Monopile, the pile diameter of the three legs is significantly reduced. Tripods can be used for water depths up to 50 metres. An alternative solution for nearly the same water depths is the Tripile developed by BARD Engineering (see Figure 3, right).

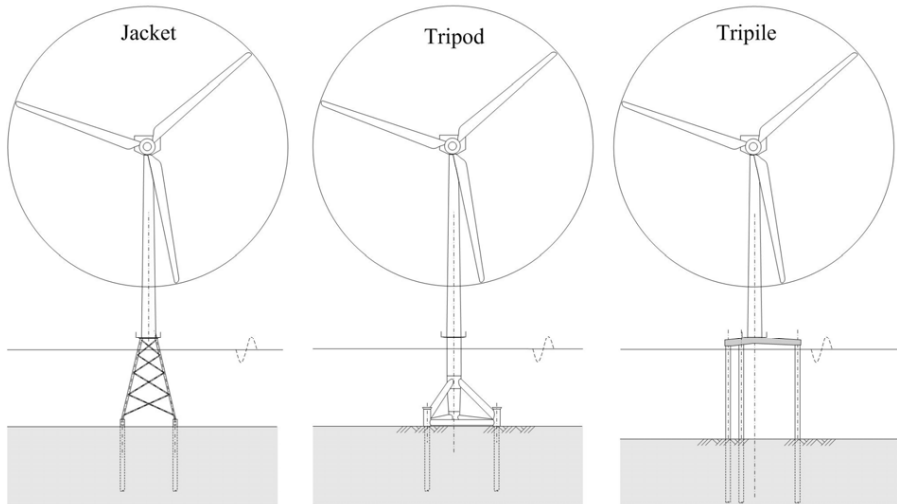


Fig 3: Support structures of offshore wind turbines (Jacket, Tripod, Tripile)

The Tripile is suitable for water depths of 25 to around 40 metres and is more compact, lighter and cheaper than other offshore substructures, but the torsional stiffness is smaller. This influence has to be considered thoroughly. The supporting crosspiece and struts are welded from flat steel elements. All the assembly work can be done with a heavy-duty crane on a construction vessel. The structural members of the Tripile are produced in series. The necessary length of the piles depends on the soil conditions. The three pre-piled piles are driven into the seabed using a template. Subsequently the steel crosspiece is placed on top of the three piles. The annulus between piles and crosspiece are grouted with a high performance mortar.

Typical construction details of the support structures of offshore wind turbines are welded, bolted, or grouted joints. Welded joints can be found in tower and substructure. The tower consists of tower sections with ring flanges. Steel plates are connected with longitudinal welds to rounds and they are connected with circumferential welds to tower sections. Furthermore, the above described lattice substructures like Jacket, Tripod or Tripile contain lots of complex welds. The tower sections are connected with bolted ring flange connections to the tower. The high strength bolts have a regular preload. Grouted connections as well as bolted connections with ring flanges are used for the transition between tower and foundation (Monopile). Grouted connections are applied between lattice substructures and foundation piles.

3. Design of offshore wind turbines

Design of offshore wind turbines has to be carried out in accordance to the rules as stated by the approving authorities. Often, reference is made to national and international standards and guidelines. The typical design phases of an offshore wind turbine in Germany are described in [3].

3.1 Modeling of offshore wind turbines

Dimensioning and modeling of offshore wind turbines are of great importance within the design process. Therefore, loadings induced by wind, sea state, and operation and their respective load effects are to be modeled. Complex models to describe the action effects are required in order to determine the structural response appropriately, cf. Fig. 4.

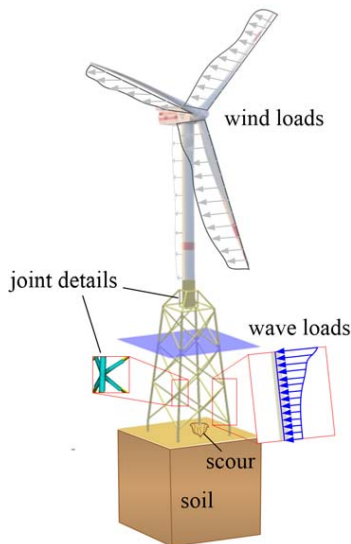


Fig. 4: Structural modeling of an offshore wind turbine with Jacket substructure (adapted from [4])

Environmental data such as wind speed, wind turbulence, significant wave height, wave period, current as well as the correlation of these environmental data are measured at the intended site. Values required for the design of the offshore wind turbine are given by extrapolation of the obtained data with respect to the intended service life time.

For verification of offshore wind turbines in accordance to valid standards and guidelines, proof of safety has to be fulfilled for the fatigue limit state, ultimate limit state, and serviceability limit state. In order to calculate the fatigue damage due to acting loads, up to 3,000 load simulations are to be carried out. Numerically generated time series of the stresses at the relevant structural components are obtained, which are evaluated for the proof of safety. For proof of the ultimate limit state, especially extreme events such as storms and faults of the controlling unit of the offshore wind turbine are decisive. For instance, the load effects of the greatest wave expected during the life time as well as the impact of breaking waves are to be considered [5].

Besides the interaction of wind, sea state, and support structure, the soil-structure interaction is of importance for the structural design. For example, cycling loads have an impact on the soil bearing capacity [6] [7]. Also, flow around the structure might lead to development of scour, if no scour protection is installed [8]. These effects have to be modeled appropriately.

The process leading to the final design of the offshore wind turbine is an iterative one, since alternating dimensions of the offshore wind turbine result in alternating loads acting on the structure. This eventually leads to an increased number of simulations which have to be carried out for an optimized, economical design of the offshore wind turbine.

Different levels of details are essential within the numerical modeling. They depend on the chosen substructure (Fig. 2 and Fig. 3) and the considered structural component. Local flexibility of tubular joints of Jackets has to be modeled by structural springs or by super elements which are included in the model of the offshore wind turbine [9]. In comparison, finite-elements modeling of Monopiles using beam elements are adequately accurate when carrying out modal analyses. Structural details such as grouted joints are to be investigated by applying separate, fine-meshed numerical finite-elements models of these components.

While the effects used for the numerical simulations are based on measurements, the numerical simulations are carried out with "perfect", deterministic parameters of modeling. Up to date, scattering of structural design, structural imperfections, nonlinearities of structure and material as well as deterioration effects are not covered within the numerical modeling. These topics are inter alia contents of the ongoing research project "GIGAWINDlife", financially supported by the Federal Ministry for Economic Affairs and Energy of Germany.

3.2 Design-relevant structural components of offshore wind turbines

Action effects of wind and sea state lead to high dynamic structural loading of the support structure with more than 10^9 load cycles which the offshore wind turbine has to withstand during its service life time of usually 20 years. In comparison to the "classic" structural engineering, the proof of safety for fatigue performance is of crucial importance, especially for notched, and highly-stressed, as well as complex structural connections. The fatigue performance of welding seams, for example at tubular joints, and the fatigue- and load-bearing behavior of grouted joints rang among these connections.

Often, the fatigue design is carried out on basis of the nominal stress approach. The detail class of the structural detail is given in tables. However, the SN curves of the detail classes do not cover the actual stresses such as internal stresses at welding seams of thick plates or stresses at tubular joints in great accuracy. In order to model notch effects at tubular joints as used for Jackets or Tripods, local concept such as structural stress approach or the notch stress approach are usually used [10] [11]. The structural stress is determined by applying numerical finite-elements models of the joints and of the design-relevant locations. Fine-meshed finite-elements models are required for the numerical determination of the local stresses when using the structural stress approach (often called hot-spot method).

Numerical models are also essential for the dimensioning of grouted joints in offshore wind turbines. The grouted joints transfer time-variant loads (axial forces, bending moments, shear forces and torsion moments) into the foundation piles. In dependence of the chosen substructure, different loadings are decisive for the design. Grouted joints in Monopile substructures are predominantly loaded by cyclic bending moments due to wind and sea state as well as normal forces induced by the dead load. In comparison, grouted joints in lattice structures such as Jackets and Tripods are predominantly loaded by axial (cf. Fig. 5).

Nonlinearities of the structure and material can be modeled accurately by applying numerical methods, even for multi-axial loading. Computational-aided modeling and determination of stresses are to be carried out for the fatigue limit state as well as ultimate limit state. Detailed

descriptions on the load-bearing capacity and fatigue behavior as well as recommendations for the structural design of grouted joints in Monopiles predominantly loaded by bending are stated in [12] and [13]. State-of-the-art as well as ongoing activities in research of predominantly axially-loaded grouted joints are given in [14] and [15].

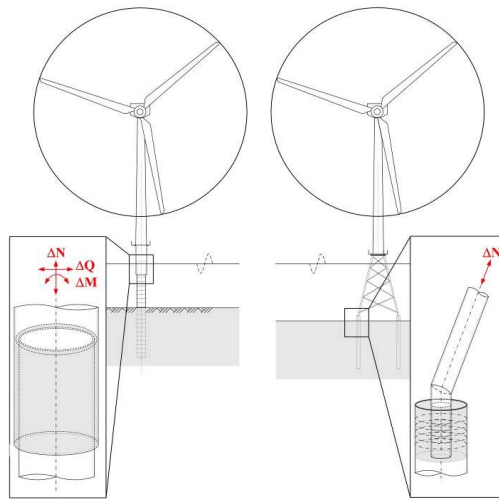


Fig. 5: Grouted joint for Monopile- und Jacket substructure as well as design-relevant loading

Accurate design of grouted joints is of sufficient importance for the load capacity of the offshore wind turbine with respect to its intended life time, and also for the economic efficiency of the offshore wind park. Damages occurring at grouted joints with "plane" tubes (no shear keys are used for the surface profiling of the tubes) led to elaborate and expensive repair work of these connections. Especially the necessary deployment of ships is a cost driver.

Considering these economic risks, revealing knowledge of load capacity and concepts for designing and optimizing of support structures of offshore wind turbines can be gained by comparatively small investments in research and development. Hence, faults during the design phases can be prevented, as well models and structural design can be optimized, eventually ensuring the economic efficiency of offshore wind parks. For example, reference is made to the ongoing research within the project "GROWup - Grouted Joints for Offshore Wind Energy Converters under reversed axial loadings and up-scaled thicknesses", financially supported by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

3.3 Sustainability

Up-to-date, economic efficiency and structural safety were the most pivotal aspects for planning and design of offshore wind turbines. However, in addition to these economic and technical aspects, further aspects such as ecologic, procedural, and social effects have to be considered within a holistic design of offshore wind turbines. They are going to be of increased importance for future offshore wind turbines. Therefore, a method as well as an application software to assess sustainability aspects during the stages of design, manufacturing and erection of steel construction of renewables were developed within the research project „Nachhaltige

Stahlkonstruktionen für Erneuerbare Energien (NaStafEE)“ ("Sustainability of steel constructions in the field of renewable energy") [16].

The assessment tool is based on existing rating systems originating from the building sector [17] [18], which are applied to evaluate office and administration buildings. Due to the different function of offshore wind turbines and the respective focuses in planning and design, transmission of these rating systems is not possible.

The developed method to evaluate the sustainability of steel support structures for offshore wind turbines contains 35 criteria and characteristics within the general sustainability topics of economy, ecology, social, technique and process, cf. Fig. 6.

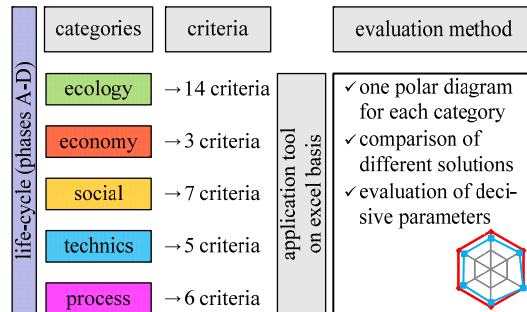


Fig. 6: Scheme of the method to assess the sustainability of steel support structures of offshore wind turbines

Data acquisition and hence the sustainability assessment covers all phases of the life cycle of an offshore wind turbine, covering the manufacturing and installation process (life-cycle phase A), operation of offshore wind turbines (life-cycle phase B), decommissioning (life-cycle phase C) as well as resulting credits (life-cycle phase D). A steel support structure is defined as reference unit, allowing comparison of design and types different support structures with respect to their sustainability. The criteria of each category are evaluated, and the respective values are represented in polar diagrams. Different realizations of support structures can be compared to each other, and possible aspects of optimization within the criteria can be found. In contrary to the assessment method of the building sector, no explicit performance factor is decisive, since no percentage weighing of the criteria is considered. However, the increased sustainability is evaluated on basis of comparison and optimization of different support structures for offshore wind turbines. Investigations on the substructures Tripod and Jacket were already carried out [16] [19]. Especially material usage and transport have a decisive impact on the sustainability. A holistic design of offshore wind turbines is possible by applying this method.

4. Conclusion

To achieve the goal of CO₂-reduction in Europe, renewable energies are gaining significantly in importance. Especially offshore wind energy and its expansion are of very high significance. Different realizations of support structures for offshore wind turbines already exist. Over the last years, they were adapted, and new support structures were developed in order to meet the specific requirements. The design of support structures for offshore wind turbines is based on extensive and elaborate numerical simulations. The iterative design process is quite complex

due to the interaction between loads, dynamic response of the structure, and structural components. Design-relevant structural components such as welding seams and grouted joints are to be investigated numerically with detail models. Also, the aspect of sustainability is gaining in significance within the design and planning process. Tools to assess the sustainability of offshore wind turbines already exist. Despite recent progress, further research and development are decisive for optimization of future support structures of offshore wind projects in order to achieve a more economic and sustainable realization of future energy supply.

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MONITORING TECHNIQUES FOR THE DETECTION OF FATIGUE DAMAGES AT WIND ENERGY CONVERTERS

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Abstract: The instrumentation scheme for a reference wind energy converter (WEC) is presented. Data from all the sensors is continuously logged and stored in a long-term database. In a first step, spatial stress cycles for the reference WEC are evaluated from compensated displacement time histories and used for a service strength check of the steel shaft of the WEC. Such approach permits a realistic estimate of damage accumulation and a subsequent estimation of the residual structural life time. In a second step, possible structural damages shall be detected and localized. This requires a drastic increase of the scanning density of displacement quantities. Suitable measurement solutions are described. An offshore WEC instrumentation scheme is also discussed.

1. Introduction

The direct excitation of structural oscillations of a WEC is in general due to wind forces from stochastic turbulence and from the non-homogeneities of the flow in the wake of windward positioned converters in group configurations. In addition, control errors of the actuators of the blades, hunting (oscillating) of the electric generator and interactions with main fluctuations can amplify vibrations of the entire system. The susceptibility of the plants grows as the next converter generation has larger rotor diameters and longer hub heights. Obviously, in the future, such wind park configurations will become customary.

In this context, main fluctuation due to liable energy feeding input can be more relevant than in the past. Also, investments for surveying and maintenance of wind energy plants will follow the modern concepts mentioned above. Figure 1 illustrates a basic concept for the service and repair that can be applied to the structure of wind turbines. The demand is that repair and/or strengthening can be planned and conducted with minimized investments and losses of service time, ensuring a reliable serviceability.

Monitoring can be a qualified basis for continuous strength checking of the wind converter's support structure. In recent years, structural elements of wind energy converters have been monitored in order to control and steer the blade and gear configuration during power production, to alert about dynamic overloading, and to detect dangerous conditions such as icing. New and modern monitoring concepts aim more at the identification of present or developing damages to provide an advanced estimation of the residual lifetime of the structure of the wind turbine. To this, the applied sensor systems for periodical and/or continuous monitoring are predominantly acceleration sensors, cycle transmitters, strain-gauges, and inductive displacement transducer, where the accuracy of such systems depends strongly on the local peculiarities. Previous sensor systems have been mainly used for sensing purposes within a specified recording concept. By contrast, relatively new applications employ optical displacement detectors or radar interferometers. Both devices are mostly based at an outside reference positions adjacent to the wind energy converter (WEC).

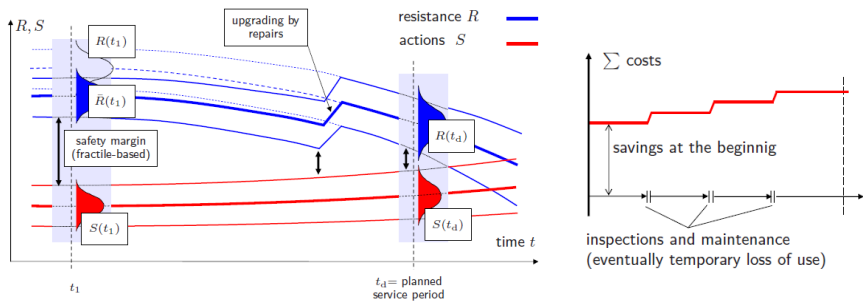


Fig. 1: Concept for an economic management of technical lifetime of WEC [1]

New research aims at the detection of detrimental alterations of system responses including the rotor, the transmitting power train, the gear mechanism, the generator as well as its interaction with the electricity network, and the load bearing structure of a WEC. To this end, the determination of clear indications for present damages or developing deteriorations using a remote observation data base is mandatory [2, 3]. A further target is the use of the sensing data for life cycle management strategies. In the future, special actuators will increasingly be employed in order to be able to instantaneously counteract excessive operational demands.

2. Classical monitoring instrumentation for WEC structures

2.1 Commonly used sensors

The most commonly used sensors for the structural health monitoring of wind energy converters can generally be classified as vibrational (structural), environmental and operational. The environmental and operational sensors do not give a direct condition of the structure being monitored, but they provide a very important input for better understanding of the measured vibrational responses. The reason is that, the response of the structure varies a lot depending upon the operational demand and environmental conditions. They are also utilized for activation of pitch angle change in order to aerodynamically reduce the rotor speed or the emergency brake, when the wind speed becomes very high that may result in unnecessary wear and tear or in the worst scenario damage to the blades and structure. [4,5]

General sensor category	Sensor type (for)
Vibration	Accelerometer
	Inclinometer
	Displacement transducer (Grout sensor)
	Strain gauge
	Bolt force sensor
Operation	Rotor speed
	Yaw position
	Pitch angle
	Power output
Environment	Anemometer (wind speed and direction)
	Temperature
	Atmospheric pressure
	Humidity
	Water depth
	Corrosion
	Wave height and direction
	Scour depth
	Dangerous gases

Table 1: Sensor categoriesa) Anemometer
(Thies Clima)b) 3D Ultrasonic Anemometer
(Thies Clima)c) Acoustic Wave and Current Profiler
(Nortek)

d) Scour depth sensor (Fondriest Environmental)



e) Acceleration sensors (3D and 3x1D)

Fig. 2: Some of the most common sensors

2.2 Onshore monitoring scheme

Subject of this example is a WEC, which is in use for about fourteen years. The present instrumentation concept of the monitoring system, which has been installed at the WEC two and a half years ago, is shown in Figure 3. Pursuant to this concept, six three-dimensional accelerometers, six inductive displacement transducer and ten temperature sensors have been installed at the tower of the WEC. The accelerometers are distributed over five levels. And mainly serve to identify the Eigen frequencies and mode shapes of the tower structure. The displacement transducers are arranged in two levels with a spacing angle of approximately 120° between them. Their nominal range of measurement amounts to ±5 mm.

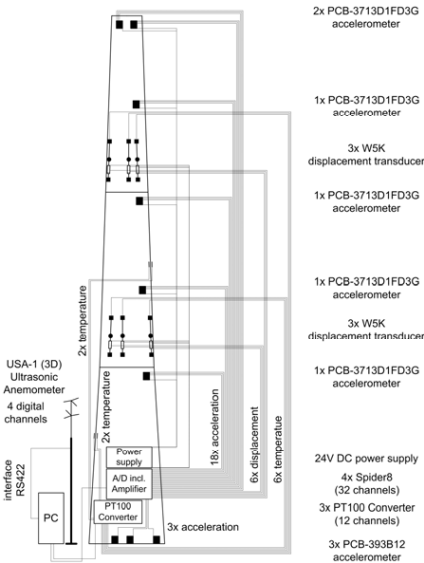


Fig. 3: Monitoring system

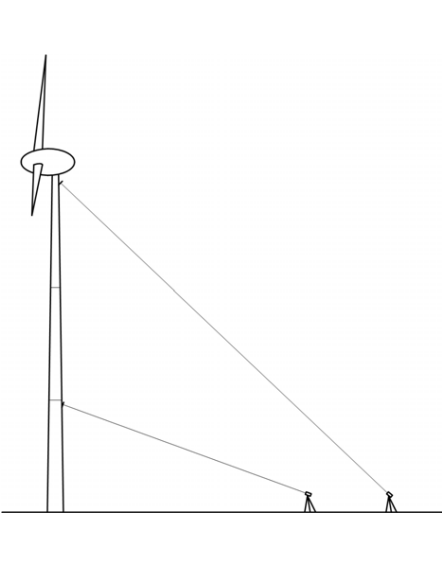


Fig. 4: Principle of the laser distance measurements

If linear material behaviour is assumed, the vertical length variations, which are collected over a distance of 500 mm, can be transformed into a corresponding stress distribution of the steel tower. For the exclusion of possible temperature influences within the measured displacements, the temperature of each round steel bar connected to the displacement transducers is measured with a surface temperature sensor (Pt100). There are two additional points on different heights equipped with inner and outer temperature sensors for measuring the temperature gradient of the tower wall.

In addition, three seismic accelerometers have been installed on the foundation. For continuous monitoring of the horizontal wind speed, the wind direction, the vertical wind component and the air temperature, a three-dimensional ultrasonic anemometer is placed on a telescopic mast in thirteen meters height, adjacent to the tower. The monitoring data is collected through three different data-loggers, which are connected to the on-site computer. This computer is also charged with the transfer of the measured data via a high-speed internet connection to a remote server system. It rests with the remote computer, to synchronize and to transfer the data to a relational database, at which a multi-agent software technology is utilized. For interrogation purposes, the database can easily be accessed by a web-service enabling the plots of various measured signals in parallel; more details can be found in [6].

Signals provided by the customer interface of the wind turbine are logged synchronously such that a tailor-made comparison is possible. The details contain revolutions per minute of the rotor, the electrical power, the azimuth angle, the pitch angle and the wind speed measured by a cup anemometer in 67 m height.

2.3 Offshore monitoring scheme

Wind energy harvesting from offshore wind farms can be preferable because of the availability of good wind source and its remoteness from population centres. However, the supporting structures are exposed to harsh marine environment and loading conditions. This added to the relatively young age and limited experience with offshore wind structures makes the implementation of a Structural Health Monitoring (SHM) scheme very important. For this reason, the BSH (Bundesamt für Seeschifffahrt und Hydrography) requires that 10% of the WECs from the offshore windfarm should be equipped with a foundation monitoring system [7]. The selection of those 10% may depend on water depth, pile length, change in type and dimension of supporting structures (if more than one used) and exposed location (in the wind farm).

The sensors used for offshore wind turbines are similar to those used for onshore but with some additional sensors to monitor the sea environment and the grout connections. It is also important to mention that more robust and durable sensors should be used for offshore, considering the sea environment and costly maintenance. The additional sensors are:

- Acoustic Wave and Current Profiler (AWAC) to measure wave height and direction along with the profile of current.
- Scour depth sensor
- Multiparameter Probe to measure temperature, pressure (depth), conductivity (salinity), turbidity, dissolved oxygen, fluorescence and pH of the sea water, which can be further used as an input to corrosion monitoring.
- Grout sensor to monitor the movement in the grouted connection between the pile and transition piece. The main purpose of this transition piece is to correct the plumb line errors of the pile, which occurred during pile driving, in order to prepare a level surface on which to place the tower structure (Fig. 5).

As can be seen in Fig. 5a and c, the grout connection is monitored by three inductive displacement sensors each at the same horizontal level and 120° to each other. The grout connection in

addition to being a weaker part of the structure, it is also vulnerable to impact loads from vessels or boats boarding, therefore monitored closely. Most of the offshore wind farms employ grout sensor in all 100% WECs.

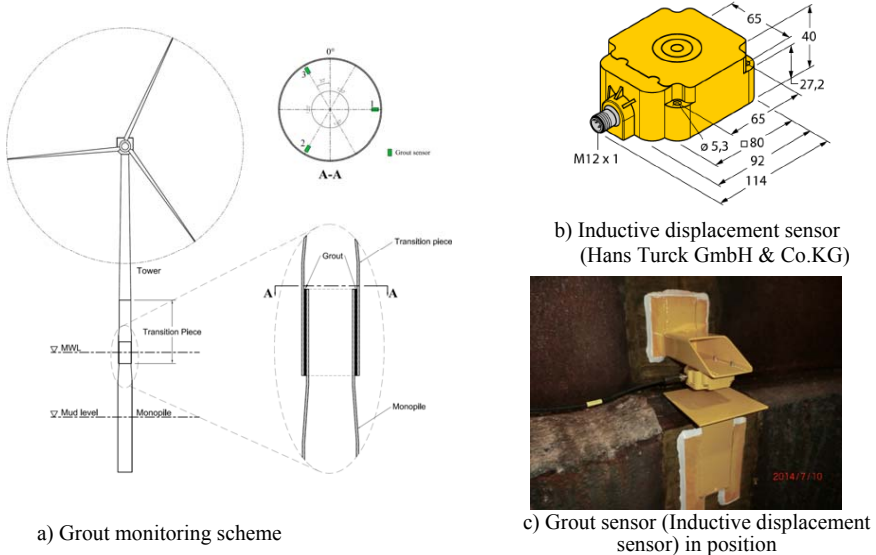


Fig. 5: Grout connection monitoring scheme

3. Fatigue analysis

It is a well-known fact that a material repeatedly bent to and forth will at some point develop a crack at the region of stress concentration. This happens even when the stress amplitude is within the elastic range of the material. This phenomenon is called Fatigue. [8]

Fatigue failures can be disastrous, if they are not detected on time. Therefore it becomes important to incorporate fatigue analysis in to the design procedures. For performing fatigue analysis the material property and dynamic loading cycles are very important. The most common method for doing fatigue analysis is Rain flow counting method, which is being applied in the railway and aviation industries.

The geometry of a structure or its local connections play an important role in the fatigue life of the global structure. For example sudden decrease in dimension, sharp edges or holes [rectangles] with sharp corners result in stress concentration and eventually became a place from where a crack develops, while smooth decrease in dimensions (tapering transitions, in turbines for example), smooth edges or circular holes result in increased fatigue strength of a structure.

The most data for doing Fatigue analysis is stress or strain time history. In our case strain gauge data, of course when they are strategically installed in order to reflect the actual resulting stresses at the critical positions of a structure. Therefore it becomes very important to place strain gauges at places of high stress concentration, where fatigue failure is expected to occur. This can be achieved by employing representative FEM models or from experience. The rain flow counting is mainly used to convert the complex stress time history in to a simple cyclic

loadings by picking only the peaks for tensile and the valleys for compressive stresses. Then the number of cycles are counted for each stress level.

3.1 Fatigue analysis for reference WEC

For the onshore reference WEC structure shown in Fig. 2, the fatigue analyses are conducted at two levels in heights of around 21.5 and 42.5 m, where the displacement transducers are installed. In relation to a reference length of 500 mm the strains and stresses in the tower wall can be calculated from the measured displacements following the linear elasticity theory. Having defined a fixed coordinate system (Figure 5a), the stress plane and the fluctuating parts of the bending moments can be calculated. The fluctuating stresses in each point of the circumference of the steel tower can be determined by means of the fluctuating bending moments.

For the analysis of the stress-time series a counting procedure is applied. A classification of each single value of the time series is performed before the rainflow count of the fluctuating stresses can be performed. In the present example (Figure 5b) each class equals a bending moment of 10 kNm. In level 1 (42.5 m) with an elastic modulus of 37899 cm^3 this equals a $\Delta\sigma$ of 0.26386 N/mm^2 . For the analysis of the classified stresses the specific rainflow counting method "Rainflow-HCM" after [9] is used. The result of the counting procedure is in general quadratic (comp. to Figure 6b). A closed hysteresis loop is arranged in the matrix by its start and target class. A closed hysteresis loop starts in the target class, arrives and turns round in the start class and closes in the target class.

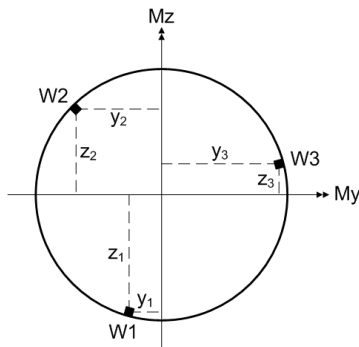


Fig. 6a: Position of the sensors in the fixed coordinate system

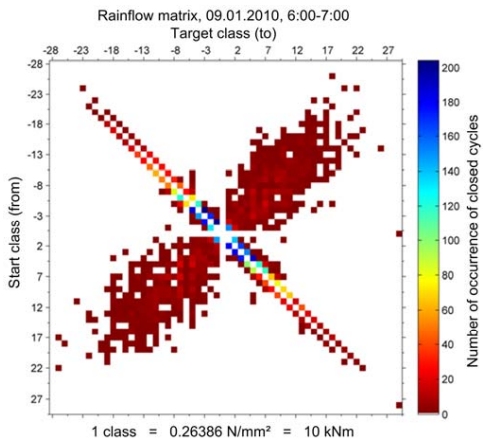


Fig. 6b: Calculated fluctuating bending moments

The rainflow matrix can easily be transformed into a matrix of mean values and amplitudes, which then can be used to build a spectrum of amplitudes of stress cycles. It is generally assumed that mean stresses have no significant influence on the fatigue strength of welded structures and thus can be neglected; such assumption is also adopted for the application of design codes for wind energy converters, [10] and [11]. The results of the rainflow count, e.g. of the hysteresis loops during one year of observation, can be extrapolated up to the estimated lifetime of the WEC, e.g. twenty years. Having defined a detail category (S-N or "Wöhler" curve) for the considered detail of the tower, the damage of the structure can be calculated by applying

the linear damage accumulation after Palmgren and Miner. The reciprocal value of the damage equals the approximated lifetime of the steel tower.

In progress is an add-on for extended fatigue analyses. Hereby, acceleration signals are evaluated. For the determination of stresses from the acceleration signals a double integration of the accelerations is necessary. For low frequencies (below $1/\omega$), however, this leads to very high and unrealistic amplitudes because of the overlaid noise. An additional problem of the integration is the unknown initial value of the displacements. For the calibration of the displacements achieved by the double integration of the accelerations, direct measurements of the tower deformations are required. Such tests can be carried out by laser distance measurements of the displacements of a sufficient number of target points along the length (height) of the structure. A second suitable method is radar interferometry, where time-resolved deflections of a numerous reflectors or just surface discontinuities along a structure are scanned. Information about the latter measurement systems is presented in the following section.

4. Advanced sensors

4.1 Laser distance measurement for the calibration of distributed deformation monitoring

As an extension of the classical monitoring system presented in section 2, direct optical measurements of the tower deformations are currently in preparation. Because of the necessary long distance between the four laser distance sensors and the tower (Figure 4), several conceptual and technical problems have to be solved. A technical problem is the synchronization of the laser distance measurements with the mechanically piezo-electrically measured signals. It has to be tested if it is possible to cascade an additional electronic measuring system with the existing ones, using a very long data cable between them. Due to the long distance, it is also necessary to point the laser at target reflectors which have to be installed at the level of the accelerometers on the outer surface of the steel tower. A drawback is that changing environmental influences can affect the measurements, which in addition can only be conducted for short time periods, and not permanently like the protected mechanical or piezo-resistive sensors.

4.2 Direct simultaneous deformation measurement by radar interferometry

A relatively new, alternative solution for distributed deformation monitoring is time- and space-resolved radar interferometry. Portable radar systems (an example is described in Figure 7 and Table 2) are increasingly used for the simultaneous measurement of deflections of large structures. High resolution electro-magnetic waves are emitted from a radar system, reflected from targets, received and analyzed. The combination of radar interferometry in [12] and high frequent emission of pulses of millimeter waves covering a large bandwidth of discrete frequencies, eg. applying the Stepped Frequency Continuous Wave (SFCW) Technique in [13], permit to monitor a time history of displacements of targets in the antenna radiation pattern. The targets can be any discontinuity of a structure, such as curbs, edges, ridges, lugs, noses, i.e. each surface form which reflects waves back to the antenna. Gentile in [15] tests the method thoroughly and demonstrates its use for different structural types. The attainable resolution of deflections of the targets is ca. 0.02 mm, the dimensions of the surface discontinuities must be considerably larger.

A generation of signal waves with extremely stable phases and low phase jitter is essential for increased measurement accuracies. Generators for the synthesis of suitable signals often use fractional frequency splitters [16]. An optimized concept of the measurement system over the whole range reaches from the design of millimeter wave circuits [17] to suitable signal processing strategies. It is required to achieve adequate detection accuracy in order to resolve deflections of about a few micrometers.

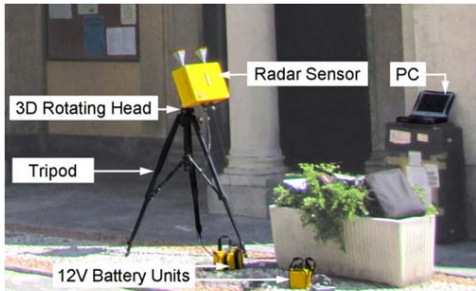


Fig. 7: View of the IBIS-S microwave interferometer (Figure and table taken from [15])

Parameter	Value	Range
Maximum operational distance (with sampling frequency of 40 Hz)	500 m	
Minimum range resolution	0.50 m	
Maximum sampling frequency	200 Hz	
Displacement accuracy	0.02 mm	
System Setup time	10 min	
Operative weather condition	all	

Table 2. Technical and operational characteristics of the microwave interferometer.

Liu in [18] demonstrated a successful localization of discrete damages at the shaft of a wind energy turbine. The cited paper assumes a physical damage at a connection flange and simulates the consequences for the dynamic structural responses. In a real case high measurement accuracy and an uncommon large number of scanned points (targets) along the height of the shaft are required to provide a suitable database for the detection of such data patterns in the eigenmodes of the structural response. At present, own measurements are prepared with the aim to conduct such a far reaching inclusion coverage of eigenmodes and the required number of detection points. Both First, a portable system is here by used to test the space resolution of the mast deformations of the reference system. As a further development, a Frequency Resolved Modulated Continuous Waves (FMCW) radar system is modified for the purpose to be integrable into the hub nose of a rotor-drive train ensemble. It shall be oriented along the blade axis in order to monitor the relevant blade deflections.

5. Conclusion

Compensated displacement time series from structural health monitoring of the steel shaft of a WEC can be used to build up a look-up table or scenario-controlled database of physical simulations as a multiple-input-multiple-output system. A database composed from the data series measured in natural scale during the ongoing converter operation delivers sufficient information to evaluate realistic estimates of structural damage accumulation. The Palmgren-Miner approach in combination with Rainflow Counting of stress cycles at selected positions of the steel shaft is used. An extension of the approach in order to detect and localize discrete structural damages requires a drastic increase of scanning density of time histories of wind forces, displacements over height, and other related operation values. First results of a conceptual study show that new, innovative sensor instrumentations are required to improve accuracy and precision of the displacement data. Respective sensor systems and measurement strategies have recently become available.

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INTEGRATED ANALYSIS SOFTWARE FOR WIND TURBINES

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Abstract: Software tools for aeroelastic analysis of wind turbines was first developed in the 1990s based on the realization that it is necessary to consider elastic deformations of blades in a nonlinear analysis. These tools are called integrated analysis software since all the important parts of the wind turbine are included: wind, rotor, drive train, control system, and tower. Over the 20 years or so that have passed, aeroelastic analysis has gotten more advanced. A significant development is the move from modal analysis with few DOFs to MBS or FEM analysis with many DOFs. Aeroelastic tools have from the beginning and is still largely used to calculate loads by the engineers in the “loads department” that are then shipped to other departments, e.g. the structural engineering department. The hypothesis upon which this article is built is that this is a sub-optimal work flow dictated largely by limitations in the software being used. A key goal of developing the software tool Ashes (Aero-servo-hydro-elastic-analysis) is that an integrated aeroelastic analysis tool can be used also by structural engineers.

1. Introduction

The principal goals for using software tools for design, analysis, and simulation of wind turbines are building reliable and secure machines as well as reducing the cost of energy. An interesting challenge of wind turbines is the intimate interconnection of a range of engineering disciplines: aerodynamics, structural engineering, cybernetics, electrical engineering, hydrodynamics. To reach an overall optimal result these areas should not be considered one by one, but in a synthesis. When it comes to software tools there are two important reasons for why overall optimization is hard:

1. Traditional software tools most often come from one particular field of engineering with limited or no possibility to include effects from related fields. Instead results are pushed around from one tool to the other. This is often time consuming, boring, and error prone. More importantly, errors are introduced in the analysis itself, e.g. as nonlinear effects are not modeled correctly.

2. Since traditional tools are focused on a single field it also becomes hard for the engineers and scientists using it to understand, learn, and appreciate the complexity of related fields. Thus, communication between “departments” become hard and unattractive. It's safer to stay in your comfort zone.

Aeroelastic software present an integrated analysis of wind turbines, and a lot of progress has been seen in this area over the last 20 years. However, the aeroelastic tools are still largely used by the “loads department.” The results are then shipped to structural, generator and control departments.

The software tool Ashes that are presented here are developed with the goal to bring integrated aeroelastic analysis out of the load department and in use by more engineers improving wind turbines. We focus primarily on merging aeroelastic loads analysis and structural engineering into one task that should be performed by one team.

2. Background

2.1 An incomplete history of aeroelastic software for wind turbines

Aeroelastic analysis software for wind turbines was born in the 1980s as a matter of necessity brought about by the resurrection of wind energy in the 1970s. Stig Øye from DTU was one of the pioneers of the early days and in 1996 he wrote [1]: *“The Department of Fluid Mechanics has been involved in the modelling of wind turbines since 1978. Although the work was mainly in the aerodynamics, it soon became clear that aeroelastic effects were important in load calculations for wind turbines. Therefore several aeroelastic computer codes were developed and used during design of large wind turbines.”* Stig Øye is the author of the aeroelastic code Flex that is in use at DTU. Flex was also the starting point for the in-house codes currently being used by Vestas and Dong Energy.

In 1996 the first version of the GH Bladed was also released. GH Bladed has grown to become the definitive market leader. Through mergers Bladed [2] is now owned by DNV GL.

Another tool with a long history is the open source software Fast[3] actively developed by NREL.

In addition to these three there are a number of aeroelastic tools available – commercial, semi-commercial and academic – but it appears that none of them has a significant market share.

Although the market for aeroelastic software has been growing for many years it is still quite small compared to the total Computer Aided Engineering (CAE) market. This is probably the reason that the big companies of the CAE industry, e.g. Dassault systems (owner of Abaqus) and Ansys, typically has not entered the aeroelastic software market.

2.2 From modal analysis to MBS and FEM

The analysis method preferred in the early tools (Flex, Bladed, and Fast) was using a very limited number of degrees of freedom (DOFs) and modal analysis. Doing this it was possible to get acceptable simulation speed given the computer hardware of the 90s. During the last decade there has been a growing interest in employing more accurate and flexible methods of

analysis, in particular the Multi Body Simulation (MBS) and the Finite Element Method (FEM), e.g. a few years ago Bladed switched from modal analysis to MBS. With typically a 10 to a 100 times increase in DOFs, MBS and FEM analyses come with a penalty in stimulation time. The gains in flexibility and accuracy have been so significant that it has been considered worth it given the improvements in computer hardware.

3. Ashes – What is it good for?

As there are a bunch of aeroelastic tools available for industry and academia it is pertinent to ask: Do we really need another one? In this section we explain why we believe Ashes will give an added value for engineers working with wind turbines in general, and for structural engineers working with wind turbines in particular.

Our main motivation behind developing Ashes is our believe that the established software industry is not moving fast enough when it comes to delivering added value to engineers, particularly enabled by progress and innovative in fields such as visualization, user experience, multiple platforms, and cloud computing.

3.1 The history

Ashes is built on a FEM framework. The origins of the framework can be traced back to ideas by Prof. Greg Miller first presented in 1988 [4]. The purpose of the framework was to serve as a flexible and innovative foundation on which specialized FE analysis tools can be built.

Until 2008 this was used to develop innovative structural engineering tools in an academic setting. Then in 2008 the development of Ashes as a aeroelastic analysis tool started at NTNU. In 2013 the technology was spun off in the start-up Simis AS.

In particular, three new capabilities was necessary to use the framework in an aeroelastic analysis:

1. Nonlinear corotated beam element was necessary to model the blades [5]
2. Aerodynamic loading on the blades was implemented using the Blade Element Momentum (BEM) method.
3. A control system for blade pitch and generator torque

3.2 The convergence on FEM for aeroelastic and structural analysis

As briefly discussed above the first wave of aeroelastic tools was dominated by modal analysis. Now, MBS and FEM are taking over. With structural engineering software often being FEM based this lays the foundation for merging aeroelastic and structural analysis in the same tool.

It appears to be no fundamental reasons not to do this, so the limitations lie more in what has been implemented and not.

3.3 Use in education also in structural engineering?

Ashes has important features that makes it attractive to use in university level education in wind turbine technology. Features of particular importance are: 3D visualization, user experience, and real-time analysis.

As the features catering to structural engineering are being expanded we believe that it will be interesting to use Ashes also in structural engineering education.

3.1 Structural flexibility

Popular FEM tools typically have an extensive range of modelling and analysis capabilities when it comes to e.g. element types. Currently, Ashes only uses beam elements. We believe that this is sufficient to model most tower configurations. However, when it comes to drive train this is probably not the case.

3.2 Visualization

We are focusing on using visualization more effectively in several stages: modelling, analysis, and interpretation of results.

3.2 (Quasi) real-time analysis

The traditional approach of preprocessing, processing, and post processing is still dominating. However, in several cases such as design and learning the feedback loop is much too long. Thus, real-time analysis is a key feature of Ashes. Real-time analysis gives a shorter feedback loop and makes it easier to investigate and understand different designs and solutions.

3.3 Batch analysis

In structural engineering in general and for wind turbines in particular it is often necessary to run a large number of load cases. Thus, it is important that the load cases are efficiently and conveniently defined, managed, and executed.

3.4 Cloud computing – private and public

Cloud computing is an emerging option to decrease the duration of a batch analysis by getting access to additional hardware. For quite a while this has been done internally in companies. It used to be called a cluster, now it's increasingly referred to as a private cloud. We are working to make setting up and using a private cloud easier and more flexible. An interesting case for universities is using the student computer labs as a private cloud.

The last few years has seen the rise of a commercially available cloud market – the public cloud. With prices falling rapidly this appears to become extremely valuable for running many load cases. The simulation time can be reduced from days to minutes for a very low cost (compared to the cost of engineering time). However, the cloud experience must be convenient and predictable to be an attractive option. That's why we are building cloud computing into Ashes giving the user the choice of running analysis locally or paying for the speed and convenience of the cloud.

3.6 Turbulent wind in urban and suburban built environment

For an aeroelastic analysis the turbulent wind is an essential input parameter. Ashes can use turbulent wind files generated by the software TurbSim[6] from NREL. TurbSim generates wind relevant for typical wind farm locations. Thus, it is not directly applicable where local conditions give additional turbulence, such as in urban areas. There are two approaches to use Ashes for wind turbines in urban and suburban built environment:

1. Modify the TurbSim generated wind in Ashes so that it better reflects the conditions in built environment.
2. Use external software that can simulate wind that is relevant for the built environment and save it on the TurbSim format.

4. Conclusions

The main conclusions are:

1. Several emerging technologies are only partially or not at all offered in existing aeroelastic software tools, e.g. visualization, real-time analysis, and cloud computing.
2. The aeroelastic tool Ashes is being developed with the goal of delivering the benefits of these technologies to engineers
3. Merging software tools for aeroelastic analysis and structural engineering of wind turbines offers important benefit for the structural engineer.

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NONLINEAR WAVE LOADS AND DYNAMIC RESPONSE OF WIND TURBINE SYSTEMS

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Abstract: Hydrodynamic loads associated with nonlinear wave kinematics have important effects on the structural behaviour of offshore wind turbines. Recent literature has shown that steep non-breaking waves are responsible for triggering resonant vibrations of the tower with significant implications in terms of structural safety. A full hydro-aero-elastic model is used in this work in order to assess the effects of nonlinear wave contributions on the whole system, including the rotor blades. The paper shows that, in severe climate conditions, standard linear wave theory leads to unacceptable inaccuracies in assessing the response of the system.

1. Introduction

In this paper, nonlinear wave loads and their effects on a fixed bottom 5-MW wind turbine [1] are reproduced by coupling a fully nonlinear wave solver [2], with a hydro-aero-elastic simulator of the entire system [3]. This study is motivated by the fact that though current aero-elastic models provides an acceptable accuracy level for the numerical simulation of wind turbines, still overly simplistic linear or weakly nonlinear models for wave propagation are routinely used for the prediction of wave-induced loads on offshore wind turbines (OWTs).

As shown by Marino et al [2], standard linear wave theory leads to dangerous inaccuracies - significant peaks in the system response are underestimated causing unacceptable prediction. More importantly, linear wave models are unable to capture important resonant phenomena, such as ringing and springing. In parked condition, resonant vibrations are induced by the interaction of the structure with steep wave front. These phenomena are suppressed in power production [6]. When a slamming event associated with a breaking wave occurs, the maximum loads undergo a tremendous increase that is almost independent on the working condition of the turbine. Very high-frequency oscillations are observed in the tower-base fore-aft shear force

and bending moment [5], whereas, apparently no evident influence on the tower-top displacements is observed [2,4,5]. Finally, limitations of weakly nonlinear wave models in capturing these phenomena are highlighted in [7,8].

This paper gives an overview about the global hydro-aero-elastic response of a system emphasizing the effects that high-order wave components, up to the extreme case of impacts caused by plunging breakers, have in terms of dynamic response and structural loads.

The paper is organized as follows: Section 2 gives a brief summary of the global numerical model. The main features of the wind turbine model used for the simulation are recalled in Section 3. Then, Section 4 presents the main simulation outcomes. Finally, some concluding remarks are given in Section 5.

2. Global hydro-aero-elastic model

The global strategy is based on the coupling between the NREL open-source FAST software [3], used for the hydro-aero-elastic simulation, and free-surface potential-flow models (linear and fully non-linear), used to predict the wave kinematics and the associated hydrodynamic loads acting on the substructure.

FAST is a combined modal and multi-body solver able to model the rigid and flexible components of a wind turbine. Aerodynamic loads acting on the blades are calculated by means of AeroDyn [10]. Hydrodynamic forces are calculated by means of a user-defined subroutine [5]. The subroutine, at each time step, reads the nonlinear wave kinematics as input for the calculation of the hydrodynamics forces. The fully nonlinear wave model is shortly recalled in the following.

2.1 Fully nonlinear wave kinematics

The wave model is based, within a domain-decomposition (DD) strategy [2,4-6], on the spatial and temporal coupling between the linear analytical wave solution and a fully nonlinear (FNL) numerical algorithm (see Fig. 1).

The DD method ensures low computational time because the FNL numerical wave solution is used only on well defined sub-domains where nonlinearities matter. The sub-domains are identified using a simple criterion based on the exceeding of a threshold value for the local steepness of the wave estimated through a linear solution [6]. From the theoretical point of view, the linear model is not accurate to simulate very steep waves. In this sense, the use of the FNL model on a sub-domain identified through a linear strategy could be questionable because this steep wave could have been a numerical artifact of the linear assumption. To prevent such a circumstance much care has been paid to the choice of the sub-domain size (both in space and time) as well as to the steepness threshold value [6].

Under the hypothesis of inviscid fluid and irrotational flow, the FNL method is based on the solution of a potential flow model (Laplace's equation) with fully nonlinear kinematic and dynamic free-surface boundary conditions. Laplace equation is discretized in space by means of a High-Order Boundary Element Method (second-order accuracy) [6]. Fourth-Order Runge-Kutta scheme is used for the time integration of the free-surface boundary conditions, ensuring a fourth order accuracy in time. The linear analytical solution, besides roughly identifying the temporal region where the nonlinearities have to be taken into account, is also used to initialize the fully nonlinear algorithm. Suitable transition zones at the inflow and outflow sections are used to smoothly pass from the outside linear solution to the nonlinear one.

2.2. Hydrodynamic forces

Since the wavelength of the sea interacting with a wind turbine is much larger than the diameter of the monopile, inertial and viscous hydrodynamic forces prevail on the diffraction load.

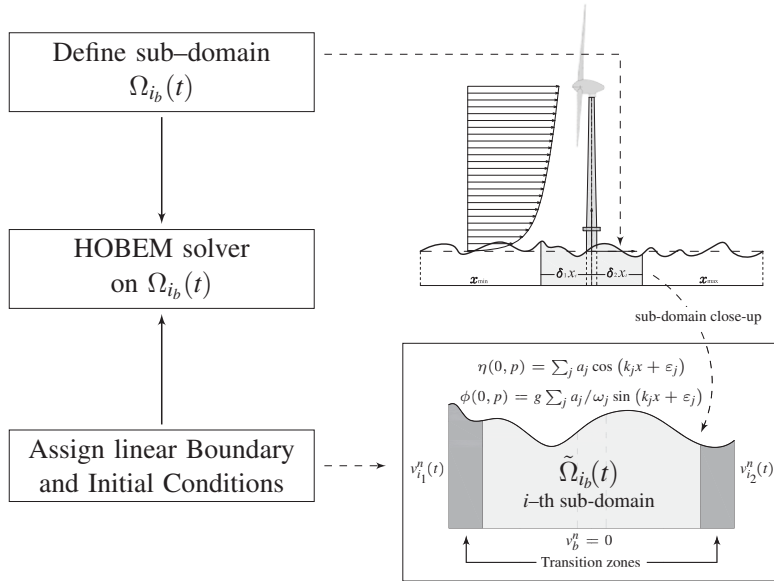


Fig. 1: Schematic representation of the domain decomposition method for the i -th sub-domain.

When no breaking waves occur, hydrodynamic forces are computed by means of the Morison equation [9,11]. In case of breaking waves, impact forces are taken into account by calculating the impulsive contribution f_I using the Winke and Oumeraci model [12]. The hydrodynamic forces per unit length are calculated with the following scheme:

$$f(t) = \begin{cases} f_D + f_M & \text{if no breaking wave occurs} \\ f_D + f_M + f_I & \text{if breaking wave occurs} \end{cases}$$

where f_D and f_M are the drag (viscous) and inertial terms per unit length, respectively.

3. Wind turbine model

The turbine model used in this study is the 5-MW Reference Wind Turbine for Offshore System Development [1], whose main characteristics are listed in Table 1. The diameter and the wall thickness vary linearly with the tower height. The base diameter of 6 m is equal to the diameter of the monopile.

Table 1: Main parameters of the baseline wind turbine model.

Rating Power	5 MW
Rotor orientation / conf.	Upwind, 3 blades
Rotor / hub diameter	126 / 3 m
Hub Height	90 m
Cut-in / Rated / Cut-out Wind Speed	3 / 11.4 / 25 m/s
Cut-in / Rated Rotor Speed	6.9 / 12.1 rpm
Rotor Mass	110 t
Nacelle Mass	240 t
Tower base and pile diameter	6 m
Tower top diameter / Wall thickness	3.87 / 0.019 m
Pile length	30 m
Pile mass	190 t
First Fore-Aft monopile natural frequency	0.28 Hz

4. Numerical simulations

We analyse the case of a severe sea state characterized by a significant wave height $H_s = 7.5$ m and spectral peak period $T_p = 15$ s. These sea conditions would likely occur under wind speeds much higher than the cut-out limit reported in Table 1, therefore the wind turbine is set in parked configuration with blades pitched to feather and the rotor idling. In parked condition, wind turbulence plays a minor role; thus, according to the chosen sea state, characterized by a wind speed of 26.5 m/s at 19.5 m asl [9], a hub-height constant wind speed of 33 m/s is used.

Given a wave steepness threshold of $ka = 0.18$, five sub-domains are identified in 1-hour simulation. The effects of the nonlinear hydrodynamics are highlighted in Fig. 2, where the response obtained using the proposed DD model are compared with the one based on the linear wave theory.

Breaking wave occurs in three of five sub-domains, i.e. 2nd, 4th and 5th, causing impact events on the structure. In the following, we focus on the 5th event; similar features characterizes the impacts occurring on the sub-domains 2 and 4 (not shown here in details). Fig. 3 shows four snapshots of the wave breaking at the monopile location. The accuracy in reproducing the fully nonlinear wave at the breaking position plays a crucial role in assessing the impact force. Indeed, within the model used in this work, the slamming contribution is fully determined through the wave impact velocity and the wave elevation.

4.1 Time-domain study

Fig. 4 shows a close up of sub-domain 5: at approximately 3080 s, a steep and asymmetric wave triggers a resonant vibration. At about 3095 s a steeper wave amplifies (doubles) the oscillations amplitudes for approximately one period T_p . Each of the subsequent nonlinear waves causes resonant vibrations persisting for about one T_p , whose amplitudes are related to the local steepness of the incoming wave.

An impact event occurs at 3168.5 s, it causes two different effects: (i) a very high-frequency vibration in tower-base shear force (TwrBsFxt) and bending moment (TwrBsMyt) that persists for approximately one T_p ; (ii) an amplification of the fore-aft tower-top oscillations amplitudes

(TTDspFA) which is about 80% larger than the underlying springing-like vibration. From the TTDspFA we observe that type (i) excitation is filtered out by the dynamical system and no trace is found in the tower-top motion.

Fig. 5 shows the time series of the shear force at the blade root (RootFxc1), the out-of-plane and in-plane tip deflections (OoPDefl1 and IPDefl1) and the rotor speed (RotSpeed). Note that RootFxc1 is expressed in the coned coordinate system [3].

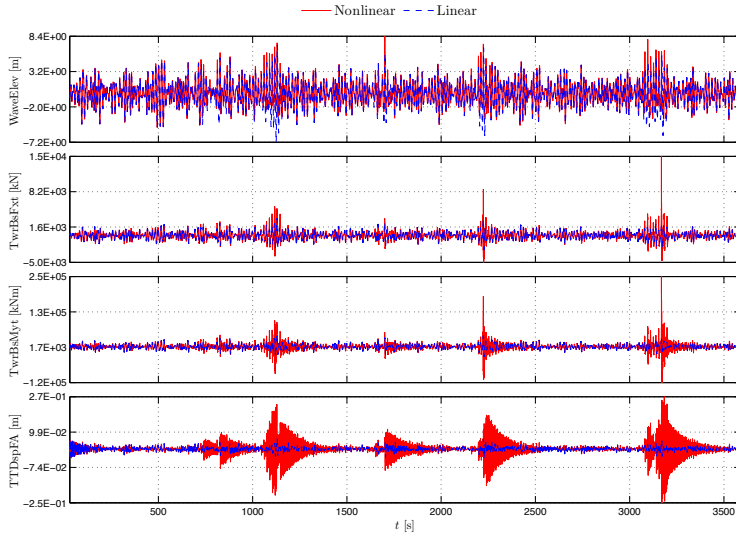


Fig. 2: Comparison between the linear (blue dashed) and nonlinear (red solid) solutions of free surface elevation WeveElev (top panel), tower-base shear force TwrBsFxt, tower-base overturning bending moment TwrBsMyt, tower-top displacement TTDspFA.

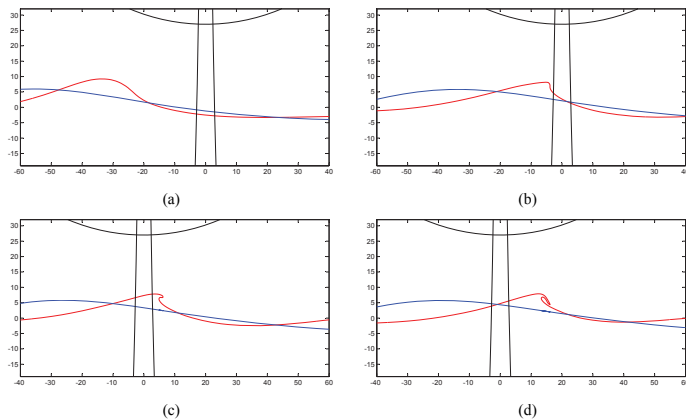


Fig. 3: Evolution of the plunging breaker (event 5). The non-breaking wave evolution represents the linear prediction. (a) $t = 3166.50$ s; (b) $t = 3168.25$ s; (c) $t = 3168.88$ s; (d) $t = 3169.44$ s. Distances on the axes in m.

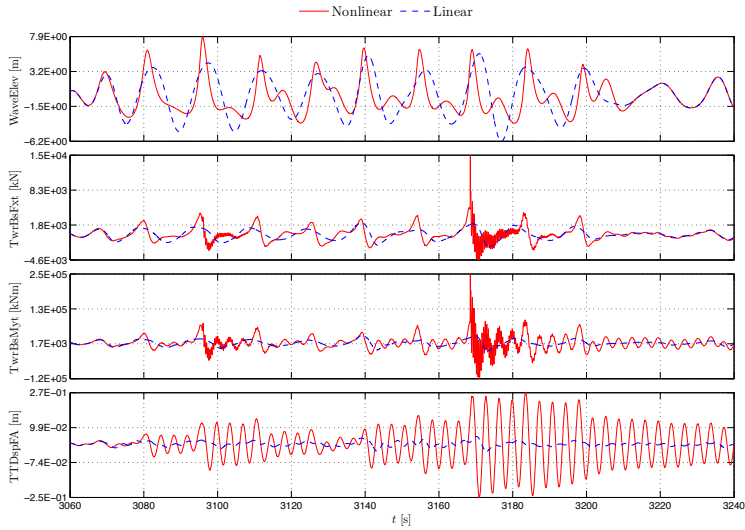


Fig. 4: Sub-domain 5: comparison between the linear (blue dashed) and nonlinear (red solid) solutions of free surface elevation WeveElev (top panel), tower-base shear force TwrBsFxt, tower-base overturning bending moment TwrBsMyt, tower-top displacement TTDspFA

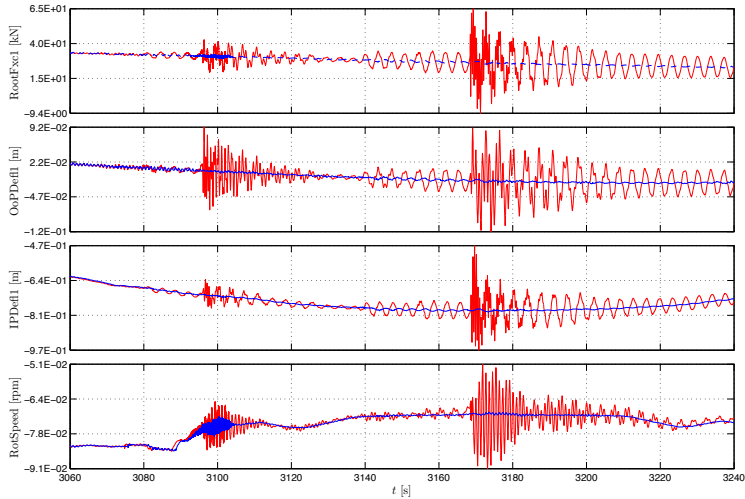


Fig.5: Sub-domain 5: comparison between the linear (blue dashed) and nonlinear (red solid) DD solutions. From top to bottom: shear force at the root of the blade (RootFxt1: top panel), out-of-plane (OoPDefl1: second panel) and in-plane (IPDefl1: third panel) tip deflections, rotor speed (RotSpeed: bottom panel).

This system has the origin in the intersection of the rotor axis and the plane of rotation. For the i -th blade, $X_{c,i}$ is orthogonal with the $Y_{c,i}$ and $Z_{c,i}$ axes such that they form a right-handed system. $Y_{c,i}$ axis points towards the trailing edge if the pitch and twist were zero and parallel

with the chord line; $Z_{c,i}$ axis points along the pitch axis towards the tip of blade. Note that the system rotates with the rotor but does not pitch with the blades. Therefore, since the blades are pitched to 90° , RootFcx_i , with $i = 1, 2, 3$, denotes the edgewise shear force (in the direction orthogonal to the rotor plane). At the instant of the impact, RootFcx_1 and IPDefl1 (which refer to the same direction, given the 90° blades pitch) oscillate with a higher frequency with respect to OoPDefl1 .

In general, in every response channel considered in Fig. 5, we can distinguish a low-frequency instability, caused by the nonlinear non-breaking wave contribution exciting the lowest tower mode, and high frequency instability due to the impact, which excites the lowest blade modes.

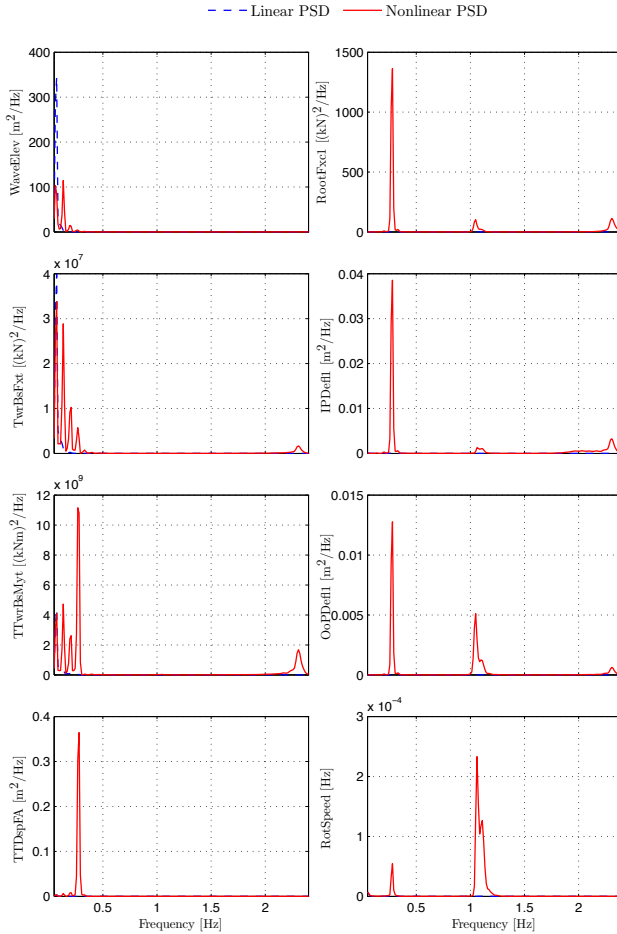


Fig. 6: From top to bottom: PSD of the wave elevation (WaveElev), tower-base shear force (TwrBsFxt), tower-base bending moment (TwrBsMyt) and tower-top fore-aft displacement (TTDispFA) (left column); blade-root shear force (RootFcx1), out-of-plane (OoPDefl1) and in-plane (IPDefl1) blade tip deflection, rotor speed (RotSpeed) (right column). Both linear (blue dashed) and fully nonlinear (red solid) hydrodynamic solutions are reported.

4.2 Frequency-domain study

The power spectral densities (PSDs), see left column of Fig. 6, of the wave elevation and of the structural load of the monopile show that the supporting structure contrasts mainly the wave action (in parked condition the aerodynamic loads are negligible with respect to the hydrodynamic ones).

The main peaks of the *TwrBsFxt* and *TwrBsMyt* PSDs appear at the fundamental sea frequency ($1/T_p$) and at the higher order forcing frequencies (approx $2/T_p$, $3/T_p$); the latter are totally missed by the linear wave model. In addition, the springing-like resonant vibrations in the tower motion justify the peak in the *TwrBsMyt* at 0.28 Hz that is the first fore-aft natural frequency of the structure.

When a breaking wave slams the structure, the impulsive load excites the first in-plane and out-of-plane natural frequencies of the blades causing their oscillation in a coupled mode. The first natural edgewise (*IPDefl1*) bending frequency of the blades is 2.3 Hz, while the flapwise (*OoPDefl1*) frequency is around 1.05 Hz. The former, at 2.3 Hz, excites the tower in the fore-aft motion affecting the *TwrBsFxt* and *TwrBsMyt*. On the contrary, the out-of-plane blade vibration (at 1.05 Hz) does not influence the tower base shear force and the overturning moment. The PSD of *IPDefl1* (see second panel on the right column of Fig. 6) shows a dominant frequency at 2.3 Hz, while the PSD of *OoPDefl1* (see third panel on the right column of Fig. 6) points out the largest energy content at 1.05 Hz. The PSD of the shear forces at the root of the three blades (*RootFxc1*, see first panel on the right column of Fig. 6), though governed by the natural frequency of the tower, contains comparable energy contents at both the frequencies of the blades, proving the coupled vibration mode. Since the rotor is idling, the out-of-plane vibrations (at 1.05 Hz) of the blades have some minimal effects also on the rotor rotational velocity (*RootSpeed*).

5. Conclusions

A domain-decomposition (DD) model based on the coupling between the open-source FAST software for the aero-elastic simulation and an in-house solver for the hydrodynamic solution is used to study the hydro-aero-elastic instabilities on an OWT.

The hydrodynamic solver couples a linear algorithm for the far-field of the incoming wave with the fully nonlinear algorithm to describe the wave kinematics in the near-field. The latter is used as input to calculate the hydrodynamic loads, as well as the impacting forces, induced by breaking waves on the monopile.

The paper has shown that linear wave models (still used in the design practice) are unable to capture important resonant phenomena, such as ringing and springing. Significant underestimations of the of response takes place not only at the tower-base level. Rotor blades undergo a low-frequency excitation due to the resonant vibration of the tower superimposed to a high-frequency excitation induced by the wave impact exciting the lowest modes of the blades. The latter causes high-frequency oscillations in the tower loads. All these instabilities, which are expected to have important implications in terms of ultimate and fatigue loads, are missed by the linear wave model.

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AERODYNAMIC LOSSES OF TRANSPORT SYSTEMS AS A NEW WIND ENERGY MARKET: EVALUATION OF THE BEHAVIOUR OF A MINI-VAWT

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Abstract: Recent patents worldwide address the concept of harvesting wind energy from aerodynamic losses in motorways, but there is a lack of characterization of the traffic-induced resource, and of the major unsteady features. An evaluation of the behaviour of a mini-VAWT is proposed, including the estimation of the capacity factor and the LCOE to assess the potential new wind energy market..

1. INTRODUCTION: A NON-CONVENTIONAL WIND ENERGY CONVERSION

A considerable number of patents addressed recently the general concept of harvesting wind energy generated by traffic aerodynamic losses of ground vehicles, though none describe a brand-new specific device, and the market does not yet acknowledge a related technology. On the other hand, HORIZON2020 goals for renewable energies in the smart-cities, and emerging integrated energy & transport policies worldwide [1] push for development in this area. Recent CFD [2] and experimental activities [3] of our research group characterized the non-conventional energy resource by investigating the flow field generated by traffic in motorways: analyzing the strong correlation between heavy vehicles flow and wind speed classes, it is found that during weekdays daytime hours the traffic generated resource can allow an energy conversion beyond a threshold possibly permitting the positive energetic balance of the system. In principle the mini wind turbine module can be positioned on-site (sideways or as a bridge over the traffic lanes) or embedded in the vehicle.

In the following, a stand-alone on-site application of a mini 1-3 kW vertical axis wind turbine (VAWT) will be considered as is the simplest energetic system. The major feature of traffic appears to be the effect of heavy-vehicles clusters, displaying a separation bubble in the trailed direction over the top of the carriers: such trailed wave, in high-density traffic, might convey sufficient energy to allow the start-up of the turbine, just as atmospheric wind. In Figure 1 is

highlighted the gross energy harvestable by a single VAWT module in the average weekday, for 2 typical heavy vehicle flows (550 h⁻¹ and 875 h⁻¹ maxima per lane): the conversion is obtained by 2 different aerodynamic concepts Savonius (common practice $C_p=0.15-0.2$) and Darrieus (common practice $C_p=0.3-0.4$).

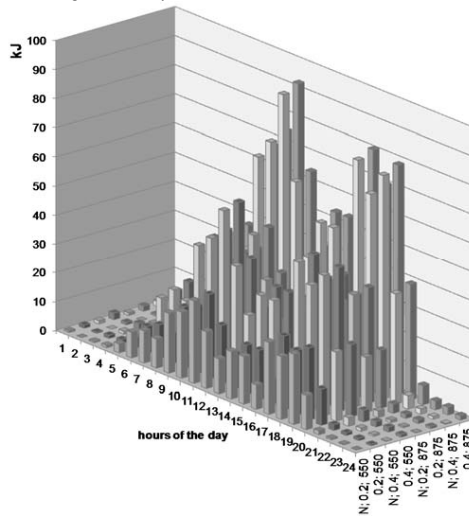


Fig. 1: Gross energy [kJ] harvestable per hour from traffic-generated wind, for Sav and Dar (C_p 0.2 and 0.4) rotors, and for 2 typical heavy vehicle flows (550 h⁻¹ and 875 h⁻¹ maxima) on a week-day. Net energy columns (marked N) account for the power reduction factor associated to unsteady features (wind drops between two clusters of carriers)

The population of wind speed classes considered for Figure 1 estimations is that of pure traffic-generated wind, meaning that samples of non neglectable atmospheric wind (anemometer far enough from road >0.5 m/s) were excluded.

Major concerns about the possible operation of a conversion device with aerodynamic losses of vehicles are due to wind-drops occurring between two clusters of carriers, as corresponding transient wind inlets will strongly influence the performance of the turbine. In conventional estimation of wind energy production, unsteady features are not accounted for, meaning that reference is made to a site where average wind is the rated speed, and standard deviation should be as small as possible. Nevertheless, variable speed operation and long wind drops of the site will generally affect production to the extent that the wind turbine capacity factor commonly decreases from 1 (ideal production at rated speed) to 0.25.

To estimate the net gain in capacity factor caused by the traffic-generated wind contribution we need therefore to consider unsteady features. In Figure 2 is shown a typical time signal recorded on-site: positions of the probes are numbered by increasing distance from the carrier top (pos. 1 at 1m, pos. 4 at 8m), while the dashed line indicates a possible cut-out speed (3 m/s) limit for the turbine. Time intervals where pos. 1 is less than cut-out speed are the voids corresponding to the wind-drops between carriers travelling at $U_0=100$ km/h.

In Figure 3 one can appreciate the most interesting feature of such wind-drops, i.e. their incredibly high correlation ($R^2>0.85$) with the heavy vehicles flow, in terms of mean duration, standard deviation and number of voids.

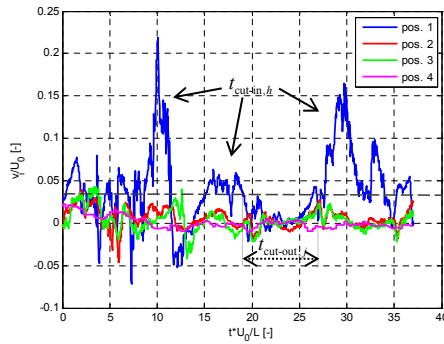


Fig. 2: Example of traffic-generated wind time signal (adimensional): positions of the probes are numbered by increasing distance from the carrier top (pos. 1 1m, pos. 4 8m), dashed line is cut-out speed, and $U_0=100$ km/h is the avg. vehicle speed, L vehicle length (standard European truck 16m)

2. UNSTEADY FEATURES: TOWARDS THE ESTIMATION OF A POWER REDUCTION FACTOR

Assuming that start-up conditions of the device can be met (triggered by traffic-generated or atmospheric wind), we want to possibly estimate a power reduction factor to be applied directly to C_p in order to give the net gain in the capacity factor associated to the new wind source, as a function of its unsteady features. If $n_{void,h}$ is the number of voids in the hour h extracted from Figure 3, and $t_{cut-in,h}$, $t_{cut-out,h}$ are respectively the total amount of samples above cut-in speed, and the single void duration (see Figure 2), then time can be expressed by:

$$T_h = t_{cut-in,h} + \sum_{j=1}^{n_{void,h}} t_{cut-out,j} \xrightarrow{\sigma_{cut-out} \rightarrow 0} t_{cut-in,h} + n_{void,h} \cdot \bar{t}_{cut-out,h} \quad (1)$$

where the first expression in (1) can be fairly approximated by the second expression for high enough traffic flow, as Figure 3 shows that the standard deviation of $t_{cut-out,j}$ decreases more than linearly with increasing heavy vehicles flow, while $\bar{t}_{cut-out,h}$ becomes a constant.

If we assume to neglect the $(n_{void,h} \cdot t_{cut-out,h})$ in the energy count (device below cut-in speed),

and we consider $t_{cut-in,h}$ with the associated frequencies $f_{h,j}$ of wind speed classes V_j , then the total net energy, that can be harvested per day summing over h can be written as:

$$E_d = \sum_h (1 - \Delta C_p) C_p 0.5 \rho (2RH) \left(\sum_j f_{h,j} V_j^3 \right) t_{cut-in,h} \quad (2)$$

where $\Delta C_p(I, D, t_{cut-out,h})$ is a power reduction factor to determine, depending only on the mean wind-drops durations and on the machine mechanical properties (mainly inertia and damping). To determine this factor we developed a family of mini-VAWT H-Darrieus prototypes whose power curves were measured by boundary layer wind tunnel (BLWT) tests, and we implemented a blade element momentum (BEM) transient code, whose steady results were validated through the corresponding BLWT tests; finally from transient runs of the BEM code, a power reduction factor as ΔC_p in (2) could be estimated.

3. A TRANSIENT BEM CODE TO INVESTIGATE THE BEHAVIOUR OF A MINI-VAWT

3.1 A. Boundary Layer Wind Tunnel tests

With the aim of eventually calibrating a time-dependent code based on a theoretical approach derived from the Blade Element Momentum Models, an experimental campaign has been carried out in the CRIACIV (Inter-University Research Centre on Building Aerodynamics and Wind Engineering) boundary layer wind tunnel laboratory at Prato, Italy. The facility is an open-circuit wind tunnel with a total length of about 22 m, a test section 2.4 m wide and 1.6 m high with an upstream fetch of about 8 m, Wind speeds up to 30 m/s can be obtained with a free-stream turbulence around 1%.

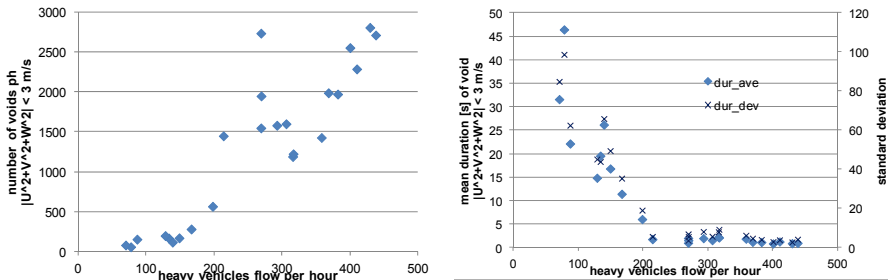


Fig. 3: Measured correlation of mean duration, standard deviation and number of wind-drops with heavy vehicles flow

The analyses were performed on six prototypes of rotors of small VAWT H-Darrieus wind turbines, composed by three blades made by NACA asymmetric carbon fiber profiles. The VAWTs differed each other for the values of the chord (47 and 94 mm), the rotor diameter (50 and 100 cm) and for two different lengths of the blades (75 and 150 cm).

The characteristic WT power curves are directly measured in wind tunnel thanks to an appropriate experimental set-up. It consisted of three main parts, the drive shaft of the VAWT, the support system and the chain measurement. The shaft on which was located the WT was supported at two points, outside the test section of the wind tunnel, through 4 bearing units SLB UKFC 206 and connected to the Brushless motor by means of a torque sensor. The Brushless motor may act as a Brake in case the turbine delivers a positive torque (production), or by a real Motor dragging the rotor at a fixed torque or RPM (absorption). In these two modes of operation Engine and Brake, it is possible to measure directly the torque of the rotor as a function of RPM. The instrumentation used during tests consisted of a bidirectional Torque Sensor DR20 of Lorenz Messtechnik with $FS \pm 20Nm$ and accuracy of 0.1% FS and an optical encoder (optoNCDT 1605 of Micro-epsilon) used to measure the RPM of the rotor (0÷1500 RPM). The approaching wind speeds (4÷15 m/s) were checked by means of a Pitot tube, connected to a high precision SETRA pressure transducer, located 3 meters upstream of the turbine in a position of undisturbed flow. The signals acquisition were performed with A/D card NIcDAQ 9239 24-bit at sampling frequency of 2000 Hz. and post processed in LabView and MATLAB environment.

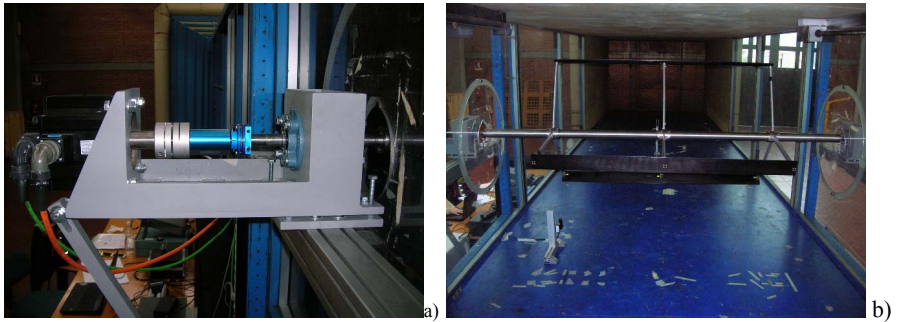


Fig. 4: Particular of the experimental set-up: a) connection between motor-torque-VAWT (chain of measurement), b) overview of the prototype TREO 94x1500 R50 during the tests.

Figure 4 and 5 reports for the model TREO 94x1500mm R50cm the power coefficient curves as a function of the tip speed ratio. They are obtained by subtracting the influences of friction due to the drive shaft and the WT support arms.

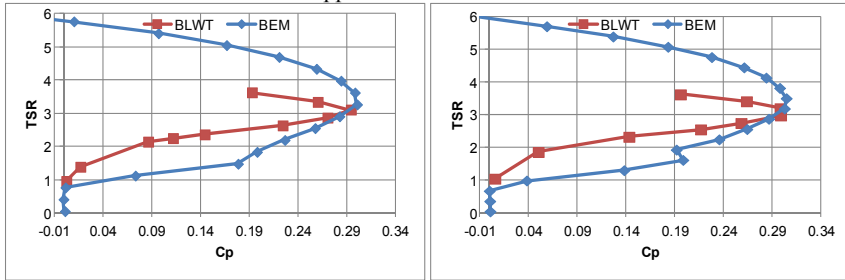


Fig. 5: Power coefficient VS tip-speed ratio adimensional Power Curves for calibration between Boundary Layer Wind Tunnel tests (BLWT) and Blade Element Momentum numerical code (BEM): 8.3 m/s (up) and 11 m/s (down) inlet.

3.2 BEM code Implementation Notes

Though according to Simão-Ferreira [4] new tendencies and perspectives are increasingly applied to investigate in depth the complex aerodynamic phenomena which take place during a VAWT functioning, a theoretical approach based on the Blade Element Momentum (BEM) method can still provide some advantages under defined circumstances, particularly when a reduction of the computational cost is needed. The issue is mostly relevant in approaching the transient analysis of a turbine, in which the aerodynamic interactions must be solved instant by instant, with a sensible increase of the computational efforts [5]. The numerical tool for the evaluation of the transient behavior was conceived as a direct subroutine of the main BEM multiple-streamtube code dealing with steady aerodynamics of an H-Darrieus turbine and having the torque maps library as an output. The library contains the torque value of a single blade as a function of the machine rotating speed $\dot{\theta}$ and azimuth angle θ for a fixed inlet wind velocity V_{∞} . Starting from these input parameters and from some boundary conditions (i.e. initial turbine azimuth position θ_0 , revolution speed $\dot{\theta}_0$, damping D, inertia I), the time-dependent code, instant by instant, solves the equation of motion (3) in the time domain with a non-linear Newmark scheme:

$$I\ddot{\theta} = D\dot{\theta} + T_{\text{LOAD}}(t) + T_{\text{PARA}}(\theta, \dot{\theta}) + \sum_{i=1, \dots, N} T_{\text{AERO},i}(\theta, \dot{\theta}, V_{\infty}(t)) \quad (3)$$

where the loading (generator) torque $T_{\text{LOAD}}(t)$ can also be a component in equilibrium. The aerodynamic torque value $T_{\text{AERO},i}(\theta, \dot{\theta}, V_{\infty}(t))$ at each instant is determined by an interpolation within the torque map libraries for each of the blades $i=1, \dots, N$, corresponding to the actual instant wind velocity $V_{\infty}(t)$, and past iteration tip-speed and azimuth position. Parasitic torque $T_{\text{PARA}}(\theta, \dot{\theta})$ arriving from shaft shadow effect and radial arms, and Betz limit correction are also applied. Other improvements such as the account for streamtube expansion and virtual camber effect due to pitching blade motion still need to be implemented. From Figure 4 it can be stated that calibration between BEM and BLWT power curves has been achieved.

3.3 Transient analyses and Power Reduction Factor

To estimate a power reduction factor as in (2) the transient BEM code has been run in a number of tests providing a common set-up of all the parameters, and a different choice of $\bar{t}_{\text{cut-out},h}$. In particular, the geometry of the H-Darrieus mini-VAWT is taken so that $2RH=1.5$ and a best practice damping (two roll bearings, with average oil depth), inertia (aluminium material) and radial solidity $Nc/R=0.6$ (where $N=3$ number of blades and c chord) are selected. The wind inlet $V_{\infty}(t)$ is assumed as $\frac{v_i}{U_0}=0.2$ consistently with Figure 2 peaks, and is perturbed by a wind-drop between two carriers (or clusters of vehicles) having different $\bar{t}_{\text{cut-out},h}$ duration per each transient run. As can be seen from Figure 5, the device is initially (up to 400 s) let to start-up and reach its free-run speed associated to $\frac{v_i}{U_0}=0.2$ (zeroes in C_p axis for higher TSR in Figure 4), while the maximum power point torque ($C_{p,\text{opt}}$ in Figure 4) is then applied as a constant load to the turbine, causing it to speed-down (to TSR_{opt} in Figure 4) generating aerodynamic torque for the equilibrium in (3), and thus power.

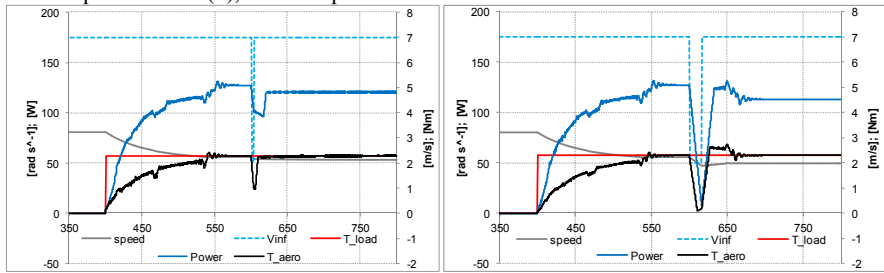


Fig. 6: BEM transient analyses for wind inlet including perturbations in the form of wind-drops, similar to the aerodynamic losses case: 2s duration (top) and 15s duration (bottom)

In Figure 5 are then shown 2 perturbations in $V_{\infty}(t)$ occurring at $t=600$ s and caused by the traffic wind-drops: in particular in the upper run $\bar{t}_{\text{cut-out},a}=2$ s is taken as characteristic of heavy vehicles flow in the range of 250 h^{-1} (see Figure 3), and in the lower run $\bar{t}_{\text{cut-out},b}=15$ s is taken as characteristic of heavy vehicles flow in the range of 100 h^{-1} (see Figure 3). Measuring power reduction from the corresponding curves in Figure 5 it can be obtained:

$$\Delta C_p(I, D, t_{\text{cut-out},a}) = \frac{(P_{\text{max}} - P_{\text{min}}(t_{\text{cut-out},a}))}{2P_{\text{max}}} \square \left[\frac{(P_{\text{max}} - P_{\text{min}})}{2t_{\text{cut-out},a}} \cdot \frac{1}{P_{\text{max}}} \right] t_{\text{cut-out},a} = \alpha_1(I, D)t_{\text{cut-out},a} \quad (4.a)$$

$$\Delta C_p(I, D, t_{\text{cut-out},b}) \square \dots = \alpha_1(I, D)t_{\text{cut-out},b} \quad (4.b)$$

Thus the analyses demonstrate that the power reduction factor can be fairly approximated as a constant depending on the machine properties, times the wind-drop duration: $\Delta C_p = \alpha_1 t_{\text{cut-out}}$, where $\alpha_1 \cong 0.025$. The wind-drop durations of Figure 3 that are averaged in the hour of the corresponding heavy vehicles flow, can therefore be used in (4) to calculate the power reduction factors as in Table 1. The net energy harvestable in the typical weekday by the sole traffic-induced wind can finally be calculated with (2), and the contributes subdivided by hours are highlighted in the light-gray columns of Figure 1.

Tabela 1: Net energy calculation: wind drops duration and power reduction factor

hour (day time)	8	9	10	11	12	13	14	15	16	17	18	19
heavy vehicles flow	358	410	382	429	368	292	306	269	317	438	400	269
average wind drop [s]	1.97	1.37	1.24	1.01	1.3	2.09	1.67	1.64	2.23	1.08	0.96	1.09
power reduction factor	0.950	0.965	0.969	0.974	0.96	0.947	0.958	0.959	0.944	0.973	0.976	0.972
hour (night time)	20	21	22	23	24	1	2	3	4	5	6	7
heavy vehicles flow	214	167	149	139	70	134	78	87	128	198	316	269
average wind drop [s]	1.88	11.54	16.93	26.28	31.7	19.65	46.55	22.25	14.95	6.15	2.35	2.12
power reduction factor	0.953	0.711	0.576	0.343	0.207	0.508	0.163	0.443	0.626	0.846	0.941	0.947

From Figure 3 (top and bottom) is clear that above a critical flow ($>200 \text{ h}^{-1}$) the amount ($n_{\text{void},h} \cdot \bar{t}_{\text{cut-out},h}$) tends to 3600s, and that is why it is a realistic assumption to calculate net energy as in (2), where C_p is affected permanently by ΔC_p . In fact, in equation (2) it is implicitly assumed that the continuous and rapid transit of vehicles in clusters results in cycling and superposition of the simple pulses, separated by wind-drops that are so short to allow the measured wind to energize the conversion device, even though at a reduced C_p , as calculated in (4).

4. RESULTS AND DISCUSSION: ESTIMATION OF REDUCTION IN LEVELISED COST OF ENERGY (LCOE)

From the data presented by IRENA is possible to retrieve a normal distribution of capacity factors for on-shore wind turbines in different regions of the world [6]: in particular, in Figure 6 is presented the capacity factor distribution for Europe and Central Asia (gray curve). The total net energy extracted from the higher density of traffic in Figure 1 in 5*52 weekdays has

been added to the same distribution, and thus the red curve in Figure 6 has been obtained, allowing to estimate the capacity factor distribution of a wind turbine for which the atmospheric wind operation is coupled to the transport system induced wind. The mean value increases by a substantial amount coupling the aerodynamic losses energy harvesting.

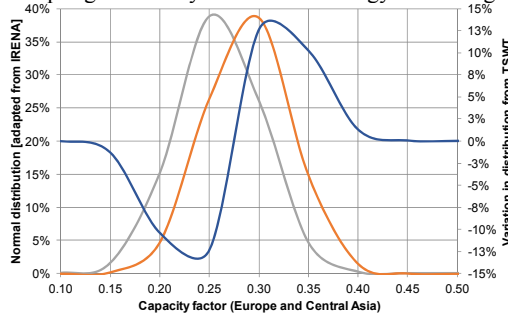


Fig. 7: Capacity factor for Europe and Central Asia: atmospheric wind case (gray curve, adapted from IRENA), and atmospheric-traffic wind coupled case (red curve). Variation in capacity factor distribution caused by the transport system application is indicated by the blue curve.

The new capacity factors can be used to estimate the LCOE with equation (5), where I are investments, M are O&M costs, and E is the extracted energy.

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (5)$$

Because I and M can be reasonably estimated in atmospheric-traffic wind coupled case, a 15 to 20% mean capacity factor increase is also interpreted as a 15 to 20% LCOE reduction, as illustrated in Figure 8. In column 3 the mini-VAWT is operating in coupled atmospheric and traffic-generated wind, and is assumed to be integrated into existing road signals, bridges or overpasses. In column 4 the mini-VAWT is again operating in coupled atmospheric and traffic-generated wind, but is assumed to be installed in an independent steelwork structure.

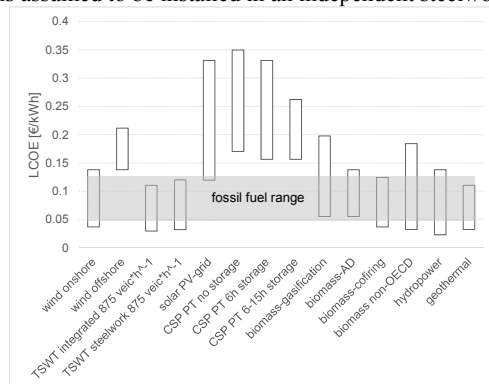


Fig. 8: LCOE data 2012 in OECD countries for different renewables (all columns except 3rd and 4th are adapted from IRENA [6]): atmospheric-traffic wind coupled cases are highlighted in columns 3 and 4 (transport systems wind energy technology, TSWT)

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REVIEW OF POWER CONVERTERS FOR WIND ENERGY SYSTEMS

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Abstract

The paper presents commonly used power electronic topologies in Wind Energy Conversion Systems. It discusses the main differences between partially and fully rated converters, their control methods and their application in large and small scale wind turbines. The paper also presents methods of tracking the optimal power point for permanent magnet synchronous generator based wind energy systems.

1. Introduction to wind energy conversion systems

A wind energy conversion system consists of a rotor that captures energy from the wind and converts it into mechanical energy as torque and speed. This energy is then converted to electrical energy using an electrical generator. In the majority of cases, generated electrical energy is fed to the grid at an appropriate voltage level.

1.1 Aerodynamic energy conversion

The power available in a wind stream P_{air} is given by Eq. 1, [1, 2].

$$P_{air} = \frac{1}{2} \rho A V_w^3 \quad (0)$$

where ρ is the air density [kg/m^3], A is area swept by the rotor [m^2] and V_w is the free wind velocity [m/s]. This power cannot be completely extracted and the conversion efficiency is dependent on the power coefficient C_P which is the ratio between the extracted power P_w and the available power P_{air} as defined by Eq. 2, [3].

$$C_P = \frac{P_w}{P_{air}} \quad (0)$$

This coefficient can have a maximum of 0.593, known as the Betz limit. It is a function of two variables: the blade pitch angle β and the tip speed ratio λ , which is given by Eq. 3 [1].

$$\lambda = \frac{\omega_{rot} R}{V_w} \quad (0)$$

where R is the radius of the rotor [m] and ω_{rot} is the rotational speed of the rotor [rad/s]. Hence, the power extracted by the rotor of a wind turbine is given by [1]:

$$P_w = \frac{1}{2} \rho A V_w^3 C_P(\beta, \lambda) \quad (0)$$

A typical variation of C_P as a function of the tip speed ratio for different pitch angles is shown in Fig 1. It can be observed that there is only one tip speed ratio value at each pitch angle that gives a maximum C_P . Therefore, by controlling the speed of the rotor (generator) to follow the tip speed ratio that maximises C_P , maximum power extraction can be achieved at different wind speeds [4]. This is one of the motivations for using variable-speed operation.

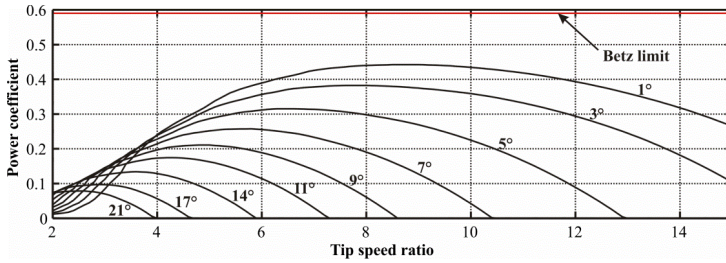


Fig 1: Variation of C_P as a function of the blade pitch angle β and tip speed ratio λ

1.2 Operating Regions of variable-speed wind turbine

A typical power vs. speed characteristic of a variable-speed wind turbine in per unit¹ is shown in Fig 2, where the optimal rotor speeds for maximum power extraction at different wind speeds are highlighted. Also as shown, the operating regions of a wind turbine can be divided into mainly three regions. The amount of wind power available in Region 1 is not enough to overcome the turbine losses and therefore it is unproductive. In this region, for large scale wind turbines the rotor is held stationary and the generator is disconnected from the utility grid until the cut-in wind speed is reached. Typical cut-in wind speeds vary between 3 to 5 m/s depending on the scale and turbine design [5-7]. In Region 2, the turbine is operated at variable speed to maximise the extracted power from the wind. This region ranges from the cut-in to the rated wind speed at which rated power is produced. Region 3 is mostly relevant for large scale wind turbines and is the constant torque region which ranges from rated to the cut-out wind speed, which for most turbines is 25 m/s. In this region, the rotor speed is controlled using the pitch mechanism to maintain rated power not to overload the turbine component design ratings. Above this region, the wind turbine is shut down for protection.

¹ 1 pu speed and power denote the rated speed and power of a wind turbine

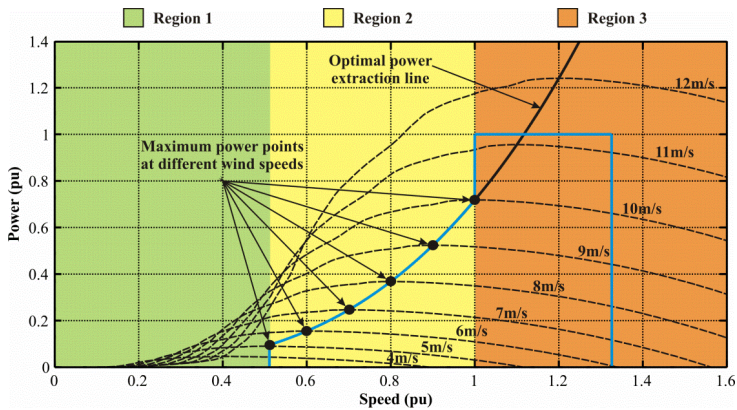


Fig 2: Power vs. speed characteristic of a variable-speed wind turbine

1.3 Variable-speed wind turbine architectures

The present techniques for converting mechanical to electrical energy in a wind turbine are shown in Fig 3. It shows different possible technological options such as with or without gearbox, using synchronous or induction machines and different power converter topologies. These concepts can be split into two groups according to their power converter rating: partially rated (PRC) and fully rated converters (FRC).

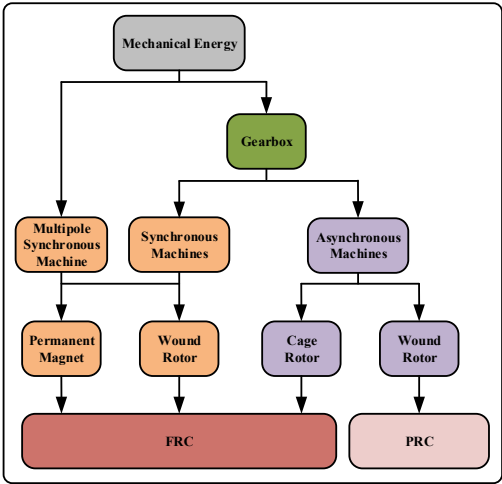


Fig 3: Wind energy conversion technology routes [8]

Wind turbines are generally divided into two broad categories, large scale and small scale systems. Large scale systems are intended to generate power in bulk to replace conventional generation. Energy yield and availability are then the main objectives. Small scale wind turbines are intended to supplement conventional generation or for remote areas. The design

of such systems is driven by cost optimisation of the turbine components and the converter. Due to the different objectives, the adopted solutions are generally different with large scale systems driving the technology and small scale systems opting for the simpler alternatives.

2. Large Scale Wind Energy Systems

Large scale wind turbines comprise systems whose power ratings exceed 100kW. Power ratings rise substantially up to 8MW, with current plans pushing the ratings up to 10MW. Such systems are generally located in prime wind locations, and due to the current energy prices, have also been installed offshore. Large scale systems are generally grid connected and are interfaced to the grid at high voltage levels. Apart from the active power control, they are also generally required to control the flow of reactive power. Different architectures, classed by the power converter topology are described below.

2.1 Wind Turbine Architectures

2.1.1 Wind turbine architectures with partially rated converters (PRC)

A wind turbine equipped with a wound rotor asynchronous machine with a PRC has been a very popular approach for achieving variable-speed operation. The advantages of this architecture are lower converter costs and losses, since the power converter handles only a fraction (20–30%) of the total power [9]. The disadvantages of such system is a limited variable-speed operation range and higher maintenance costs due to the slip rings required to access the rotor windings [10]. There are two variants of this approach: the variable-slip operation and the doubly-fed [8, 11].

Fig 4 shows the block diagram of a wind turbine equipped with a wound rotor induction generator (IG) configured for variable-slip operation. The wind turbine rotor is coupled to the generator through a gearbox since the rated speed of induction generators is usually higher than that of the wind turbines. The pitch control adjusts the angle of the blades to lower the power coefficient and limit the energy capture in Region 3. The three phase generator rotor windings are connected to external resistors through a power electronic converter. Variation in the effective rotor resistance will result in a variation of the generator slip, which ultimately affects the rotational speed [10]. The typical speed variation with the variable-slip operation is less than 10% [8, 9]. In this configuration the generator draws reactive power from the grid to build up the magnetic field. Therefore, capacitor banks are usually installed to compensate for the reactive power absorbed [10]. Moreover, a soft-starter is needed to limit the inrush current during start-up [11]. The system is interfaced to the grid through a transformer to step up the voltage level as required.

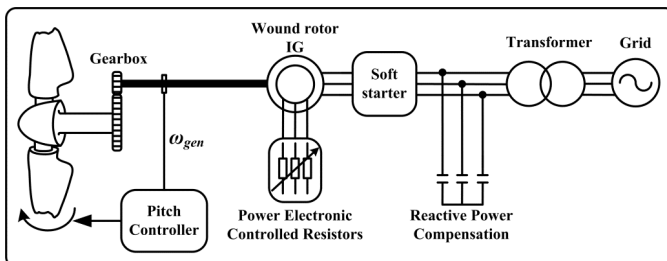


Fig 4: Wound rotor induction generator with variable-slip configuration

A typical configuration of a doubly-fed induction generator based wind turbine is shown in Fig 5. The mechanical interface to the turbine rotor and the pitch control is similar to that of Fig 4. The rotor of the wound rotor induction generator has its rotor connected to the grid through a PRC. The converter is typically a back-to-back voltage source converter with a typical rating of 30% of the rated power [8]. This converter decouples the rotor frequency from the grid frequency, hence enabling variable-speed operation [3]. The speed variation is directly related to the power of the rotor side converter and is typically $\pm 30\%$ of the synchronous speed [8, 10]. In this configuration, electrical power can be delivered to the grid through both the stator and the rotor depending on the generator speed. In the case of super-synchronous speed operation, electrical power is delivered to the grid through both the stator and rotor. On the other hand, when the generator is operating in sub-synchronous speed, electrical power is delivered to the grid through the stator only whilst the rotor side absorbs active power [3]. The crowbar protects the generator and the converter from any over-currents during grid failures.

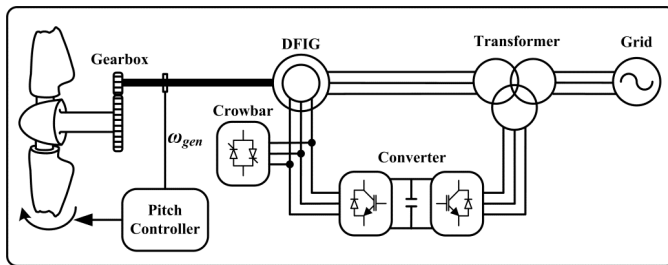


Fig 5: Doubly-fed induction generator configuration

2.1.2 Wind turbine architectures with fully rated converters (FRC)

A typical configuration of a FRC based wind turbine is shown in Fig 6. The FRC configuration is characterised by a broad variable-speed operation ranging from stand-still to the full rated speed [1]. This is one of the advantages of a FRC over the PRC based turbines. However, in this case the converter cost and losses are higher due to the full power rating [9].

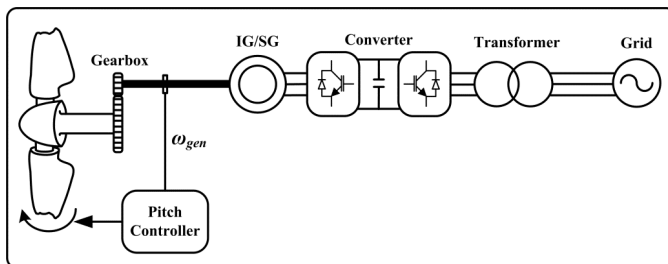


Fig 6: Fully rated converter configuration

In this configuration, the generator is connected to the grid through a back-to-back voltage source converter. Therefore, it offers complete decoupling of the generator from the grid frequency, thereby enabling variable-speed operation. Moreover, full control of the active and reactive powers is possible with this type of converter [10]. This is highly desirable in order to

fulfil Grid-Code requirements [11]. As indicated in Fig. 6, the FRC configuration applies for both synchronous generators (SG) and IGs.

A SG has the ability to provide its own excitation on the rotor, either by having a wound rotor or by permanent magnets. The two generator variants are referred to as the electrical excited (EESG) and the permanent magnet synchronous generators (PMSG) respectively. Recently, PMSG are gaining more popularity particularly for offshore applications. SGs allow multipole construction that enable matching of the generator speed to the rotor speed. This allows direct mechanical connection between the rotor and the converter, hence eliminating the gearbox as shown in Fig 7.

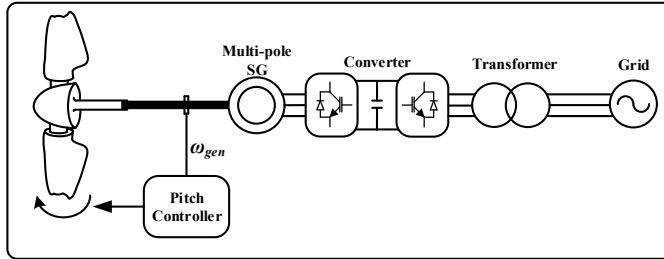


Fig 7: Gearless configuration

In the case of a SG, the voltage source converter on the machine-side can be replaced by a diode rectifier as shown in Fig 8. This makes the converter cheaper; however, the control of the whole system becomes more difficult. A boost converter is normally used to increase the DC link voltage more than the grid line to line voltage in order to achieve full control of the grid current [12].

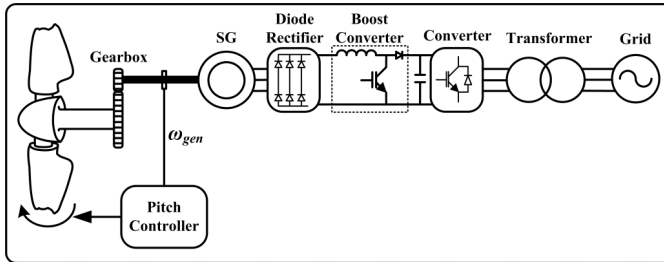


Fig 8: Fully rated converter with diode rectifier configuration

The EESG based wind turbine configuration is shown in Fig 9. It can be observed that in addition to the FRC there is a diode rectifier to provide the DC excitation current to the rotor. In the EESG, the rotor is often a salient pole type which is typically used for low speed applications. This configuration is attractive for direct-drive applications [9].

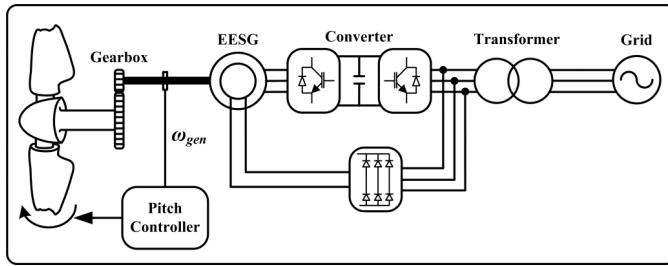


Fig 9: Electrically excited synchronous generator configuration

2.2 Wind turbine control

Large scale wind turbines have several layers of control [13]. These can be classified into three categories: Supervisory, Power production and Safety. The supervisory control is responsible for starting, stopping and emergency stops sequences, braking, yawing and health monitoring of the turbine. The power production aim is to maximise power below rated wind speed and controlling the rotor speed above the rated wind speed. An additional control task in this category is load alleviation. The safety system ensures that the turbine is kept within the normal operating limits if the supervisory control fails. Therefore, this control system has to be independent of the other systems and must have its own power source.

3. Small Scale Wind Energy Systems

Wind turbines whose power rating do not exceed 100kW are known as micro or small scale wind turbines. The different designs that are presently available can be generally of two types: Horizontal Axis (HAWT) or Vertical Axis Wind Turbines (VAWT).

3.1 Wind Turbine Architectures

3.1.1 Horizontal Axis Wind Turbines

HAWTs follow similar designs used for large scale wind turbines. Due to the overriding cost considerations, they generally do not include sophisticated pitch and yaw control mechanisms. Typical solutions for orienting the rotor into the wind generally vary from the use of a tail vane for upwind to self-aligning designs for downwind turbines. The tail vane mechanism can also include features of furling of the rotor above rated wind speed. The power extraction in Region 3, identified in Fig 2, is also limited by furling, where the blades are appropriately designed to lower the conversion efficiency at such wind speeds.

3.1.2 Vertical Axis Wind Turbines

The HAWTs are popular in rural areas, have a higher C_P than the vertical type, however they do not operate efficiently in turbulent winds [14]. VAWTs are ideal for installations where wind conditions are not consistent, such as in built up areas as they do not need a yaw mechanism to turn the rotor into the wind. The VAWTs can be of three types: Savonius, Darrieus and H-Rotor type as shown in Fig. 10. The Savonius is a drag-type turbine and is the least efficient of the three vertical types, on the other hand the Darrieus is complicated to manufacture and can suffer from starting problems. The H-rotor is a derivative from the Darrieus and requires less complex

control. To date, the HAWT remains the most popular turbine due to its greater efficiency and ease of control.

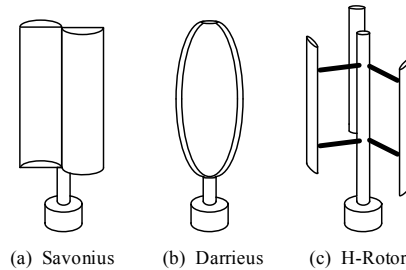


Fig. 10: Types of Vertical Axis Wind Turbines

3.2 Converter Topologies for Micro-Wind Turbines

Micro wind turbines normally make use of a PMSG as the means of converting the mechanical rotational power into electrical power. As identified before, the main advantage of this type of electrical machine is that the magnets on its rotor provide the magnetic field (self excitation). Although there can be plenty of power converter topologies used for PMSG power extraction and transfer to the electrical grid, the two most common systems set-ups follow those of Fig 7 and Fig 8. In the case of the latter figure, for a small wind turbine there is no gear box or pitch control, moreover for both figures, the connection to the grid is generally at low voltage, single phase and not three phase.

The most common set-up found in commercial micro-wind systems consists of a diode-bridge rectifier, a boost converter and a voltage source converter (VSC) as shown in Fig 8. The rectifier converts the PMSG three phase output into a DC voltage and the boost converter is used to control its power operating point. A braking chopper is installed on the DC link to limit the voltage during wind gusts and grid faults. The grid-connected inverter is a current controlled VSC which transfers power to the electrical grid.

For micro-wind applications, the set-up shown in Fig 7 is more expensive than that of Fig 8 however it allows for better generator speed control and higher quality of the machine's currents [15]. This system consists of two back-to-back converters which allow bidirectional power flow. The machine-side converter acts as an active rectifier and can be controlled to achieve a sinusoidal current output from the generator which is of superior quality to the non-linear output current achieved by the rectifier in Fig 8. The DC link voltage needs to be higher than the peak of the grid voltage at all times, this voltage is kept constant by proper control of the grid-side converter.

4. Control of FRC PMSG based Wind Turbines

The FRCs shown in Fig 11 and Fig 12 make use of a machine-side and a grid-side converter. Both converters have their own individual control; this section shall focus mainly on common methods of control of the machine-side converter.

In Fig 11, assuming a fixed or zero pitch angle, the maximum power point tracking (MPPT) strategy uses a wind speed reference to determine the optimum tip speed ratio for maximum power coefficient (Fig 1). From this ratio the optimum rotational speed of the generator's rotor

can be deduced, this type of control is sometimes called Tip Speed Ratio Control [15,16]. The wind speed can be directly measured or estimated. The outer speed loop is used to determine the torque current reference (I_q^*). The other current, (I_d^*), also known as the field current, is used for field weakening however this is normally set to zero. Using field oriented vector control, the two dq-current demands are used as reference for the inner current control loops which generate the V_d and V_q references. These are transformed to the equivalent three phase reference voltages (V_a, V_b, V_c) which control the machine-side converter.

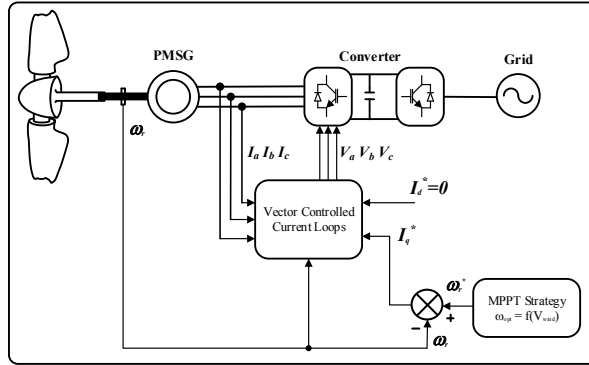


Fig. 11: Tip Speed Ratio Control of PMSG side inverter

The second type of control shown in makes use of a predetermined wind turbine power curve. During commissioning this curve is derived as a function of the rotor angular speed (rather than the actual wind speed) and stored in a look-up-table (LUT). This eliminates the need of wind speed measurement or its estimate. The output of the LUT gives the maximum power point value for a given rotational speed, which is used to obtain the torque current reference (I_q^*) as shown in Fig 12. As in the former case the field current (I_d^*), is normally set to zero.

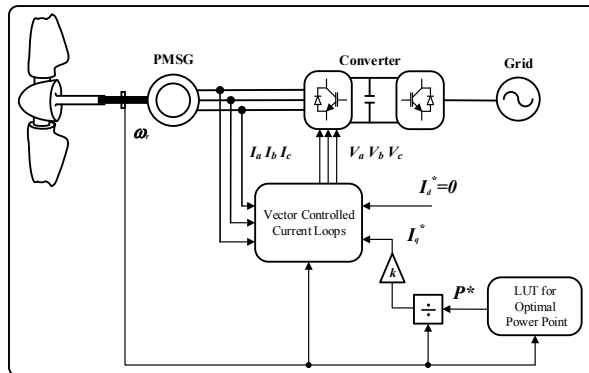


Fig. 12: Power Control of PMSG side inverter

Although not shown in Fig 11 and Fig 12, the grid-side converter also requires a control mechanism. This converter allows for the flow of both active and reactive power to the grid. The grid-side converter control scheme ensures that the DC link voltage remains constant and

at the same time controls the converter to absorb/produce grid reactive power whilst allowing the maximum active power to be supplied to the grid.

4.1 Control of Small Scale Wind Turbines

The control strategies described previously apply to both small and large scale wind systems. However due to cost considerations, strategies that require the use of speed or wind sensors are not usually applied. The common configuration for commercial systems is the set-up shown in Fig 13. The rotational speed of the PMSG is controlled indirectly through variation of the DC link voltage (V_{dci}) at the input of the boost converter. A LUT is used to map the optimal DC link voltages to output power levels. During operation, the output power is measured and used to select the optimal setting of the dc link voltage. This is then forced through the controller, which adjusts the duty ratio of the boost converter as shown in Fig 13. The variation in the input DC link voltage causes the rotor to accelerate or decelerate accordingly until the operating point converges to the maximum power point (MPP), where the power output and the set DC link voltage match.

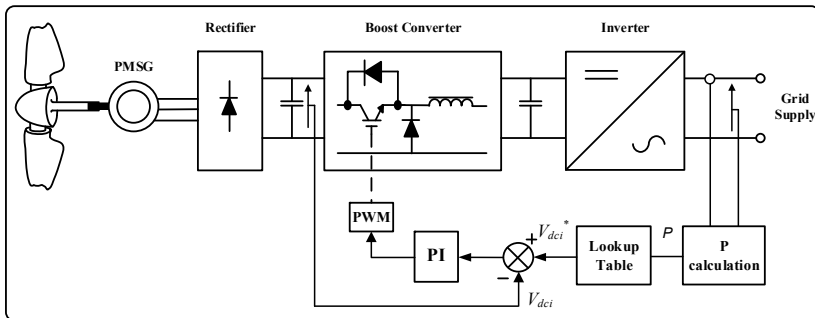


Fig. 13: MPPT Control of Boost Converter for Single Phase Micro Wind Turbine System

Another control strategy that can be applied on the topology of Fig 13 is the Hill Climb Technique. The technique continuously searches for the MPP condition by introducing small perturbations in the DC link voltage set-point and the resulting output power is compared to the previous value. If there is an increase in power, the perturbations are continued with the same polarity, otherwise their polarity is reversed. This process is shown in Fig 14. It can be observed that starting from both sides of the desired point leads to small changes in the rotational speed until subsequent convergence at the MPP. Refinements to the algorithm include the use of variable perturbation to avoid oscillations around the desired operating point. This technique is based on the assumption that although the wind varies highly with time, the generated power varies slowly because of the dynamics of the wind turbine and interconnected generator [17]. The same topology as shown in Fig 13 can be used, where the reference for the dc link voltage is obtained through the algorithm instead of the lookup table.

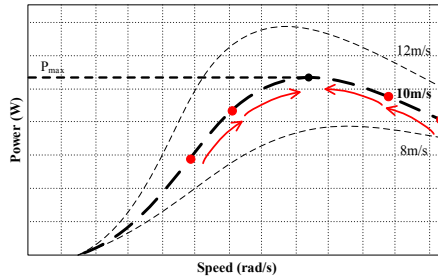


Fig. 14: Hill Climb Technique

5. Conclusion

This paper presented a review of the power electronic configurations for large and small scale wind energy systems. The paper described the basics of wind energy conversion, how to obtain the maximum power point according to the wind speed and tip speed ratio and how this can be implemented in practice. The paper also discussed the difference between geared wind turbines and direct drive systems using partially and fully rated converters. The different types of small scale horizontal and vertical axis wind turbine configurations and the difference in their performance were described briefly. To conclude, a description of the commonly used fully rated power converter topologies and the control mechanisms for permanent magnet synchronous generator based wind turbines were presented.

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Workshop Part 3

Society Acceptance and Related Issues

SOCIAL, ENVIRONMENTAL AND PLANNING CONSIDERATIONS OF WIND ENERGY TECHNOLOGY IN THE BUILT ENVIRONMENT. WORK GROUP 3: INTRODUCTION

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1 Introduction

The climate and energy package of the European Union, consists of binding legislation which aims to ensure that the European Union meets its ambitious climate and energy targets for 2020 [1]. These targets, known as the "20-20-20" targets, set three key objectives for 2020:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

The major contributors to locally produced renewable energy are principally photovoltaic systems, solar panels and combined heat power systems, whereas there is also a significant potential contribution from small and medium (15kW-100kW) wind turbines. In recent years, a significant growth in the sector of small and medium turbines has been noted with further expansion of this sector being expected in the coming years.

In this framework, COST Action TU1304 WINERCOST (WIND Energy technology Reconsideration to enhance the CONcept of Smart ciTies) addresses the objective of wind energy integration into urban and suburban built environment and identifies methods towards the acceleration of related applications to overcome technological, societal and other barriers [2]. For the purposes of this research activity, the COST Action aims at gathering the existing knowledge on onshore and offshore wind energy technology and to address the built environment wind energy technology. The aim is to provide the necessary tools and to contribute towards the strategy for Future Smart Cities.

2. Wind Energy Technology Reconsideration and Smart Cities.

The feasibility of installations of Small and Medium Wind energy Technologies (SMWT) in urban areas is significantly influenced by the acceptance of the local communities. A catalogue on social acceptance at the European level does not exist yet, although there have been some preliminary initiatives in international energy fora. This results from a different understanding and acceptance of SMWT. Nevertheless a thorough investigation of the social acceptance criteria is required and needs to be based on the existing knowledge about wind power in general, SMWT and the first examples of wind power in the built environment. This required research in different countries based on case studies. It is therefore crucial to discuss European energy policy and strategy for advancement of the BWT with consumers, municipalities, industry (turbine manufacturers) and grid operators. The investigation of optimized centralised or de-centralised grid-integration needs to be considered.

During Phase 1 of the WINERCOST Action, existing knowledge on on-shore, off-shore WT and other application of wind energy structures in particular BWT including Building-Integrated-Wind-Energy Technology applications, shall be assessed.

During Phase 2 of the WINERCOST Action, the activities shall focus on the development of a strategy to enhance the Smart Cities Concept by effectively introducing WT projects in the built environment. The activities also address barriers for technological implementation, possible non-technical negative effects (e.g. noise, production/installation costs, logistics, reliability, integrity, system robustness, aesthetic) and European energy policy as well as societal acceptance issues.

In this sense, the WINERCOST network of all relevant BWT-stakeholders will develop an overall view on required research needs and necessary research and development actions for the future of BWT in urban environments.

3. Challenges in Wind Energy Technology in the Built Environment

Built environment Wind energy Technologies (BWT) and related structures and infrastructure are expected to form an integral part of the Smart Cities of the future. Wind Technologies are expected to be integrated into urban spaces and closer to spaces where people. As past and current experience with wind energy shows, large WT moving structures very often receive significant opposition from the communities. This is most often relevant for new technologies and changes in society, and may relate to aesthetics, nuisance, processes or communication issues. Therefore, acceptance issues have to be considered when addressing new technologies including in particular BWT, both in the general planning as well as for integration in specific projects. The factors that need to be considered carefully include aspects related to policy, legislation, planning and environmental issues. Communication and processes also need to be respected while industry needs to address the challenges to design and produce socially acceptable products.

Working Group 3 targets at gathering information on the current state of knowledge and also in comparing the situation in various European countries. This is achieved through the review of published sources and literature but also through surveys and interviews with stakeholders, interested parties and groups in society. Based on the findings of this assessment, some approaches are developed for future implementation. In the last phase, a strategy for stakeholder dialogue is proposed bringing together the authorities, industry and research entities to test the approaches and to prepare the ground for the BWT to become reality through implementation in Smart Cities.

In Working Group 3 (WG3) of the COST Action TU1304 the aim is to provide an improved understanding of the challenges in the implementation of WT in the Built Environment. WG3 focuses on social, environmental and strategic planning aspects of Wind Energy Technology. This will be achieved through two phases: WG3A and WG3B. WG3A focuses on non-technical issues of WET including societal acceptance, European energy policy and municipalities-researchers-industries dialogue. WG3B will focus in more detail on societal acceptance, European BWT policy and other non-technical BWT issues. The WINERCOST aims to contribute to the advancement of the Wind Energy harvesting in the urban habitat by enhancing the Future Smart City concept

4. Social, Environmental and Strategic Planning Considerations

The proceedings present the contributions of Work Group 3, focusing on Social, Environmental and Strategic Planning issues and Wind Energy Technology.

4.1 Non-Technical Issues

Non-technical issues play an important role to be able to implement wind power in a specific environment. This was demonstrated through various debates on various projects in past years. Huber presents a review of Non-Technical Issues and Wind Power in the context of municipal energy and climate policy, based on the general acceptance of wind power and smart city approaches. There is a lot of knowledge and experience on non-technical issues of wind power as well as smart cities that can be used as a basis for the activities of WINERCOST, but further investigations and eventually case studies for wind power in the urban context are required [3].

4.2 Life Cycle Impact Analysis

Renewable Energy (RE) sources, such as wind energy, are preferred over non-renewable sources, due to the potential reduction in greenhouse gases (GHG) emissions. On the other hand, large scale WT also present significant challenges. Recent developments in micro-generation, and hence small scale WTs, relate to state-of-the-art technologies to effectively manage the demand, load and instabilities through effective planning, control and efficiency yield. A life cycle assessment (LCA) allows for environmental impact evaluation during the whole life cycle stages from production, to operation and generation of energy on site. In this way a LCA leads to a comprehensive evaluation of performance of a technology. This paper presents a comprehensive life cycle assessment review of Wind Turbine (WT) technology. Bertasiane, Borg and Azzopardi present a review of Life Cycle Impact Analysis of Wind Energy Systems [4].

4.3 Planning and Environmental Considerations.

Norton draws from current theory and practice to set out the main environmental and planning considerations relating to planning and developing wind energy in the urban environment in Europe. The role of wind energy in the urban environment within the renewable energy sector and progress to date on technical and wind resource issues are considered. A set of environmental considerations that are appropriate to the urban environment are identified and the main functions and considerations for spatial planning systems in the development of wind energy in the urban environment are presented. Recent practice guidance for spatial planning and a wind energy project in a new neighbourhood are presented as better recent practice in this area [5].

4.4 Local Authorities & Wind Trubines in Urban Areas.

Europe faces moments of transition. One of the main goals of Europe for the next decades is the implementation of clean and efficient energy, not only from the environmental point of view, but also considering financial, employment and security aspects. Meeting EU's objective of achieving 20% of renewable energy by 2020 has the potential to create more than 600,000 jobs and result in a reduction of €60 billion in oil and gas imports by 2020. Towards this goal, local authorities have an important role to conduct, concerning both large energy projects as well as urban energy facilities like photovoltaic systems and built environment wind energy technology. Efstathiades addresses the role of Local Authorities in the engagement of Wind Turbines in Urban Areas [6].

4.5 Social acceptance: Urban Wind Energy

Apart from urban wind turbines' contested energy generation capability, research undertaken so far is inconclusive on the social acceptance of the visual exposure to and physical presence of urban wind turbines. Research suggests that when the public are asked about their acceptance of a new technology, they show higher levels then when asked after it is actually built and its performance scrutinized in the media. Parallels will be drawn with the realm of the 'High tech' style in architecture and architects' attempts to deal with public perception. This leaves us with the following questions: How much of it do we need to expose of what is considered a supporting energy generation technology to urban living? What hypothesis can be drawn on challenges facing the public acceptance of urban wind and its possible appreciation as a reliable mechanism as well as a desired symbol for urban sustainability? Hamza explores the mutually exclusive relationship between public acceptance, its impact on building policies and the current architectural endeavours and their attempts to integrate this technology [7].

4.6 Economic, Environment, Social Factors and Efficiency: Lithuania

Marčiukaitis et al examine developments in wind power and future prospects in Lithuania. Additionally, the performance of operating wind farms is analysed comparing their technical parameters and economic indicators. Analysis has shown that the main factors influencing the efficiency of wind turbines are tower height and the distance from the Baltic sea. Also, environmental aspects and permission requirements are analysed and the main barriers for wind power development are identified. Despite numerous hindrances related to administrative procedures, planning system, technical aspects and social acceptance, wind energy may be considered as one solution to reduce Lithuania's energy dependence [8].

5 Conclusions

Social, Environmental and Planning considerations offer significant challenges for wind energy technology. The challenges are even more significant for WT in the Built Environment. Acceptance of Wind Technology, is a wide field with a large number of factors to be taken into account including economic, planning, ecological and health issues. Municipal and community-based energy and climate policies are key for the implementation of WT in the built environment. The strategy should be based on existing programmes and on past experience, but Wind Technology should also link with the concept of "smart cities". The cities and urban environments offer challenges for redevelopment but also opportunities for integration of new technologies in the urban areas and the built environment, particularly for site redevelopment as in the upgrading of industrial sites. WT and wind energy harvesting in the urban habitat promises to

contribute towards the concept of the Future Smart City. The effective implementation of the integration of WT in smart cities requires the contribution of different experts from specialised fields and necessitates an inter-disciplinary approach. This can be achieved through a collaborative approach by bringing different stakeholders together and through the assessment of case studies and the adaptation of existing experience.

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AN OVERVIEW OF NON-TECHNICAL ISSUES OF WIND POWER AND SMART CITIES

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Abstract: Non-technical issues play an important role to be able to implement wind power in a specific environment as the debates around various projects have shown in the last years. The following paper aims at giving an overview on the non-technical issues of wind power in the context of municipal energy and climate policy, based on the general acceptance of wind power and smart city approaches. There is a lot of knowledge and experience on non-technical issues of wind power as well as smart cities that can be used as a basis for the work of WINERCOST, but the combination will need further examination and eventually draw on case studies for wind power in the urban context to become successful.

1. Introduction

We need the wind power technology and detailed knowledge about this resource. But to be able to actually implement this expertise, we have to convince the population and the authorities concerned about the advantages of such projects. The legal and financial conditions connected to these projects also play an important role.

By now there are many years of experience what might foster social acceptance of wind power technology: It is important to consider the concerns of the local stakeholders, be it for health or environmental concerns; it's necessary to give the affected population a possibility to have a word in the process; you have to find a fair balance of give and take for everybody involved. However, the experience is mostly limited to off-shore plants or to rather remote or rural areas. So far there are only few wind turbines installed in city centres, Amsterdam being an example. Different programmes exist in Europe that drive the development of cities and villages towards sustainability, use of renewable energy sources or becoming smart, such as the European Energy Award [1, 2], the Covenant of Mayors [3] or the European Innovation Partnership on Smart Cities and Communities [4]. Additionally, with many former industrial sites today being converted to new urban quarters, there is a lot of potential in introducing renewable concepts to tomorrow's cities.

WINERCOST - WIND Energy technology Reconsideration to enhance the CONcept of Smart ciTies – therefore creates an interesting challenge to combine the experience of wind power technology, its acceptance and its feasibility with the municipal energy policy. The following paper briefly introduces the various concepts and programmes involved and provides an outlook on the issues to be discussed.

The content of the paper stems from the experience in the Task 28 project and discussions at the 2014 meetings of WINERCOST where the author was involved. References are included for the relevant projects and organisations mentioned in the text. As the statements are kept rather general, there are no references for specific statements.

2. Non-technical issues of wind power

2.1 Wind power acceptance

Around 2007, the question of wind power acceptance started to become an issue: While wind power installations saw quite a growth since the 80s, by then, permission procedures became increasingly slower and opposition to wind power projects came into media. At the same time, many countries made wind power an important pillar of their energy policy! [5]

Wüstenhagen et al. developed a first concept in 2007 [6], based on three dimensions of wind power acceptance: socio-political and market acceptance on a societal level and community acceptance on a project level. In 2008, Task 28 of the International Energy Agency Wind Implementing Agreement was founded as an interdisciplinary group to discuss issues around the social acceptance of wind power [7]. Task 28 further developed Wüstenhagen's concept and also worked on the various variables and stakeholders involved in social acceptance of wind power (see Fig. 1).

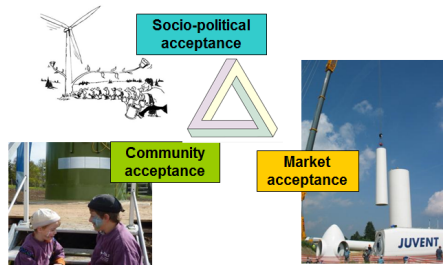


Fig. 1: Concept of Social Acceptance (Wüstenhagen et al. and IEA Wind Task 28)

The range of issues to be discussed for wind power projects is endless – an attempt to structure them to give an overview is represented in Fig. 2.

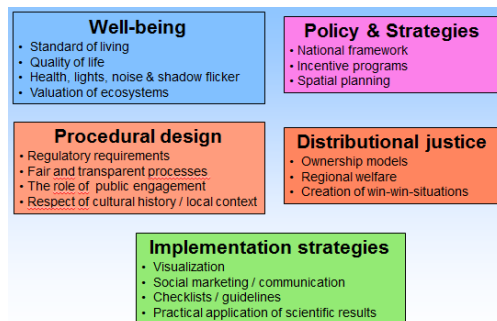


Fig 2: Issues of Social Acceptance of Wind Power (by IEA Wind Task 28)

It is not possible to discuss all conclusions found during this work, and for the details one may have a look at the State-of-the-Art Report, the final report of the phase 2008-2011 or the website of Task 28 [7]. Some of the key points concerning WINERCOST might be the following conclusions: Wind power projects touch a variety of issues that will always prevent us to hand out standard recipes to foster social acceptance. Every project is unique with its constellations of community, history, geography, ecology, culture, values etc. But there are some general “no-go’s” such as intransparency, disregard of local concerns or unbalanced “win-lose-situations”.

The project developers have learned a lot with the experiences of the last 10 years and the knowledge about the importance of social acceptance has spread. However, knowing about the importance and successfully applying are two quite different matters.

Many other projects tackle similar questions to those discussed in Task 28 or WINERCOST, such as Wind2050 [8], the WISE project [9], Wind Barriers [10], to mention just a few. There is also literature available, see for example the web database of IEA Wind Task 28 [7]

Wind power acceptance has mostly seen studies for rural or remote areas as well as for offshore plants. The adaptation of the knowledge to an urban context will need a thorough literature research and eventually some case studies to check the assumptions made based on the studies available.

2.2 Ecological and health issues

Ecological and health issues are very often at the root of resistance to wind power and are therefore included in the above mentioned paragraph. But for the comprehensiveness of the overview, they are here mentioned specifically.

Our society has already diminished many originally valuable ecological eco-systems. Wind power projects being started additionally provoke a lot of resistance among people concerned about their natural environment. This may concern the beauty of the landscape, birds, bats and other important/endangered species, the integrity of the soil, just to name a few common ones. Ecological issues are usually addressed in the frame of the Environmental Impact Analysis.

Health issues are a very difficult field for analysis as there is a strong individual component and scientific results are often discussed controversially. The main issues arising are noise, low frequency waves, shadow flicker and lighting.

2.3 Financial issues

This paper doesn't attempt to give a thorough overview on financial issues of wind power projects, but rather, mentions the issue category for the completeness of the discussion. Some points to mention in the broader context include the following:

Financial issues are often linked to acceptance issues, especially when balancing the disadvantages for the local communities by ensuring an adequate benefit for the people and municipalities concerned.

The subsidy schemes of the countries and regions have played an important role in the development during the last two decades. However, the low electricity prices in European markets do change that picture.

Renewable energy requires a more long-term view also on the financial issues. Therefore, the financial calculation should also include repowering or removal or enable the investment on a longer-term scheme. This enables to include regional households, municipalities or local energy suppliers as investors for the projects. Additionally, the method of life cycle analysis also strengthens a holistic view on wind power projects.

Wind power may be seen as a possibility to develop economically rather weak areas, by bringing work or financial benefits into the area. People often fear it might not be positive for tourism – however, studies usually couldn't corroborate this thesis; there are even first movers that made a touristic attraction out of wind power installations! It's going to be interesting to discuss this issue in the case of wind power in the built environment.

2.4 Legal conditions & planning

Wind power plants feature specific characteristics compared to other infrastructures, amongst others: one turbine delivers less energy than conventional power plants. Therefore, we need more installations at more places, which also increases the visual and audio impact. Wind turbines are moving which is something we're not too much accustomed to in the landscape and buildings. Therefore, planning has to deal with new issues. The municipalities involved often only have to deal once with a wind power project on their territory and therefore, they're often lacking the knowledge and experience necessary. Regional planning is therefore crucial – even more as wind power plants usually concern the population of more than one community.

The different issues linked to wind power plants do not facilitate project development and it is not uncommon for project developers having to deal with countless different authorities on a local, regional and national level additional to grid operators etc.

3. Municipal energy and climate policy for smart cities

A newer term in relation to energy and climate policy on the local context is the notion of "Smart Cities" as it is used in the WINERCOST-proposal. In general, smart cities are described as places where the possibilities of information technology are combined with traditional infrastructure or energy networks to improve energy and resource efficiency, quality of life and to minimize the impact on the environment. In this context, renewables energies such as wind power play an important role in combination with the capabilities of IT and building technologies.

3.1 Issues of municipal policy in the context of energy and climate

At the municipal level, tasks of the public authorities become very concrete and visible. Energy and climate policy is a very good illustration of this: every power plant has to be built within a community and while CO₂ has to be reduced globally, it is the municipalities together with the population, companies and non-governmental organisation that have to take the action. On the other hand, energy and climate are only one aspect of the many policies a municipality has to stem. And while the room for manoeuvre is still large at the municipal level, the other policy issues often leave no room for voluntary action in terms of financial and personal resources within the administration. Therefore, energy and climate issues with their often long term benefits have to be fought for and defended against seemingly much more pressing issues, such as social or financial topics.

What makes energy and climate policy additionally difficult, is the cross-sectionality of the issues. They require collaboration between the planning, the building, the traffic, the environmental, the financial people as well as with the communication department or the works providing water, electricity, gas or those dealing with waste. Today, coordination between these various bodies often only takes place occasionally, but not institutionalised.

As already mentioned above, wind power isn't really known to the municipal authorities in most cases as they haven't dealt with the issue before, and integration of wind power in urban areas presumably hasn't been discussed in many cities yet. However, there are some examples of wind turbines in the urban background.

3.2 Programmes for municipal energy and climate policy

In order to maximize the output of wind power in an urban context, integration into municipal energy and climate policy plays an important role.

One of the examples where this is already being attempted is the European Energy Award resp. Energiestadt programme [1, 2]. The project "Smart City Switzerland" [11] tries to bring together cities, their energy suppliers and innovative companies, to develop new concepts and to apply smart solutions directly. The broad Swiss Energiestadt network and the excellent basis of municipal energy policy developed over the past 20 years could be the basis to substantially bring to life the sometimes superficially used term Smart(er) City.

There are more programmes in Europe that support municipalities and that want to push energy and climate policy by supporting the efforts already being pursued on a local level (e.g. Covenant of Mayors [3], ICLEI Local Governments for Sustainability [12] or the Climate alliance [13]). As the international climate policy debates have shown, cities are first movers in setting and attaining climate goals. An important element of these programmes is the idea of networking to enable widespread of good examples.

3.3 Smart City Initiatives

The European Commission has already noticed the potential of smart city approaches and has launched the European Innovation Partnership on Smart Cities and Communities [4]. Their aim is to speed up the deployment of these solutions by bringing together European cities, industry leaders, research and representatives of civil society. The programme is closely linked to the EU's 20/20/20 climate action goals [4].

The Smart Cities Member States Initiative [14] is already working on specific projects, currently an ERA-NET call being open [15]. The objectives of this initiative are to enable coordinated collaboration within the Strategic Energy Technology Plan of the EU with currently 21 member states or to best support national cities and industry stakeholders in the development of knowledge and in the sharing of best practice.

Questions about standardisation and certification of such city developments are becoming more and more important. That's where general standards such as ISO are addressed. A technical committee (ISO/TC 268 on sustainable development in communities) is working on this issue [16].

3.4 The development of former industrial sites

There are industrial sites all over the cities that are being rebuilt and prepared for new use. These locations are often owned or developed by one company or organisation which is inclined to have a holistic look and to also include some innovative or sustainable aspects. In Switzerland, the "2000 watt site" [17] or the "sustainable quarters" [18] are examples for programmes tackling exactly these sites with their developers. While many building labels are based on the planning and construction, the 2000 watt sites intend to continue the accompaniment throughout the life span of a site development. Where such aspects are taken into account from the planning phase on, innovative wind power concepts will be integrated more easily than in existing already established neighbourhoods.

An international exchange has been set up with the "EBC Annex 63 Implementation of Energy Strategies in Communities" [19].

4. Conclusions

There is a general knowledge available on non-technical issues of wind power as well as decentralised practical experience. Acceptance of wind power together with ecological, health, economic and planning issues is a wide field with a large number of issues to be taken into account.

Municipal and community-based energy and climate policies are key to implement wind power into the built environment. There are many programmes and there is experience of more than 25 years in some programmes that can help us introduce our concepts. However, the understanding and implementation of the "smart city" is still being developed and there is room to closely link wind power to it. Apart from cities as a whole, site rebuilding or industrial site developments offer good possibilities to bring wind power into the built environment.

The specific combination of wind power and smart cities is an interesting issue to be looked at in combining the knowledge with different stakeholders. It is therefore a very inter-disciplinary field and requires partners from various fields of study. Case studies based on the available experience and adaptation of some existing concepts will bring this field forward.

Acknowledgments

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A REVIEW OF LIFE CYCLE IMPACT ANALYSIS OF WIND TURBINES

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Abstract: Renewable Energy (RE) sources, such as wind energy, are preferred over non-renewable sources, due to the potential reduction in greenhouse gas (GHG) emissions. On the other hand, large scale Wind Turbines (WTs) also present significant challenges as discussed in this paper. Meanwhile, recent developments in micro-generation and hence small scale WTs, through state-of-the-art technologies effectively manage the demand, load and instabilities with effective planning, control and efficiency yield. A life cycle assessment (LCA) allows for environmental impact evaluation during the whole life cycle stages from production, to operation and generation of energy on site. In this way a LCA leads to a comprehensive evaluation of performance of a technology. This paper presents a comprehensive LCA review of WT technologies.

1 Introduction

Society is affected by climate change through the impacts on various social, cultural, and natural resources. Climate change could affect human health, infrastructure, and transportation systems, as well as energy, food, and water supplies. The use of non-renewable resources has a negative effect on the environment as a result of emissions into the atmosphere. This supports the drive in Europe and other regions around the World to use renewable energy (RE) such as wind energy. RE reduces the reliance of remote regions and states on the main suppliers. In addition near-zero energy and zero-energy buildings relying on the energy produced on site have been demonstrated and developed for different climatic regions. Micro-scale systems which are either stand-alone or grid-connected via smart energy dispatch have made the development of urban sites with a local energy unit feasible. Micro-generation has therefore evolved through different stages in planning, control and efficiency yield, through state-of-the-art technologies which are designed to manipulate the needs, loads and instabilities.

Globally electricity demand is on the increase despite large portions of the world population still being without access to electricity. Moreover, the use of non-renewable sources of

energy is significant and directly linked to GHG emissions. RE sources, such as wind energy, are an important field for investigation and their importance will be even more evident in the future. RE sources have significant advantages over non-renewable energy sources as a result of the production of clean energy. However a comprehensive assessment based on a life cycle analysis is necessary in order to assess the true impact on the environment. A comprehensive assessment is based on the determination of use of resources, emissions and evaluation of all environmental impacts during the various stages in the life cycle up to operation and generation of energy on site.

A comprehensive analysis can be conducted through a Life cycle assessment (LCA), addressing the various stages throughout the life cycle of the system. A LCA is the assessment of the environmental impact of a given product throughout its lifespan. The aim of LCA is to compare the environmental performance of products in order to be able to choose the least burdensome. The term life cycle of a product refers to the notion that for a fair, holistic assessment the raw material production, manufacture, distribution, use and disposal (including all intervening transportation steps) need to be assessed. The LCA approach can also be used to optimise the environmental performance of a single product (eco-design) or that of a system or organisation [1, 2].

An LCA includes resource and material use and energy needs in the production of the wind harvesting systems through manufacture and assembly. It also includes construction and site works, and further, the use, harvesting of energy and end of life scenarios including reuse. LCA presents a systematic approach for the evaluation of impacts, addressing environmental, social and economic aspect. LCA is based on defined and quantifiable indicators and has a broad field of application for manufacturers, scientists and experts concerned with sustainability. The tool helps develop options for an increased sustainability of the system through the definition of the impacts at different stages of the life cycle. Eventually, environment-friendly materials, state-of-the-art technologies and high efficiency smart systems lead to a reduction in emissions into the atmosphere and result in improvements in the system.

The scope of the review is to define common trends in the analysis and factors investigated in initial LCA studies, and to compare to more recent LCA studies with reference to inputs and outputs in the system. This investigation is intended to highlight gaps in information, assumptions taken, selection of impact categories and interpretation aspects, merits and drawbacks of overall procedures. Therefore this paper investigates the environmental impact of WTs through a comprehensive literature survey. The survey establishes the relative environmental impact of various Wind Turbine Technologies at various scales, through a comparison. In addition, results of sustainability criteria such as Energy Pay-back Time (EPB-T), greenhouse gas (GHG) emissions and energy intensity are compared. The methodology used in the analysis is based on a review of LCA reports as presented by several authors in order to define the limits and emerging key indicators for evaluation.

In the past the overall growth of installed capacity of large-scale WTs have underestimated small to medium-scale ones which are today considered to have a significant potential particularly in urban areas, even though limitations exist as a result of lower efficiencies due to the large velocity threshold, weak torque and large inertia. Inevitably, a very clear definition of Small Scale WTs should follow but regrettably is still not quite properly expressed [3]. Basically, Small Scale WTs are associated with WT rotors of less than 100 cm, capable of extracting power up to 50 kW [4, 5]. Small-to-medium scale WTs, encompass units up to 350 kW depending on the adoption of EU standards in the particular country.

This comprehensive review makes reference to various types of WTs. The paper consists of 3 main parts: (i) literature review with the definition of the key indicators, (ii) analysis and discussions, and (iii) conclusions of analysis and recommendations for further investigations.

2 Literature survey

Since the 1960's, LCA has developed significantly, starting with the assessment of raw material and energy use, estimation of costs and environmental impact. It is a standardised and globally accepted tool [1, 2]. LCA is based on different steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation. LCA also includes sensitivity assessment and uncertainty analysis with weighted indices that go beyond the ISO standards and also the improvement assessment [6]. During the last decades, LCA has been applied to distinct applications. All LCA studies have provided a wide range of assumptions and boundaries to their studies and therefore lack a coherent comparable approach. This is also in the case of Wind Energy technologies LCA studies. However this paper collects a comprehensive review on Wind Energy technology LCA to highlight the trends in performances and gaps in research.

LCA results for Wind Turbine Technologies provide relevant broad information about the systems. However the interpretation of the results offers challenges due to the variations with regards types of turbines, size, power rating and technology of WTs, their locations and installation. LCA studies are in general mostly dealing with the assessment of embodied energy, consumed energy in the long chain of services and production. In turn this process will translate into the embodied emissions and greenhouse gases related to CO₂-equivalent emissions during all stages from material extraction, service life and up to end of life including recycling. These impact assessments are then interpreted into energy cost and energy payback time for example.

Lenzen et al (2002) present the development in LCA with reference to 72 research papers [7]. The authors consider energy and emission parameters as well as methodology and scope definition and the estimation of uncertainties in embodied energy. The authors reported a significant scatter in results for the energy intensities that amounted in a difference of two orders of magnitude for large scale Wind Turbines with a power rating of 0.3-3000 kW. This scatter in results was due to the technical parameters of the WT themselves, differences in technologies, place of manufacture and economies of scale. The variation in CO₂ intensity was up to 16 times and partly because of differences in the regional fuel mix ratios. Indeed, the scatter might have possibly also been due to the scope definition and principles and boundaries set for the analysis.

The study presented by Lenzen et al [7] covered the period 1982-2001, and the state of LCA at the time was limited with studies addressing single aspects or parameters. Improvements in LCA methodology were reported in 1991, 1993 and in 1997 when refinements and expansion in the procedures were presented by the Society of Environmental Toxicology and Chemistry (SETAC) and through Standardization by ISO in 1997 – 2002 [6]. This explains why after 1991 and up to early 2000s, extended analysis as presented in literature was performed with the assessment of uncertainties and errors involving indirect factors, introducing various types of methods comprising interpretation of comprehensive list of indicators. Older technologies in manufacture, embodied energy for various processes, materials, production and transportation of the reviewed large scale WTs (above 300 kW) or wind farms, resulted in quite low energy intensities. However, the capacity factors have been assumed to be quite low with the mean value at around 20-30 %. This may possibly be due to the significantly low heights of wind capture (30-50 m) as well as small swept areas (30-40 m). In comparison the swept area of state-of-the-art WTs rated at 10 MW has today already reached 190 m [8]. However, these WTs have still not been extensively analysed since they are relatively new on the market [9]. Lenzen et al (2004) present a summary of a number of German studies highlighting the specific energy relations of components produced for WTs [10]. Such relations indicate separate and different requirements for the optimisation of distinct materials. The

comprehensive assessment of components led to the definition of the main requirements of the WT components. The analysis indicated a small scatter in the normalised energy intensity caused by the dominating market and safety policy [7]. It was concluded that energy intensity increases in cases of sites which have a higher wind probability, with increase in the capacity factor. A decrease of Wind Turbine rated power was linked to a significant energy intensity dependency on production and material recycling considered by the particular country [7].

Another significant research was presented by Arvesen et al (2012) for the period 2000 to 2012 [11]. The research outlines the qualitative analysis of scope, methodology and limits in LCA, together with key stressors and indicators towards environmental sustainability in a much broader approach, than in previous studies. A significant development in Wind Energy Technology and LCA is reported at this point in time. The authors [11] report that the amount of emissions is comparable for both, on-shore and off-shore wind farms, independent of size (MW). They concluded that the bulk emissions are due to the component production stage. Information related to the implementation of more recent technologies such as floating wind turbines and deep – ocean wind farms is limited. Among all the stages of the LCA, the end of life phase has been lacking detail. However, this latter phase supports the reuse of resources and better management of wastes to reduce emissions and consumption of new resources.

Haapala et al (2014) assessed various LCA studies from different regions of the world, in America, Europe and Asia for the period 2001-2012 [12]. A hypothetical 2 MW onshore wind farm was analysed with reference to the performance characteristics, using different design models. The environmental impact was compared for different scenarios with different policies in order to assess distinct variations as a result of the different decision makers. Weights and normalisation of impact categories with varying importance were selected using the damage oriented method reported by Goedkoop et al (2000), with three main endpoints namely human health, ecosystem quality and resources [13].

Using this method, authors reduced the uncertainty level, since all data and model uncertainties were clearly characterised as short, Individualist; long, Egalitarian and balanced time, Hierarchist, perspectives. Hierarchists placed higher importance on resources and ecosystem quality and less importance on human health; Individualists placed lower importance on ecosystem quality but greater importance on resources; and Egalitarians placed higher importance on human health. The assessed end of life stage reflected a benefit to the environment with recycling. Significance was given to the sustainability at design and manufacturing levels.

Glassbrook K A et al (2014) present a hypothetical assessment of different scale of Wind Technology in Thailand [14]. The region, having small to moderate wind capabilities, was defined to have potential for small-scale WTs to meet the goals of the government strategy plan. Therefore the study assessed several WTs in a range of 400 W, 2.5 kW, 5 kW and 20 kW with regards to economic and environmental issues. The analysis indicated a relatively low intensity of CO₂ and embodied energy in comparison to diesel generators and the Thai grid, but implementation of such WTs was found not to be economically feasible without incentives from the government. These rated WTs were selected to cover rural house needs only since the energy demand of urban houses is very high, amounting to over 80 kWh/month. Wind availability was listed for 7 classes. The classification was not in accordance to the International Electro-Technical Commission standard IEC 61400-1 (2005), dividing wind turbine classes into I-IV (High-low wind speeds) [15]. Here extended divisions were used namely 1.1, 1.2, 1.3, 1.4, 2, 3, 4, 5, 6 and 7, which do not reflect the wind speeds directly but refer to power densities [16].

Table 1: Analysis of LCA outputs

Ref., date	Technology	C _p	Size, kW	A, m ²	Site	LFT, yrs	EPB-T, mths	Energy intensity	CO ₂ intensity
[14], 2013	N/A	0.2	0.4 2.5 5 20	1.08 19.6 31.9 70.9	Thailand, <i>On</i>	20	1.2-0.7 2.3-1.0 7.6-2.1 11-2.3	29.75-3.59 2.89-0.24 3.62-0.19 2.15-0.09	36.06-5.11 2.59-0.29 1.94-0.15 1.09-0.057
[17], 2009	<i>H</i>	0.33- 0.34	850 3000	2123.72 6361.74	Australia, <i>On</i>	20 / 30	12	N/A	23-26
[7], 2002, [10], 2004	N/A		S; M; L	1.77-283.5; 707-3217	Brasil/ Ger- many	N/A	6-49	0.09-0.77	2-81
[11], 2012	N/A	0.18; 0.22; 0.31; 0.43	S; M; L <i>Off</i>	N/A	<i>On</i> <i>Off</i>	15-30	N/A		16-12
[18], 2014	<i>V</i> ; <i>H</i> ;	0.35	0.3-0.5	N/A	Thailand	20	0.08-0.25	0.01-0.05	5-12
[12], 2014	upwind pitch regulated	0.35	2×2000	Blade length 39 and 40	US Pacific Northwest, <i>On</i>	20	0.43-0.53	N/A	
[19], 2012	N/A		>1000	N/A	Various re- gions: USA, EU, East sites	N/A	1.3-20.4-49	N/A	2-20.246.4-81- 168-185
[20], 2009	<i>V</i> ; <i>H</i> ; gearbox, grid	0.3	0.25 4500	N/A 132.73	France	20	2.29 0.58	0.3 1.2	46.4 15.8
[21], 2008	N/A		11×660	N/A	Italy	N/A	<12; (3-6.5)	0.04-0.07	8.8-18.5
[22], 2015	N/A	0.19- 0.53	250-6000	N/A	Italy	N/A	2.4-27.5	0.01-1.2	6.2-46
[23], 2011	N/A	0.21	15133	N/A	Spain	20	N/A	0.0573 0.0691	8.7-12

Table 1: Analysis of LCA outputs

Ref., date	Technology	C _p	Size, kW	A, m ²	Site	LFT, yrs	EPB-T, mths	Energy intensity	CO ₂ intensity
[24], 2010		0.29 0.45	100× 3000	N/A	China; <i>On; Off</i>	20	N/A	0.18 0.12	15.83 10.74
[25], 2008			N/A		Taiwan		1.3	0.05	3.6
[26], 2006	H; plants; gearbox; grid;	0.30 0.54	2000 3000	N/A	Denmark; <i>On; Off</i>	20	9; 6.6 6.8	0.098 0.102	4.64 5.23
[27], 2013	N/A	0.34	141500	N/A	Brasil; <i>On</i>		N/A		7.1
[28], 2009	Scenario 2000-2030	0.375	60×5000		Scandinavia; <i>Off</i>	25	N/A		16.5+/- 1.3
[29], 2009	Off-grid; Batteries	0.17	0.4	1.08	Canada; <i>On</i>	20	N/A		11.43
[30], 2013	N/A		330 500 810 2050 3020	876 1560 2198 5281 5281	Turkey	20	35.6	N/A	15.1-38.3
[31], 2013		0.2	25×2000		Denmark; <i>On</i>	20	8-11	N/A	7-10
[32], 2012	Grid;	0.23 0.22 0.24	20×5 or 5×20 or 100	23.75 70.14 346.4	Canada	25	16.8 9.6 7.2	0.424 0.221 0.133	42.7 25.1 17.8
[33], 2012		0.23 0.4 0.3 0.54	800 1650 3000	N/A	China, <i>On; Off</i>	20	N/A		0.28 8.21 5 6
[34], 2012	Gearless; geared		1800 2000	3848; 6362	Europe	20	7.7 7.8	N/A	8.82 9.73

Ref. – reference, c_p – capacity factor, A – Swept area, *On* – Onshore, *Off* – Off-shore, S<30 kW, M∈[100 kW÷1 MW], L – >1 MW, H – horizontal, V – vertical, LFT – Lifetime, yrs- years, mths – months, EPB-T – energy payback time.

All the output quantities were obtained using this scaling in a thorough manner. Swept areas were mentioned to be as most important factors to determine the energy potential, apart from wind speed and the overall efficiency. Due to the lack of real data, the efficiency of the WTs for the near best case scenario was assumed to be 20 %. However it was emphasised that small scale WTs are not capable to return this efficiency consistently. The energy payback time indicated that the technical capabilities of almost all WTs could cover the embodied energy, over the course of a functional unit, which was set at 50 kWh/month. As expected, all indices were reported to decrease with increase in wind speed.

The authors reported significant differences in all output units for different classes of wind. The levelised cost of electricity (LCOE) was very dependent on wind classes and showed a linear dependency with WT efficiency. With increase in efficiency, LCOE decreases. Consequently, it was confirmed that WTs' LCOE is much lower than in the case of diesel, though investments are less for these latter systems. However, WTs' investments were reported to be too high for rural communities. The analysis showed that the decrease in the efficiency of WTs, has a more significant impact on global warming potential (GWP), payback time and embodied energy but is less pronounced for the GWP value.

On the other hand, a comprehensive test was done on large-scale WTs using VESTAS V90-3 MW models for onshore and offshore plant applications (VESTAS, 2006) [26]. The goal of this LCA was to gain life cycle assessments for environmental improvement and product development as well as to use LCA data to document the environmental performance of the turbine. The study involved all basic stages from manufacturing of WT parts to transportation, mounting, grid connection and operation, dismantling and waste management. Toxicity and waste measures were involved in the evaluation of environmental impact as well as basic metrics – GWP, ozone depletion, eutrophication and acidification potential. Environmental impacts were divided into LCA stages where manufacture and recycling stages showed the highest impact on the results. For the offshore plant, operation was also significant due to the emissions into water. The transport stage and the operation stage for onshore WTs were considered as insignificant. Environmental impacts per kWh_{el} generated by these power plants were close and within the expected uncertainties of the results. Naturally, the resource consumption by the offshore plant was significantly higher than for the onshore one. However, increased energy output by the offshore WTs outweighed the increased inputs. An improvement in environmental impact was evident when comparing to older VESTAS WT V80-2.0 MW model as EPBT was noted to decrease from 9 to 6.8 months for the offshore case. Guezuraga et al (2012) defined a similar time of 7.2 months, for 1.8 MW gearless and 2 MW geared WTs [34].

3 Analysis and Discussion

A large number of life cycle analysis (LCA) studies on WTs, have been presented in the scientific literature mostly concerning MW-size. Table 1 summarises the most recent WT LCA studies. The technical noted details of WT technology include the capacity factor (c_p), site, rated power, swept area and lifetime are summarised in the table. Meanwhile the comparable outputs are the GHG emissions in CO_{2-eq} intensity, Energy Payback Time (EPBT) and energy intensity. Energy payback is used to measure the time during which a system must operate to generate sufficient energy to offset the amount of energy required during its entire life [34]. Energy intensity is considered to be the amount of embodied energy in MJ to yield a certain amount of kWh of electricity (kWh_{el}); CO₂ intensity is equivalent to CO₂ in g per kWh_{el}. The significant deviation in final outputs was evident in many reviews and singular specific analysis. This supports the need for a comprehensive research with comparable and measurable conditions, inputs and methodologies.

Methodologies are structured clearly in general but the outcome and results show significant scatter which is undesirable. The reason for this is rarely highlighted but may arise due to inconsistency in many stages which includes differences in procedures and sources for input assessments, access to and limitations of real data or site-specific assumptions. Differences were expressed very clearly with regards energy intensities for different regions and even continents taking similar rated power. The differences amounted to one or even two orders of magnitude both for small scale WTs and even for farms with large scale WTs. Differences in models, sizes and technology of WTs, local market impact and installation sites and heights lead to variations in results and it is difficult to determine which of these may have the most significant impact and carries most weight on the results. CO₂-eq intensity variation varied less and was often related to regional fuel mix ratios. In general, the analysis of older WTs and known technologies indicated that despite these being less developed, lower CO₂ impact and lower energy intensity were reported. This is taken to be mainly due to the lower installation heights and smaller dimensions inherent for older systems at the time of their installation. Environmental metrics may be issued due to regional requirements of safer technologies and materials used in manufacture and recycling options. Economies of scale also play an important role on environmental impact and energy consumption.

The varying boundary conditions, different assumptions considered, inconsistent inputs and outputs both in quantity and quality, all increase the uncertainty levels in interpretation of results and preclude further development and possible replication of the analysis.

Assumptions lead to overestimation of impacts and do not reflect the real case scenarios and the unique characteristics of specific locations, especially in the case of offshore structures. The near best scenario is not an optimal solution. However, there seem to be little possibilities for improvements for the state-of-the-art wind farms in this regard, since there are ongoing developments in technologies adopted, lack of complete data leading to inaccuracies of the assessments. Small scale WTs are of less interest due to cost issues and very broad spectrum of technologies adopted. However smart city strategies lead to an increased interest in Built Environment Wind Technology and in urban applications.

4 Conclusions

A comprehensive review of LCA studies for Wind Technology is presented. Comparable sustainability metrics were reviewed and analysed for efficiency and lifetime considerations, as related to environmental issues. The following main conclusions are drawn:

1. Due to the recent increase in size of WTs and rated power as a technological improvement, the trade-off of required energy to yield these factors namely size and energy output require further assessment. This further assessment is required to determine whether it covers and compensates for the embodied energy requirements.
2. Variability of a number of LCA studies lead to difficulties in the comparison of results. It is difficult to assess whether results are comparable with distinct assumptions and boundaries
3. LCA studies differ from very simple to very detailed ones, going into different aspects. Therefore while some studies base their analysis on assumptions and published results, others refer to up to date and actual data. Thus, the uncertainty of results offers significant challenges in comparative assessments.
4. Economies of scale play a vital role in energy intensity and system outputs.
5. Small to Medium-scale units are not adequately covered in literature.

On the basis of the data presented in this paper it is shown that developments and improvements in WT lead to an improved environmental performance. The cost and technical limitations suggest that future WT systems can be well integrated into the market with favourable conditions for reasonable energy prices and improved environmental performance.

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PLANNING AND ENVIRONMENTAL CONSIDERATIONS FOR THE DEVELOPMENT OF WIND ENERGY IN THE URBAN ENVIRONMENT.

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Abstract: This paper draws from current theory and practice to set out the main environmental and planning considerations relating to planning and developing wind energy in the urban environment in Europe. It considers the role of wind energy in the urban environment within the renewable energy sector and progress to date on technical and wind resource issues. This paper identifies a set of environmental considerations that are appropriate to the urban environment and it presents the main functions and considerations for spatial planning systems in the development of wind energy in the urban environment. Recent practice guidance for spatial planning and a wind energy project in a new neighbourhood are presented as better recent practice in this area.

1. Introduction

Energy plays a key role in sustaining social and economic development and enabling the wide spectrum of human activity. However, greater and greater reliance on the combustion of fossil fuels in generating energy has resulted in serious environmental problems at the global and local levels. The combustion of fossil fuels has given rise to levels of air pollution, which are a significant factor in climate change and global warming [1]. Addressing anthropogenic pollution and climate change is a global priority. The Kyoto Protocol [2] was signed in 2002 and obliges the EU and its member states to meet greenhouse gas emissions targets over commitment periods benchmarked to 1990. Renewable energy is seen as an important aspect of a diversified energy sector which is needed to address the global energy problem and it has been estimated that about half of global energy supplies will come from renewable sources by 2040 [3].

European energy policy and legislation has evolved rapidly in recent years [4]. Renewable energy is now central to EU energy policy, where targets of at least 55% gross energy consumption are expected by 2050 [5]. The EU Directive (2001/77/EC) on the promotion of electricity produced from renewable energy sources in the internal electricity market [6] was

followed by the EU Directive (2009/28/EC) [7] on the promotion of the use of energy from renewable sources. It sets out to ensure that 20% of EU energy consumption will come from renewable resources by 2020, with each country being assigned a legally-binding individual target. Each member state was obliged to prepare a national renewable energy plan to set out how these targets were to be met. Many member states also have high-level climate change strategies in place, which underpin the role of renewable energy in national policy (for example, The National Climate Change Strategy in Ireland) [8].

1.1 Wind energy in the urban environment

With the urbanisation of communities worldwide, there is a need to reduce the energy requirements of cities and move towards more sustainable energy generation and supply. Wind energy is a very important aspect of the mix for renewable energy and one of the most mature technologies in this area. The Wind Energy Integration in the Urban Environment (WINEUR) project found that small energy applications had the potential to contribute to an increase in renewable energy in European towns and cities and should be the subject of systematic investigation [9]. Since then, there have been sustained efforts to study the resource and technical aspects of wind energy in the urban environment. In terms of the wind resource, research has focussed on aspects of modelling and mapping in different urban contexts. A number of studies have shown that there is a viable wind resource at accessible heights above urban areas [10]. In terms of location, the urban fringe would appear to have significant potential given that wind speeds are generally greater there [11]. However, the wind resource and potential for microgeneration is likely to be widely distributed across the urban area given the assumption that wind turbines will be positioned on the adequately spaced and exposed roof tops of buildings.

1.2 Microgeneration in the urban environment

There has been a noticeable shift in the scale and nature of energy generation towards microgeneration operating in parallel with larger conventional generation and distribution networks [10]. Small to medium sized wind energy generation in urban areas comes with some key benefits; the possibility of higher installations on roof tops, delocalised local power resulting from a high number of potential installations and integrating of renewable energy systems in the urban environment [12]. Significant efforts have been made to adapt renewable energy technologies to the urban environments, particularly in suburban locations [13]. While there remain significant technical issues around installations such as micro-wind turbines roof mounted in terms of their size and low wind speeds [13] technologies are emerging rapidly and a range of solutions, such as incorporating sustainable energy generation into low-energy building design, are being developed and tested [14]. In the future, distributed, small-scale, renewable energy technologies are expected to make a strong contribution to renewable energy in the urban environment and as part of planned energy systems at the municipal level [1].

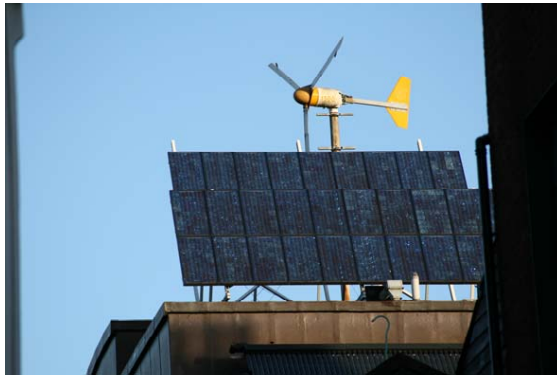


Fig. 1: Experimental roof top microgeneration in the city centre from 1994 (The Green Building, Temple Bar, Dublin).

2. Environmental considerations

The development of wind energy infrastructure is not always benign environmentally and can lead to conflicting environmental goals (low carbon energy generation versus local environmental conservation) and it may not always be possible to secure low carbon energy at acceptable environmental costs [15]. Most work in the area of environmental considerations for wind energy has been focussed on larger scale wind energy projects in rural or coastal environments and there is a concern that there is a poor understanding of environmental impacts in urban environments [3,11]. Too often, environmental considerations are dealt with superficially, excluded or deferred in research into technologies and wind resource (for example, recent studies in cities such as Guelph, Canada [16] and Leeds, UK [11] which make only minor reference to planning and environmental considerations or local planning or regulatory regimes).

Although there is a dynamic relationship between the siting, design and layout of the wind installations and the receiving environment that makes each and every plan and project unique, it is possible to identify a core set of environmental considerations from the literature and practice guidance in the area [3, 17, 18, 19, 20]. This set could be described as including natural heritage, human and community, humans and local community, landscape, urban heritage and character and other considerations (See Box 1).

Box 1. Summary of the set of environmental considerations for wind energy in the urban environment.

Natural heritage considerations

- Bird mortality due to risk of collision, disturbance for migratory paths and foraging, possible loss of habitat or use of habitat.
- Bats mortality due to risk of collision during migration period or feeding and sudden pressure drops.
- Loss of local biodiversity.
- Pollution arising from construction.

Community and human considerations

- Loss of public access to amenity areas (parks).
- Health and safety risks.
- Disturbance and annoyance from aerodynamic and mechanical noise.
- Disturbance and annoyance from shadow flicker (interaction of blades and sunshine).

Landscape, urban heritage and character considerations

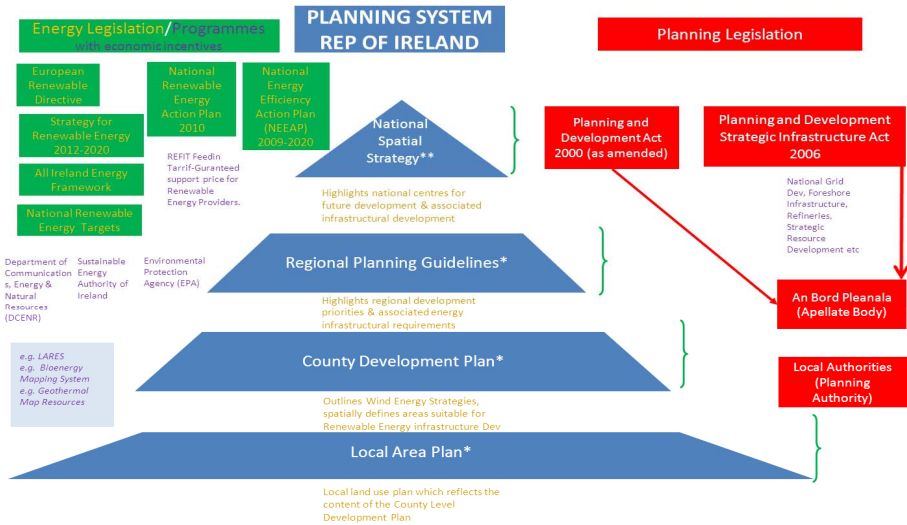
- Landscape or urban character and quality.
- Nature or type of the landscape from rural to industrial.
- Key urban views, vistas, prospects and the skyline.
- Impact on concentrations of archaeology or an archaeological landscape.
- Impact on character or integrity of architectural conservation or character areas.
- Impact on character or integrity of protected buildings or structures.

Other considerations

- Interference with telecommunications and aviation.
- Building structural issues from vibration.
- Grid connections and energy storage infrastructure.
- Cumulative impacts resulting in over-concentrations.
- Micro-climatic effects such as wake turbulence and air mixing and 'windtake'.
- Local economy - potential for spin-off employment or knock-on impacts to local tourism sector due to damage to landscape, urban heritage or character.

3. Spatial planning considerations

Spatial planning is an important process and regulatory system for the natural and built environment across Europe. While processes vary, reflecting local and regional differences and identities [21], most aim to secure the social, economic and environmental objectives of sustainable spatial development [22]. The administrative structures for spatial planning systems also vary across member states. Larger states may have up to four administrative levels for spatial planning, spanning Federal/National, State/Region, Sub-Region/County and Municipality (for example, Germany and Sweden) whereas others may only have two (for example, the UK and Ireland with only National and Local level administrative tiers). Spatial planning also has important interactions with energy and environmental legislation through the various energy Directives and national energy policies and programmes in Member States [23].



*Subject to reform

** Under review

Figure 2: Diagram of the Irish Planning System and its relationship with energy policy and legislation [23].

There are features of the spatial planning systems of Europe [24] that impact either directly or indirectly on the planning, development and management of urban wind energy. These include national legislation, high-level planning guidance, the hierarchy of spatial plans, development management, the incorporation of EU environmental legislation and aspects of public consultation.

3.1 Spatial planning legislation

Legislation for planning the urban environment is typically set out at National/State/Federal level. Planning legislation may be produced at the regional level if Member States operate this tier of administration. Legislation that provides for a tiered spatial framework or strategy for wind energy is key to success [15].

3.2 Spatial planning guidance

High-level or national guidance provides direction for regional and local authorities, developers and communities in planning and developing wind energy. Guidance sets out important methodologies and mitigations for plan-making and decision-making for wind energy projects. Wind energy guidance can be stand-alone as, for example, is the case in Ireland [18], or integrated with other planning guidance as, for example, is the case in Scotland [25]. There may also be other areas of planning guidance, for example in the area of landscape and urban heritage, which might impact on plans and decisions for wind energy in the urban environment. A key consideration is whether the guidance adequately addresses the urban environment as most current guidance in this area focuses on the rural or coastal environments.

3.3 Spatial plans

Appropriate spatial strategies in spatial plans which are vertically integrated between the region, the county/city and local area are a feature of successful planning for wind energy, and this has been shown in the case of Germany [15]. The regional level, spatial strategy for wind energy is particularly important as it can effectively consider and match wind resource, environmental sensitivity and areas of potential. The urban or city plan and the more detailed local area plan normally provide the basis for decision making on wind energy projects in the urban environment and it is important that urban wind energy and its various applications are included in the vision and detailed strategies of spatial plans [9]. Importantly, the urban plan also provides the framework for area selection. If the approach currently applied (mainly to rural areas) in some Member States [15, 18, 25] is extended to urban areas, then urban or city plans could; (i) map all 'no-go' areas (areas with sensitive land uses, built and natural heritage or urban character) and buffer zones, (ii) analyse wind potential of remaining areas, and (iii) prepare detailed studies for local level plans in the remaining areas. The more detailed local level plan provides a coherent local spatial structure and can integrate urban wind technologies into the urban form by targeting key areas and sites [9] and providing detailed guidance on siting and design. This is of key importance to wind energy applications as poorly informed or short-term decision-making could diminish the wind resource or the capacity to avail of it [10].

3.4 Development management

Development management or development control is the principal system of control of projects and proposals in the spatial planning system and it is a function that is normally applied at the city or local level. Decision-making is based on the relevant urban or local area plan and any other relevant designations and guidance. Authorities normally have the ability to grant permission, with or without conditions or modifications, or to refuse permission. The development management process provides a rigorous appraisal of the many potential environmental effects of proposals. The ability to apply conditions to permission is a powerful tool in mitigating negative impacts and achieving better outcomes, including matters such as siting, scale and design, management and community involvement and betterment.

3.5 Environmental legislation

The spatial planning system is central to the operationalisation of the range of European environmental Directives. The Strategic Environmental Assessment (SEA) Directive (2001/42/EC) on the assessment of the effects of certain plans and programmes on the environment [26], offers an opportunity to consider wider and the more general environmental implications of spatial plans. SEA is a key process in planning for wind energy in the urban environment, where the full range of issues such as natural heritage, human and community, humans and local community, landscape, urban heritage and character are considered. Normally, urban and local area plans will require an SEA and this brings a structured approach to the scoping of likely environmental effects, potential area and technology alternatives or mix, and mitigation measures. It also provides for public consultation and monitoring. The EU Habitats Directive (92/43/EEC) [27] the Birds Directive (79/409/EEC) [28] relate to the protection of the integrity of designated Natura 2000 sites. The interaction of birds and bats with wind turbines and is a particular environmental concern and the EU has produced key guidance in this area [17].

At the later, development management stage, Environmental Impact Assessment (EIA) Directive (85/337/EEC) on the assessment of the effects of certain public and private projects on the environment (as amended) [29] is required for wind energy projects of a certain scale or where significant environmental effects are likely. EIA requires scoping of likely environmental effects, the consideration of alternatives, such as siting and technologies, detailed mitigation measures for likely negative effects (such as revised siting and design, reduced dimensions and noise insulation) and proposals for monitoring of effects.

3.6 Consultation, participation and social acceptance

The spatial planning system provides for consultation at a range of levels and stages. Consultation forms part of plan-making processes in most Member States, and this is enhanced by the public consultation requirements of the EU environmental Directives. Although some studies indicate low levels of current public participation at this level [15], the SEA and plan-making stage is particularly important in gaining greater social acceptance of wind energy development in the urban environment, where density of population and human impacts can give rise to a NIMBY ('Not in my back yard') or even a BANANA ('Build absolutely nothing anywhere near anything') response. Conversely, plan-making can also provide a proactive framework for community energy planning, where communities have a stake in the industry [16]. Although most spatial planning systems provide for public involvement in the development management stage, this is often perceived by communities as being 'too late in the day' and undermines social acceptance.

4. Case examples of better practice

Better practice in planning and developing wind energy in the urban environment is emerging across the Europe. The following two case examples are taken from Ireland to exemplify; (i) better practice in guiding plan-making for wind energy at the local level; and (ii) the delivery wind energy in the urban environment with positive outcomes for low carbon energy and the local environment.

4.1 Guidance for Local Authority Renewable Energy Strategies

The Methodology for Local Authority Renewable Energy Strategies (LARES) is a recent, non-statutory guidance published by the Sustainable Energy Authority of Ireland (SEAI) in 2013 [30]. It is of particular assistance to planning and developing wind energy at local and urban context as it considers location, land use and site issues as part of an integrated plan-making and environmental assessment process. The guidance is currently being used to inform City and County Development Plans and Local Area Plans across Ireland.

ONSHORE WIND (Refer to Wind Energy Development Guidelines – DECLG (2006) for full details)	
Location and Land Use	Proximity of the windfarm to: <ul style="list-style-type: none"> — Dwellings & businesses — Other windfarms (cumulative impact) — Habitats & flight paths of protected species, particularly airborne species — Watercourses — Archaeology — Aviation flight paths — Grid location — Protected Structures and Architectural Conservation Areas
Landscape and Visual Impact	<ul style="list-style-type: none"> — Layout and positioning of turbines along the horizon — Speed, direction and synchronising of blade rotation — Visual impact of access tracks on the landscape — Positioning of cables and transformers — Specific Landscape Sensitivity, Cumulative Visual Impact and Zone of Visual Influence
Site Conditions and Operation	<ul style="list-style-type: none"> — Slope stability and landslide risk — Noise levels — Shadow flicker — Reflected light; depending on the material finish of the turbines, reflected light may be visible from some distance — Electromagnetic interference, e.g. TV and radio reception or air-traffic signalling — Wind take — Ground-water contamination — Silt traps for surface run-off (after excavation) — Lightning protection <p>The local authority may need to ensure that all guidance in respect of development of wind energy infrastructure in peatland areas, as outlined in Appendix 4 of the Wind Energy Development Guidelines – DECLG (2006), is followed by developers in cases where peat is present at a proposed windfarm site. Due regard to any additional relevant policy documentation in relation to development in peatland areas should also be considered.</p>
Infrastructure	<ul style="list-style-type: none"> — National Grid connection — Access roads for construction and decommissioning — Capacity of local roads — HGV and crane accessibility — Local access roads in peat/bog or very wet lands may need special provisions — Low-flying aircraft and flight paths may be an issue

Fig. 3: Land use interactions and on-shore wind energy [30].

4.2 Sustainable urban park

Fr Collins Park is 26 hectares urban park which was opened in 2009. It is located in the heart of a new sustainable neighbourhood on the northern fringe of Dublin City [31]. The park was developed as an early and focal piece of local infrastructure and included 5 wind turbines, providing for local wind energy generation. The park also provides for enhanced biodiversity (notably birdlife) with extended wild vegetation and new wetland ecology. The wind turbines are prominent and distinctive landmarks for the northern fringe of the city.



Fig. 4: The design concept for Fr Collins Park (above) and the completed park following installation of the wind turbines (below) (Images courtesy of Dublin City Council).

5. Conclusions

This paper has drawn from current theory and practice to set out the main environmental and planning considerations relating to developing wind energy in the urban environment. The main conclusions of this paper are summarised as follows:

1. Much of the research in the area of wind energy in the urban environment has focused on the technical and wind resource considerations. There is a need to better integrate planning and environmental considerations in future research and guidance in this area;
2. Rooftop wind turbine technologies are the main focus of current research in the area of urban wind energy. There is potential to look at different wind technologies on an area basis, and these could be related to spatial planning strategies, for example, clusters of wind turbines in extensive industrial areas or alignment along road rail or

- communications infrastructure;
3. Most research and guidance on the environmental considerations of wind energy is focused on the rural or coastal environments. Although a set of environmental considerations can be adapted from existing literature and guidance in the wider area of wind energy development, there is a clear need to prepare a more robust set of environmental considerations that are of particular relevance to the urban environment;
 4. The plan-making and SEA/AA stage is critical in achieving coherent area-based approaches to urban wind energy. More robust guidance in this area would lead to more informed and better plan-making and development management;
 5. The plan-making stage provides good opportunities for public consultation and engagement in wind energy in the urban environment. This is important in improving social acceptance and may provide a basis for initiatives such as community energy planning and development; and
 6. The development management/EIA stage is important in dealing with detailed siting, design and management matters, and the mitigation of environmental effects. It can also provide a framework for community betterment and engagement.

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SMART CITIES - THE ROLE OF LOCAL AUTHORITIES IN THE ENGAGEMENT OF SMALL WIND TURBINES IN URBAN AREAS

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Abstract:

Europe faces moments of transition. One of the main goals of Europe for the next decades is the implementation of clean and efficient energy, not only from the environmental point of view but also considering financial, employment and security aspects. Meeting EU's objective of achieving 20% of renewable energy by 2020 has the potential to create more than 600 000 jobs and result in €60 billion less in oil and gas imports by 2020. Towards this goal, local authorities have an important role to conduct, concerning both large energy projects as well as urban energy facilities like photovoltaic systems and built environment wind energy technology.

1. Introduction

In accordance with European Commission Report "EU Energy, Transport and GHG Emissions Trends to 2050" [1], for electricity generation, renewable energy sources (RES) will provide 35% of the total energy by 2020. The share will increase up to 50% in 2050 provided that current support schemes, financial instruments and enabling policies will continue and that authorization procedures together with priority access will enable local population to have benefits from investing in local RES.

Moreover, wind energy investigation is growing rapidly worldwide and will continue to do so in the foreseeable future, as it offers significant perspective to reduce the use of conventional fuels and GHG emissions [3]. From all renewable energy sources, wind energy is expected to provide the largest contribution supplying 15% of total net electricity generation in 2020, rising to 22% in 2030 and 26% by 2050 (figure 1) [1, 2].

Even if a share of about 30% of the total wind generation is expected to be produced from wind off-shore facilities, urban wind turbines have an important role to play since they have the advantage that the production of the energy is located just in the place where it is to be used.

Because of this there is no need for extensive transmission networks and other related infrastructure. Furthermore, the turbines can be directly connected to the electric authority grid, minimizing energy losses.

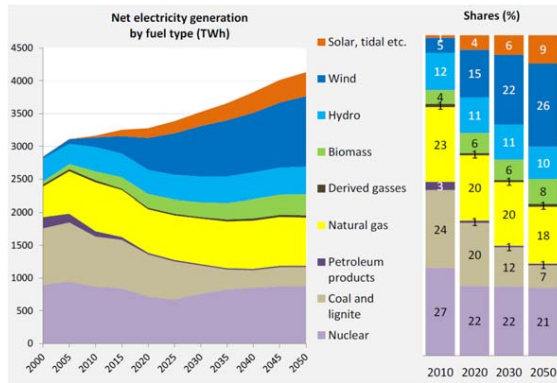


Fig. 1: Electricity Generation by Fuel type
(EU Energy, Transport and GHG Emissions Trends to 2050), [1]

2. Current state / regulatory framework

In many European countries there is a tradition of exploitation of wind energy with small scale windmills for more than a century. For instance, windmills first appeared in Cyprus at the beginning of the 20th century. Around 1912, there were a few of them, until 1930 they reached a number of 30 and then multiplied up to 1000. Mostly, traditional windmills were used for pumping water and grinding grain (figure 2).

Despite this tradition, only recently Cyprus has started to estimate the wind potential for investment [4]. Nowadays, in the case of Cyprus, a country with estimated overall wind power potential of 250-350MW per year, five (5) wind parks with a total capacity of about 150MW exist whereas there are not more than a few urban wind turbines, with negligible power production [5].

This is mainly because of the current regulations which set barriers to the use of wind energy. According to the regulations, individual wind turbines and wind farms are not allowed in the following areas:

- specified areas of development (mainly all residential areas)
- strip occupancy or registered in a public register of roads, footpath etc.
- ancient archaeological site or monument
- State Forest (excluding in state forest with sparse or low shrubby vegetation)
- Nature Reserve Coast, Geomorfoma, Landscape Protected, Protected Network Nature 2000 Area
- designated Special Protection areas of wild birds and habitats defined by Laws and up to a distance of 500 m. corridor of transit passage and migratory birds, as determined by the Game Fund.
- airport, airfield and military establishment, project or site.

In the case of Cyprus, regulations are extremely strict, basically prohibiting the installation of urban wind turbines. Similar regulations, with not so strict barriers, exist in most European countries.



Fig. 2: Old wind energy systems used in Greece and Cyprus for water pumping and grain grinding

On the other hand, the installation of small wind turbines, in many European countries, is sponsored by Plan Grants for energy saving and encourage the use of Renewable Energy. In the case of Cyprus [6], the specific grand is for wind power systems of capacity up to 30 kW, and it is 55% of eligible costs with a maximum grant amount of 50.000 €. Further to the grant, the produced energy can be transferred to the network of the Electricity Authority of Cyprus at a certain price (at present is about 0,11€/kWh and it is regulated by the Regulatory Authority Energy Association) [7, 8].

As an example, if we consider the installation of a small wind turbine, in a coastal region of Cyprus where the mean annual wind speed is 6 m/s, and accepting the assumptions stated below, the total years of invested return are presented in Table 1.

Table 1: Small wind turbine installation in Cyprus - Years for return of investment

	Without Loan	With Loan
Annual Energy Production	5.237kWh	
Initial Cost + VAT	8.625 €	
Grand (55%)	4.125 €	
Initial Cost with grand	4.500 €	
Annual Service cost	112 €	
Interest Rate	-	7%
Monthly cost	-	52€
Income from energy	681 €	681 €
Years for the return of investment	8 years	11 years

- Assumptions:
- Purchase cost of wind turbine 2.500 €/kW
 - Installing a small 3 kW wind power (annual production of electricity is calculated as 5000 kWh, in areas with an average wind speed of 5 m/s, the energy is reduced to 2,900 - 3.000 kWh, whereas for a 15m mast the produced energy is calculated to be 6000 kWh).
 - Mean electricity price for next 15 years will be 0,13€/kW

3. Main concerns about small wind turbines in urban environment

There are many areas in which there are concerns for the use of small wind turbines in urban environment. Concerns, not only for financial and technical aspects but also for environmental, social, safety and other reasons [5]. From the stage of the technoeconomical study and even if the cost for the supply and installation of the turbine is known, there are many issues regarding the turbines output. Some of these issues are analyzed below.

3.1 Safety issues and Noise

A main concern about the installation of small wind turbines in the urban environment is safety issues. Since such turbines are to be installed in the urban environment and because of the proximity of them with main people activities, neighbours feel a kind of uncertainty regarding potential projects. Safety issues arise also from lightning strikes that can be a problem for urban turbines, because in a case of a strike the turbine may be destroyed and parts of it may fall adjacent to turbines. Furthermore, the proximity of small urban wind turbines with the daily activities of many people, make noise levels a critical issue for discussion. Noise is related to tip speed, thus vertical axis small wind turbines are much quieter than horizontal ones because of their lower moving speed [9].

3.2 Wind measurements

Another concern for the installation of build environment wind energy technology (BWT) and one of the main factors regarding the financial feasibility of such installations is wind resource in the certain spot of installation [15]. In most countries or even for the whole Europe (figure 3) there are wind maps for extensive areas but not for the microscale of urban environment [10]. Because of the complexity of the building terrain, it is not feasible to have detailed wind maps for an urban area below a certain height (e.g. 30m) [11, 12, 13]. Thus, for an owner, in order to proceed with the installation of BWT a great number of prolonged in situ measurements are needed. The only reliable way to collect such data for a specific spot is using anemometers [14].

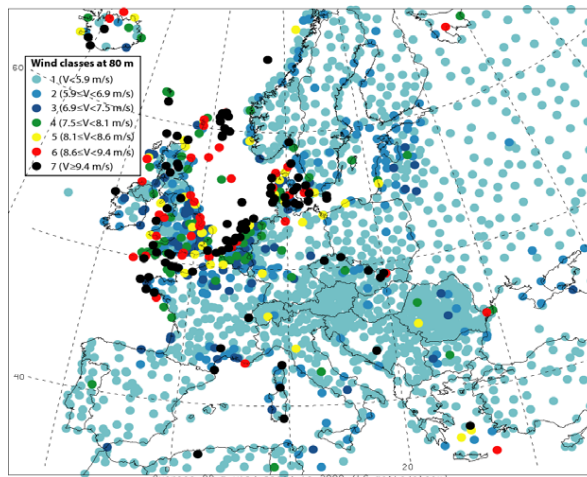


Fig. 3: Mean Wind Speed in Europe at 80m height [10]

3.3 Comparison with other renewable energy sources

In most countries, especially in South Europe, the most popular urban renewable energy systems are photovoltaic panels [7]. Even if in some locations small wind turbines can produce the same or even more energy with lower investment cost, there is no extensive experience and technical data for this.

3.4 Protection of birds and flightpaths

Regardless that concerns sometimes arise regarding the protection of birds, dissimilar large scale wind farms, birds protection cannot be considered to be a problem for BWT because of their small scale. Moreover, except very specific cases, BWT do not influence in any way planes or flightpaths.

3.5 Influence on building heritage

A critical aspect for implementing BWT in buildings is the influence in their architectural and visual assessment. For a new building it is rather easy to implement BWT since it will be part of its initial overall design, but when we discuss energy upgrade of an existing building, the case becomes more complex in the certain aspect. For historical and listed buildings, in most cases, it is prohibitive to implement BWT, whereas in existing buildings visual and architectural aspects have to be taken into account. For standalone wind turbines, the status is simpler since they are not mounted into the buildings but they can be treated as separate structures.

3.6 Buildings bearing capacity

One of the main differences between installing photovoltaic panels and a wind turbine in the roof of a structure (new or existing) is the differentiation of the imposed loads in the structure. A system of photovoltaic panels imposes a certain vertical load whereas a wind turbine except from the static load it will introduce torque and bending moment to its supporting structure. The overall loads can be easily calculated and taken into account, but the case becomes critical when we have to install small wind turbines in existing industrial facilities (mainly steel structures).

3.7 Interference to electromagnetic signals

Some decades before, a concern for urban wind turbines was the interference of them with electromagnetic signals. Specifically, when a wind turbine was in line between the transmission tower of television and the residential receiver, the signal was "chopped" causing a ghosting effect on screens [9]. This was because of the metal blades of the turbines. Modern urban turbines have much smaller blades made of fiberglass or other materials that do not affect electromagnetic fields, resulting to negligible interference.

4. Role of local authorities

Local authorities in order not only to minimise energy dependence but also to face all the above concerns have a substantial way to go through. Covenant of Mayors (CoM), offers a useful path in which local authorities can step.

4.1 Covenant of Mayors

After the adoption, in 2008, of the EU Climate and Energy Package, the European Commission launched the Covenant of Mayors (CoM) [16]. Considering that 80% of energy consumption and carbon dioxide emissions is associated with urban activity local authorities involvement is critical. EU in order to endorse and support the efforts deployed by local authorities in the implementation of sustainable energy policies, launched CoM.

In the framework of CoM local authorities committed to go beyond the objectives set by the EU for 2020, reducing the CO₂ emissions in our respective territories by at least 20%.

In order to achieve its CO₂ reduction objective, a city that signs the CoM commits to a number of actions (figure 4) [16]:

- prepare a Baseline Emission Inventory (BEI)
- submit a Sustainable Energy Action Plan (SEAP), officially approved by the local authority (SEAP is a key document that shows how the Covenant signatory will reach its commitment by 2020)
- adapt city structures in order to undertake the necessary actions, and mobilise civil society in their respective geographical areas to take part in developing the Action Plan
- prepare regular Monitor Emission Inventories (MEIs) in which progress towards target is measured
- submit an action report at least every second year after submission of the Action Plan (contains qualitative information about the implementation of the SEAP)

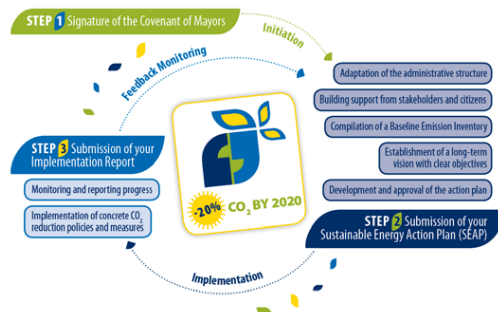


Fig. 4: CoM actions [16]

Furthermore, local authorities are committed to:

- share experience and know-how with other territorial units
- organise Energy Days or City Covenant Days, allowing citizens to benefit directly from the opportunities and advantages offered by a more intelligent use of energy, and to regularly inform the local media on developments concerning the action plan
- attend and contribute to the annual EU Conference of Mayors for a Sustainable Energy Europe

Until today, 6259 local authorities with a total number of 196,312,095 inhabitants signed CoM, mainly from the EU-27 but also from other European countries outside the EU-27 as well as countries like ex-Soviet countries and countries from Africa, South America and Australia.

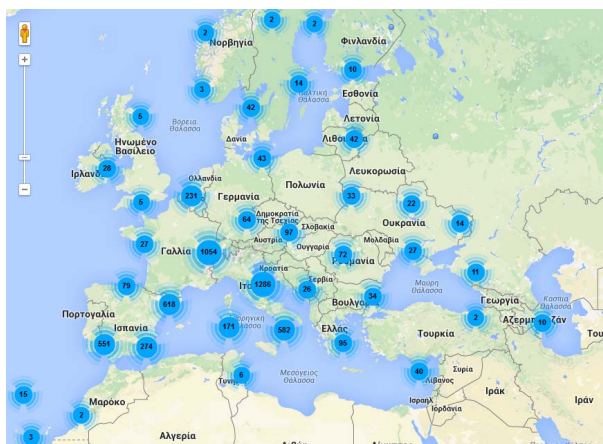


Fig. 5: Local authorities that signed CoM across Europe [16]

Figure 5 presents local authorities that signed CoM across Europe whereas figure 6 presents signatories over time. For the local authorities that signed the CoM, administrative promotional and technical assistance is provided by the Covenant of Mayors Office, whereas further support is provided by Joint Research Centre and other EU institutions (Committee of the Regions, European Parliament, European Investment Bank, etc.).

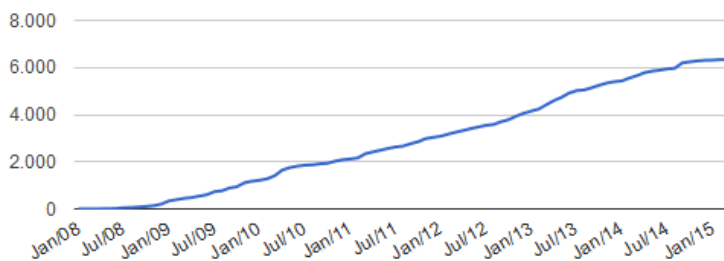


Fig. 6: presents signatories over time [16]

Within the scope of CoM local authorities can decide to take action on the supply side, for example by fostering the deployment of locally available RES to produce electricity. Figure 7 presents local production of electricity, in total figures and per capita, in CoM sectors (data 2013). Energy saving in 2020 is estimated to be 49 764 GWh together with the increase of energy production from RES of 10 352 GWh.

	Number of BEIs including LPE	Population in BEIs including LPE	LPE (MWh)	LPE per capita (MWh/capita)	Share of each technology on LPE	Share of each technology on TCE**
Wind power	17	3 254 415	631 983	0.19	2.99%	0.19%
Hydroelectric power	39	5 178 003	991 734	0.19	4.69%	0.30%
Photovoltaic	64	2 604 020	291 254	0.11	1.38%	0.09%
Combined heat and power	35	9 669 174	7 395 131	0.76	34.98%	2.23%
Others	26	13 716 926	11 828 187	0.86	55.96%	3.56%
of which from waste management	16	9 282 165	6 846 757	0.74	32.39%	1.98%
BEIs including at least one sector	128*	18 207 966	21 133 099	1.16	100%	6.36%

Fig. 7: Local production of electricity, in total figures and per capita, in CoM sectors (Data 2013) [16]

4.2 Activity areas of local authorities

One of the areas that local authorities committed to take action in the framework of CoM is fostering the deployment of locally available renewable energy sources. This is also in line with promoting use of BWT. For the fulfilment of this scope local authorities have to act in several ways/areas, some of which are analysed below.

4.2.1 Local authorities as consumers

Local authorities occupy many buildings which use substantial amounts of energy, such as for heating and lighting. Introducing measures for localized production of energy in public buildings is an area where considerable savings can be achieved. Many local authorities have started implementing renewable energy systems, mainly installation of photovoltaic systems and small wind turbines in municipal/community buildings or on school buildings [17, 18].

4.2.2 Local authorities as producers and suppliers

Local and regional authorities can promote local energy production and the use of renewable energy sources. BWT can be a great example if it is developed in public buildings. Local and regional authorities can also encourage citizens to implement renewable energy projects by providing financial or administrative support (participate in consortiums with private companies) for local initiatives [19, 20].

An important potential benefit for local authorities for the development of BWT is the proximity of the production of the energy, leading to less dependence from a small number of generators (carbon, gas, renewable or any other) thus increasing individuality and local control of energy sources.

4.2.3 Local authorities as planners and regulators

Land use planning and control of development are responsibilities of most local and regional authorities. Strategic decisions concerning urban development are of great importance regarding forwarding of use of renewable energy sources in built environment.

Local and regional authorities can often have a regulator role for example by setting energy performance standards, or stipulating incorporation of renewable energy equipment in new buildings [6, 17, 21].

A crucial aspect is the legalization and distinct differentiation of the legal regulations / codes, regarding the spot of placement of the wind turbine (urban/residential, urban/industrial, rural surroundings, etc.), in order to make clear owners obligations. There is an explicit need to set up regulations for preventing BWT from creating visual disorder, like satellite antennas and air-conditioning systems in the last decades.

Specifically, for BWT a possible implementation of an overall development program that will include certain guidelines not only for owners but also for architects/engineers, will be a very useful tool in order to help them have a clear perspective. Such a plan shall include wind data, preliminary environmental impact study and suggestions about spots of potential placement of urban wind turbines.

For this scope, and since it is not feasible to have detailed wind maps for an urban area because of the overall building landscape and the best way to collect useful data are anemometers, local authorities can collect data for certain potential locations of urban wind turbines installation and make them available to the public. Furthermore, if requested from the owners they can proceed with measurements to specific locations.

4.2.4 Local authorities as advisor, motivator

Local and regional authorities can encourage the use of BWT by informing and motivating residents, businesses and other local stakeholders on how they can use energy more efficiently. Awareness-raising activities are important to engage the whole community to support sustainable energy policies. Children are an important audience for energy saving and renewable projects: they will pass on the lessons learned also outside the school. It is very important that local authorities should lead by example, and play a leading role in sustainable energy activities [22].

Furthermore, local authorities can act in several ways like promoting exhibitions of manufacturers/suppliers in order to inform public about small wind turbines, develop a registration for suppliers and installers of renewable energy sources, organization workshops on community acceptance of wind energy, etc.

For instance, within the framework of Covenant of Mayors and for Intelligent Energy Days 2014, Oriahovo (Bulgaria) organized last year (20-27 June 2014) a public discussion on "Small wind turbines in urban environments or the benefits of small wind" with the participation of representatives of the municipal administrations of other local authorities, citizens and local stakeholders on renewable energy sources [22].

Especially, for BWT significant efforts shall be put in explaining the differentiation, explanation of advantages of built environment wind energy technology against large wind parks and for explaining the necessity of the combination of several renewable energy sources, like wind energy combined with solar energy.

Another, interesting aspect can be promoting “lessons learned” or “success stories” from BWT projects as well as experience from other countries.

4.2.5 Local authorities as promoters of public acceptance of BWT

Public acceptance of a project or infrastructure is considered to be positive when the majority of citizens are convinced that the project or infrastructure has more positive effects in the community than negative [19, 23].

In most cases when a new project is to be implemented, welfare decreasing aspects are highlighted by people representing various interests. Local authorities have to act in such a way that they will inform citizens not only for the negative but also for positive aspects of the project. In the case of BWT positive aspects are minimization of Co2 emissions, local production and control of clean energy, etc.

5. Conclusions

Local authorities have an important and extensive role to play for the implementation and establishment of BWT. They have many different activity areas with which they can deal supported by other National Authorities and European Institutions.

For the fulfilment of the above scope local authorities have to lead the right path as planners and regulators, educate and inform citizens as advisors, behave as motivators but also act as producers, suppliers and even consumers.

Concluding, it's worth to remember Abraham Lincoln's phrase [24] *“Of all the forces of nature, I should think the wind contains the greatest amount of power”*. Let's take advantage of this power, financially affordable, environmentally friendly and just in the spot where we need it.

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Urban Wind Energy: exposing Sustainability Symbolism or a hidden existence

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Abstract: Apart from urban wind turbines' contested energy generation capability, this paper argues that research undertaken so far is inconclusive on the social acceptance of the visual exposure to and physical presence of urban wind turbines. Research suggests that when the public are asked about their acceptance of a new technology they show higher levels than when asked after it is actually built and its performance scrutinized in the media. Parallels will be drawn with the realm of the 'High tech' style in architecture and architects' attempts to deal with public perception. This leaves us with the questions on how much of it do we need to expose of what is considered a supporting energy generation technologies to urban living? Drawing hypothesis on challenges facing the public acceptance of urban wind and its possible appreciation as a reliable mechanism as well as a desired symbol for urban sustainability? This paper, explores the mutually exclusive relationship between public acceptance, its impact on building policies and the current architectural endeavours and their attempts to integrate this technology

1. Introduction

According to DeMeo & Parsons (2003) It is important to appreciate that urban wind turbines, due to their intermittent operation, have to be backed up by other sources of grid electricity supply and renewable energy generation to provide year round energy yield. This will have a visual impact on the built environment, architectural form and design.

Generally there are three methods of integrating wind turbines into the built environment;

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- The third is the building augmented wind turbines where the building form is shaped to concentrate wind flow and is shaped towards the wind turbine

This paper reviews the current successes/ failures of all three methods of integration and relates this to effects on public perception and policy initiatives, leading on to how architecture design is influenced by this discourse.

2. Performance on the Ground what we know!

Urban wind turbines integration is based on their capability to work close to buildings and taking advantage of the augmentation in wind flow caused by surrounding buildings. Their performance can be modelled to a certain degree of accuracy and incorporated in the design of a new or existing urban area where the whole design accounts for the existence of the wind turbine. The performance gap between predicted energy yield and their actual performance is attributed to turbulence and natural variability of the disrupted wind patterns in urban areas, positioning issues, reliability of the technology, the size of the blades and masts allowed for in urban contexts and their maintenance requirements. Cace et al. (2007) found that turbine height has a significant effect on capturing higher mean wind speed and power generated, while output varied considerably with wind direction. Horizontal axis wind turbines with a yawing system may be used to allow the turbine to change direction facing the prevailing wind. However, if the wind frequently changes direction, this would affect the energy yield of the turbine negatively. A vertical axis wind turbine would be recommended as it is dependent on the wind speed rather than the wind direction and can withstand changing wind direction and turbulent wind flow. Mithraratne (2009) concluded that building form manipulation based on wind flow assessments would play an important role in reducing the turbulence and wind shear around buildings by 10–15% and 15–30% respectively, considering the uncertainty margin in wind simulations around building combines with the building form implications, these would have impacts on the technologies performance and acceptance.

In the case of building integrated wind turbines: The Lions House in the historic and preserved areas of Northumberland, England, UK was first hailed as a sustainable building with its integration of PV and 3 stand alone wind turbines on site.

After its completion, the local community complained about their visual appearance of the wind turbines and expressed their disappointment that they stood idle in the landscape. © Jane Coltman, Northumberland Gazette, 12th of January Saturday 11 February, 2012 <http://www.windbyte.co.uk/northumberland.html> and [Northumberland Gazette](#).

'Much-criticised wind turbines on the edge of Alnwick have been out of action for almost half the time they have been installed, according to figures released following a Freedom of Information Act request by the Gazette. The statistics, provided by the Department for Environment, Food and Rural Affairs (Defra), show that the three generators at its flagship Lion House were offline for a total of 494 days since they went live on March 2, 2009. By comparison, they were working for 581 days during the same period.'

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Figure1: Photomontage of public's perception on the usefulness of building integrated wind turbines

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Building integrated wind turbines are expected to take advantage of the building height as a mast towards less turbulent flows at lower urban levels. Although the building integrated wind turbine may yield more power than the building mounted wind turbines, the cost per kilowatt tends to be relatively high (compared to medium/large scale wind turbines) in part to cover for required foundations, tower and cabling. According to the WINEUR project (2005), for building mounted wind turbines to be successful in generating electricity, the average wind speed should not be less than 5.5 m/s. According to Bahaj et al. (2007) and Müller et al. (2009) high-rise buildings have the largest potential for wind turbine integration when compared to low-rise structures. In locating the building wind turbine, the building roof should be approximately 50% higher than its surroundings, and the turbine located near the centre of the roof on the most common wind direction for the location, with the lowest position of the rotor at least 30% of the building height above the roof level. The Warwick Wind Trials Project states that the poor sites for mounting wind turbines are the single story buildings and the good sites are 45m tall exposed flats in isolated settings on hilltops (Encraft, 2009). Figure 3, demonstrates two case studies highlighting the limitations of this integration method.



Figure 2. Left: The Green Building in Temple Bar, Dublin / Right: The Kirklees council building (civic centre 3) in the town centre of Huddersfield, UK

Anderson et al. (2008) studied the Green Building in Temple Bar, Dublin, as an earlier attempt for mounting three small horizontal-axis wind turbines combined with solar hot water and photovoltaic collectors (Figure 2). The application resulted in excessive noise, vibration, and eventual cracking of the turbine blades. The wind turbines were determined to be uneconomical and were eventually replaced by photovoltaic cells. Another example is the Kirklees council building (civic centre 3) in the town centre of Huddersfield, UK was retrofitted to house a large array (143m²) of solar photovoltaic panels and two 6kW wind turbines to generate electricity and a set of solar energy collectors (48m²) to heat the building's water (Figure 2). Kirklees council spent £15,000 on preparing the roof to take the structural load, vibration and improve the insulation of the roof. The Council wanted to demonstrate leadership targeting a reduction in its building's carbon footprint by around 8% (15 tonnes of Carbon dioxide/annum) and reduce dependency on grid generated electricity.

It is interesting to note that the average electricity generated from the photovoltaic array and the wind turbine was 5% of the total electricity demand. However, similar to the Green building in Temple Bar the wind turbines failed to generate a reliable electricity supply, and were eventually disconnected from the grid and left to promote a demonstration of good intentions. Wind mounted turbines in both cases were seen as an Urban Wind Turbines Integration in the Built Form and Environment. It left the public with a perception that this is an expensive add on.

In addition to being the most expensive technical installation and an unplanned aesthetic effect, failing to deliver the expected performance. The view of a wind turbine that doesn't rotate or even worse that is known to rotate without yield increases public scientism of these systems (Kirklees Environment Unit Report, 2006).

The Warwick Wind Trials Project in the U.K. measured turbine performance of 26 building-mounted wind turbines from October 2007 through October 2008 and found an average capacity factor of 0.85%. All were very small ("microwind," defined as less than 2 kW) turbines, including the Ampair 600 (600 W), Zephyr Air Dolphin (1,000 W), Eclectic D400 StealthGen (400 W), and Windsave WS1000 (1,000 W). For each installation, measured electricity production was compared with predicted production based on the manufacturers' supplied power curves and both predicted and measured wind speeds. The study found that predicted performance exceeded actual performance by a factor of 15 to 17. With the worst-performing systems, the electricity required to run the electronics exceeded the electricity production, so the wind turbines were net consumers of electricity!

Reducing the effect of the changing wind direction could be overcome if the building form is shaped in a way to direct wind towards the installed turbine such as the Building Augmented wind turbines.

Building augmented wind turbines (BAWTs)

In this type of integration the form of the building harnesses wind to be driven towards a turbine. In this case the building form acts as a support for the integrated wind turbines and a wind collector. Here the architect plays a major role in sculpting the building to be based on aspects related to aerodynamics. The building design may require some modifications based on wind flow assessment using wind tunnel test or CFD simulations (Dutton et al., 2005). Denoon et al. (2008) illustrated a number of new developments that were based on the principle of aerodynamic building form to enhance the performance of the integrated wind turbines. For example Figure 3 includes the Bahrain World Trade Centre, Pearl River Tower in China, Strata SE1 project in London, all implemented BAWTs (Figure 3) (Peel & Lloyd, 2007; Cochran & Damiani, 2008). However, Müller et al. (2009) noted that it cannot be assumed that such projects will become the norm as urban wind turbines may not always be visually appropriate and hence not be put forward by architects and designers. Therefore, a successful wind turbine design would be integrated to add to the architectural value of the building.



Figure 3. From left Integrated wind turbine in Pearl River Tower (courtesy SOM), Pearl River Tower in China (courtesy SOM), Strata SE1 project in London

The Strata, voted '[Britain's ugliest new building](#)' by readers of Building Design magazine (and thus the holder of the 2010 [Carbuncle Cup](#)). Local press expressed the dismay of having to endure the ugliness of the building in addition to its rarely rotating three wind turbines. A symbol that hung over the London horizon to remind Londoners of the failing technology performance.

'It seems that the posh folks living in the upper floor penthouses objected to the noise and vibration of the spinning blades, prompting project director Ian Bogle to suggest that they should be turned off between 11pm and 7am each night ([Londonist](#), March 2010).

Although local press blamed it on the vibration, Tom Hawkins commented (<http://www.urban75.org/blog/>)

'It's not so much the noise or vibration that has shut the turbines off, more like the £54,000 + vat a year maintenance costs for generating hardly anything that is the real factor. I know, I was involved in the second year budget for that building.'

Capeluto et al. (2003) and Ricciardelli & Polimeno (2006) asserted that wind flow within the built environment depends on the exact geometry of all buildings on site. It is important to note that technical issues when integrating and positioning wind turbines on roofs need to consider roof construction materials. Turbulent flow creates stress on the drive gear in a turbine, creating vibrations. These vibrations can, in turn, create harmonic resonances within a building structure. Metal roof decks made from thin roll-formed steel sheet, common in commercial buildings, can act like drumheads and amplify these resonances. In fact, AeroVironment, the building-integrated wind energy suggests in its sales literature that their turbines are only appropriate for buildings constructed of concrete.

3. Policy, incentivization and community acceptance: the vicious circle

The term social acceptance is widely used but has varied meanings for different individuals Wustenhagen et al. (2007). There are three-tiered characterization of social acceptance is broken down into the concept of social acceptance into issues of socio-political acceptance, market acceptance, and community acceptance.

Socio-political acceptance is defined as broad-based support for wind energy among policy-makers, the public, and other significant stakeholders. Wustenhagen et al. (2007) point to public opinion surveys as a sign of socio-political support, but one may also consider policy support as an indicator of broad-based socio-political acceptance.

Market acceptance refers to wind energy technology adoption by consumers, investors, and the power generation industry. At some levels, this is a reflection of technological maturity and reliability such that utilities and investors are willing to make significant investments in wind energy and consumers believe that wind energy will not jeopardize ready access to electric power.

Table 1: indicates that the average cost of MWh electricity generated from wind farms has reduced by about 60% over just five years. However, I would argue that this was not reflected on urban wind technology market nor its acceptance by urban dwellers

Community acceptance is that element of social acceptance that deals with local opposition to individual wind power projects, particularly by residents and local government. Because local approval for a proposed wind project is required before construction can begin, community acceptance is a fundamental aspect of social acceptance of wind energy. This element of social acceptance typically comes to mind first when one reflects on the concept of social acceptance and wind power. Although this is the level of social acceptance from which the term NIMBY ("not in my back yard") has emerged, research has demonstrated that community acceptance of wind power projects cannot be reduced to simple NIMBYism but is actually a complex and dynamic social phenomena, influenced by an array of factors, including perceptions of justice and trust, and fear of losing property market value

Year ▼	Cost	MWh	Average Price
2015	£17,035,416	232,706	£73
2014	£53,175,234	658,611	£81
2013	£32,707,351	379,817	£86
2012	£5,924,231	45,463	£130
2011	£12,826,756	58,708	£218
2010	£174,128	976	£178

Who is first Feed-in Tariff or public perception?

Although Table 1: indicates that the average price of electricity production from wind generated electricity has fallen over the last 5 years. It would be hard to prove that the contribution of urban wind turbines had a major contribution to this even if it followed the incorrect assumption that all of the micro-small wind turbines were urban based.

The Feed-in Tariff scheme is the primary support mechanism introduced by Government to incentivise deployment of small and medium-scale (<5MW) renewable energy generation in the UK. The scheme was launched in April 2010, and a review referred to as 'Phase 2B' came into effect in December 2012. This review implemented significant changes to tariffs and structures for non-PV technologies such as wind, hydro and anaerobic digestion. It introduced lowered tariff levels for wind generation; amalgamated the tariff bracket for all turbines under 100kW; and introduced a capacity-driven depression mechanism effective from April 2014. Although figures suggest that there is an increase in power generated by small wind generation technology. The growth experienced by the small wind market sector in previous years has been dramatically reversed throughout 2013 and 2014. The report among other official sources points out that this decline in the market is due to the implementation of Phase 2B of the Feed-in Tariff in December 2012, the deployed capacity of turbines within the sub-100kW sector decreased over 2013 by a combined total of almost 55% compared with 2012. When broken down, this represents a 49% capacity decrease in the 15–100kW bracket, a 72% capacity decrease in the 1.5–15kW bracket, and a 33% capacity decrease in the 0–1.5kW bracket. (ref: small and medium wind UK market report, RenewableUK, March 2015, www.renewableUK.com). What this argument fails to highlight is the relationship between government based policies and how they are built on factual evidence of how the consumers have previously been buying the product and the social acceptance of this technology that would underpin its growth. The impact of media coverage of urban wind energy in the previous section couldn't be marginalized and could be argued to have failed the market regardless especially that there is a complete lack of success stories!

4. Behaviors and value systems towards decentralized systems

Based on Devine-Wright (2012) and IEA task 28 reports, there is an aspiration that adopting decentralized energy generation per se encourages energy citizenship and is a counterpart to the social and psychological detachment of the public from centralized energy systems

Their research continues to advocate that people will be willing to get involved and engage with various technologies to make urban wind turbine work, research suggests that we cannot rely on this as lay people are usually used to the 'plug and forget' attitude they have with centralized energy supply

The social rejection for the construction of nuclear plants and altruistic values of carrying about climate change will increase the appeal of engaging with micro generation

That societies are less individualistic, lazy and passive and seek to be engaged and socially motivated to deal with the micro generation systems, and would allocate the necessary time to familiarize with the technology and be able to run it properly. While there is evidence on the ground that this is happening with PV and solar heating systems, this is not the case for urban wind generation.

When I was involved in suggesting strategies for integrating renewables in a historic Abbey in England (Hexham Abbey). The public consultation indicated that the community accepted the

installation of PV cells on the Abbey's roof but rejected the installation of wind turbines as inappropriate for the historic fabric of the buildings

Public perception of large scale wind farms can be extrapolated in relation to small scale urban wind integration mechanisms, research suggests that hazards of Noise perception are associated with visual impacts. In stormy conditions, ice throw (Shed) creates a physical danger on people and vehicles. IEA wind reports suggests mitigation by utilizing setbacks between wind turbines and residential areas which might not be feasible for urban small wind generation mechanisms. Although appearing as planning and siting issues, related risks to the technology affect public perception where the presence of these systems might lead to depreciation of land and property value.

That local communities will accept renewable energy developments, if such developments are conducted in a manner that these developments give control as well as financial benefits to these communities. This hypothesis is based on the installations affecting a small rural community. In urban areas where social relationships tend to be distant and rarely residents of wards participating in community meetings the application of the principle is doubtful.

5. How visible do we actually want urban wind turbines to be? The unspoken question..

While all the ethical theories of public participation and awareness point out to strategies that may improve engagement with micro generation such as of citizenship, appropriate siting and operation, local management, the main issue still remains. As opposed to passive measures, and 'static and quiet' renewable micro generation systems in reducing the carbon footprint of the urban environment, the tolerance for the length of visual and noise exposure to urban wind turbines remains unanswered. This draws on the analogy of visualizing the human body as a set of valves and pumps or do we prefer to see it the way we are used to? Would ducted wind turbine with their huge structure offer a visually less intrusive model? Figure 4.

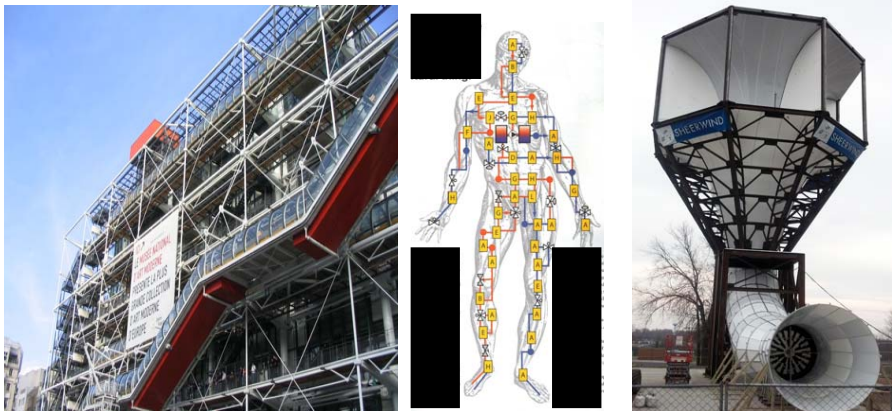


Figure 4: Centre Pompidou with its exposed building services(left), the analogy of a human as a set of building services mechanisms(middle) and the ducted wind turbine(right)

In architecture although exposing the building services as a 'high tech' style was hailed by the architecture community, there is no evidence that this style became widely nor universally accepted. Building services with their rotating fans for mechanical ventilation remained hidden. In fact in some cases such as the main university student services' Kings Gate' building in Newcastle University, planning permission was only accepted when architects agreed to house

building services on the underground floor to avoid visual pollution to the councilors and staff offices from the opposite city council building.

Why would urban wind turbines be dealt with differently? Although ducted wind turbines seems to offer a solution where the rotating blades are hidden and could be incorporated within artistic installations in the future their performance and efficiency are still doubtful.

There needs to be social studies at this micro level and whether housing wind turbines as an unseen element and part of the building configuration paves the way to exploring public acceptance.

It can be argued that about a decade from the Bahrain's world trade centre three exposed wind turbines, the latest form of building integrated wind turbines in the Skidmore, Owings & Merrill (SOM) Pearl River Tower, opted for vertical-axis turbines to minimize noise and vibration but still put them in unoccupied "technical floors" to isolate them from occupants in the building. Whether this will be the trend remains to be seen

6. Conclusions

This paper argues that the societal acceptance of urban wind generation has been affected by experience and media exposure. Although research suggests that public perceptions and acceptance of micro wind generation maybe supported by value believes and excitement in participation in new forms of technology, there is no evidence found that this is the case on the ground

Public perceptions and their engagement with the market dictates growth patterns and can underpin incentivization schemes and government policy. Similarly this also affects building regulations.

Architectural styles and the integration of renewables are directly affected by all of the above factors. It is interesting to see the discourse on how much of micro renewable energy should be seen and heard by the public. This in its wake will lead to raising questions on how to advance other forms of micro generation such as the ducted systems and the possible involvement of artists to improve the aesthetic of these systems.

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URBAN WIND ENERGY: EXPOSING SUSTAINABILITY SYMBOLISM OR A HIDDEN EXISTENCE

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Although local press blamed it on the vibration, Tom Hawkins commented (<http://www.urban75.org/blog/>)

'It's not so much the noise or vibration that has shut the turbines off, more like the £54,000 + vat a year maintenance costs for generating hardly anything that is the real factor. I know, I was involved in the second year budget for that building.'

Capeluto et al. (2003) and Ricciardelli & Polimeno (2006) asserted that wind flow within the built environment depends on the exact geometry of all buildings on site. It is important to note that technical issues when integrating and positioning wind turbines on roofs need to consider roof construction materials. Turbulent flow creates stress on the drive gear in a turbine, creating vibrations. These vibrations can, in turn, create harmonic resonances within a building structure. Metal roof decks made from thin roll-formed steel sheet, common in commercial buildings, can act like drumheads and amplify these resonances. In fact, AeroVironment, the building-integrated wind energy suggests in its sales literature that their turbines are only appropriate for buildings constructed of concrete.

3. Policy, incentivization and community acceptance: the vicious circle

The term social acceptance is widely used but has varied meanings for different individuals Wustenhagen et al. (2007). There are three-tiered characterization of social acceptance is broken down into the concept of social acceptance into issues of socio-political acceptance, market acceptance, and community acceptance.

Socio-political acceptance is defined as broad-based support for wind energy among policy-makers, the public, and other significant stakeholders. Wustenhagen et al. (2007) point to public opinion surveys as a sign of socio-political support, but one may also consider policy support as an indicator of broad-based socio-political acceptance.

Market acceptance refers to wind energy technology adoption by consumers, investors, and the power generation industry. At some levels, this is a reflection of technological maturity and reliability such that utilities and investors are willing to make significant investments in wind energy and consumers believe that wind energy will not jeopardize ready access to electric power.

Table 1: indicates that the average cost of MWh electricity generated from wind farms has reduced by about 60% over just five years. However, I would argue that this was not reflected on urban wind technology market nor its acceptance by urban dwellers

Community acceptance is that element of social acceptance that deals with local opposition to individual wind power projects, particularly by residents and local government. Because local approval for a proposed wind project is required before construction can begin, community acceptance is a fundamental aspect of social acceptance of wind energy. This element of social acceptance typically comes to mind first when one reflects on the concept of social acceptance and wind power. Although this is the level of social acceptance from which the term NIMBY ("not in my back yard") has emerged, research has demonstrated that community acceptance of wind power projects cannot be reduced to simple NIMBYism but is actually a complex and dynamic social phenomena, influenced by an array of factors, including perceptions of justice and trust, and fear of losing property market value

Year ▼	Cost	MWh	Average Price
2015	£17,035,416	232,706	£73
2014	£53,175,234	658,611	£81
2013	£32,707,351	379,817	£86
2012	£5,924,231	45,463	£130
2011	£12,826,756	58,708	£218
2010	£174,128	976	£178

Who is first Feed-in Tariff or public perception?

Although Table 1: indicates that the average price of electricity production from wind generated electricity has fallen over the last 5 years. It would be hard to prove that the contribution of urban wind turbines had a major contribution to this even if it followed the incorrect assumption that all of the micro-small wind turbines were urban based.

The Feed-in Tariff scheme is the primary support mechanism introduced by Government to incentivise deployment of small and medium-scale (<5MW) renewable energy generation in the UK. The scheme was launched in April 2010, and a review referred to as 'Phase 2B' came into effect in December 2012. This review implemented significant changes to tariffs and structures for non-PV technologies such as wind, hydro and anaerobic digestion. It introduced lower tariff levels for wind generation; amalgamated the tariff bracket for all turbines under 100kW; and introduced a capacity-driven depression mechanism effective from April 2014. Although figures suggest that there is an increase in power generated by small wind generation technology. The growth experienced by the small wind market sector in previous years has been dramatically reversed throughout 2013 and 2014. The report among other official sources points out that this decline in the market is due to the implementation of Phase 2B of the Feed-in Tariff in December 2012, the deployed capacity of turbines within the sub-100kW sector decreased over 2013 by a combined total of almost 55% compared with 2012. When broken down, this represents a 49% capacity decrease in the 15–100kW bracket, a 72% capacity decrease in the 1.5–15kW bracket, and a 33% capacity decrease in the 0–1.5kW bracket. (ref: small and medium wind UK market report, RenewableUK, March 2015, www.renewableUK.com). What this argument fails to highlight is the relationship between government based policies and how they are built on factual evidence of how the consumers have previously been buying the product and the social acceptance of this technology that would underpin its growth. The impact of media coverage of urban wind energy in the previous section couldn't be marginalized and could be argued to have failed the market regardless especially that there is a complete lack of success stories!

4. Behaviors and value systems towards decentralized systems

Based on Devine-Wright (2012) and IEA task 28 reports, there is an aspiration that adopting decentralized energy generation per se encourages energy citizenship and is a counterpart to the social and psychological detachment of the public from centralized energy systems

Their research continues to advocate that people will be willing to get involved and engage with various technologies to make urban wind turbine work, research suggests that we cannot rely on this as lay people are usually used to the 'plug and forget' attitude they have with centralized energy supply

The social rejection for the construction of nuclear plants and altruistic values of carrying about climate change will increase the appeal of engaging with micro generation

That societies are less individualistic, lazy and passive and seek to be engaged and socially motivated to deal with the micro generation systems, and would allocate the necessary time to familiarize with the technology and be able to run it properly. While there is evidence on the ground that this is happening with PV and solar heating systems, this is not the case for urban wind generation.

When I was involved in suggesting strategies for integrating renewables in a historic Abbey in England (Hexham Abbey). The public consultation indicated that the community accepted the

installation of PV cells on the Abbey's roof but rejected the installation of wind turbines as inappropriate for the historic fabric of the buildings

Public perception of large scale wind farms can be extrapolated in relation to small scale urban wind integration mechanisms, research suggests that hazards of Noise perception are associated with visual impacts. In stormy conditions, ice throw (Shed) creates a physical danger on people and vehicles. IEA wind reports suggests mitigation by utilizing setbacks between wind turbines and residential areas which might not be feasible for urban small wind generation mechanisms. Although appearing as planning and siting issues, related risks to the technology affect public perception where the presence of these systems might lead to depreciation of land and property value.

That local communities will accept renewable energy developments, if such developments are conducted in a manner that these developments give control as well as financial benefits to these communities. This hypothesis is based on the installations affecting a small rural community. In urban areas where social relationships tend to be distant and rarely residents of wards participating in community meetings the application of the principle is doubtful.

5. How visible do we actually want urban wind turbines to be? The unspoken question..

While all the ethical theories of public participation and awareness point out to strategies that may improve engagement with micro generation such as of citizenship, appropriate siting and operation, local management, the main issue still remains. As opposed to passive measures, and 'static and quiet' renewable micro generation systems in reducing the carbon footprint of the urban environment, the tolerance for the length of visual and noise exposure to urban wind turbines remains unanswered. This draws on the analogy of visualizing the human body as a set of valves and pumps or do we prefer to see it the way we are used to? Would ducted wind turbine with their huge structure offer a visually less intrusive model? Figure 4.

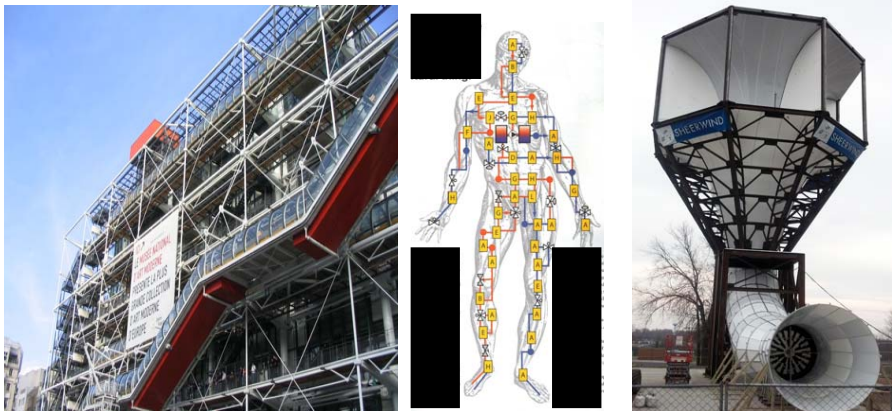


Figure 4: Centre Pompidou with its exposed building services(left), the analogy of a human as a set of building services mechanisms(middle) and the ducted wind turbine(right)

In architecture although exposing the building services as a 'high tech' style was hailed by the architecture community, there is no evidence that this style became widely nor universally accepted. Building services with their rotating fans for mechanical ventilation remained hidden. In fact in some cases such as the main university student services' Kings Gate' building in Newcastle University, planning permission was only accepted when architects agreed to house

building services on the underground floor to avoid visual pollution to the councilors and staff offices from the opposite city council building.

Why would urban wind turbines be dealt with differently? Although ducted wind turbines seems to offer a solution where the rotating blades are hidden and could be incorporated within artistic installations in the future their performance and efficiency are still doubtful.

There needs to be social studies at this micro level and whether housing wind turbines as an unseen element and part of the building configuration paves the way to exploring public acceptance.

It can be argued that about a decade from the Bahrain's world trade centre three exposed wind turbines, the latest form of building integrated wind turbines in the Skidmore, Owings & Merrill (SOM) Pearl River Tower, opted for vertical-axis turbines to minimize noise and vibration but still put them in unoccupied "technical floors" to isolate them from occupants in the building. Whether this will be the trend remains to be seen

6. Conclusions

This paper argues that the societal acceptance of urban wind generation has been affected by experience and media exposure. Although research suggests that public perceptions and acceptance of micro wind generation maybe supported by value believes and excitement in participation in new forms of technology, there is no evidence found that this is the case on the ground

Public perceptions and their engagement with the market dictates growth patterns and can underpin incentivization schemes and government policy. Similarly this also affects building regulations.

Architectural styles and the integration of renewables are directly affected by all of the above factors. It is interesting to see the discourse on how much of micro renewable energy should be seen and heard by the public. This in its wake will lead to raising questions on how to advance other forms of micro generation such as the ducted systems and the possible involvement of artists to improve the aesthetic of these systems.

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ANALYSIS OF ECONOMIC, ENVIRONMENT, SOCIAL FACTORS AND EFFICIENCY OF WIND TURBINES IN LITHUANIA

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Abstract: In this paper wind power development situation and future prospects in Lithuania are presented, performance of operating wind farms is analysed comparing their technical parameters and economic indicators. Analysis has shown that the main factors influencing the efficiency of wind turbines are tower height and the distance from the Baltic sea. Also environmental aspects, permission requirements are analysed and main barriers for wind power development were identified. Despite numerous hindrances related to the administrative procedures, territorial planning system, technical aspects and poor social acceptance it is obvious that wind energy will be one of the main ways to reduce country's energy dependence.

1. Introduction

After the recovery of independence in 1990, the consumption of energy from renewable energy sources (RES) was very low in Lithuania. Lithuanian Government since early 1990s was concerned about the political and economic consequences of high dependence on import of primary energy sources from Russia. Therefore the main strategic objectives in the country's energy policy has been to stimulate and increase the use of RES.

According to Directive 2009/28/EB on the promotion of the use of energy from RES the Republic of Lithuania must ensure that the share of energy from RES will be not less than 23% in gross final consumption of energy by 2020 (20% in electricity sector, 60% in heat production, 10% in transport). Directive 2012/27/EU has a target to reduce EU primary energy consumption by 20% till 2020 and to reduce greenhouse gas emission by 80-95% till 2050 compared to 1990. These objectives are promoting the development of energy economy and RES in Lithuania.

In order to achieve these targets a number of legal acts were adopted in Lithuania. Various estimations and strategies show that the largest potential in power generation from renewables is assigned to wind energy. Estimations provided in Lithuanian National Renewable Energy Action Plan (2009) disclose that electricity produced in wind power plants (WPPs) should make 42.3% of total electricity produced from RES in 2020. 1250 GWh of wind generated

electricity should be produced in 2020. The latest data shows that 636 GWh of wind electricity has already been produced in Lithuania in 2014 and wind electricity covered 44 % of total electricity production from RES.

The Law on Renewable Energy (2011) states that the share of electricity generated using RES by the year 2020 should comprise not less than 20% of total final electricity consumption. In 2013 about 15 % of all consumed electricity was produced from RES. For the implementation of the above target total installed capacity of WPPs should grow to 500 MW (excluding small wind turbines, with capacity up to 10 kW). This limit was assumed on the basis of the study, elaborated by Lithuanian Energy Institute in 2009 [1]. The Study states that this volume of wind power capacities can be integrated with existing reserve capacities and possibilities of transmission grid.

2. Wind power development in Lithuania

Like in most EU countries, wind power share in Lithuanian power system is constantly increasing. Wind power sector is relatively new in Lithuania – first industrial wind turbine started its operation in 2003.

The main document regulating wind power development and promotion till the end of 2010 was the “Procedure for the Promotion of Sales of Electricity Produced from Renewable and Waste Energy Sources” (approved in 2001, amended in 2006), where 6 regions were determined for wind powers development and maximum power limits were set for each zone. Zones were determined considering the access to the transmission network, wind conditions, environmental constraints and other factors. The total quota of 200 MW was distributed through tenders in 2004. Later additional 40 MW were distributed to the winners of the tenders for expansion of generating capacity. Feed in tariff was chosen and still remains the most attractive and efficient support scheme.

This promotion procedure was valid until the year 2010. The implementation of this wind power programme had been going with some delay, but the target of 200 MW was reached in 2011. Further target of 500 MW, as mentioned, is set in the Law on Renewable Energy (in force since May 12, 2011), and is to be achieved till 2020.

During last decade installed wind power capacity has increased significantly (Table 1), and the role of wind energy has been growing rapidly in the Lithuanian renewable electricity sector. In 2014 wind power share among renewable energy sources was about 44 %.

Table 1. Wind power development in Lithuania in 2005-2014 (data of the Lithuanian TSO)

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Installed capacity MW	1	49	52	54	90	155	202	274	278	284
Electricity produced GWh	1.78	13.7	106.1	131	157	202.2	475	540.1	602.7	636.2
Share of electricity consumption %	0.15	0.1	0.8	1.1	1.4	1.9	4.4	5	5.6	5.9

WPPs with installed capacity of more than 350 kW make the majority in Lithuania. They are mainly built as wind farms consisting of several turbines (from 2 to 19 units) or as stand-alone high power units (from 600 to 2000 kW). As the world's wind energy future is

associated with the development of multi-megawatt turbines, manufacturers' supply of this category of equipment is large and there is a possibility to choose from more than ten largest producers. However, wind turbine market in Lithuania consists of three manufacturers. Enercon company is the leader (88.6 % of the market), there is also one Vestas wind farm (6.1 %) and Siemens wind farm (5.3 %).

Currently total installed wind farms' power exceeds 284 MW. Megawatt-size wind farms comprise major part of wind power plants, but there are also many medium-scale (up to 350 kW) standalone wind turbines operating. The reason of small-scale wind turbines popularity is wind turbine power limit differentiation in national legislation. In the Law on Renewable Energy wind turbines are differentiated according to their installed power:

- up to 30 kW;
- from 30 kW to 350 kW;
- beyond 350 kW.

Different planning requirements are applied to these categories. Territorial planning procedures are not obligatory for turbines with up to 350 kW power. Changing of the land use purpose is not necessary as well, technical project requirements are also easier. The differentiation of wind turbines according to their installed power has recently lead to the expansion of smaller scale stand-alone turbines, and it is likely that this situation will remain in the future.

Majority of wind turbines are concentrated in the western part, especially in the coastal region of Lithuania (Fig. 1), as this region stands out with the best wind conditions.

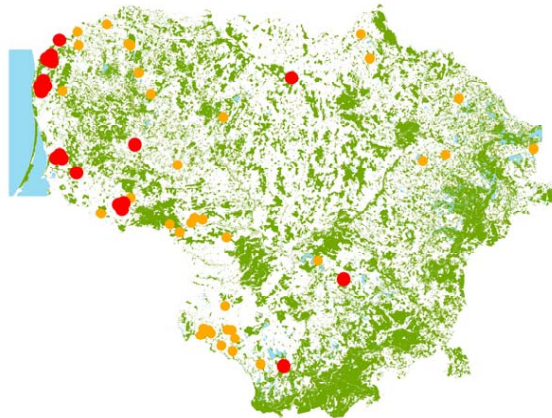


Fig. 1. Geographical distribution of wind power plants in Lithuania in 2014. Red circles represent wind farms (total capacity about 252 MW), orange ones represent medium scale wind turbines (total capacity about 32 MW).

Several wind farms and numerous medium scale wind turbines are located further from the Baltic sea. Analysis of capacity factor dynamics in the paragraph 3 will show that efficiency of wind turbines in deeper inland areas can be as high as in the coastal region.

2.1. Wind power potential in Lithuania

First international research of the conditions for wind power development in Lithuania was conducted in 2000-2003 by the scientists of Risoe national laboratory (now DTU), Lithuanian Energy Institute and innovations company „Ekspontente“ during the project „The UNDP/GEF Baltic Wind Atlas“ [2]. A number of wind measurement campaigns were carried

out in the Baltic countries, the measured data have been analysed according to the “Wind Atlas Method”, implying cleansing the wind data for nearby terrain effects, and resulting in regional wind climates. In order to represent long term wind conditions (>10 years) correlation techniques were used based on long term reference data from meteorological stations. The resulting wind resource map is given in Fig. 2. It is still the main map being referred each time wind conditions in various Lithuanian regions are estimated.

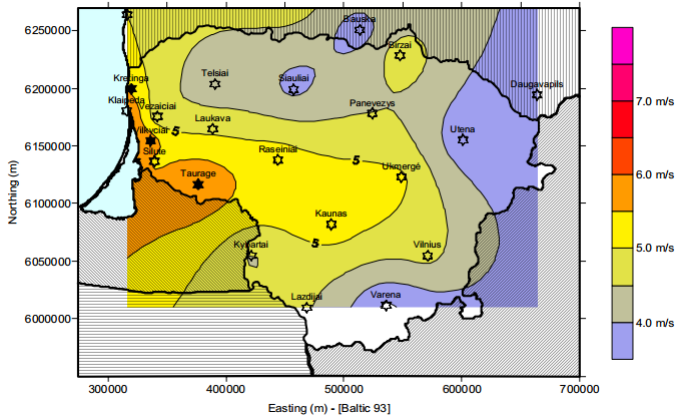


Fig. 2. Average wind speed distribution in Lithuania (height 50 m, roughness class 2)

This Baltic wind atlas showed that wind energy is sufficient for wind power development in the Baltic countries. Lithuanian coastal region falls in the zone where average wind at the height of 50 m is about 5-6 m/s, it means that at the hub height of conventional wind turbines (100 m) wind speed reaches 7 m/s and above. Similar conditions dominate in the northern part of Germany, leading country in EU regarding installed wind power capacity.

Wind atlas is a firm basis for the strategic decisions regarding further wind power development at national scale. However, wind resource map for the major part of the country was made according to the data from meteorological stations, hence it cannot be used for site planning, it just shows how wind conditions change with the distance from the Baltic sea. As wind resources in certain locations can vary significantly, numerous additional measurement campaigns have been carried out for wind power projects since then.

If wind power plants were distributed all over the country, real wind energy potential is estimated to reach 1000 MW. Additionally about 1000 MW of offshore wind farms in the Lithuanian economical zone of the Baltic Sea are considered economically feasible. Recent study [3] has revealed that such amount of wind power would require an expansion of existing electricity network and introduction of new flexible fossil fuel power plants to keep the energy system safely balanced. Nevertheless other experts are confident that existing generating capacities and Kruonis pumped storage hydroelectric plant will be capable of balancing the system with additional wind power capacities introduced.

3. Analysis of wind farms' efficiency and economic factors

3.1 Investigation of wind farms' power capacity factor

Power capacity factor is one of the main indicators which describe efficiency of wind turbines [4]. It is the relation between the actually generated and potential electricity:

$$C_p = \frac{E_{fact}}{E_{pot}} * 100 \% , \quad (1)$$

where C_p – power capacity factor, E_{fact} – generated electricity during the period (GWh), E_{pot} – potential electricity, which could be generated in the same period if wind turbine operated at maximum installed capacity (GWh).

6 wind farms were chosen for the comparison of efficiency (Fig. 3). Period covers one year from January till December 2012. All wind farms consist of Enercon E82 wind turbines.

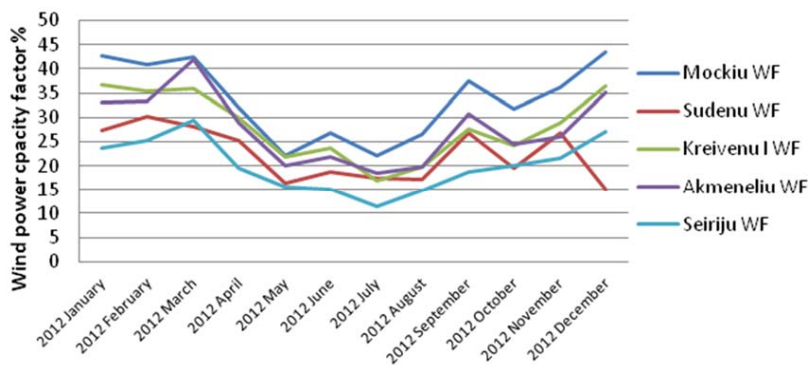


Fig. 3. Wind power capacity factor in different regions of Lithuania in 2012

Capacity factor dynamics shows strong correlation between the curves which indicates similar variation of wind conditions in the country. Power capacity has lowest values in summer (lowermost point in Seiriju WF in July, $C_p = 11.5\%$). At the same time Mockiu WF shows $C_p = 22.5\%$. Tower heights are 78 and 108 m respectively and Mockiu WF is situated in the flat terrain close to the Curonian lagoon.

Best wind power capacity factor results are in winter (December-January). For the comparison, Mockiu WF demonstrates best result with $C_p = 43.5\%$ and the lowest Sudenu WF with $C_p = 15.1\%$ (it is rather an exception than a real feature). Lowest C_p rate during the year was in Seiriju WF (18%). As all wind turbines are of the same model, conclusion can be made that tower height and the distance from the Baltic sea are the main factors affecting the annual energy yield.

Iglesias et al. claim that power capacity factor depends on wind farm's installed capacity – the bigger capacity, the higher C_p indicator, because when wind turbines are dispersed in a wider area, there is a greater probability to catch wind [5]. Figure 4 presents the variation of C_p of 3 wind farms with different installed power (tower height 108 m).

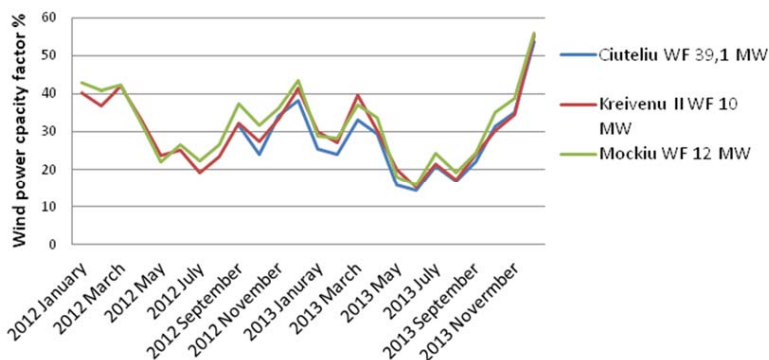


Fig. 4. Wind power capacity factor in wind farms with different installed capacity

Ciuteliu WF installed power capacity is approximately 3-4 times bigger than Kreivenu II and Mockiu WF, but during the year it demonstrates lower efficiency than Ciuteliu and Mockiu WF. To compare, in 2012 October Ciuteliu WF C_p equals to 24 %, Kreivenu II WF C_p = 27.4 %, Mockiu WF C_p = 31.7 %. In 2013 average power capacity factor demonstrates similar results: 26.8 %, 28.8 %, 29.9 % respectively. These results prove that wind farms' installed power is not directly related to the power capacity factor in western part of Lithuania.

3.2 Analysis of wind farms economic parameters

The main target of wind energy systems manufacturers is to optimize wind turbines with aim to generate electric power for the lowest available price [6]. Wind manufacturers usually suggest several WT options optimized for different wind conditions. Optimally chosen wind turbines give maximum annual electric energy yield. Huge rotors with small generators produce electricity most of the time, but also convert just a small part of wind energy in high winds. On the other hand, powerful generators can generate electricity only in strong winds [7]. Therefore design of wind turbines requires the evaluation of wind conditions and proportions between generator and rotor swept area in different locations. Also tower height has significant influence on annual energy production – wind turbines with higher tower generate relatively more electricity, but they are more expensive, therefore it is important to estimate and compare their economic parameters [8].

13 biggest wind farms were chosen for the analysis (Table 2). Although in most of wind farms Enercon E82 wind turbines are used, each project is unique by its local conditions, connection solutions and total investments made during the planning. They are situated in different geographical regions, tower height and installed power also differs which makes it possible to compare similar wind farms and draw some conclusions about factors influencing their economic efficiency. Wind farm investments reach 1.2-2.2 thousands EUR/kW.

Table 2. Economic evaluation of Lithuanian wind farms

Location	Type of wind turbines	Installed power capacity MW	Tower height	Investments mln. EUR/MW	Electricity generation GWh (average 2012-2013)	Payback time
Kreivenu II WF	Enercon E82 (2 MW)	10	98	2	26.44	8.7
Akmeneliu WF	Enercon E82 (2 MW)	6	98	1.22	13.95	8.4
Vydmantai WF	Enercon E70 (2 MW)	30	85	1.24	59.95	7.2
Ciuteliu WF	Enercon E82 (2,3 MW)	39.1	108	1.45	65.72	9.8
Kreivenu WF	Enercon E82 (2 MW)	20	78	1.48	46.88	7.3
Silales WF	Siemens SWT-2.3-101 (2 MW)	13.8	80	1.56	37.65	6.6
Seiriju WF	Enercon E82 (2 MW)	6	78	1.74	10.13	11.8
Laukzemes WF	Vestas (5 - 2,75 MW, 1 - 2,25 MW)	16	100	1.77	35.38	9.2
Benaiciu I WF	Enercon E82 (2 MW)	34	98	1.79	81.84	8.6
Didsiliu WF	Enercon E82 (2 MW), E53 (0,8 MW), E48 (0,8 MW)	21.5	8 - 108	1.91	38.99	12.1
			2 - 78			
			2 - 73			
Sudenu WF	Enercon E82 (2 MW)	8	78	2.06	15.67	12.1
Kreivenu III WF	Enercon E82 (2 MW)	15	98	2.14	37.85	9.8
Mockiu WF	Enercon E82 (2 MW)	12	108	2.23	33.48	9.2

Economic indicators of different wind farms were evaluated by power capacity and tower height. Simple payback time of wind farms was calculated using real feed-in tariff (8.69 EURct/kWh. Vydmantai WF and Kreivenu WF present the best results of payback time – about 7 years. Tower height of this Vydmantai WF shows comparatively small investments for 1 MW and effective location for wind farm. Similar investments – 1.24 mln. EUR were put to Akmeneliu WF, but there is 8.4 years payback time. The explanation of this situation can be different location of WF. Akmeneliu WF is located in the northern part of Lithuania and Vydmantai WF is situated in the coastal zone. Akmeneliu and Seiriju WF are located at similar distance from

the Baltic sea, but Seiriju WF has 12 years payback time which is among the longest. The main reason is the tower height (respectively 98 and 78 m). These results are confirmed by Sudenu and Didsiliu WF located in coastal zone with tower height 78 (Sudenu WF) and 73, 78, 108 m (Didsiliu WF).

Levelized cost of energy (LCOE) calculations showed that under the current market conditions a 2 MW wind turbine is able to generate electricity for 4.45 EURct/kWh, which is lower than market price (4.89 EURct/kWh on average in 2013). However, such a small difference between electricity market price and LCOE is not enough to make it attractive for private investors. Thus support scheme is needed for this category of WPPs. Currently the majority of operating wind farms sell electricity to the grid for a fixed tariff of 8.69 EURct/kWh. This tariff is valid for the period of 12 years from the start of wind farm operation. After this period wholesale market price will be paid for the rest of wind farm's lifetime.

Since 2013 feed-in tariff for new wind power plants has been continuously decreasing and now it makes only 6.1 EURct/kWh. For wind turbines up to 350 kW it is slightly higher – 7.5 EURct/kWh. These electricity prices are not attractive for wind farm developers. Lowest feed-in tariff of 7.09 and 6.95 EURct/kWh will be paid to the winners of the last tenders which were finished in 2013. New wind farms are expected to be planned as soon as new quotes for wind power at national level are announced by the government.

There is a separate category of small wind turbines (up to 10 kW) in Lithuania. They are commonly used for the individual energy needs, because experience shows that despite the relatively higher feed-in tariff for electricity (7.8 EURct/kWh in 2015) and free of charge connection to the distribution network, commercial projects are not economically attractive. Reasons for this are high investment per unit of power, small amount of produced energy, investment rate of return, frequent malfunctions of equipment and expensive maintenance.

4. Permission requirements and environmental aspects of wind power planning in Lithuania

4.1 Permission requirements

Location of each wind farm is determined during spatial planning procedure, which is a long process in Lithuania (up to 2 years). As stated in the Law on Renewable Energy, detailed planning stage is not necessary for a stand-alone wind turbine with up to 350 kW of installed power. All other cases need detailed planning.

Formal permissions required during the project implementation period are:

- *permission for power expansion* (issued by the Ministry of Energy; time – 30 calendar days from the submission of application);
- *construction permission* (issued by local municipality; time – 35 workdays for >350 kW turbines and 20 workdays for <350 kW turbines);
- *permission to generate electricity* (issued by the Ministry of Energy; time – 30 calendar days from the submission of application).

Main delays are related to the changing of land-use category for wind turbine construction, EIA procedures, discussions with local communities and the number of different institutions, which have to confirm the documents.

Sizes and distances

There are no legal regulations for distances from wind farm to the dwellings, protected areas and other objects, therefore they have to be estimated and discussed for each project separately. Wind turbine size matters when the turbine is planned close to the living or protected area. In former and current wind energy projects distances to the closest dwellings are selected considering the maximum permissible noise levels, stipulated in the Hygiene Norm on Noise HN 33:2011 (in force since the 1st of November, 2011). Wind turbines do not appear in the list of objects having specific sanitary zones, therefore sanitary zones are defined for each turbine according to the noise distribution modeling results during the procedure of the assessment of impact on public health (this procedure is separate from EIA).

Distances to the protected areas are checked during the EIA selection procedure. Wind turbines and farms are not on the list of objects, which need EIA procedure. Selection procedure shows whether EIA is necessary or not. If a wind farm is too close to a certain protected area, an EIA procedure is necessary. If distance is big enough, EIA may be not necessary. EIA procedures are pursued by accredited enterprises.

Information for the selection procedures (both for EIA and the assessment of the impact on public health) about the wind power project and its possible impacts can be submitted by the applicant, and no proof of competence is required. However, applicant (investor) carries full responsibility for the correctness of this information as at the end of the project and during wind turbine operation noise levels and other parameters are measured and compliance with projected data is checked. If it appears that noise levels are higher, wind turbines may have to be removed.

It should be mentioned that there is a lack of coordination of actions and cooperation between responsible institutions regarding the permission issues. As the number of wind power projects is big and increasing, territorial planning specialists need professional guidance related to the requirements for wind turbine size and distances from sensitive areas.

4.2. Noise, infrasound and flickering issues

Different wind turbine models emit different noise levels, therefore distances to the closest living areas are calculated separately for each wind energy project before or during the impact assessment procedures.

Hygiene Norm on Noise HN 33:2011 [9] states that noise level outside the residential building cannot exceed 45 dBA at night time, this value is the benchmark for noise modeling. This means that a wind turbine with the height of 50 m must be located at least 100 m away. For higher turbines this distance is bigger, but it is defined according to noise distribution modeling results.

In the former Hygienic Norm on Noise HN 33:2007 this limit was 55 dBA, so MW-sized wind turbines could come much closer to people's homes. Due to active opposition of local inhabitants, especially in the coastal region, Hygienic Norm eventually has been improved setting planned wind turbines further away from the houses.

In the urban areas noise issue is not that relevant because of higher level of background noise. Authors of this paper have estimated that during the working day the equivalent background noise level on the roof of a public institution building is 55-60 dBA and in the night time it drops to 45 dBA, while in the countryside background level may be as low as 33 dBA.

Another important aspect is the wind speed at which the wind turbine noise is measured. It is not stated in legal acts, but from practice it is determined that during winds stronger than 6 m/s background noise starts to interfere with the wind turbine noise and it is difficult to distinguish the real source of increased noise level. This fact provides some freedom for the EIA specialists when modeling wind turbine noise propagation zones.

Infrasound prediction is a more complicated issue because there is no standard software to model the infrasound propagation. The only way to find out the real levels of infrasound in the residential area is measurements on the site. Now, as there are many wind farms and different wind turbines operating, measurement results are used for the EIA procedures of the planned wind farm projects. According to the Hygiene Norm 30:2009 [10] the maximum permissible infrasound level in frequency band of 8-16 Hz is 79-103 dBA respectively.

There are no legal national regulations for the maximum duration of shadow flickering on dwellings. Limit of 30 hours/year or 30 min/day is usually applied (based on regulation in Germany). Means of elimination of possible flickering effect must be provided for each project during the EIA procedures. Such means include shutting down wind turbine temporarily at the time of high probability of flickering, planting extra vegetation as a screen from wind turbine blade shadows.

4.3. Impact on landscape

Wind turbines' impact on landscape is a relevant aspect which hasn't been addressed right way yet. A PhD study carried out in 2014 has revealed that there are no objective criteria for the assessment of wind turbines' impact on landscape. Moreover, there is almost no legal regulation of visual pollution of landscape and wind turbine locations are usually approved without having evaluated the consequences of this impact. Although AIE procedure incorporates evaluation of wind turbines' visual impact on landscape, there are no criteria available. Therefore location of wind turbines mostly depend on the solution of land lease and sanitary protection zones issues.

During the above mentioned study several districts with highest wind farm concentration were analysed and visual impact, significance and contrast level were evaluated. It was determined that strongest negative impact of wind turbines is caused by turbines situated 1-3 km from the observer. The hub height of modern wind turbines reaches 80-120 m and the total height is even bigger, up to 170 m. Under clear weather conditions such turbines are visible from 25-30 km distance, but the presence of large or sharp landscape elements (forest, terrain, electricity lines, industrial skyline) softens the visual impact.

The poll of public opinion has proven that wind farms make significantly stronger visual impact than stand-alone wind turbines. The view of wind turbines from a relatively short distance (up to 3 km), when they dominate in the landscape, is perceived as negative. Increasing distance results in more positive estimations. In order to reduce the visual impact it is recommended to group wind turbines into compact wind farms and site them away from the settlements, protected areas and scenic landscapes.

5. Public acceptance of wind turbines

In general people have positive attitude towards wind energy, because they have heard or know that it is renewable, wind turbines don't contribute to climate change, pollution of environment, etc. But things typically change when turbines come closer to the dwellings. Then local inhabitants get more interested in all aspects of wind turbine neighbourhood and find out that in the end they can get disadvantaged. Consequently conflicts arise due to the changes or restrictions of land use, different economical benefits, possible impact to health, etc.

In coastal region, where wind turbine concentration is the highest, there are locations where turbines stand only about 100 m away from the closest dwellings. People living in the neighbourhood are informed about the wind farm to be built at the beginning of the detailed planning procedures and they can take part in the decision making by giving their proposals and expressing their opinion about the wind farm location and possible environmental or health

impact. No further steps are taken without having the signatures of all owners of adjacent land sites. However, discussions and negotiations with local inhabitants are one of the most difficult parts of the project, often ending in the courtroom. Local inhabitants often abuse their rights seeking unjustified financial benefit by appealing the decisions of detailed plans or demanding a certain reward for their signatures. Typical arguments against wind turbines are: increased level of noise, potential negative impact to their health, drop in the price of land sites adjacent to wind turbines, impact on their economic activity. These arguments often stem from the lack of knowledge and education about wind power technology, its advantages and possible impacts. Also wind turbine neighbours often increase the price of land, which needs to be purchased or rented for the erection of wind turbine.

Resistance to wind turbines is becoming typical in coastal region as people share negative experience arising from the proximity of wind farms. In other districts, further from wind farm concentration, situation is not that tense as there are still more open uninhabited lands, and people's preconceived attitude towards wind farms is not that negative.

The behaviour of the wind power project developer can make the difference between success and failure. Wind farm owners or potential investors use various approaches to achieve communities' support or to overcome their antagonism and indifference. Some of them make contribution to the development of local village or town infrastructure - there have been several cases when wind farm investors built a school stadium or contributed to the renovation of local tourism infrastructure. However, most often owners of private land must be dealt with.

There was also one interesting project implemented in small Smalininkai town, where local community owns 250 kW wind turbine, which was supported by several programmes (Lithuanian Environmental Investment Fund, The GEF Small Grants Programme). Part of the incomes from sold electricity is used for the improvement of town's infrastructure.

Another idea is to use experience from foreign countries, where corporate capital projects are often implemented. The financial model, where a wind turbine or a wind farm is owned by a group of physical persons or community, is very attractive and successful in Denmark and usually solves the public acceptance issue in the early stage as community has economic interests in such case. However, in Lithuania this model faces barriers related to poor economic situation in the province, and the only way to come into agreement with the land owner is to acquire or rent the land for the lifetime of wind turbine.

6. Major barriers for further development of wind energy in Lithuania

Analysis of the barriers for wind power development was the main activity during the international project "Wind Energy in the Baltic Sea Region 2 (WEBSR2)", partly financed by EU Interreg programme. Lithuanian Energy Institute together with partners from Germany, Sweden and Poland made extensive research on the national situation, identified main hindrances and prepared a set of recommendations for project developers and decision makers. Main barriers are given further in this chapter.

Investors and project developers would name many difficulties, which are faced during the implementation of wind energy projects, but the main drag to wind energy development in Lithuania has been caused by the lack of consistent state policy in renewable energy sector.

Other main hindrances may be categorized as follows:

Administrational:

- long spatial planning procedures (1-2 years) due to the lack of special territorial plans for wind energy development. According to existing legal acts, procedure of land category change must be passed for the construction of wind turbine (>350 kW), which is done during

the detailed planning. With a special plan for wind power expansion territorial planning procedures would take significantly less time, and many misunderstandings and conflicts would be avoided. In districts, which don't have a special plan concerning wind power development, local municipality board makes decision regarding the permission for further detailed planning, and here a problem of the lack of competence is often faced;

- disinterest and unconcern of local authorities towards renewable energy development projects. Territorial planning processes on regional level are run by local municipal boards, which impede the detailed planning procedures by the lack of competence and sometimes even by intentional delay. Permission issuing process is a good soil for corruption;

- lack of administrative planning tools for wind energy development;

- due to the lack of justified planning tools and strong social opposition, the confirmation of special territorial plans for wind power development (district or local level) by the local Municipality Board is complicated;

- lack of coordination of actions and cooperation between different institutions regarding the detailed planning and permission issues.

Economic:

- smaller wind energy projects are not feasible without support for investments because costs of project preparation and implementation are almost not dependant on the size of the project, therefore expenditures of small energy producers are disproportionately big.

Technological:

- differentiation of wind turbines to the groups of less than or equal to (≤ 350 kW) and bigger than 350 kW power is not adequate to the choice of wind power technologies available in the market.

Social acceptance:

- problems of public acceptance during detailed spatial planning procedures appear to be favourable environment for the owners and users of neighbouring land to seek a certain reward for their signature;

- lack of objective, research based and publicly available information about wind power technologies and their possible impact on environment and public health leads to the strong opposition from local communities, especially in the areas with higher wind farm concentration.

7. Conclusions

- Analysis shows that wind conditions are favourable for wider wind power development in Lithuania: average wind speed at the height of 100 m is estimated at 7 m/s and above. Similar conditions dominate in the northern part of Germany.
- Electricity generation in wind turbines mostly depends on the geographical location: E82 wind turbines with the same tower height in coastal zone generate 15 % more electricity than those in the midland regions.
- Wind farm capacity factor dynamics show that the main factors influencing wind farm performance are tower height and the distance to the Baltic sea.
- Numerous hindrances to wind power project development related to the administrative procedures, territorial planning system, technical aspects and poor social acceptance have been identified. However, it is obvious that wind energy will be one of the main ways to reduce country's energy dependence.

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