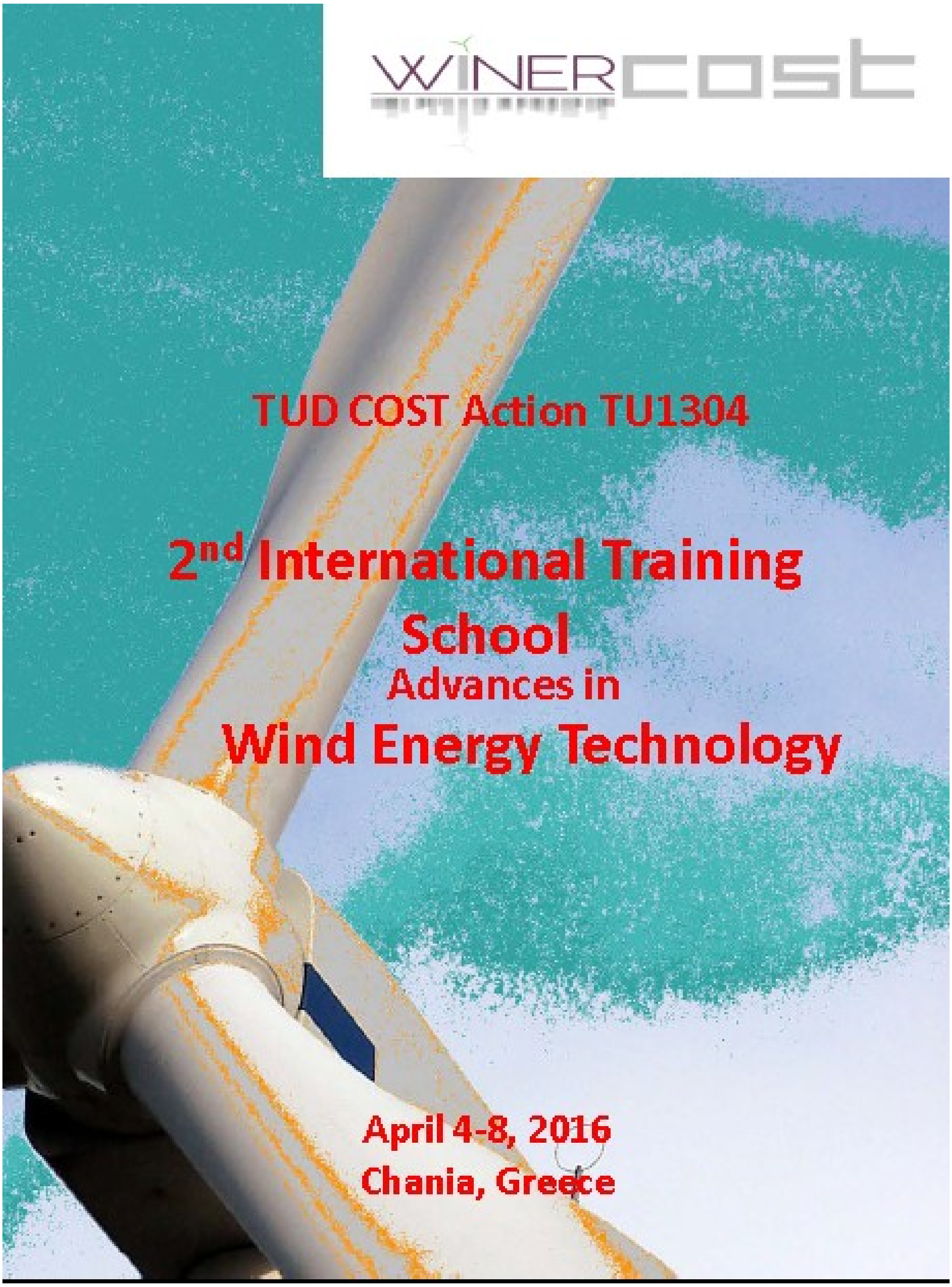

TUD COST Action TU1304

2nd International Training School

Advances in

Wind Energy Technology

April 4-8, 2016

Chania, Greece

Advances in Wind Energy Technology

COST Action TU1304 WINERCOST

2nd International Training School, Chania, Crete

Wind Energy Technology to enhance the concept of Smart Cities

Editors

Charalambos Baniotopoulos, Claudio Borri, Bert Blocken, Hassan Hemida, Milan Veljkovic, Tommaso Morbiato, Ruben Paul Borg, Stefanie Huber, Evangelos Efthymiou, Georgios E. Stavroulakis.

Technical University of Crete Press

ΕΚΔΟΣΕΙΣ ΠΟΛΥΤΕΧΝΕΙΟΥ ΚΡΗΤΗΣ

Chania, Greece 2016

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TU1304 WINERCOST ACTION
2nd TRAINING SCHOOL
"ADVANCES IN WIND ENERGY TECHNOLOGY II"

Charalampos Baniotopoulos[a,b] and Claudio Borri[c,d]

[a] *School of Civil Engineering, University of Birmingham,* [b] *WINERCOST Chair*
[c] *Department of Civil and Environmental Engineering, University of Florence,* [d] *WINERCOST Vice Chair*

Abstract: The 2nd WINERCOST Training School on the *Advances in Wind Energy Technology II* is the second Training School organised within the framework of the activities of the COST 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 are presented by the lecturers and discussed in details with the trainees during the days of the present 2nd Training School.

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 revisits safe, cost-effective, sustainable and societally accepted wind energy technology for consideration in the design and development of the future urban and suburban habitat.

To this end, 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
- investigate effective adoption methods for enabling the concept of smart future cities.

In addition, the utmost important issue of the social acceptance strategy is 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, combined heat power systems, and wind energy systems where a significant potential from small and medium scale (15kW-100kW) wind turbines is still to complement them. As a matter of fact, the upper limit of 100kW is the maximum power that can be connected directly to the low voltage grid in most European countries. 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 one of the leaders in on- and offshore wind energy technology with respect to size, expansion trends and innovation applications like the Built Environment Wind Energy Technology, it becomes mandatory for all COST countries stakeholders to:

- intensively collaborate in order to exchange expertise,
- discuss any open problem (like noise, integrity, societal acceptance, etc.),
- disseminate the respective outcomes to engineers/designers/researchers (in particular Early Stage Investigators) by means of Training Schools, Seminars and Conferences 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 way, WINERCOST strongly contributes to the benefit of the future smart cities concept by:

- identifying prerequisites and conditions for the adoption of wind energy technology into the urban and suburban built fabric,
- supporting relevant measures and actions,
- 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 (CO_2 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 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 60º, 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 are so far 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.

This way, following the discussions of the yet open problems (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 built environment. In this framework, a wealth of expertise on the previous wind energy technology topics has already 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 as established are 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 wind conditions and installed capacities of small and medium wind technology systems in the urban environment are collected and evaluated with reference to different turbines sizes, installation capacities, and grid integration. Aim of this task is to collect actual knowledge, assess relevant wind energy technology applications and evaluate assets and weaknesses.

- 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 small and medium size wind energy technology.
- evaluate regional differences including energy policies, design requirements and building rules for small and medium wind energy technology in urban areas. Due to the differences in installation capacities of small and medium size wind energy technology in urban areas, a review of policy-based factors like energy harvesting is discussed. Political-based installation and design requirements reveals local needs for possible improvements in actual design guidelines. Furthermore, differences in fixed price purchase is also taken into account.
- assess wind conditions in urban and suburban environment, wind maps/roses quality and wind comfort problems in neighbouring areas. Compared to large on- and offshore wind turbines, small and medium wind energy technology is 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 shows the challenges for small and medium wind energy technology in the built environment.
- determine societal acceptance criteria: in fact, the installation of small and medium wind energy technology in urban areas is influenced significantly by the acceptance by the local communities. A European catalogue of criteria for 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 small and medium wind energy technology. 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.
- discuss European energy policies and strategy for advancement of the small and medium wind energy technology with consumers, municipalities, industry (mainly 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 concept.

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 small and medium size wind energy technology 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. 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 29 countries (Austria, Belgium, Bosnia and Herzegovina, Croatia, Cyprus, Czech Republic, Denmark, Finland, FYR of Macedonia, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom) collaborate and contribute towards the successful completion of the WINERCOST aims and objectives.

3. Dissemination activities

WINERCOST has as scopes to:

i) 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) 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) convince industry (WET manufacturers and WET/BWT service providers) to invest to this sector by communicating to them all the wealth of findings and outcomes of WINERCOST

iv) 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 and

v) train Early Stage Investigators in wind energy harvesting technology so that a new generation of scientists and engineers is ready to lead the challenge of the built energy wind energy harvesting to materialise the concept of intelligent smart cities.

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 1st International WINERCOST Conference organised in Ankara, 21-22 April 2016, as well as the WINERCOST website (www.winercost.com) being both broad international fora 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, 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 steps forward. 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 CO_2 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 is to 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 was the first open forum within the lines of the previously described dissemination framework. Within these two days, three cycles of discussions corresponding to the activities of the three WINERCOST Working Groups were organised.

The first one concerned 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 onshore 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 Workshop Proceedings.

The 1st WINERCOST Training School "Advances in Wind Energy Technology" that took place in Malta, 26-31 May 2015, that is followed by the 2nd WINERCOST Training School "Advances in Wind Energy Technology II" organised in Chania, 4-8 April 2016 aim to train Early Stage Investigators on the advances of wind energy technology and the related topics.

4. Future steps

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

Eventually, in 2018 the 2nd WINERCOST International Conference will be organised to provide a broad international forum for the presentation and discussion of the final output of the WINERCOST Action where different aspects of wind energy technologies in the built environment will be presented aiming to enhance the concept of intelligent future cities.

Acknowledgements

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TU 1304 – WINERCOST
Advances in Wind Energy Technology II
Chania, 4 - 8 April 2016

Wind energy technology reconsideration to enhance the concept of smart cities

C Baniotopoulos[a]

[a] *Prof and Chair, Sustainable Energy Systems, School of Civil Engineering, University of Birmingham, United Kingdom*

COST OVERVIEW

- What is COST?
  - Founded in 1971, COST is the oldest and widest European intergovernmental framework for transnational Cooperation in Science and Technology.
  - COST has been supporting networking of research activities across all 35 Member countries and beyond for more than **40 years**.
  - COST is open to all disciplines, to all novel and ground-breaking S&T ideas, to all categories of partners where mutual benefit is real.

COST Mission Statement

COST enables breakthrough scientific and technological developments leading to new concepts and products.

It thereby contributes to strengthening Europe's research and innovation capacities.

Through trans-European networking of nationally funded research activities.

COST Key Principles

- Bottom-up
- Pan-European
- Openness
- Capacity-building
- Provide equal opportunities
- Spreading of knowledge – dissemination of results
- Output and impact oriented
- Leverage nationally funded research
- Light structure and administration

COST POLICIES

Inclusiveness Target Countries

Originated from:

- The political context of the Innovation Union (Horizon 2020)
- The intergovernmental context of the COST Member Countries

With the aim to:

- **Encourage and enable researchers from less research-intensive countries across the COST Member Countries to set up and/or join COST Actions and get more intensively involved in all COST activities**
- Counterbalance research communities unequal access to knowledge infrastructures, funding and resources distribution
- Connecting "pockets of excellence" in science and technology operating from diverse locations in Europe

Excellence and Inclusiveness

Implementation Strategy by the MC

The Action should have a plan towards inclusiveness **(Geographical Coverage, Early Career Investigator involvement and Gender Balance)** that is revised and updated at every MC meeting and develop a strategy to attract researchers and stakeholders

Examples

- Leadership roles
- Organising and locating Action meetings and events
- Benefiting from COST networking tools
- Promoting STSMs
- Action Think Tank for Early Career Investigators

ECI = PhD + up to 8 years

SME and Industry Cooperation

Implementation Strategy by the MC

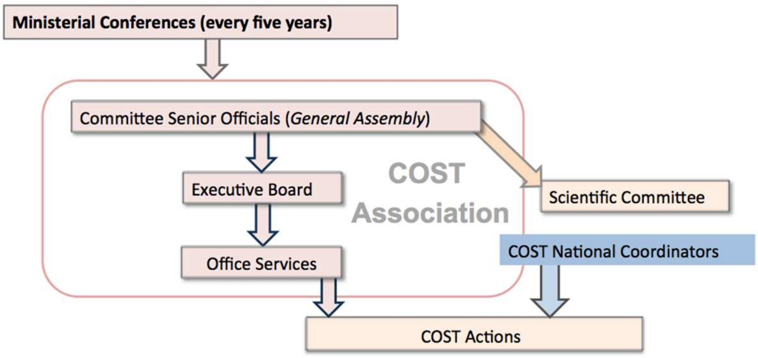
Aiming to facilitate/ encourage industry participation

SOME EXAMPLES:

- Session dedicated to industrial participation at Action events
- Roundtable discussions with industrial partners at Action events
- STSMs with industry acting as home/ host institution

COST STRUCTURE

COST Association organisation and relation with other actors

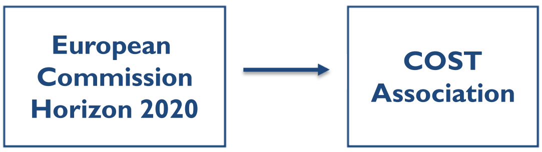


See: http://www.cost.eu/about_cost/who

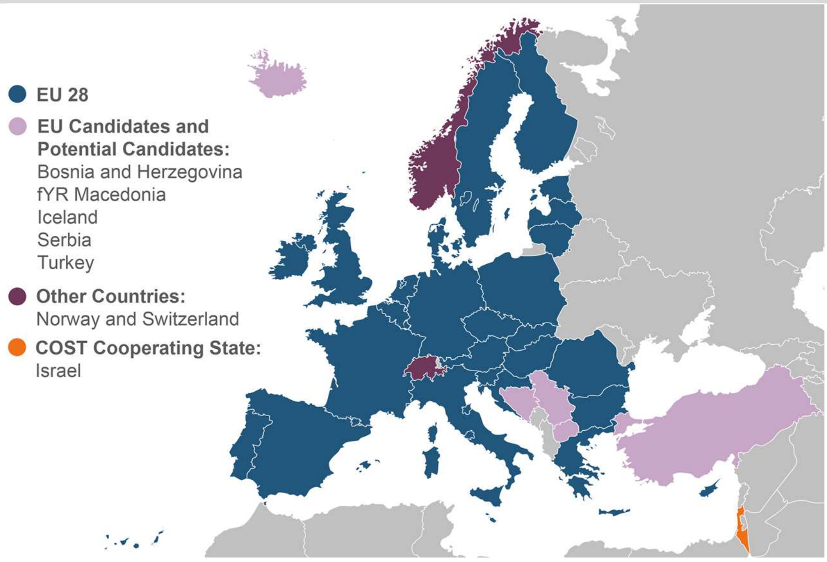
COST Budget in H2020

EUR 300 million for 7 years from two H2020 work programmes:

- Challenge 6 "Europe in a changing world – inclusive, innovative and reflective Societies"
- "Spreading Excellence and Widening Participation"



COST Countries



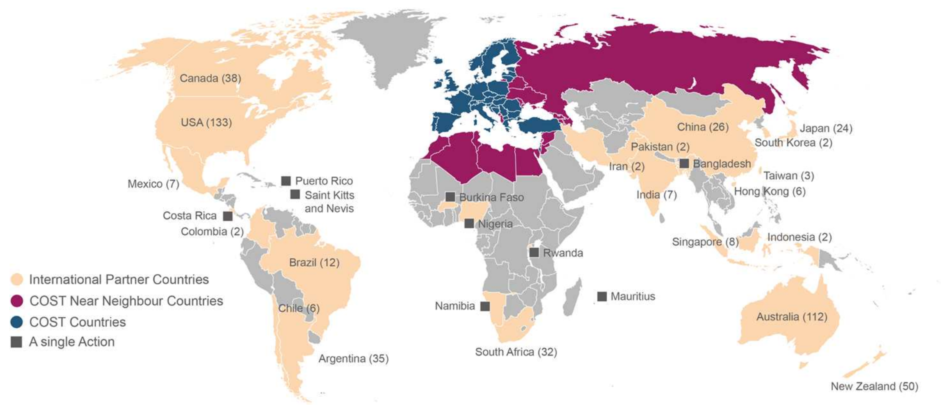
International dimension of COST

The participation of Institutions from Near Neighbour Countries (NNC) and International Partner Country (IPC) is welcome and is based on *mutual benefit*

- **Institutions in Near Neighbour Countries (NNC):**
  - Balkan countries (Albania and Montenegro),
  - Mediterranean countries (Algeria, Egypt, Lebanon, Libya, Morocco, the Palestinian Authority, Jordan, Syria and Tunisia)
  - Eastern European Countries (Armenia, Azerbaijan, Belarus, Georgia, Moldova, Russia and Ukraine)
- **Institutions in all other International Partner Countries (IPC)**

International Partner Countries

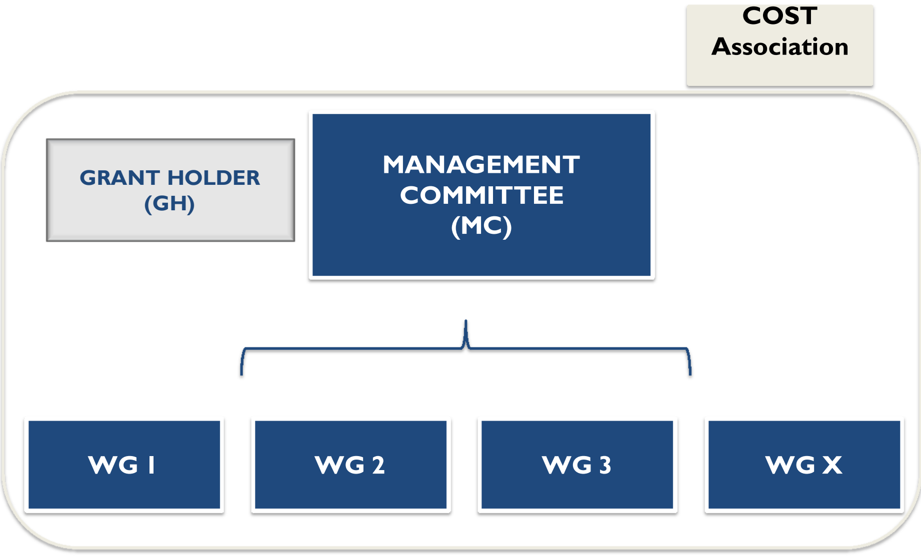
519 participations in running Actions across 29 countries



COST ACTIONS

- A network of researchers with nationally funded research pursuing the fulfilment of the objectives and deliverables described in the approved proposal (MoU)
- Based on a joint work programme for 4 years
- In fields that are of interest to at least 5 COST Countries (average 21-22 countries)
- Selected via a COST Open Call

Action Structure



Management Committee

DECISION MAKING BODY

Coordination, Implementation, and Management of an Action

Supervising the appropriate allocation and use of funds

Achieving the Action's MoU objectives

COMPOSED OF

Delegates nominated by their respective COST National Coordinator (CNC)

Up to 2 representatives per Participating COST Country

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C BANIOTOPOULOS – Wind energy technology reconsideration to enhance the concept of smart cities

Management Committee

KEY ROLES in order to ORGANISE THE WORK

ACTION CHAIR
ACTION VICE CHAIR
WG LEADERS
GRANT HOLDER Scientific Representative
And other horizontal activities

CORE GROUP:

Prepare MC decisions

CORE GROUP MEETINGS

Management Committee

MAIN TASKS TO BE PERFORMED by the MC

Action Strategy

Work & Budget Plan

Dissemination & Exploitation Strategy

Memberships

Implementation of COST Policies

Approval of new Countries and Organizations

Reporting

Supervising the appropriate use of funds

Working Groups

PRODUCTION & EXCHANGE OF RESEARCH

Achieving the scientific objectives as defined in the MoU

WG Leaders must be MC Members

COMPOSED OF

Researchers from Participating COST Countries
MC members (all MC members should become members of WGs)
MC Observers from approved NNC, IPC, Specific Organisations

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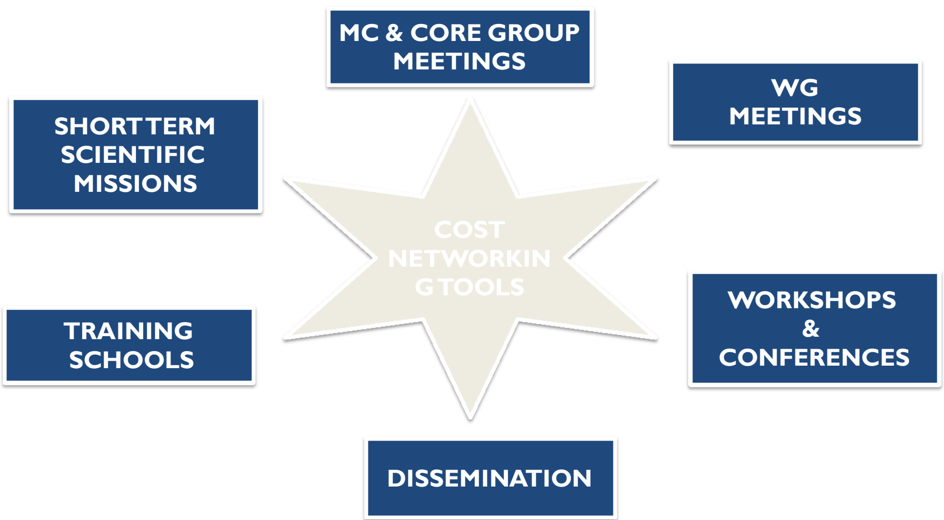
COST Networking Tools



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COST Networking Tools: Training School

TRAINING SCHOOLS

- Provide intensive training on a subject that contributes to the aim of the Action (new or emerging subject)
- If applicable, offer familiarization with unique equipment or know-how in one of the laboratories of the Action

Our Action (TU1304 COST Action)

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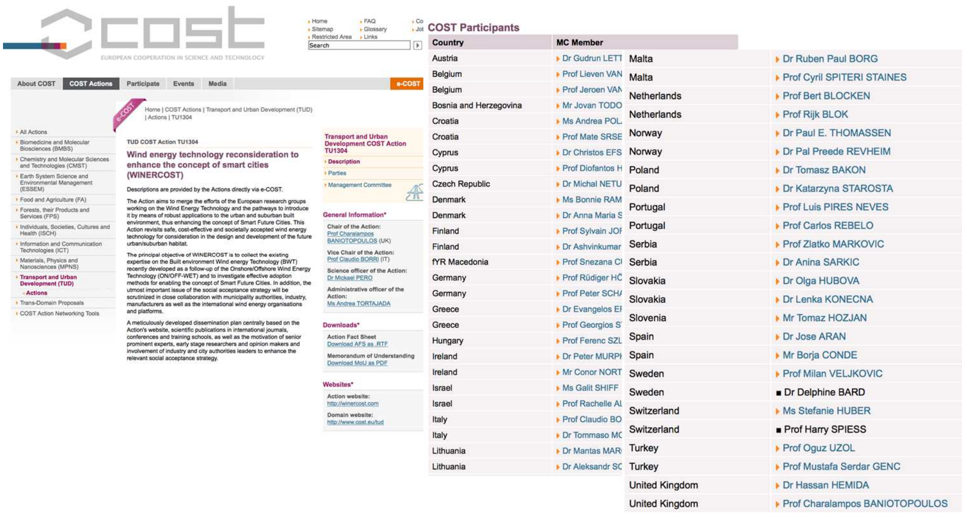
TU1304 WINERCOST ACTION



- **Aim**
- To merge the efforts of the European research groups working on WT and find the pathways to introduce it
- by means of robust applications to the **urban and suburban built environment**, thus enhancing the concept of ***Smart Future Cities.***

- **WINERCOST will collect the existing expertise**

on the WET & Built environment Wind energy Technology (BWT) and investigate effective adoption methods for enabling the concept of Smart Future Cities.

Social acceptance strategy

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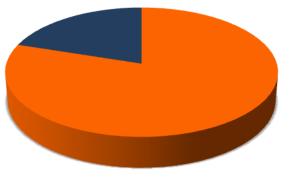

The objective of *Future Smart Cities* (HORIZON 2020) aims at 20% of renewable energy

Significant potential
small and medium size (15kW-100kW) wind turbines

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Reasons for launching the WINERCOST

To meet the increased demand for energy in **Smart Cities**, it is imperative to search for the most environmental friendly technologies:

WET and the **BWT** emit zero greenhouse gasses that is considered as the principal CO_2-zero strategy criterion for the ***Smart Cities Concept***

BWT is an efficient and economic alternative of the immensely expensive large Aeolian park concept!

Objectives

1. WET as a source of knowledge for BWT

1. Foster and enhance BWT apps

1. Society acceptance strategy and other non-technical issues to accelerate the use of BWT

4. Disseminate the outcomes

WINERCOST Objectives

will be obtained by

(1)evaluating assets and disadvantages of the existing variety of ON- and OFF-WT systems

(2) widely and thoroughly **working on innovative methods of adaptation** of BWT in the urban environment

(3) **initiating a social debate on the use** of BWT with municipality authorities in the presence of stakeholders

Impact of the WINERCOST Action

(1) **Solve** technical and non-technical problems by using the existing experience from onshore/offshore WT systems

(2) **Promote** the BWT good practice applications

(3) Thoroughly **discuss** the strategy to obtain social acceptance and therefore, accelerate its implementation

(4) **Educate** and **specialize** early stage researchers and engineers on BWT and

(5) **Start a** fruitful **dialogue** with municipality authorities and the rest of the stakeholders on the use of BWT

Principal research tasks

(1) To **collect** any available **data** of **existing small, medium and large wind turbines & supporting structures** and evaluate assets and weaknesses.

(2) To **transfer the knowledge from on- and offshore wind energy projects** (Could "large" wind energy be effectively downscaled to SMWT?)

(3) To **evaluate regional differences** including **energy policies** and **design requirements and building rules** for SMWT in urban areas.

(4) To **assess wind conditions in urban and suburban environment, wind maps quality** and **wind comfort problems in neighboring areas**.

(5) To **determine social acceptance criteria** as the installation of SMWT in urban areas is significantly influenced by the acceptance by the local communities.

(6) To **discuss European energy policies** and **strategy for advancement** of the BWT with consumers, municipalities, industry (turbine manufacturers) and network providers.

First half of the WINERCOST (existing expertise)

Second half of the WINERCOST Action (development of a strategy to enhance the Smart Cities Concept by effectively introducing BWT projects into the built fabric)

Key issues

- **Technological implementation** difficulties
- **Non-technical negative effects** (e.g. noise, production/installation costs, logistics, reliability, integrity, system robustness, aesthetic problems)
- **European energy policy**
- **Society acceptance issues**

3 Working Groups

- **WG1A**: Wind simulation, characterization etc. issues (CFD, Maps, etc) with reference to theoretical, experimental and numerical research approaches
- **WG2A**: ON- and OFFSHORE WT projects and the respective accumulated expertise
- **WG3A**: Non-technical issues of WT including social acceptance, European energy policy and municipalities-researchers-industries dialogue

- **WG1B**: Built environment Wind Energy Technology (BWT) advances
- **WG2B:** Built environment Wind energy (BWT) pilot projects and good practice examples
- **WG3B:** Social acceptance, European BWT policy and other non-technical BWT issues.

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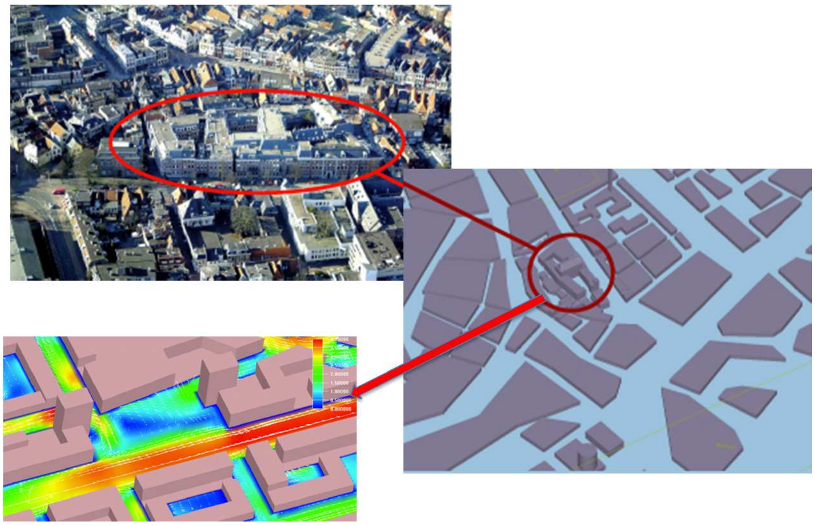
Urban scale approach



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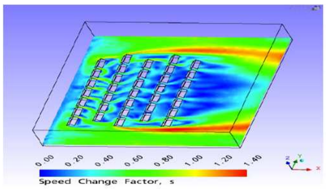
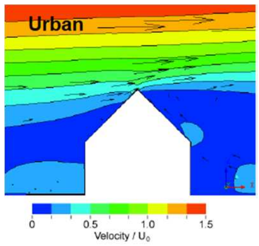
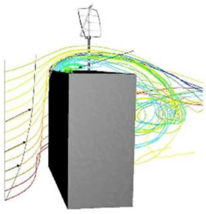
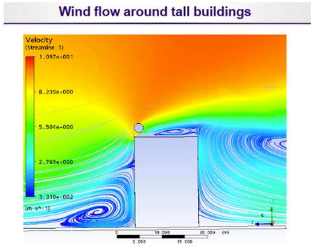
Building scale









Society acceptance

iea wind

The International Energy Agency
Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems

Projects Intranet pages

Task 28, Social Acceptance of Wind Energy Projects

Dissemination plan

4 Major Axes

(1) To approach, open dialogue with and incorporate decision making administrative structures

(2) To coordinate relevant activities of the academia and research centers

(3) To convince industry (WET manufacturers and WET/BWT service providers) to invest

(4) To motivate general public (citizens to support the implementation of BWT for Smart Future Cities) .

TU 1304 | WINERCOST | Chania, 4-8 April 2016
C BANIOTOPOULOS – Wind energy technology reconsideration to enhance the concept of smart cities

WINERCOST website

www.winercost.com

- Scientific books
- Papers in scientific/technical journals or proceedings of Intern. Conferences
- Teaching material
- Articles to non-technical journals, newspapers and interviews to national and local television

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Training Policy

STSMs	Training

Training Schools (Malta, Chania, ...)

Gender Balance Strategy
(Encouregement to female participation)

Early Stage Investigators

Thank you very much
for your attention!

Lambis Baniotopoulos

Notes

Notes

TU 1304 – WINERCOST
Advances in Wind Energy Technology II
Chania, 4 - 8 April 2016

Wind flow and CFD

Bert Blocken [a,b]

[a] Professor and Chair, Building Physics, Department of the Built Environment, Eindhoven University of Technology, The Netherlands
[a] Professor, Computational Fluid Dynamics, Department of Civil Engineering, KU Leuven, Belgium

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KU LEUVEN

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CFD: what, why and how?

What is Computational Fluid Dynamics?

CFD is "solving fluid flow problems **numerically**"

"CFD is the art of replacing the integrals or the partial derivatives (as the case may be) in the Navier-Stokes equations by discretized algebraic forms, which in turn are solved to obtain numbers for the flow field values at discrete points in time and/or space." *(John D. Anderson, Jr. 1995).*

Computational Fluid Dynamics is a tool that allows us to solve flow problems that do not have known analytical solutions and **cannot be solved in any other way**.

CFD: what, why and how?

Why use Computational Fluid Dynamics?

Advantages

- Relatively **inexpensive** and **fast** (computational costs decrease as a function of time)
- CFD provides "**complete**" information (all relevant variables in the whole domain)
- Easily allows **parametric** studies (= important in design)
- **No similarity constraints** (simulations can be performed at full scale)
- Allows **numerical experiments** (e.g. study of explosions, failures, … which you do not want to reproduce in reality)

Disadvantages

- **Accuracy and reliability** are major concerns
- Results are very **sensitive** to large number of parameters to be set by the user
- **Verification and validation** are imperative (and validation requires experiments)

Approximate forms of the NS eqs

Instantaneous 3D Navier-Stokes equations for a confined, incompressible flow of a Newtonian fluid:

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu s_{ij}\right) \qquad s_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \frac{1}{\rho c_p}\frac{\partial}{\partial x_j}\left(k \frac{\partial \theta}{\partial x_j}\right)$$

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D \frac{\partial c}{\partial x_j}\right)$$

6 equations

6 unknowns (u_i, p, θ, c)

Closed system

Nonlinear, coupled, partial differential equations. Even with the above assumptions, no analytical solution is known.

Vectors u_i and x_i are instantaneous velocity and position, p is the instantaneous pressure, θ instantaneous temperature, t is time, ρ is density, ν is molecular kinematic viscosity, c_p specific heat capacity, k thermal conductivity and s_{ij} is the strain-rate tensor. c is instantaneous concentration and D molecular diffusion coefficient or molecular diffusivity.

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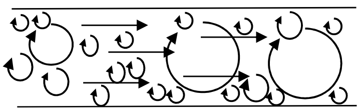
Approximate forms of the NS eqs

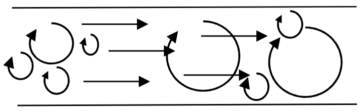
DNS: Direct Numerical Simulation

- Solve the exact Navier-Stokes equations completely
- All vortices/eddies are “solved”, nothing “modeled”
- Very time-consuming, huge computational resources, only very simple geometries, huge amounts of data



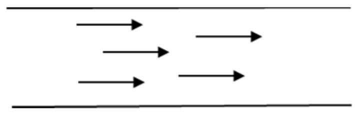
LES: Large Eddy Simulation

- Solve the “filtered” Navier-Stokes equations
- Only large eddies are “solved”, small ones are “modeled”
- Not exact, but less computationally demanding



RANS: Reynolds Averaged Navier Stokes

- Solve the “averaged” Navier-Stokes equations
- Only the mean flow is “solved”, all eddies are “modeled”
- Not exact, less accurate, but generally applicable



In the RANS approach, the “effect” of turbulence on the mean flow is modeled

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Approximate forms of the NS eqs

3D Reynolds-averaged Navier-Stokes equations
for a confined, incompressible flow of a Newtonian fluid:

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu S_{ij} - \overline{u_j' u_i'}\right) \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

$$\frac{\partial \Theta}{\partial t} + U_j \frac{\partial \Theta}{\partial x_j} = \frac{1}{\rho c_p}\frac{\partial}{\partial x_j}\left(k\frac{\partial \Theta}{\partial x_j} - \overline{u_j'\theta'}\right)$$

$$\frac{\partial C}{\partial t} + U_j \frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D\frac{\partial C}{\partial x_j} - \overline{u_j' c'}\right)$$

6 equations
→ New unknowns: the Reynolds stresses and turbulent heat and turbulent mass fluxes
→ Represent influence of turbulence on mean flow, heat and mass transfer
→ ***Unclosed system***

Approximate forms of the NS eqs

Unsteady RANS (URANS)

- Steady RANS = **time-averaging** of NS equations
- URANS = **ensemble-averaging** of NS equations. **URANS does not simulate the turbulence, but only its statistics**.
- URANS can be a good option **when the unsteadiness is pronounced and deterministic**, such as von Karman vortex shedding in the wake of an obstacle with a low-turbulence approach flow (is not the case in the ABL!)
- URANS has **up to now almost never been used** in Sports & Building Aerodynamics, so we will not devote further attention to it here.

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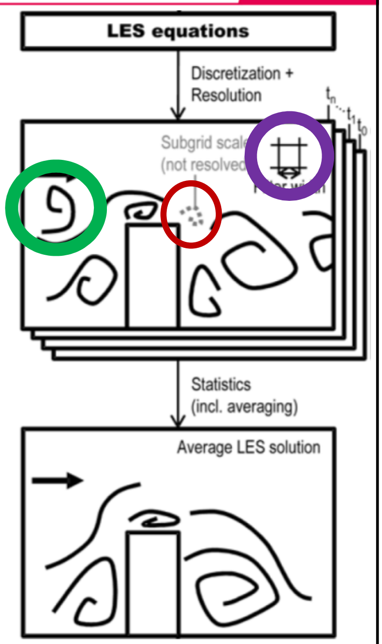
Approximate forms of the NS eqs

Large Eddy Simulation (LES)

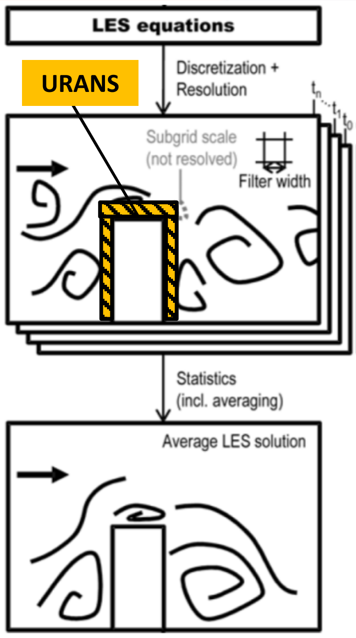
- **Filtering of NS equations**: removing small turbulent eddies (smaller than the size of a filter – can be grid size).
- Large-scale motions resolved, small-scale motions modeled.
- Filtering generates **additional unknowns** → **sub-filter turbulence model**.
- LES has **superior performance** compared to RANS and URANS, because large part of unsteady turbulent flow is actually resolved.
- More **expensive** and more **complex**



Approximate forms of the NS eqs

Hybrid URANS/LES

- URANS in near-wall region and LES in rest of domain.
- Based on the fact that near walls, eddies are very small and resolving with LES very expensive.
- Stand-alone LES often used with **wall functions**.
- Example: **Detached Eddy Simulation** *(Spalart et al., 1997)* (LES + Spalart-Allmaras turbulence model).
- **Not straightforward**: URANS and LES are **fundamentally different approaches** with specific grid requirements which have to be matched where the switch between both occurs.
- Hybrid approaches have up to now **almost never been used** in Sports & Building Aerodynamics, and therefore we will not devote further attention to them here.



Turbulence modeling

3D Reynolds-averaged Navier-Stokes equations

for a confined, incompressible flow of a Newtonian fluid:

$$\frac{\partial U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(2\nu S_{ij} - \overline{u_j' u_i'}\right)$$

$$\frac{\partial \Theta}{\partial t} + U_j \frac{\partial \Theta}{\partial x_j} = \frac{1}{\rho c_p}\frac{\partial}{\partial x_j}\left(k\frac{\partial \Theta}{\partial x_j} - \overline{u_j' \theta'}\right)$$

$$\frac{\partial C}{\partial t} + U_j \frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_j}\left(D\frac{\partial C}{\partial x_j} - \overline{u_j' c'}\right)$$

6 equations
→ New unknowns: the Reynolds stresses and turbulent heat and turbulent mass fluxes
→ Represent influence of turbulence on mean flow, heat and mass transfer
→ ***Unclosed system***

Turbulence models for RANS and URANS

Two main types of models can be distinguished:
- First-order closure models
- Second-order closure models

First-order closure:
- **Boussinesq eddy-viscosity hypothesis** to relate
  - the Reynolds stresses to the velocity gradients in the mean flow.
- **Gradient-diffusion assumption** to relate:
  - turbulent heat fluxes to the mean temperature gradients
  - turbulent mass fluxes to the mean concentration gradients

Second-order closure:
- Establishing and solving **additional transport equations** for the Reynolds stresses and the turbulent heat and mass fluxes.

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Turbulence modeling

Turbulence models for RANS and URANS

First-order closure: Boussinesq eddy-viscosity hypothesis:

Reynolds stresses as function of velocity gradients in the mean flow:

$$-\overline{u_i'u_j'} = 2\nu_t S_{ij} - \frac{2}{3} k \delta_{ij}$$

Turbulent viscosity (or: momentum diffusivity)

Mean strain rate

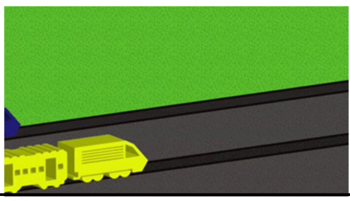
$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

Turbulent kinetic energy

$$k = \frac{1}{2}\overline{u_i'u_i'}$$

Kronecker delta

$$\delta_{ij} = \begin{cases} 1 & \text{for } i = j \\ 0 & \text{for } i \neq j \end{cases}$$



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Turbulence modeling

Turbulence models for RANS and URANS

First-order closure: Gradient-diffusion assumption:

- turbulent heat fluxes as function of temperature gradients in the mean flow
- turbulent mass fluxes as function of concentration gradients in the mean flow

Turbulent heat flux

$$-\overline{u_j'\theta'} = D_{\theta,t}\frac{\partial \Theta}{\partial x_j}$$

Turbulent heat diffusivity | Temp. gradient in mean flow

Turbulent mass flux

$$-\overline{u_j'c'} = D_{c,t}\frac{\partial C}{\partial x_j}$$

Turb. mass diffusivity | Conc. gradient in mean flow

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Some aspects of discretization

The two types of discretization

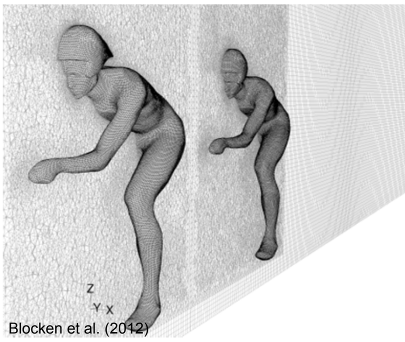
Space discretization: replacing the spatial continuum by a finite number of points or cells ("**the grid**") where the numerical values of the variables will be determined.

Equation discretization: transformation of the differential or integral equations – as the case may be – into **discrete algebraic equations** involving the unknowns at the grid points.

Some aspects of discretization

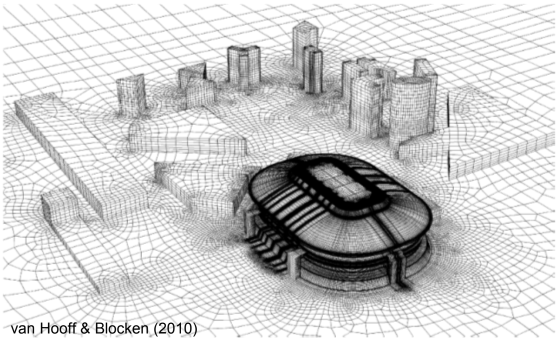
High-quality grid generation: Very time-consuming but very important.

Hirsch (2007): *"Grid generation and grid quality are **essential elements** of the whole discretization process. Not only is grid generation today a **most critical element in the cost** of running CFD simulations, but more importantly, the **accuracy** of the obtained numerical results is **critically dependent** on mesh quality."*



Blocken et al. (2012)

Non-uniform unstructured grid


van Hooff & Blocken (2010)

Non-uniform unstructured grid

Some aspects of discretization

Different discretization methods:

Finite difference method (FDM)

Finite volume method (FVM)

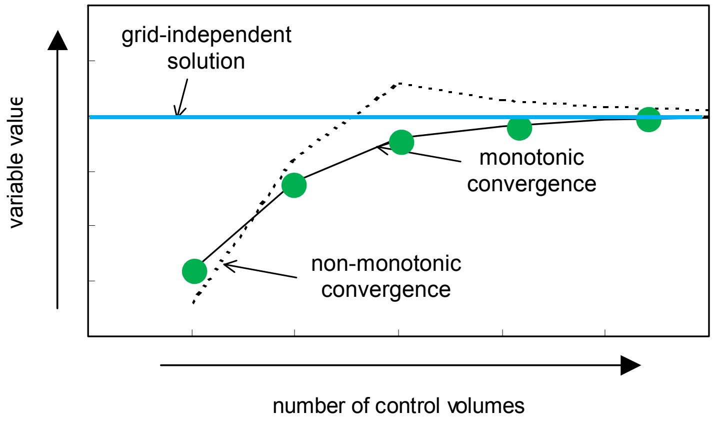
Finite element method (FEM)

(Spectral element method, Boundary element method, …)

Some aspects of discretization

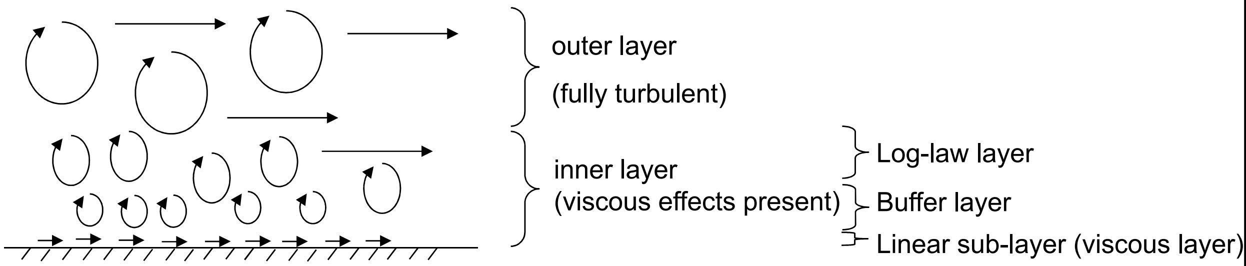
Grid convergence, discretization error and Richardson extrapolation

- **Systematically** refining or coarsening the mesh (grid) by a constant factor (e.g., 2 or $\sqrt{2}$)
- Goal is to obtain a **grid-independent** solution



Near-wall modeling

Turbulence models such as the k-ε model are only valid for the turbulent core flow, not for flow close to wall surfaces, where viscous effects become important.



Linear sub-layer (viscous layer): very close to the wall: viscous effects dominate the flow

Buffer layer: intermediate layer between the linear sub-layer and the log-law layer where the viscous and turbulent effects are about equally important

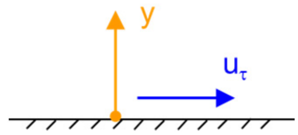
Log-law layer: inertial effects are dominant over viscous effects

Near-wall modeling

Different flow behaviour in different layers → different treatment necessary in each layer.
We need to know the extent (height) of each layer

<u>Introduction of dimensionless quantities</u>:

$$y^+ = \frac{\rho u_\tau y}{\mu}$$ *(dimensionless wall unit)*



$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$ (friction velocity, τ_w is wall shear stress)

The friction velocity is a variable that represents the magnitude of the velocity fluctuations in the wall-bounded flow.
Function of roughness, fluid speed, fluid density, …

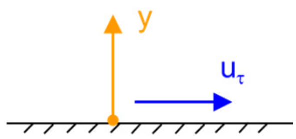
$$u^+ = \frac{U_T}{u_\tau}$$ *(dimensionless fluid speed)*

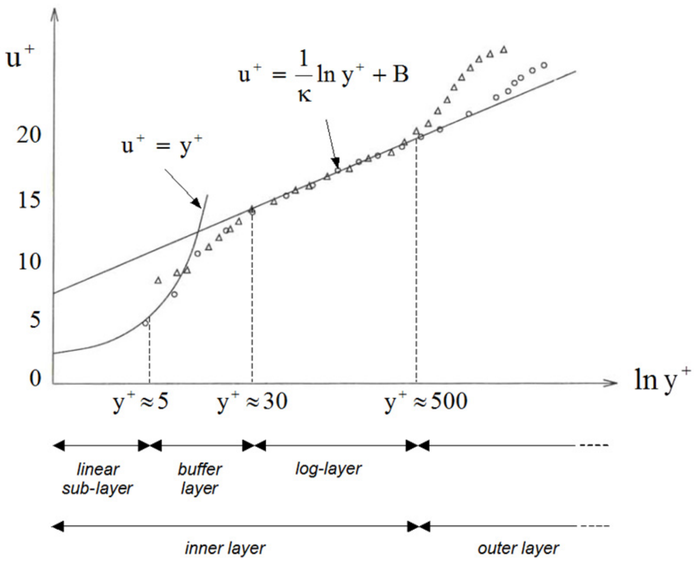
U_T is fluid speed tangential to the wall

Near-wall modeling

Universal law of the wall:

$$y^+ = \frac{\rho u_\tau y}{\mu} \qquad u^+ = \frac{U_T}{u_\tau}$$

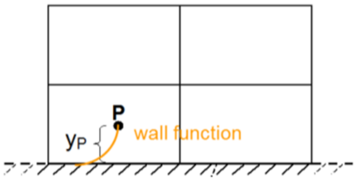




Near-wall modeling

The near-wall physics have to be taken into account in modeling the near-wall region. Two main options exist:

(1) Wall functions



approximation

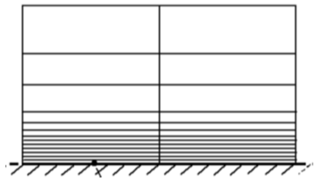
coarse mesh

needed for high-Re number flows

roughness!

invalid for near-wall flow / heat-mass

(2) low-Reynolds number modeling



more accurate

fine mesh

not for high-Re number flows

roughness?

near-wall flow, heat and mass transfer

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Errors, uncertainty, V & V

Definitions of error and uncertainty *(AIAA 1998; Oberkampf & Trucano 2002; Versteeg & Malalasekera 2007)***:**

Error: a recognizable deficiency in a CFD model that is ***not caused*** by lack of knowledge.

Causes or errors are:

1. **Numerical errors**
   1. Round-off errors
   2. Iterative convergence errors
   3. Discretization errors
2. **Coding errors**: mistakes or “bugs” in the software
3. **User errors**: human errors due to incorrect use of the software

Errors, uncertainty, V & V

Definitions of error and uncertainty *(AIAA 1998; Oberkampf & Trucano 2002; Versteeg & Malalasekera 2007)*:

Uncertainty: a potential deficiency in a CFD model that is ***caused*** by lack of knowledge.

Main sources of uncertainty are:

1. **Input uncertainty**: inaccuracies due to limited information or approximate representation of geometry, boundary conditions, etc.
2. **Physical model uncertainty**: discrepancies between real flows and CFD due to inadequate representation of physical processes (e.g. turbulence) or due to simplifying assumptions in the modeling process (e.g. steady flow).

Errors, uncertainty, V & V

Verification and validation *(AIAA 1998; Oberkampf & Trucano 2002; Versteeg & Malalasekera 2007)*:

Verification:

- The process of determining that a model implementation accuracy represents the developer's conceptual description of the model and the solution to the model.
- "**Solving the equations right**" *(Roache 1998)*
- Quantifying the **errors**

Validation:

- The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
- "**Solving the right equations**" *(Roache 1998)*
- Quantifying the **uncertainty**

Best practice guidelines

Best practice guidelines (non complete list)

2000: ERCOFTAC Best Practice Guidelines ***(Casey & Wintergerste 2000)***
2004: COST C14 Guidelines for pedestrian-level wind conditions ***(Franke et al. 2004)***
2007: COST 732 Best Practice Guideline for the CFD simulation of flows in the urban environment ***(Franke et al. 2007)***
2007: COST 732 Model Evaluation Guidance and Protocol Document ***(Britter & Schatzmann 2007)***
2008: AIJ Guidelines for practical applications of CFD to pedestrian wind environment around buildings ***(Tominaga et al. 2008)***
2008: AIJ Guidelines for numerical prediction of wind loads on buildings ***(Tamura et al. 2008)***
2012: Ten iterative steps for model development and evaluation applied to CFD for Environmental Fluid Mechanics ***(Blocken & Gualtieri 2012)***
→ Based on "Ten-steps" paper by ***Jakeman et al. (2006)***

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Best practice guidelines

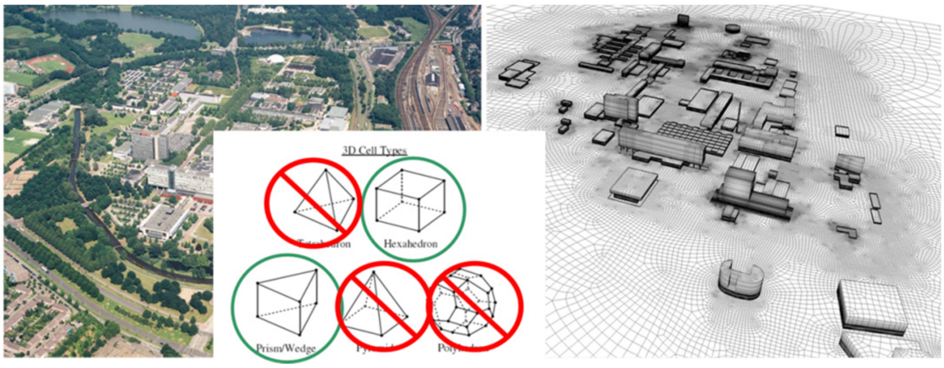
Best practice guidelines (non complete list)

1994: **Roache PJ.** Perpective – a method for uniform reporting of grid refinement studies. *Journal of Fluids Engineering – Transactions of the ASME,* 116, 3, 405-413.
1997: **Roache PJ.** Quantification of uncertainty in computational fluid dynamics. *Annual Reviews in Fluid Mechanics,* 29, 123-160.
1998: Guide for the verification and validation of computational fluid dynamics simulations, **American Institute of Aeronautics and Astronautics**, AIAA, AIAA-G-077-1998, Reston.
2004: **Oberkampf et al.** Verification, validation, and predictive capability in computational engineering and physics. *Applied Mechanics Reviews,* 57 (5), 345 - 384.
2005: **Roy CJ.** Review of code and solution verification procedures for computational simulation. *Journal of Computational Physics* 205, 1, 131-156.
2009: Standard for verification and validation in Computational Fluid Dynamics and heat transfer. ASME V&V 20-2009, **American Society of Mechanical Engineers.**
2010: **Roy CJ, Oberkampf WL.** A complete framework for verification, validation, and uncertainty quantification in scientific computing. *48th AIAA Aerospace Sciences Meeting Incl. …,* 4 - 7 January 2010, Orlando, Florida.

Best practice guidelines

Discretization schemes

For Building Aerodynamics: convergence with second-order schemes is no problem if the grid is of high quality. This includes avoiding tetrahedral and pyramid cells, which is possible even for very complex geometries!



(Blocken, Janssen, van Hooff 2012)

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Best practice guidelines

Discretization schemes

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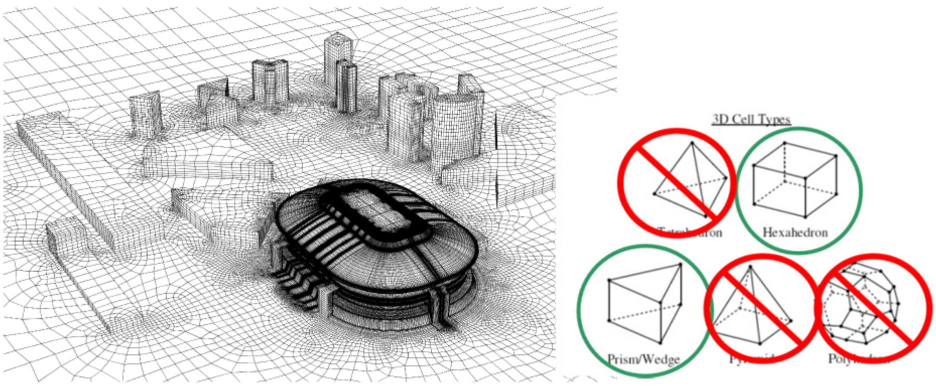
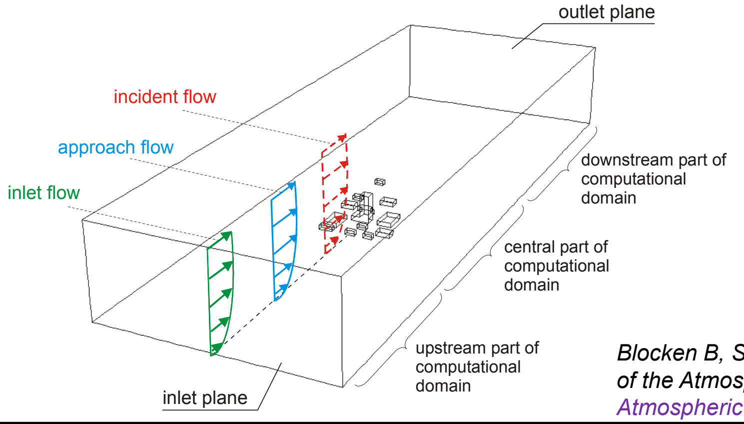


(van Hooff & Blocken 2010)

Best practice guidelines

Boundary conditions

Important problem in CFD studies of ABL flow with commercial CFD codes: "**horizontal inhomogeneity**" with the implemented wall functions *(Blocken et al. 2007)*



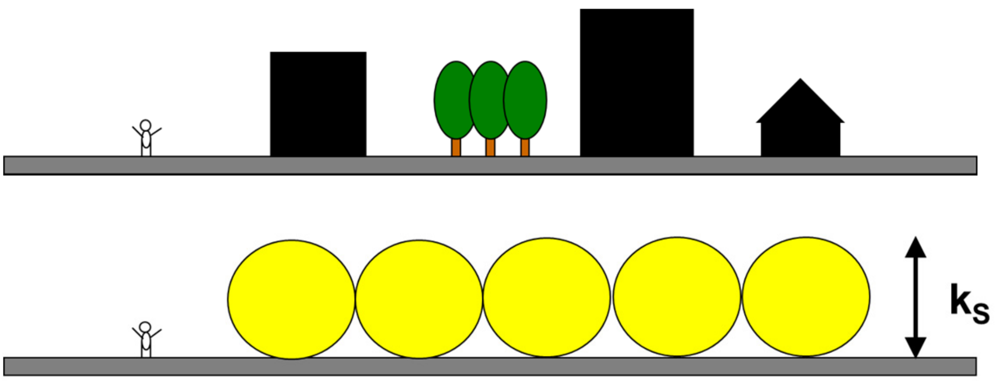
Blocken B, Stathopoulos T, Carmeliet J. 2007. CFD simulation of the Atmospheric Boundary Layer – wall function problems. Atmospheric Environment 41(2): 238-252.

Best practice guidelines

Boundary conditions: Inlet profiles and wall function roughness modifications

Required: knowing the relationship between k_S and y_0

k_S = equivalent sand-grain roughness height of the earth surface

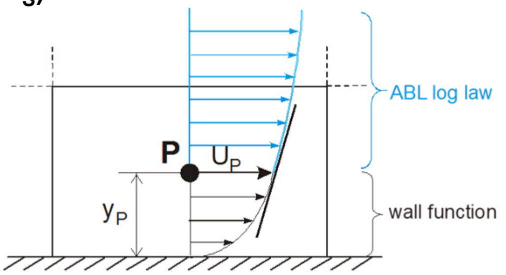


Best practice guidelines

Boundary conditions: Inlet profiles and wall function roughness modifications

Required: knowing the relationship between k_S and y_0

First-order continuity between **ABL log law (based on y_0)** and **wall function (based on k_S)**:



$$U(y) = \frac{u^*_{ABL}}{\kappa} \ln\left(\frac{y + y_0}{y_0}\right)$$

$$\frac{U_p u^*}{u_\tau^2} = \frac{1}{\kappa} \ln\left(\frac{E u^* y_p}{\nu(1 + C_s k_s^+)}\right)$$

Ansys/Fluent: $$k_{S,ABL} = \frac{9.793\, y_0}{C_s}$$ Default value for $C_S = 0.5$

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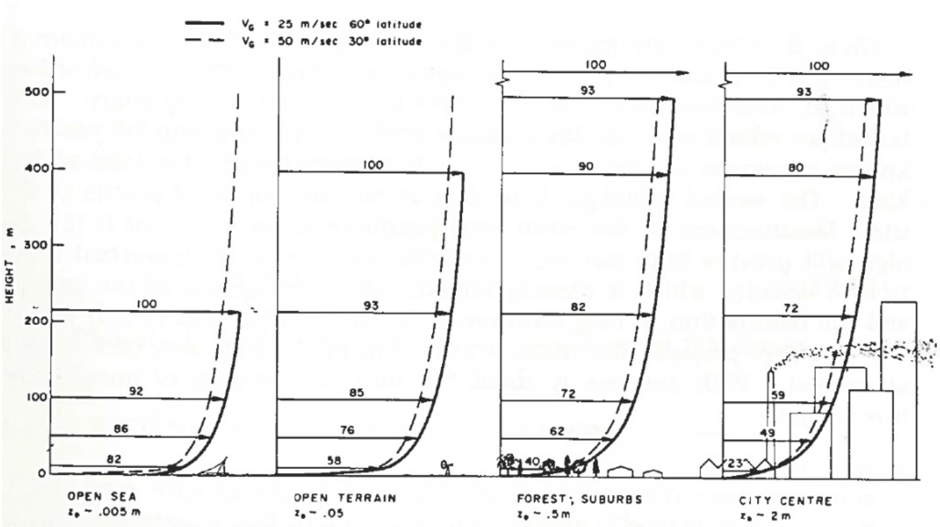
The atmospheric boundary layer

Neutral atmospheric boundary layer flow over a uniformly rough, level surface



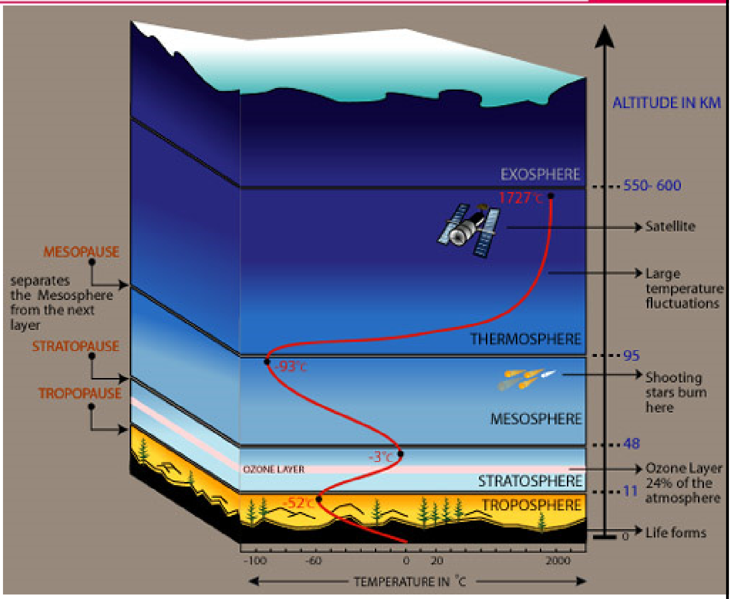
Profiles of mean wind speed over different terrain (Davenport 1967)

The atmospheric boundary layer

Definition

The **atmospheric boundary layer** or planetary boundary layer (PBL) is the lowest part of the atmosphere which forms due to the direct interactions between the atmosphere and the underlying surface (land or sea) over time scales of one day or less.

Lowest part (10%) of the troposphere



http://ds9.ssl.berkeley.edu

The atmospheric boundary layer

Characteristics

Depth: 100 m – 3 km
→ 0.01% of earth radius *(thin shell)*
→ Varies in space and time

Temperature: varies diurnally, unlike in free atmosphere above

Surface forcing: by friction and heat fluxes at the ground (land/sea)

Turbulence: generated by wind shear and **generated** or **suppressed** by temperature gradients

Presence of clouds: (fair-weather cumulus, stratocumulus and fog)

The atmospheric boundary layer

Characteristics: ABL versus free atmosphere

	Atmospheric boundary layer	Free atmosphere
Depth	Variable between 100 m – 3 km in time and space with diurnal variations over land	Less variable between 8 – 18 km and slow variations
Mean wind speed	Near-logarithmic in surface layer	Nearly geostrophic
Turbulence	Present over entire depth	Laminar to low/sporadic turbulence
Vertical transport	Turbulence dominated	Mean wind flow dominated (slow vertical transport)
Dispersion	Rapid in vertical and horizontal direction due to turbulent mixing	Molecular diffusion. Rapid horizontal transport by mean wind

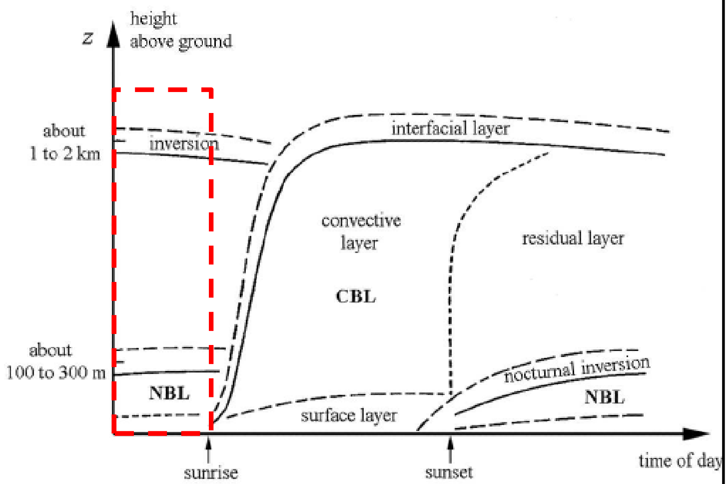
The atmospheric boundary layer

Diurnal variation of the ABL

(clear sky)

End of night:

- Shallow **nocturnal BL** in which mixing is caused by wind friction.
- Depth depends on wind velocity and surface roughness
- Depth generally below 300 m
- Air above NBL is lightly stratified due to heat loss to space during night

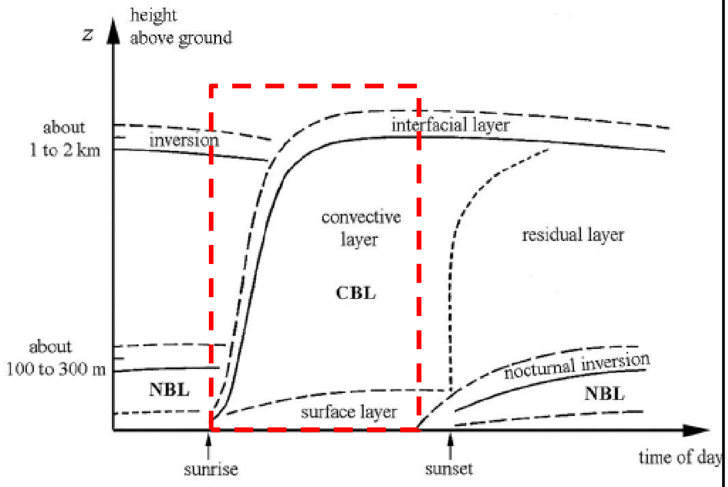


Adapted from Garratt (1992)

The atmospheric boundary layer

Diurnal variation of the ABL
(clear sky)

Start of day:
- **Solar radiation** heats up earth surface which heats up the ABL from below
- Convective motions override wind-shear turbulence → **convective BL** that develops upward
- Wind-induced turbulence is much weaker than **convection-induced turbulence** except in the surface layer
- **Surface layer**: more or less equal intensity of wind-induced and convection-induced turbulence

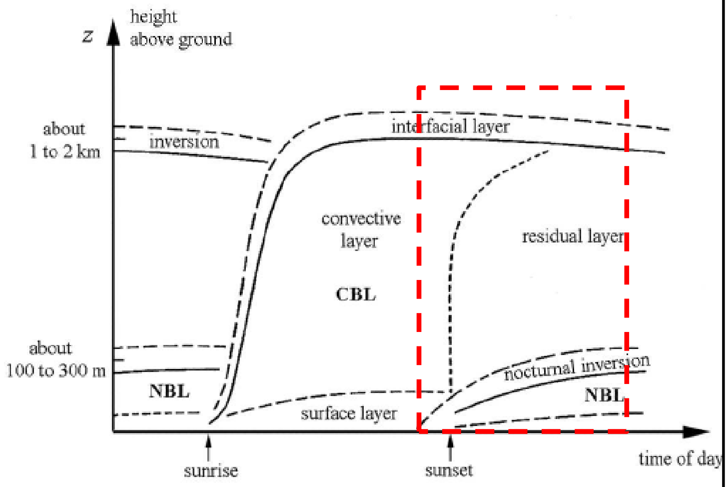


Adapted from Garratt (1992)

The atmospheric boundary layer

Diurnal variation of the ABL
(clear sky)

End of day:
- **Sunset** stops heating of the ABL
- New NBL develops



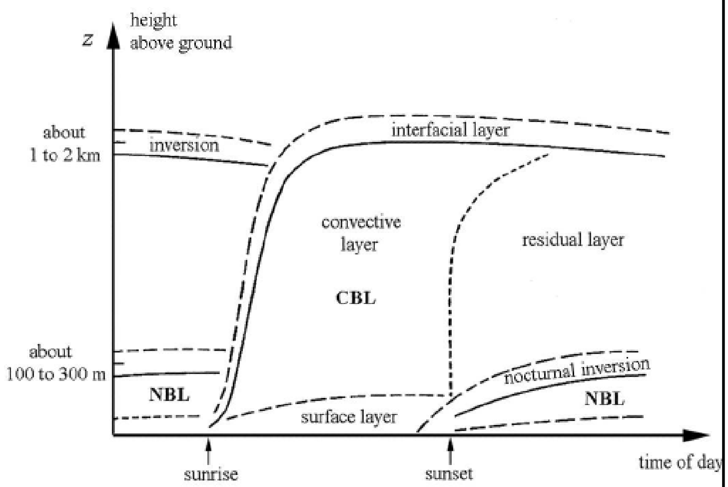
Adapted from Garratt (1992)

The atmospheric boundary layer

Diurnal variation of the ABL
(clear sky)

So what about strong winds?

- In strong winds, the thermal effects are generally **negligible**.
- This the **important and very basic concept** on which almost all wind tunnel testing in Wind Engineering relies, and most CFD simulations in Computational Wind Engineering.



Adapted from Garratt (1992)

The atmospheric boundary layer

Meteorological scales

1. Synoptic scale (L > 2000 km)
2. **Mesoscale - α (200 km < L < 2000 km)**
3. **Mesoscale - β (20 km < L < 200 km)**
4. **Mesoscale - γ (2 km < L < 20 km)**
5. **Microscale (L < 2 km) (L < 5 – 10 km)**
6. **Building scale (L < 100 m)**
7. **Building component scale (L < 10 m)**
8. Building material scale

Scales 2–4: ***Mesoscale Meteorological Models (MMM)***

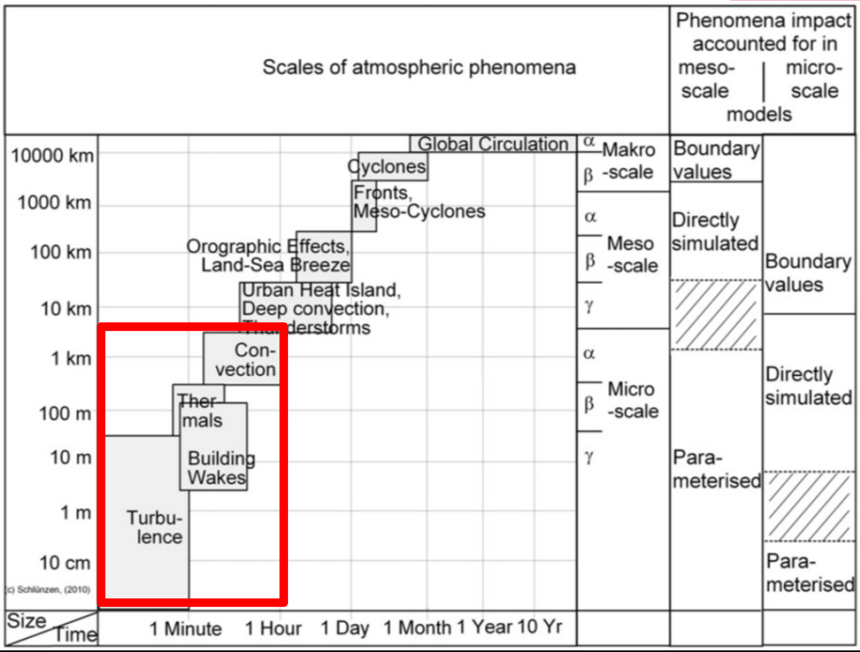
Scale 5: ***Microscale Meteorological Models (CFD)***

Scale 6: ***Building Energy Simulation Models (BES)***

Scales 7–8: ***Building Envelope Heat-Air-Moisture Transfer Models (BE-HAM***

The atmospheric boundary layer

Meteorological scales
(Schlünzen et al. 2011, based on Orlanski 1975)



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The atmospheric boundary layer

Neutral ABL over uniformly rough, level terrain

In absence of substantial thermal processes (adiabatic lapse rate), the ABL is called **neutral** or **neutrally stratified**. Mean wind speed in the surface layer can then be described by the simple **log law** or the **power law**:

Log law

$$U(z) = \frac{u^*_{ABL}}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right)$$

Power law

$$\frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

where
- $U(z)$ = wind speed at height z
- u^*_{ABL} = friction velocity
- κ = von Karman constant (≈ 0.4 – 0.42)
- z_0 = aerodynamic roughness length
- U_{ref} = reference wind speed at reference height z_{ref}
- α = power-law exponent

The atmospheric boundary layer

Neutral atmospheric boundary layer flow over a uniformly rough, level surface

How to determine z_0 and α ?

Surface	z_0 (m)	α	z_G
Rough sea	0.003	0.11	250
Prairie, farmland	0.03	0.16	300
Forest, suburbs	0.3	0.28	400
City centres	3	0.40	500

From A.G. Davenport, Boundary-Layer Wind-Tunnel Laboratory, UWO, Canada

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The atmospheric boundary layer

Roughness classification by Davenport, updated by Wieringa (1992)

	z_0 (m)	Landscape description
1	0.0002 Sea	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac, concrete, with a free fetch of several kilometres.
2	0.005 Smooth	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g. beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3	0.03 Open	Level country with low vegetation (e.g. grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g. grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 Roughly open	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g. low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 Rough	Recently-developed "young" landscape with high crops or crops of varying height, and scattered obstacles (e.g. dense shelterbelts, vineyards) at relative distances of about 15 obstacle heights.
6	0.50 Very rough	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces such as bush land, orchards, young densely-planted forest.
7	1.0 Closed	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g. mature regular forests, homogeneous cities or villages.
8	$\geq$ 2.0 Chaotic	Centres of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

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The atmospheric boundary layer

Neutral atmospheric boundary layer flow over a uniformly rough, level surface

$$U(z) = \frac{u^*_{ABL}}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \qquad \frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Important comments/limitations:

- Log law is **strictly only valid** for flow over **uniformly rough terrain**. In reality: never uniformly rough
- Log law is **not valid** for flow around individual roughness elements (obstacles) such as buildings
- Log law is only the **average representation** of the wind speed over rough terrain
- Log law provides the profile of mean horizontal wind speed over irregular, rough surfaces (e.g. towns, forests) **above a certain height** where there is no influence anymore of the individual roughness elements on the flow
- Log law describes the vertical wind profile that is formed **after having experienced a rough terrain with a fetch of at least 5 km.**

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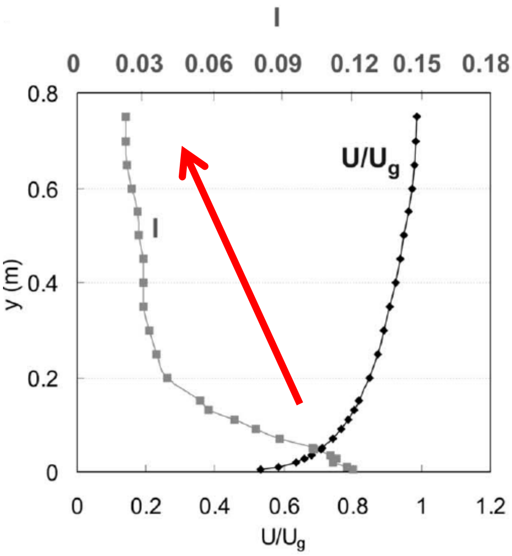
The atmospheric boundary layer

Neutral atmospheric boundary layer flow over a uniformly rough, level surface

Turbulence intensity profiles:

- Strong decrease with height
- **Example** for α = 0.125: see figure



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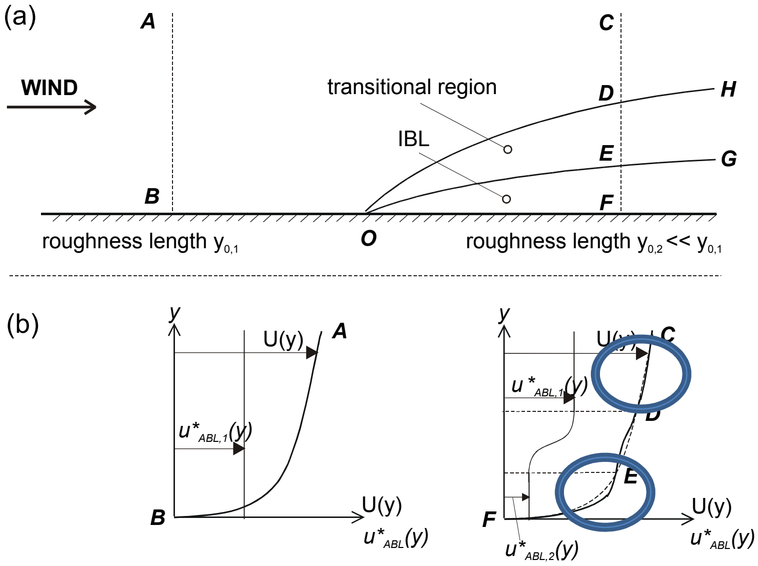
The atmospheric boundary layer

ABL flow over a 2D roughness change



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The atmospheric boundary layer

ABL flow over a 2D roughness change

Jensen et al. (1984) proposed the following formula for the IBL height h_{IBL}:

$$\frac{h_{IBL}}{y_0^+} = 0.3\left(\frac{x}{y_0^+}\right)^{0.8}$$

where y_0^+ is the largest of the two roughness lengths and x is the downstream distance.

For example, if y_0^+ = 0.5 m, a downstream distance of **1.7 km** is required before the IBL reaches a height of **100 m**.

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The atmospheric boundary layer

Wind velocity measurements in the ABL

Standard measurements

Increase of wind speed with height → measurements over open terrain are taken at a standard height of **z = 10 m** (WMO)

Standard measurements are:
- Mean horizontal wind speed (m/s)
- Wind direction (degree clockwise from north)
  (= the direction ***from which*** the wind blows!)

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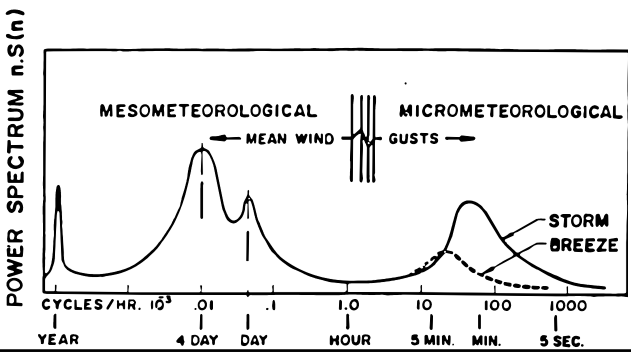
The atmospheric boundary layer

Wind velocity measurements in the ABL

Time resolution and averaging/reporting intervals

Settings: 1 minute to much less than 1 second (1 Hz)

Averaging: mean wind speed: 10 min to 1 hour: wind speed power spectrum *(Van der Hoven 1957)*



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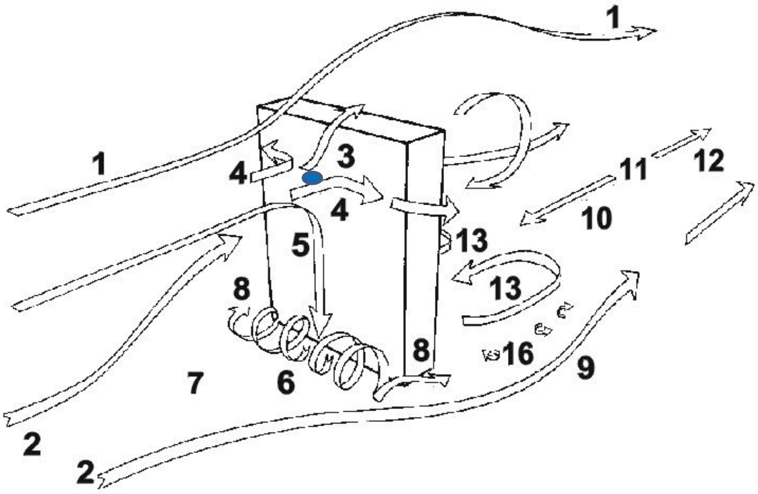
Wind flow around buildings - I

Wind-flow pattern around an **isolated building**



1. Flow over building
2. Oncoming flow
3. Flow from stagnation point over building
4. Flow from stagnation point around vertical building edges
5. Downflow from stagnation point

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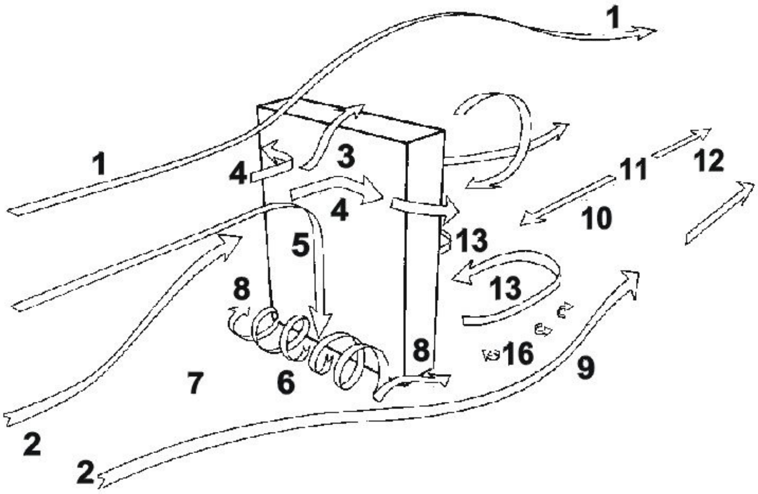
Wind flow around buildings - I

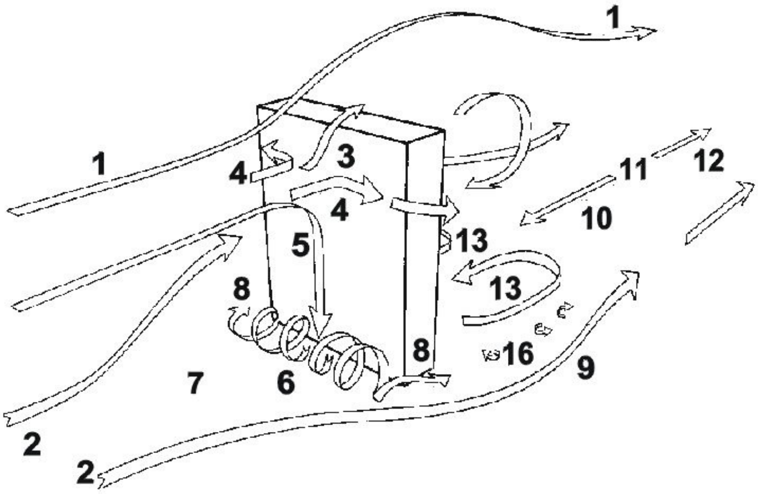
Wind-flow pattern around an **isolated building**



6. Standing vortex, base vortex or horseshoe vortex
7. Stagnation flow in front of building near ground level
8. Corner streams (vortex wrapping around corners)
9. Flow around building sides at ground level (adding to corner streams)

Wind flow around buildings - I

Wind-flow pattern around an **isolated building**

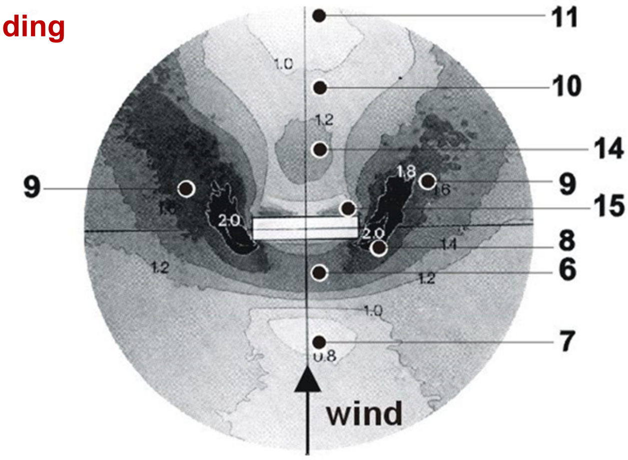


10. Recirculation flow
11. Stagnation region behind building at ground level.
12. Restored flow direction
13. Large vortices behind building
16. Small vortices in shear layer

Wind flow around buildings - I

Wind-flow pattern around an **isolated building**

Visualization by sand-erosion technique

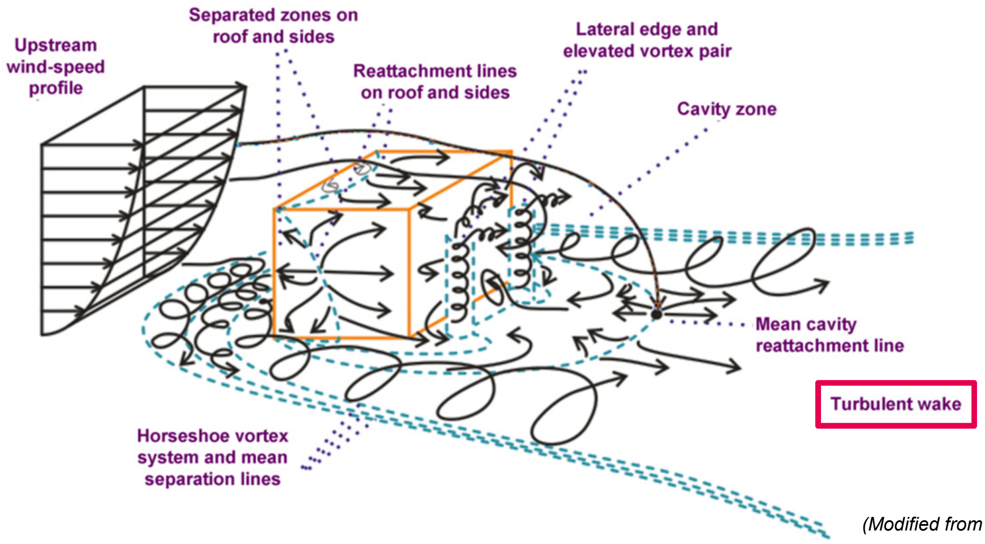


Definition of **amplification factor**:

$$K = \frac{mean\ wind\ speed\ at\ given\ point}{mean\ wind\ speed\ at\ same\ point\ without\ building(s) present}$$

Wind flow around buildings - I

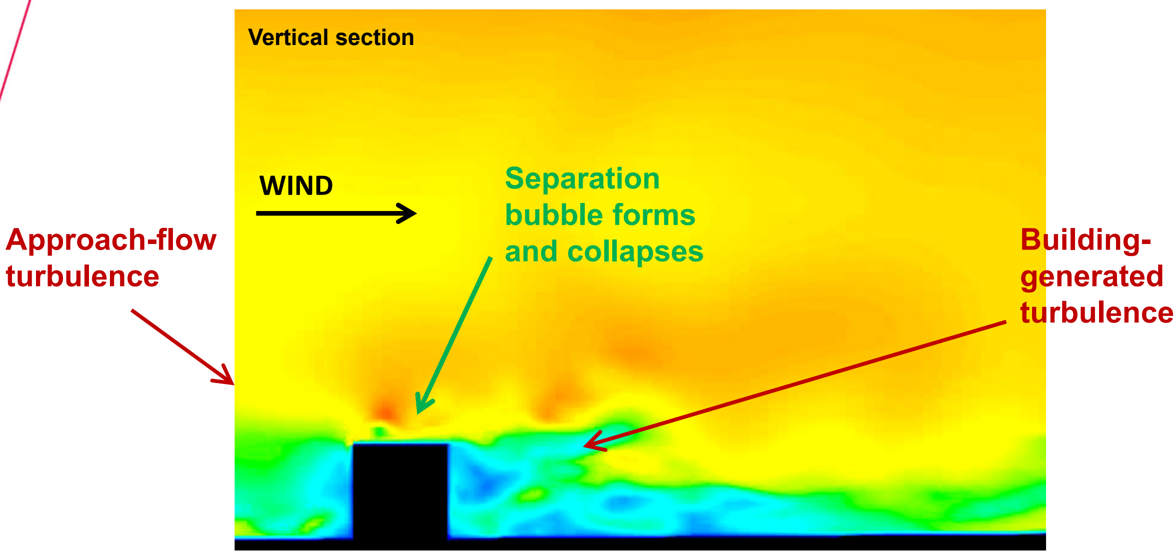
Wind-flow pattern around an **isolated building**



(Modified from Hosker, 1984)

Wind flow around buildings - I

Wind-flow pattern around an **isolated building**: **unsteadiness**



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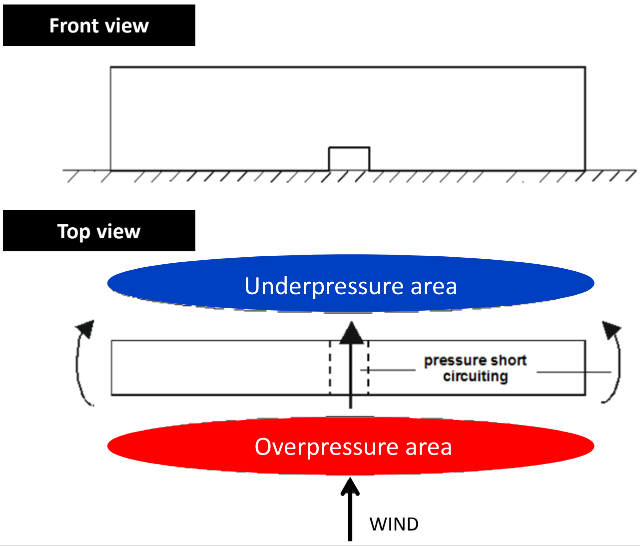
Wind flow around buildings - II

Wind flow around **buildings**: three typical problem configurations

Passage through a building



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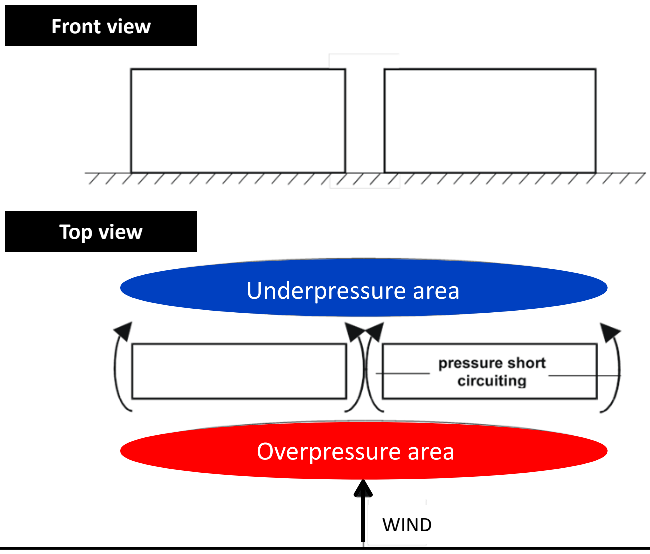
Wind flow around buildings - II

Wind flow around **buildings**: three typical problem configurations

Passage between parallel buildings



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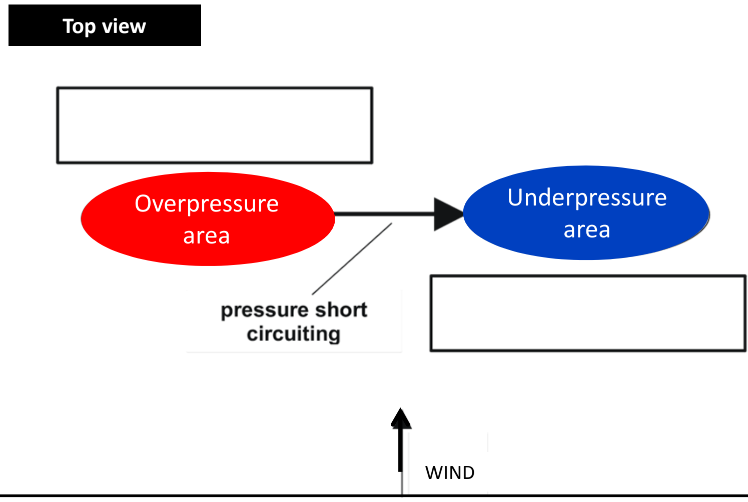
Wind flow around buildings - II

Wind flow around **buildings**: three typical problem configurations

Passage between parallel shifted buildings



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Wind flow around buildings - II

The Venturi effect between buildings: **fact or fiction?**

Here, only a brief summary will be given. More information can be found in these publications:

Blocken B, Stathopoulos T, Carmeliet J. 2008. A numerical study on the existence of the Venturi-effect in passages between perpendicular buildings. ***Journal of Engineering Mechanics - ASCE*** 134(12): 1021-1028.

Blocken B, Stathopoulos T, Carmeliet J. 2008. Wind environmental conditions in passages between two long narrow perpendicular buildings. ***Journal of Aerospace Engineering - ASCE*** 21(4): 280-287.

Blocken B, Carmeliet J, Stathopoulos T. 2007. CFD evaluation of the wind speed conditions in passages between buildings – effect of wall-function roughness modifications on the atmospheric boundary layer flow. ***Journal of Wind Engineering and Industrial Aerodynamics*** 95(9-11): 941-962.

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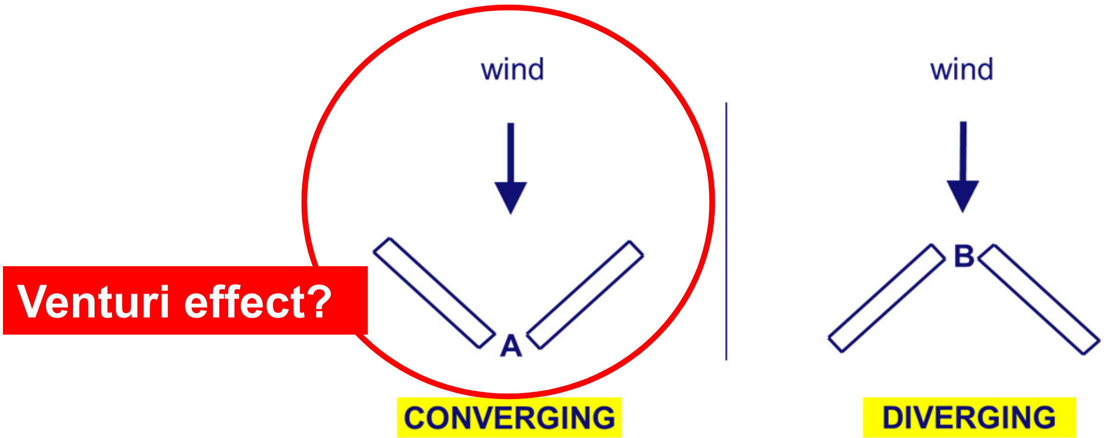
Wind flow around buildings - II

The Venturi effect between buildings: **fact or fiction?**



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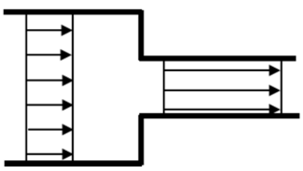
Wind flow around buildings - II

The Venturi effect between buildings: **fact or fiction?**

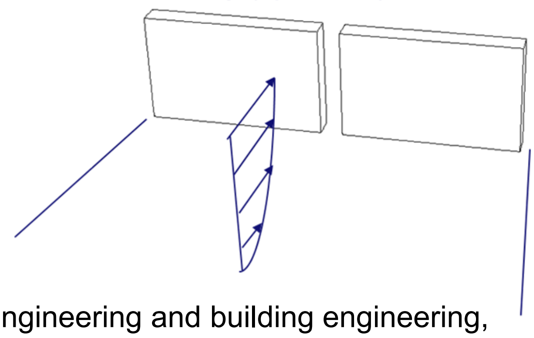
Venturi effect: ***increase of fluid speed due to a decrease of the flow section*** (*Giovanni Battista Venturi 1799*)

Confined versus **open flow**

Theory (confined flow)



Reality (open flow)

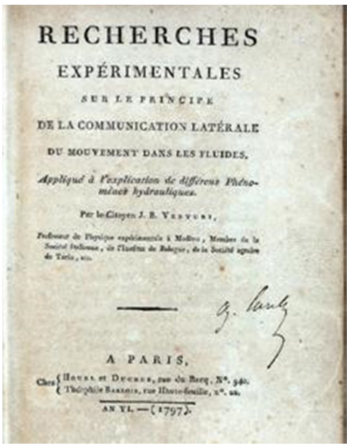


→ Frequently used term in architectural engineering and building engineering, and also in wind engineering...

Wind flow around buildings - II

The Venturi effect between buildings: **fact or fiction?**

Venturi effect: ***increase of fluid speed due to a decrease of the flow section***
(*Giovanni Battista Venturi 1799*)


RECHERCHES
EXPÉRIMENTALES
SUR LE PRINCIPE
DE LA COMMUNICATION LATÉRALE
DU MOUVEMENT DANS LES FLUIDES,
Appliqué à l'explication de différens Phénomènes hydrauliques.
Par le Citoyen J. B. Venturi,
A PARIS,
AN VI. — (1797).

Special thanks to Sandra Johnson and her colleagues from the Niels Bohr Library of the American Institute of Physics for copying this precious (and fragile) book for me.

Giovanni Battista Venturi (1746 - 1822)

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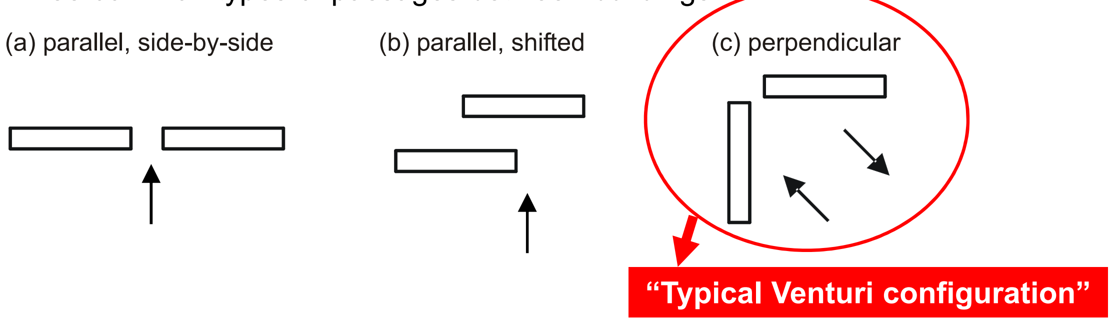
Wind flow around buildings - II

Three common types of passages between buildings



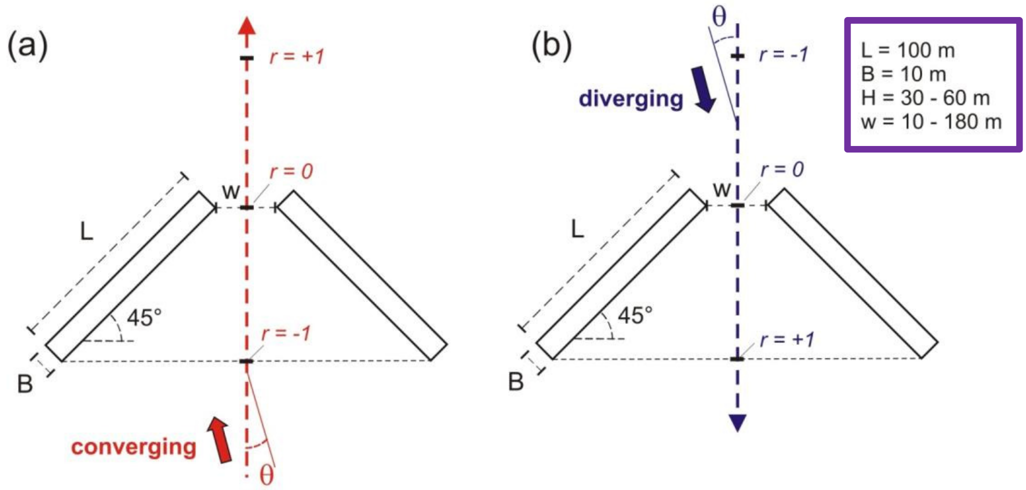
Conditions for the occurrence of the Venturi effect (Gandemer 1975):

1) H > 15 m
2) $L_1 + L_2 > 100$ m
3) Exposed site

"Maximum flow through the passage when passage width is 2 or 3 times the height"

Wind flow around buildings - II

Wind-tunnel measurements for **converging** and **diverging** arrangements:



Wind flow around buildings - II

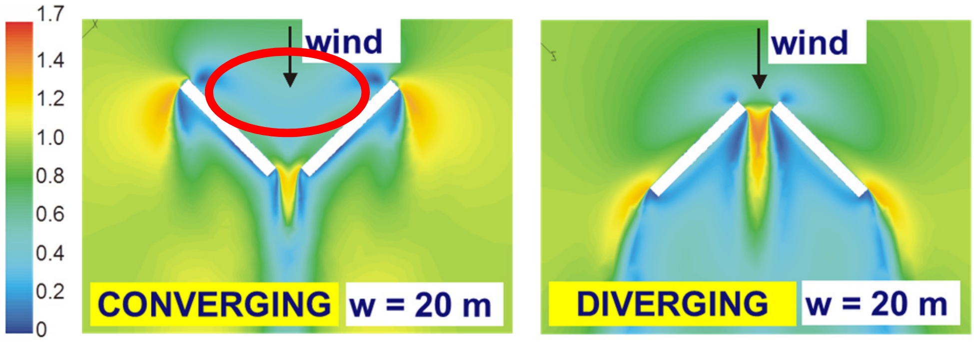
CFD simulations for **converging** and **diverging** arrangements

- ANSYS Fluent CFD code
- Steady RANS with realizable k-ε model (*Shih et al. 1995*)
- Standard wall functions with sand-grain-based roughness modification
- Equivalent sand-grain roughness k_S and roughness constant C_S based on aerodynamic roughness length y_0 and equation $\mathbf{k_S = 9.793 y_0 / C_S}$.
- SIMPLE for pressure velocity-coupling
- Second order discretization schemes
- Pressure interpolation: second order

For other computational details, see: *Blocken B, Moonen P, Stathopoulos T, Carmeliet J. 2008. A numerical study on the existence of the Venturi-effect in passages between perpendicular buildings.* ***Journal of Engineering Mechanics – ASCE*** *134(12): 1021-1028.*

Wind flow around buildings - II

CFD simulations for **converging** and **diverging** arrangements

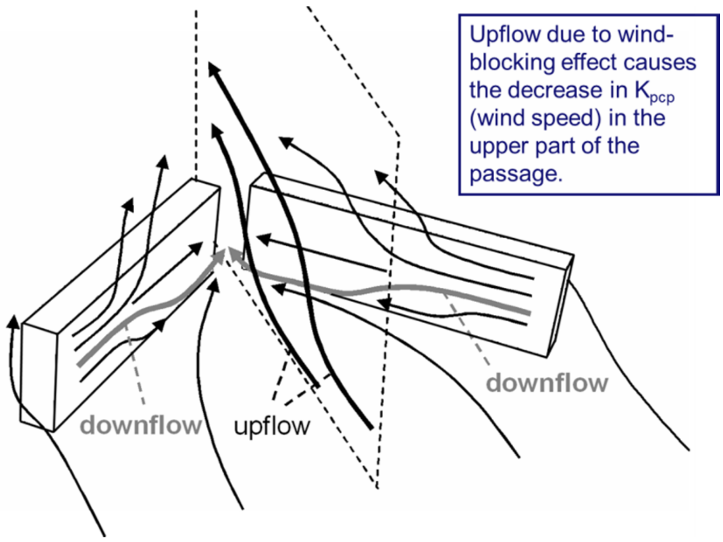


→ **Counter-intuitive result: wind-blocking effect: upstream wind-speed slow-down**

"**Subsonic upstream disturbance** in the wind-flow pattern"

Wind flow around buildings - II

Schematic of wind-flow pattern extracted from CFD results



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Wind energy - I

Wind energy in the built environment

Campbell and Stankovic* distinguish between three categories of possibilities for **integration of wind energy** generation systems into **urban environments**:

(1) siting stand-alone wind turbines in urban locations;
(2) retrofitting wind turbines onto existing buildings;
(3) full integration of wind turbines together with architectural form.

** Campbell NS, Stankovic S. Wind energy for the Built environment–Project WEB, A report for Joule III Contract No JOR3-CT98-01270 2001.*

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Wind energy - I

Wind energy in the built environment

Compared to an open (non-built) area, the built environment:

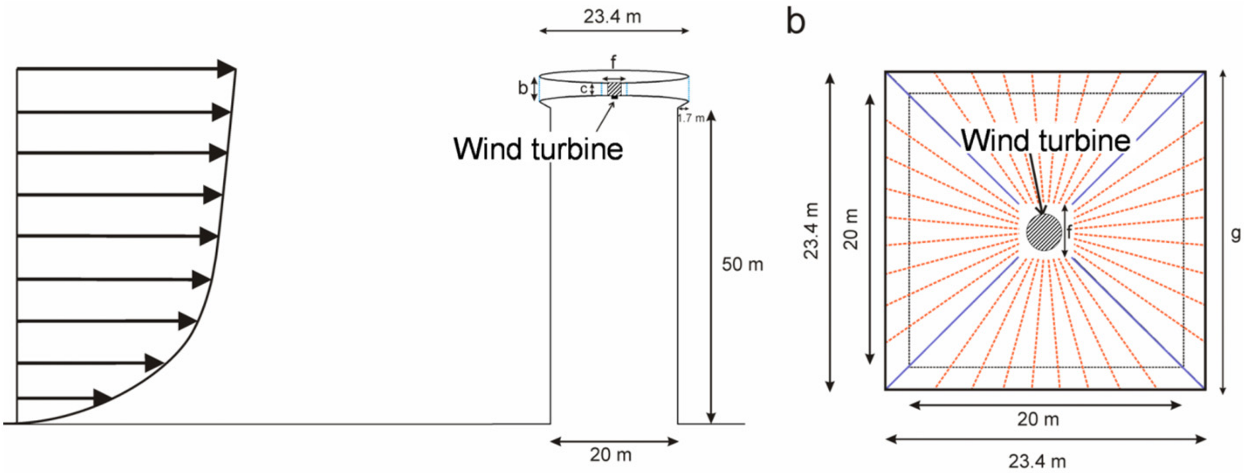
- Yields **lower** mean wind speed
- **Increases** turbulence intensities

Both aspects have **negative consequences** on wind energy harvesting in the built environment.

Acceleration effects by buildings are generally **only very local** and can generally not compensate for the overall wind speed reduction in/by the built environment.

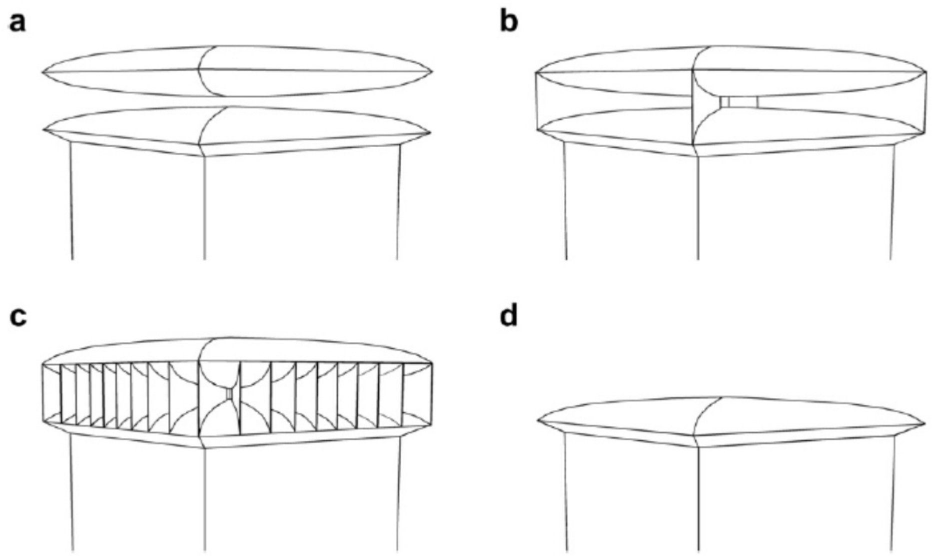
Wind energy - I

Optimization of the Ventec-roof designed by Bronsema (2005)



Wind energy - I

Optimization of the Ventec-roof designed by Bronsema (2005)



Optimization of the Ventec-roof designed by Bronsema (2005)

More details can be found in this paper:

Contents lists available at ScienceDirect

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Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

A venturi-shaped roof for wind-induced natural ventilation of buildings: Wind tunnel and CFD evaluation of different design configurations

T. van Hooff[a,b], B. Blocken[a,*], L. Aanen[c], B. Bronsema[d]

[a] Building Physics and Systems, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[b] Division of Building Physics, Department of Civil Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, P.O. Box 2447, 3001 Leuven, Belgium
[c] Peutz BV, P.O. Box 66, 6585 ZH Mook, The Netherlands
[d] Faculty of Architecture, Department of Climate Design, Delft University of Technology, Prof. Boerhaaveweg 37, 2251 HX Voorschoten, The Netherlands

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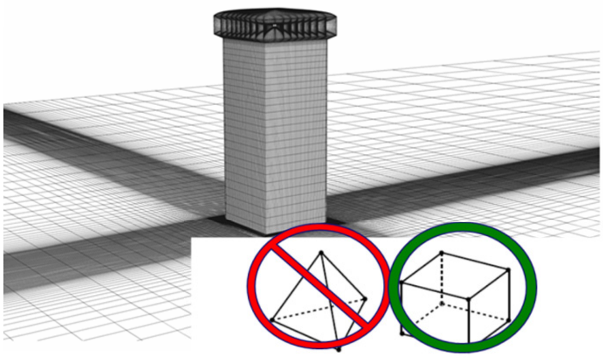
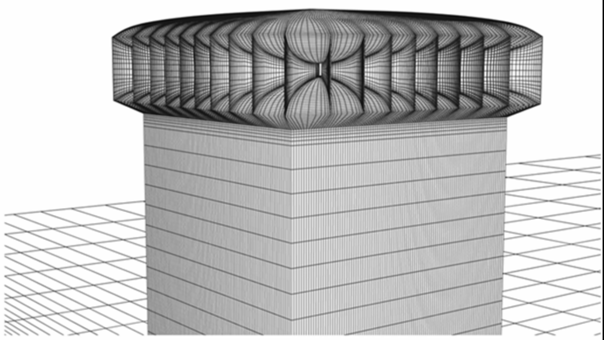
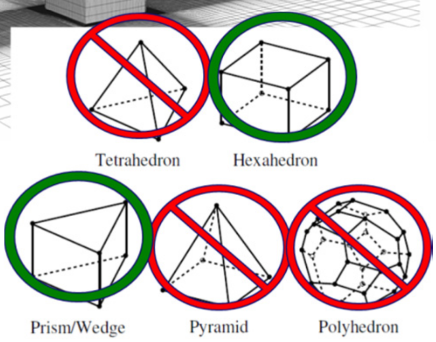
Wind energy - I

CFD simulations: computational domain and grid







No tetrahedral or pyramid cells

Wind energy - I

CFD simulations: computational settings and parameters

- Steady RANS with realizable k-ε model *(Shih et al. 1995)* and standard wall functions *(Launder and Spalding 1974)* modified for roughness *(Cebeci and Bradshaw 1977)* with sand-grain parameters by *Blocken et al. (2007)*: $k_S = 9.793y_0/C_S$.
- SIMPLE for pressure velocity-coupling
- Second order discretization schemes
- Pressure interpolation: second order

For other computational details, see:

van Hooff T, Blocken B, Aanen L, Bronsema B. 2011. A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. ***Building and Environment*** 46(9): 1797-1807.

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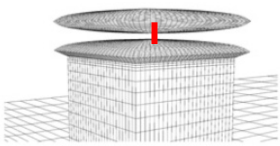
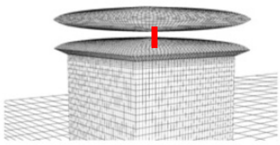
Wind energy - I

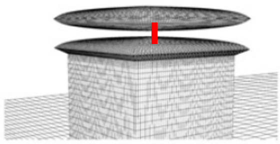
CFD simulations: grid-sensitivity analysis



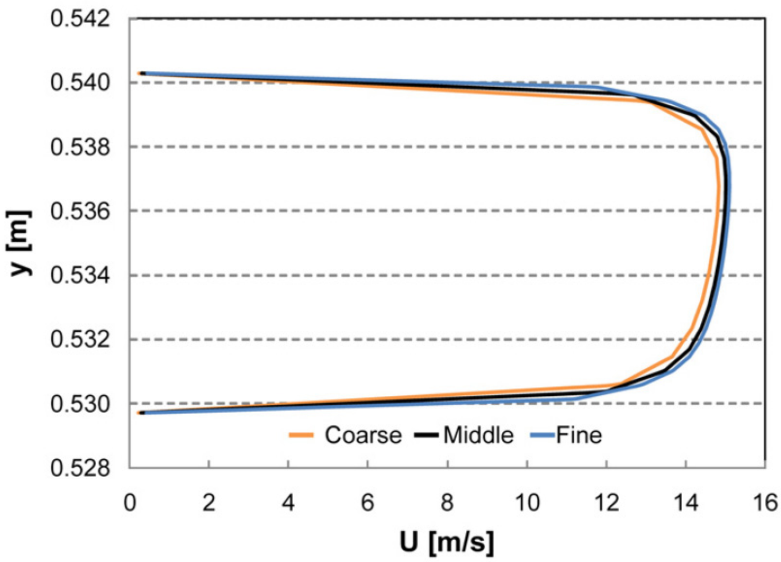
Coarse grid: 549,380



Middle grid: 2,041,268



Fine grid: 4,364,688



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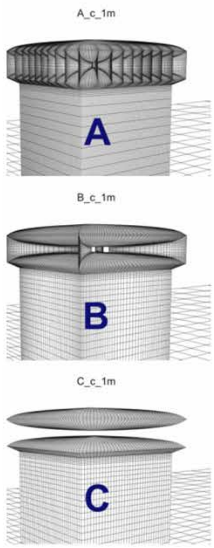
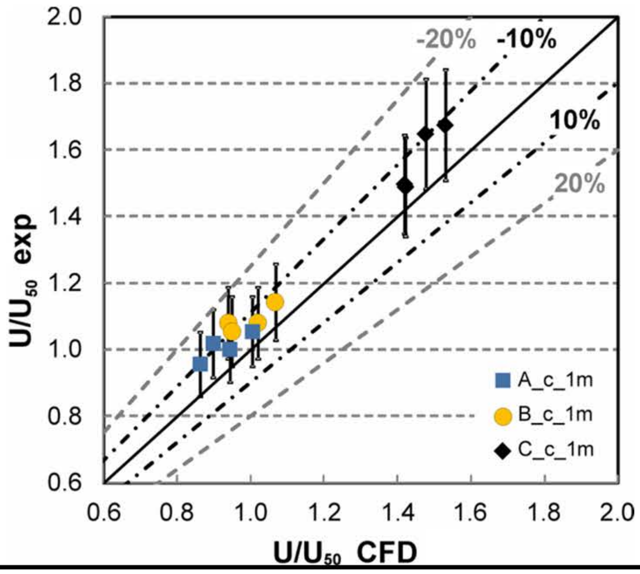
Wind energy - I

CFD simulations: validation – amplification factor in roof contraction





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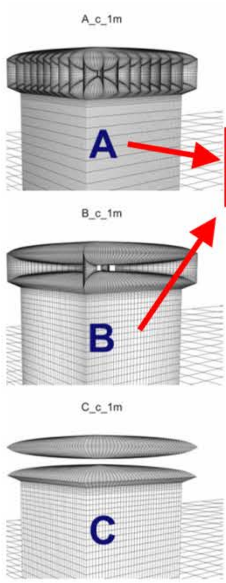

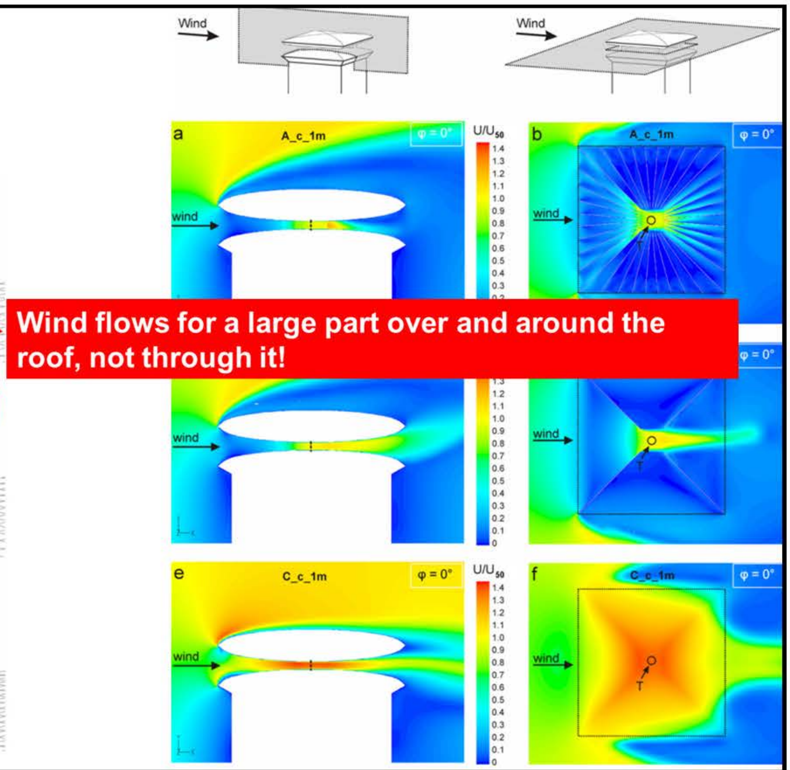

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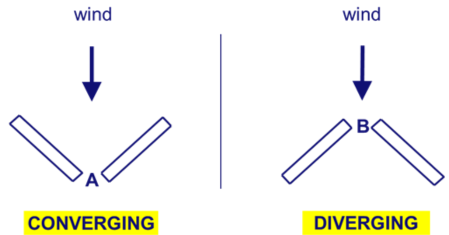
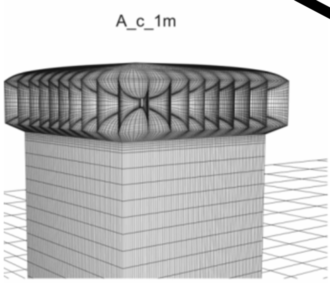
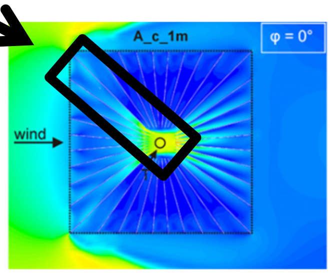
Wind energy - I

Similar counter-intuitive behavior as in the V-arrangement (so-called Venturi-effect)

1. At first sight counter-intuitive flow behavior might lead to wrong design decisions.
2. Venturi-effect does not apply to “open flows”. If the flow resistance is too large, the wind will flow around and over the “venturi-throat”, rather than being forced through it.
3. Venturi-effect only applies to the closed channels in the roof **but not to the open atmospheric flow!**







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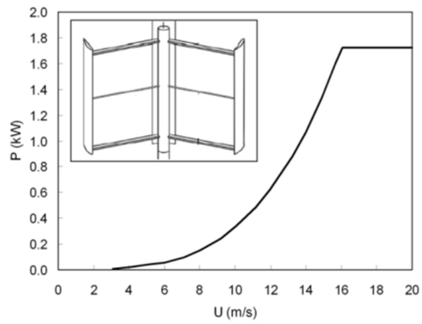
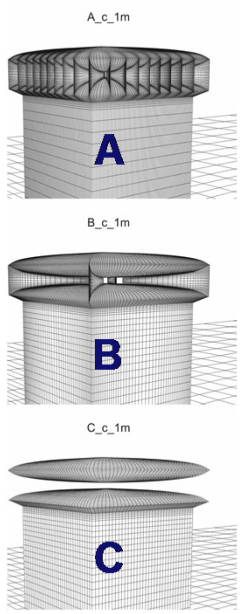
Wind energy - I

Wind energy potential



Config.	Number of guiding vanes	c (m)	b (m)	b/c	A (m²)	AF (-)	E (kWh)
A_c_1	36	1	5	5	2	0.87	336
B_c_1	4	1	5	5	2	0.83	282
C_c_1	0	1	5	5	2	1.31	1335
A_c_4	36	4	8	2	8	1.00	2218
B_c_4	4	4	8	2	8	0.97	1991
C_c_4	0	4	8	2	8	1.20	4101

X 5-10



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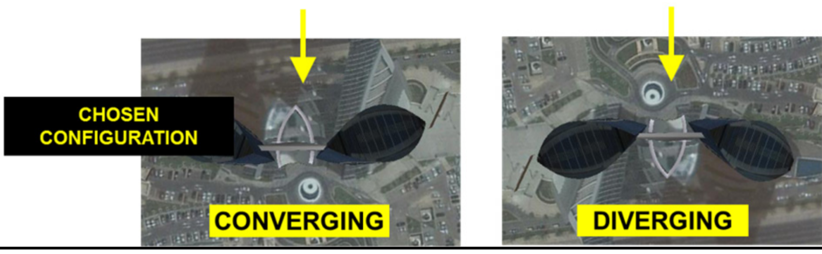
Wind energy - II

Hypothesis

The Bahrain WTC design would have yielded **higher wind energy** output if the buildings were positioned in **diverging rather than converging** arrangement.

In other words: from wind energy point of view, the towers should have been **turned 180° around**.



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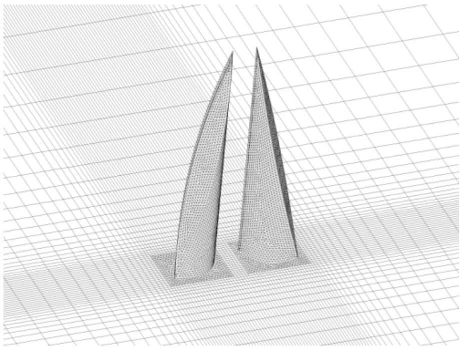
Wind energy - II

Investigation

→ Detailed study by **wind-tunnel testing** and **Computational Fluid Dynamics** simulations.



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Wind energy - II

Computational settings and parameters

Computational domain and grid

- Following best practice guidelines
- Grid-sensitivity analysis

Boundary conditions

- Logarithmic wind speed profile (U_{240} = 15 m/s, y_0 = 0.1 m)
- Turbulent kinetic energy from wind-tunnel measurements: $k = 0.5(\sigma_U^2 + \sigma_V^2 + \sigma_W^2)$
- Turbulence dissipation rate: $\varepsilon = (u^*_{ABL})^3/\kappa(y+y_0)$
- Ground surface roughness: $k_S = 9.793y_0/C_S$
- Outlet: zero static pressure
- Top of computational domain: slip wall (zero normal velocity and zero normal gradients of all variables).

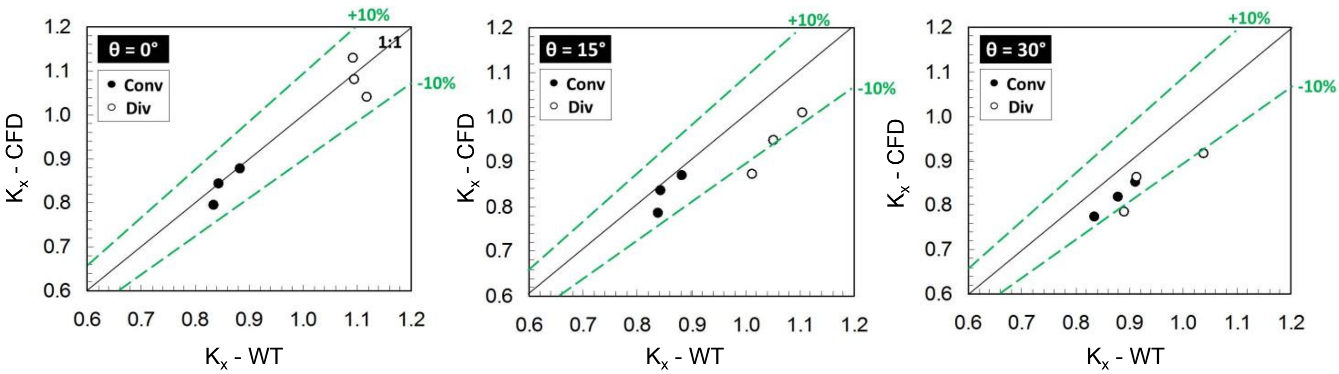
Computational settings and parameters

Additional computational settings

- Realizable k-ε turbulence model *(Shih et al. 1995)*
- Standard wall functions *(Launder and Spalding 1974)* with sand-grain roughness modifications *(Cebeci and Bradshaw 1977)* and roughness parameters according to *(Blocken et al. 2007)*
- Pressure-velocity coupling: SIMPLE
- Pressure interpolation: second order
- Second-order discretization schemes (for both convection terms and viscous terms)

CFD simulations: validation: comparison with wind-tunnel experiments

$$K_x = \frac{U}{V_{240}}$$



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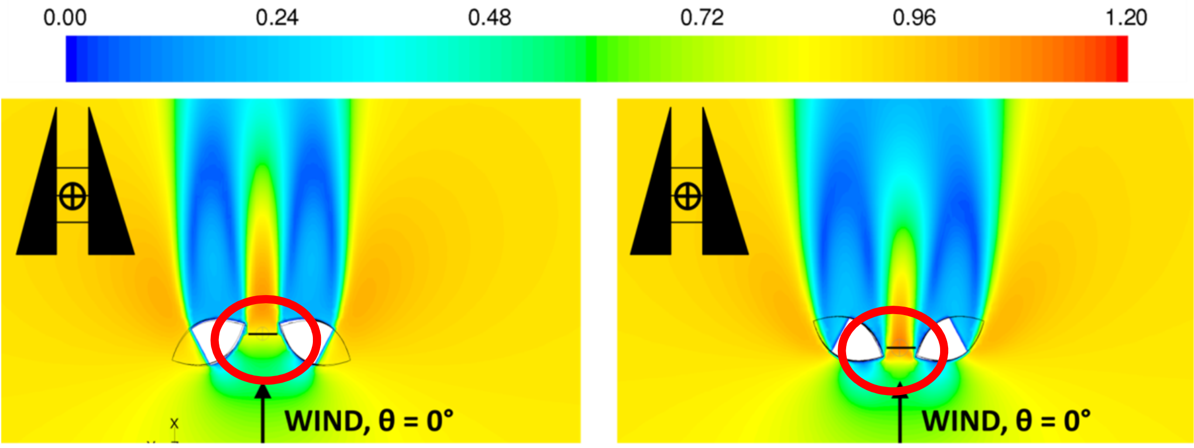
Wind energy - II

CFD simulations: amplification factor K in horizontal plane

$$K = \frac{V}{V_{240}}$$



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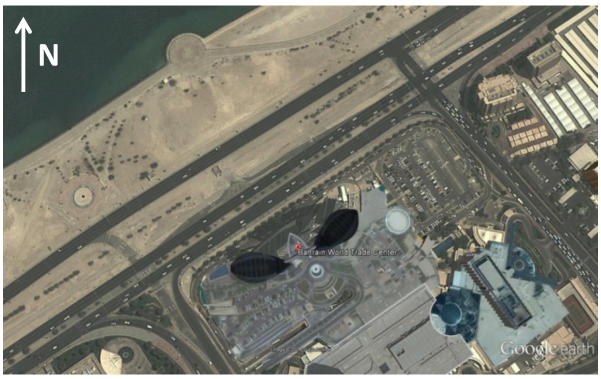
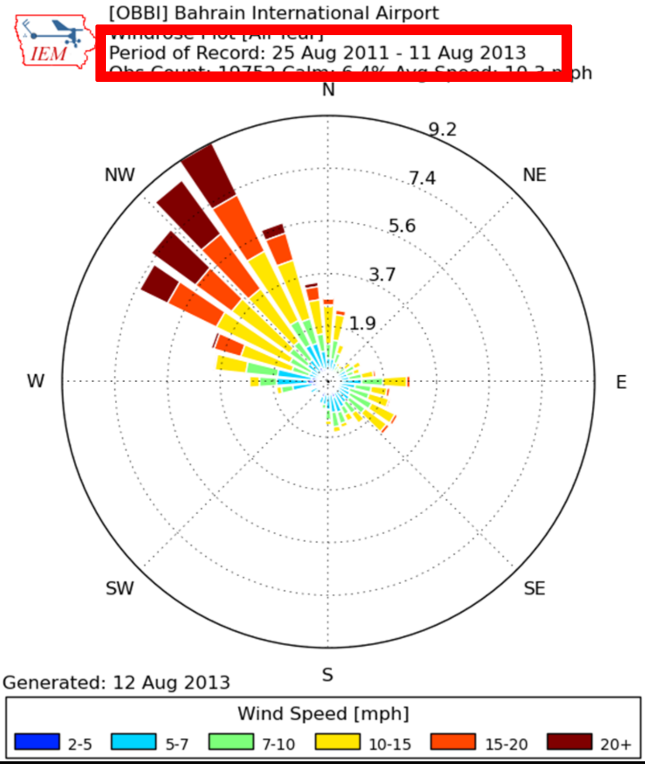
Wind statistics





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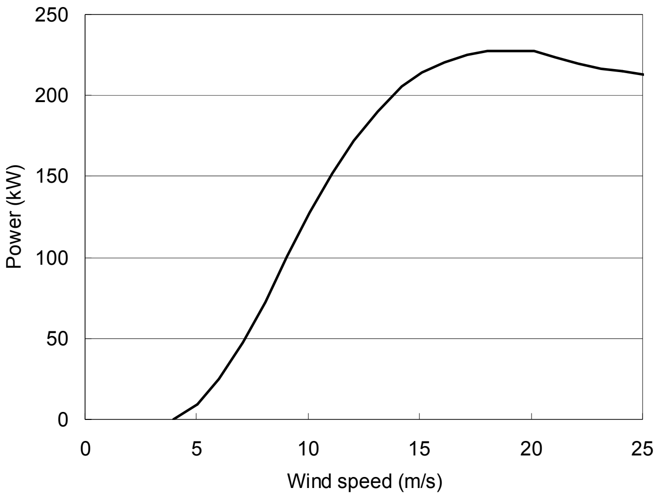
Wind energy - II

Wind turbine power curve



Reference: Shaun K, Smith RF, 2008. Harnessing energy in tall buildings: Bahrain World Trace Center and Beyond. CTBUH Technical paper.

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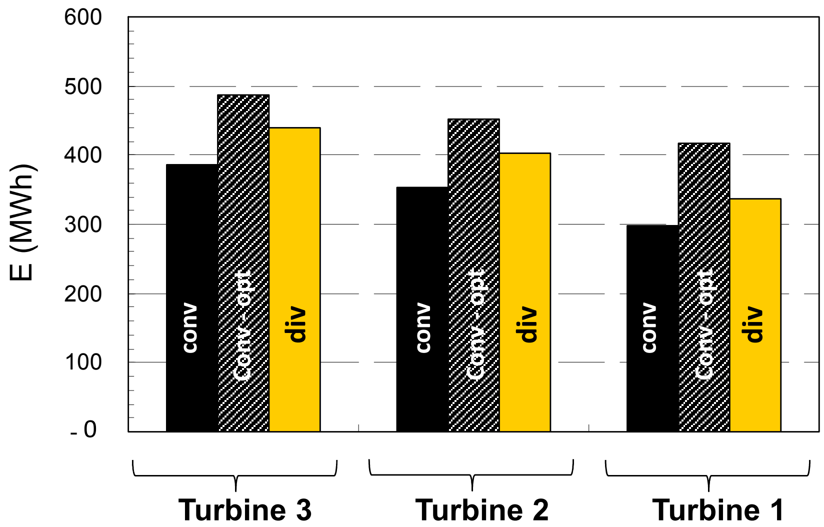
Wind energy - II

CFD simulations: yearly wind energy output



Killa & Smith (2008):

T3: 400 – 470 MWh/year
T2 : 360 – 430 MWh/year
T1: 340 – 400 MWh/year

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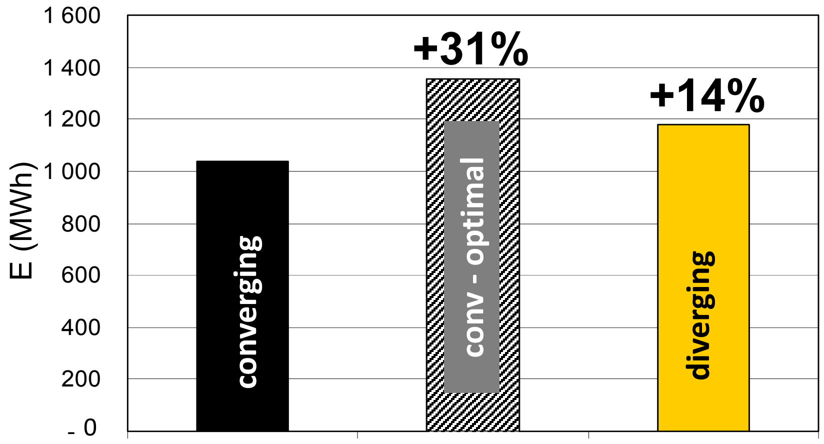
Wind energy - II

CFD simulations: yearly wind energy output



Conclusion: Bahrain WTC has a good design, but it can be improved significantly.

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Advances in Wind Energy Technology II
Chania, 4 - 8 April 2016

Large Eddy Simulation for Wind Energy

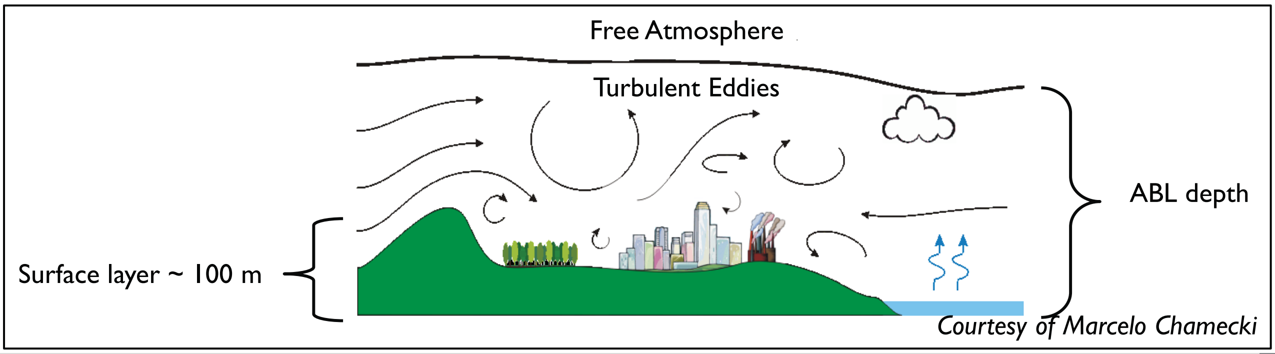
Ashvinkumar Chaudhari
School of Engineering Science,
Lappeenranta University of Technology, Finland

Outline

- Introduction
- Large Eddy Simulations
- Challenges in LES modelling
- LES for complex terrain
  - Idealized cases (wind-tunnels)
  - Real terrains
  - Forested terrains
- Modelling of wind-turbine wakes
- Importance of atmospheric stratification
- References

Atmospheric Boundary Layer (ABL)

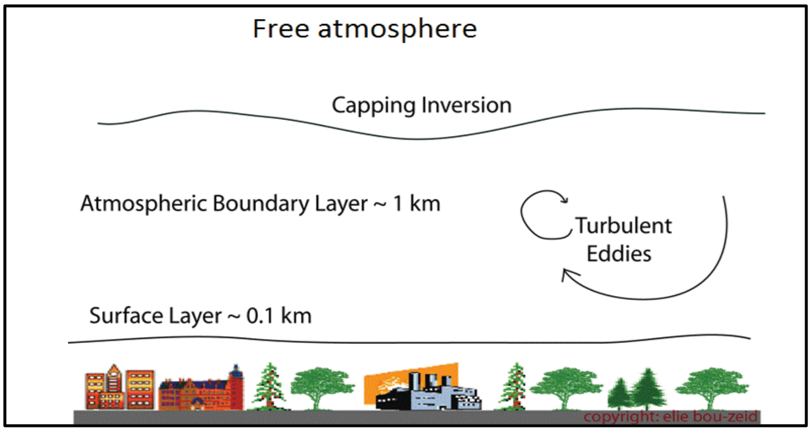
- ABL is the lowest region of the atmosphere, directly connected to the Earth's surface
- ABL plays an important role in many fields:
  - Wind energy, aeronautical, weather forecasting, meteorology, climate studies, etc.
- ABL depth: about 100 m up to 2 km depending largely on weather conditions
  - Atmospheric stratification plays an important role in controlling the ABL depth
- The lowest part is roughly known as a surface layer, affected with surface roughness (building, forest, hills, mountains, etc.)



Courtesy of Marcelo Chamecki

Characteristic of ABL

- The lowest 500 m of ABL is much important to wind energy
- Highly complex flows in the surface layer, inherent flow variability, large-scale unsteadiness, very high Reynolds number (~10^{8-9}), flow separations, etc.
- Strongly affected by buoyancy forces



Wind resource assessment:
Measurement vs numerical

- Any potential wind farm location must have the site thoroughly surveyed and the wind climatology analyzed before installing any hardware.

• **Field measurements**	• **Numerical (CFD) modelling**
• Only way to measure the realistic wind resource	• Provides a valuable set of data where no field data available
• long and (can be up to 3 years!), thus costly	• Faster and realiable results with extremely low cost
• Only point measurements at a limited number of locations	• Turbine wake can be simulated
• Do not characterize the wind flow on entire wind farm site	• Also account for turbulence and atmospheric stability
• Do not use to optimize wind-turbine positions	• Must be validated against field measurements

CFD for environmental flows

- In CFD (Computational Fluid Dynamics), a wide range of diverse numerical methods/approaches have been introduced and utilized to simulate wind flow over complex terrain.
- DNS (Direct Numerical Simulation) captures all of the relevant scales of the turbulent motions and thus no modelling is needed.
  - The approach is extremely computationally expensive, making it not possible for high Reynolds-number flows, such as ABL flows. The grid requirement in DNS is proportional to $Re^{(9/4)}$
- RANS (Reynolds-averaged Navier-stokes) approach with two-equation turbulence models has been widely used to simulate atmospheric flows
  - Good compromise between result accuracy and computational cost
  - Poor prediction in complex phenomena such as strong streamline curvature, acceleration, deceleration and flow separation
  - limited accuracy for the turbulence quantities
- LES (Large-Eddy Simulation) is encouraged to be applied to such atmospheric simulations

Turbulent flows

- Turbulent flows are characterized by eddies with a wide range of length and time scales.

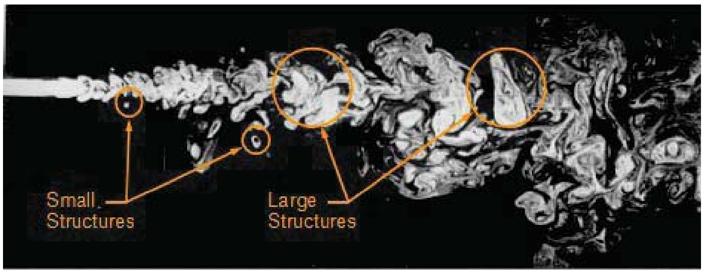


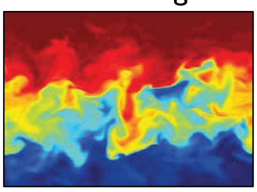
Fig.: Large and small scales of smoke flow at some time instant

Figure courtesy: Ansys Fluent

- **Large eddies**: typically comparable in size to the characteristic length (L);
  - Large eddies are more problem-dependent and they are dictated by the geometries and boundary conditions of the flow involved.
- **Small eddies**: responsible for the dissipation of turbulence kinetic energy
  - The small eddies are less dependent on the geometry, tend to be more isotropic, and are consequently more universal

Large Eddy Simulation (LES)

- Large Eddy Simulation **(LES)** is method to simulate turbulent flows in CFD, in which, the larger energy carrying eddies are resolved directly, whereas the smaller eddies modelled using a sub-grid scale (SGS) models
- It was initially proposed in 1963 by Joseph Smagorinsky to simulate atmospheric air currents and the first real applications were made by Deardorff in 1970, where he simulated the convective ABL.
- Over the past four decades, the atmospheric community has done much work using LES to accurately simulate ABL flows
- Why LES (??) => Some applications need explicit computation of accurate unsteady fields, such as bluff body aerodynamics, where the flow is governed by large turbulent scales
  - Wind-turbine wake, ABL flows, aerodynamically generated noise, combustion & Mixing



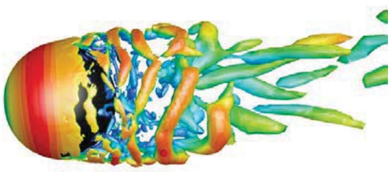


Figure courtesy of Ansys Fluent

LES Modelling

- Filtering the original Navier-Stokes equations gives the filtered Navier-Stokes equations which are the governing equations in LES.
- The large turbulent eddies which are responsible for the majority of turbulent transport are resolved directly in a computational grid (see the figure).
- Eddies smaller than the grid size are more isotropic are modeled using a sub-grid-scale model
- LES captures the important unsteadiness of the flow
- Larger computational resources are required in LES than RANS.

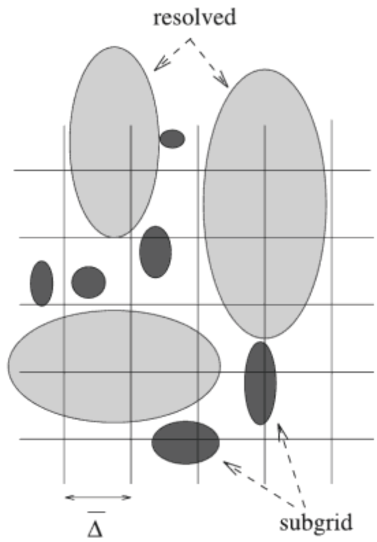


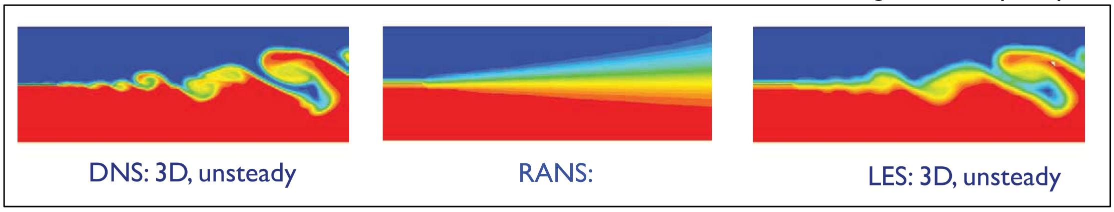
Figure: P. Sagaut (1998)

Unsteady turbulent flow

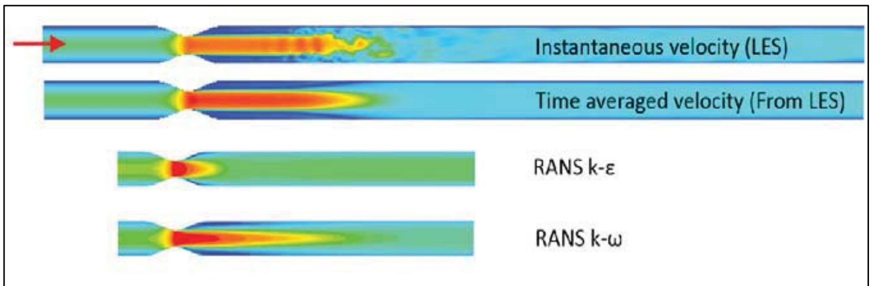
- By resolving only the large eddies allows one to use much coarser meshes in LES than those require in DNS.
- Compared to RANS, LES can be computationally more expensive, requiring about 1000 times greater computational resources, however, it yields fidelity solutions for flow configurations where RANS fails.

Figure courtesy: Ansys Fluent

Example 1:



Example2:



RANS vs LES

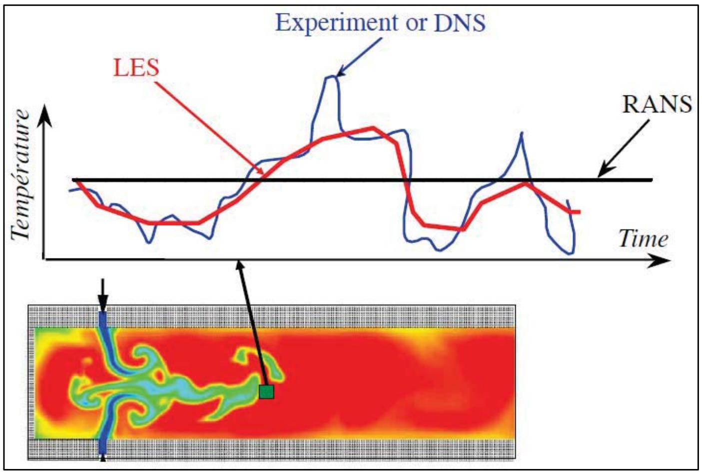
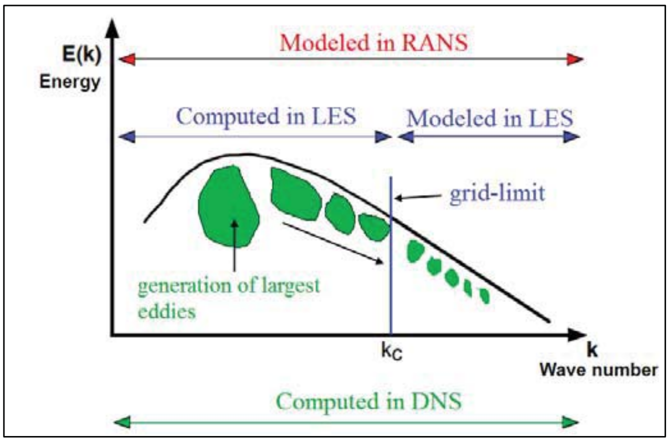


Figure source: T. Poinsot (2013)

- The averaging is performed over time in RANS
- By definition, RANS variables do not depend on time
- LES solution is always time-dependent



- Everything of importance has to be resolved in LES!

SGS modelling

- Generally, LES does not resolve eddies smaller than the grid size, and thus their effects need to be modelled using a Sub-Grid Scale (SGS) model.
- The effect of small scales appears through the sub-grid-scale (SGS) stress tensor

$$\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$$

- SGS models usually employ the Boussinesq hypothesis, and seek to calculate (the deviatoric part of) the SGS stress as

$$\tau_{ij}^D = \tau_{ij} - \frac{\delta_{ij}}{3}\tau_{kk} = -2\,\nu_{sgs}\,\widetilde{S_{ij}}$$

- $\widetilde{S_{ij}}$ is the resolved strain rate tensor, ν_{sgs} is the SGS viscosity and is the project of length scale l and velocity scale q_{sgs}
- The velocity scale can be chosen as the square root of the sub-grid stress tensor trace $q_{sgs}^2 = \tau_{kk}$
- The isotropic part $\tau_{kk}\delta_{ij}/3$ is added to the filtered pressure (pseudo pressure), i.e. $\tilde{p} + \tau_{kk}\delta_{ij}/3$
- The non-resolved small scales are supposed to be homogeneous and isotropic
- Simple algebraic model may be sufficient to take their effect into account

SGS models

- The most commonly used SGS models are the Smagorinsky model and its dynamic variants.
  - Smagorinsky model (1963) → $\nu_{sgs} = \left(C_s \overline{\Delta}\right)^2 \left|\overline{S}\right|$
    - Model constant C_S is typically ranging from 0.1-0.2 (not universal value)
  - Dynamic Smagorinsky model (Germano, 1991)
    - The constant C_S is dynamically computed
  - Wall Adapting Local Eddy-viscosity model (WALE) (Nocoud and Ducros, 1999)

$$\nu_{sgs} = \left(C_s \overline{\Delta}\right)^2 \frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(\overline{S}_{ij}\overline{S}_{ij}\right)^{5/2} + \left(S_{ij}^d S_{ij}^d\right)^{5/4}}$$

  - One (k) equation model (Yoshizawa,1993)
    - K-equation has to be solved
    - Dynamic version is also available

$$\nu_{sgs} = C_k \, k_{sgs}^{1/2} \, \Delta,$$

$$\Delta = V^{1/3}$$

k_{sgs} = SGS turbulent kinetic energy

Challenges of LES

- For atmospheric flows application, the use of LES over a real topography is not a straightforward task
- Some challenges:
  - Complex topography it self
    - gives more complex flow features: flow separation, acceleration, wake, etc.
  - High grid-resolutions in all three directions
  - Correct reproduction of inlet boundary conditions
    - need accurate information especially on turbulent fluctuations
  - Surface boundary condition
    - heterogeneous ground-roughness
    - accurate wall-function modelling
  - Near-wall turbulence structures due to high Reynolds number
    - SGS model plays important role in modelling small scales
  - Large computational domains, wind-farm scale
    - lead to extremely high number of grid cells, order of 10 millions
    - large computational work load
  - Require super-computing facility

Grid-resolution requirement in LES

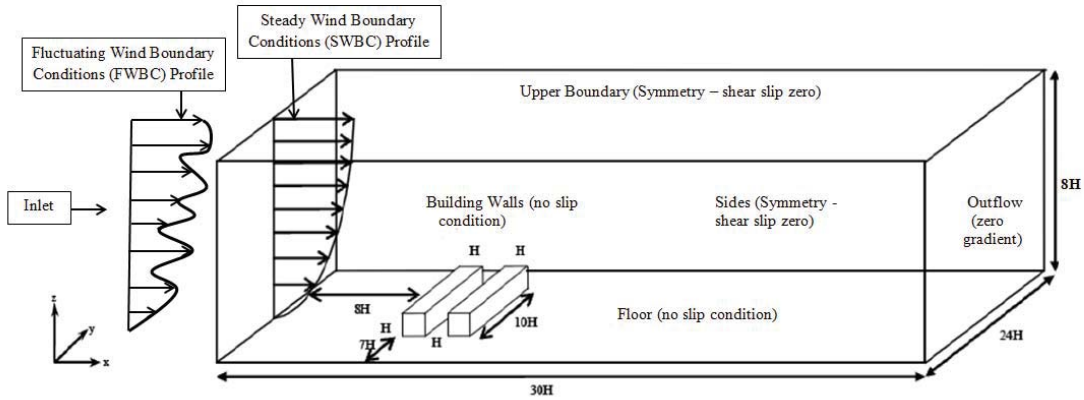
- LES resolves scales from the domain size ($\sim L$) down to the filter size Δ, and as such a substantial portion of high wave number turbulent fluctuations must be resolved.
  - Requires high-order numerical schemes, or fine-grid resolution if low-order numerical schemes are used.
- The required grid resolution for wall-resolved LES is (Davidson 2010):
  - $\Delta x^+ \simeq 100$ (stream-wise), $\Delta y^+ \simeq 1$ (wall-normal) and $z^+ \simeq 30$ (span-wise)
- There are different ways to estimate the resolution of LES data.
  - Compare the resolved turbulent kinetic energy (or stresses) to the modelled one
    - The smaller the ratio, the better the resolution.
    - Ratio of 0.8 (80%) is considered to be well-resolved (Pope 2004).
  - The energy spectra are also commonly used
    - If they exhibit a $-5/3$ slope, the flow is considered to be well resolved
  - The two-point correlations is also to identify resolution (see Davidson 2010)
    - The ratio of the integral length scale to the cell size.

Inflow boundary condition in LES

- The realistic inflow boundary condition is one of the major challenges in LES
  - Many times, vertical distributions of mean velocity and mean-level of turbulence (e.g. TKE or turbulence intensity) are available from measurements
- However, LES of spatially inhomogeneous flows require unsteady inflow boundary conditions with a proper representation of the turbulent fluctuations.
  - Turbulent fluctuations must be a function of space and time with a realistic energy distribution over the spatial directions and the simulated wave-number range
- **Periodic boundary** condition has been used widely, but not recommended for spatially inhomogeneous flows
- **Synthetic turbulence**: adding artificial (but time-dependent) turbulence with full developed steady mean-flow (e.g. logarithmic or power-law) velocity profiles
  - Example: a random 2D vortex method available in Ansys Fluent

Recycling inflow boundary

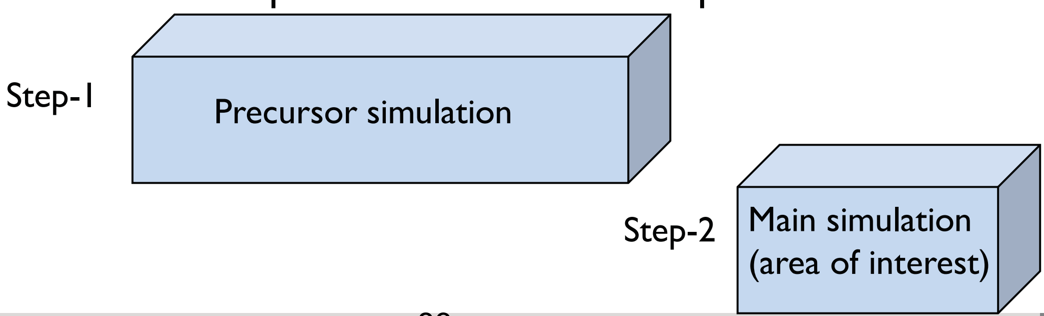
- Synthetic turbulence



Source: Kwa and Salim (2014)

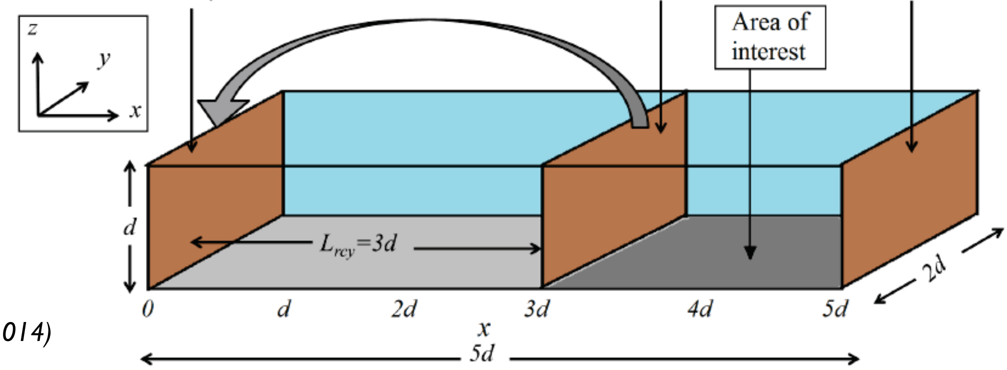
Inflow boundary: Precursor simulation

- The method works in two steps:
  - First, a separate precursor LES with periodic boundary conditions in stream-wise direction is carried out over flat terrain and the instantaneous field data is stored separately on the hard disk at each time step to create a library of turbulence or inflow velocity data
  - Then, the stored data is used as the fully developed upstream boundary condition for the terrain (successor) simulation
- Most well-know technique in LES but in two steps



Inflow boundary: Recycling approach

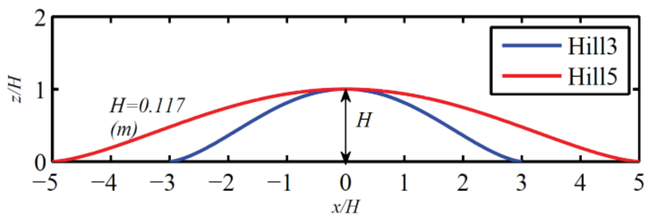
- In this method, the precursor simulation is not required and thus the entire simulation can be just performed once, as shown in the following figure.
- During the simulation, the flow variables (such as *U*, *k*) are sampled on a cross-stream plane (Recycling plane), which is sufficiently far downstream from the inflow plane, and the sampled data are then recycled back to the inflow plane at each time step.
- The so-called recycling distance L_{rcy} (between the two planes) is an important factor and should be at least 3 times the boundary layer depth (Chaudhari 2014)



Source: Chaudhari (2014)

LES for idealized (wind-tunnel) hill

- Objectives:
  - To simulate wind-tunnel hill flows by means of LES
  - To validate the LES methodology at laboratory scale (Khurshudyan et al.,1981)
  - To study the sensitivity of the flow to the surface boundary condition
    - Wall-resolved LES, but for lower Reynolds number $Re_H = 3120$
    - Rough-wall function (wall-modelled LES), implemented into OpenFOAM (Chaudhari 2014)
- LES for two hill shapes: Hill3 and Hill5



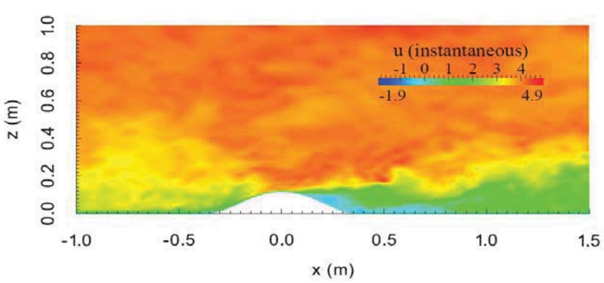
Numerical set-up

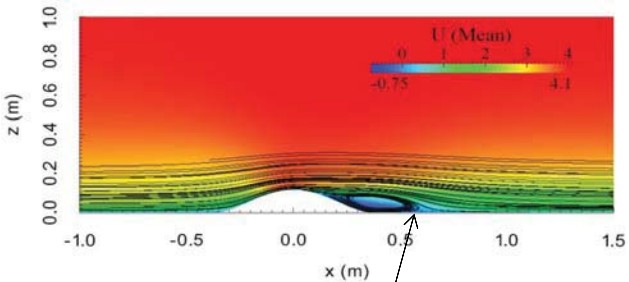
- The modeling details with differences from the two cases are listed below
- Reynolds number is based on the hill-height and free stream velocity

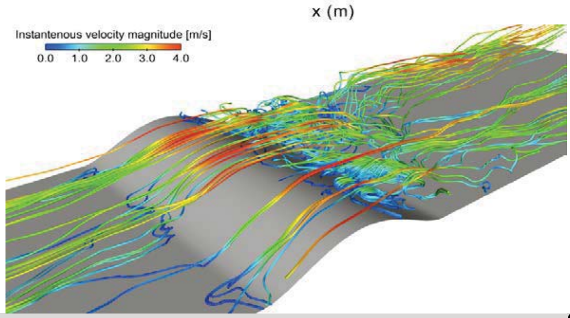
	Wall-resolved	Wall-modelled
Domain size	5.34 × 1 × 1 m³	8.34 × 2 × 1 m³
Total grid	275 × 121 × 64 (≈ 2.1× 10⁶)	495 × 136 × 70 (≈ 4.7× 10⁶)
Minimum cell-size	$z_p^+ \approx 0.5$	$z_p^+ \approx 47$
Reynolds number Re_H	3120	31200
Roughness	- (smooth)	0.000157 m
Inflow boundary condition	Artificial turbulence	Recycling approach
Wall boundary condition	No-slip (fully resolved)	Rough wall-function (wall-modelled)
SGS model	Smagorinsky	*k*-equation
Software	Ansys®	OpenFOAM®

Flow on the lee-side

- The hill shape used in the study are rather simple but flow is fairly complex.
- Especially on the lee-side, the flow is highly turbulent and reversing.



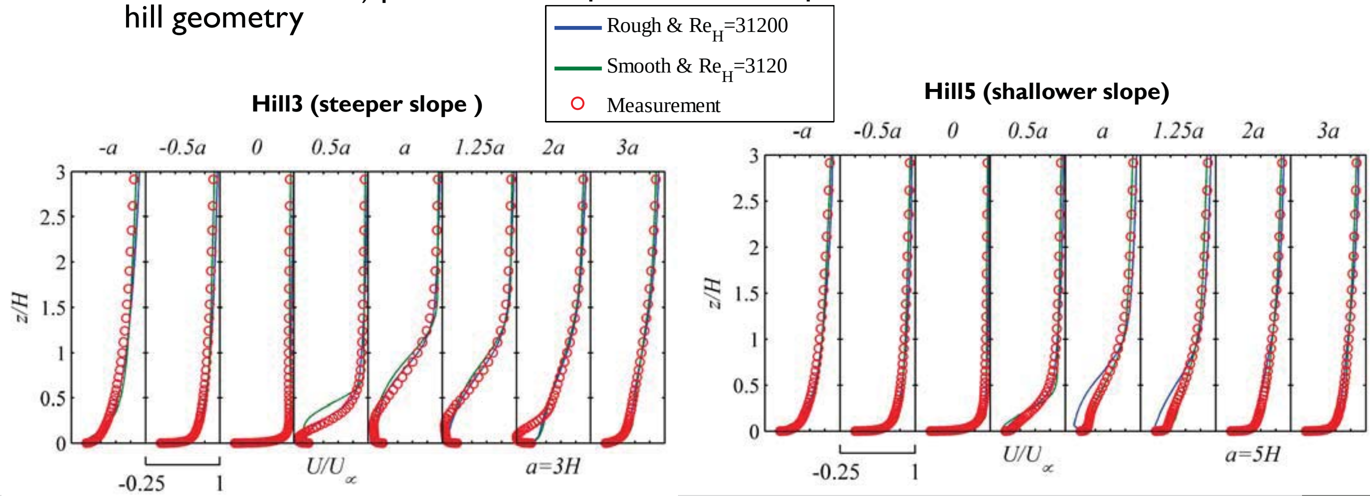




Reattachment point
LES => $x_r = 5.41H$
Wind-tunnel => $x_r = 6.5H$

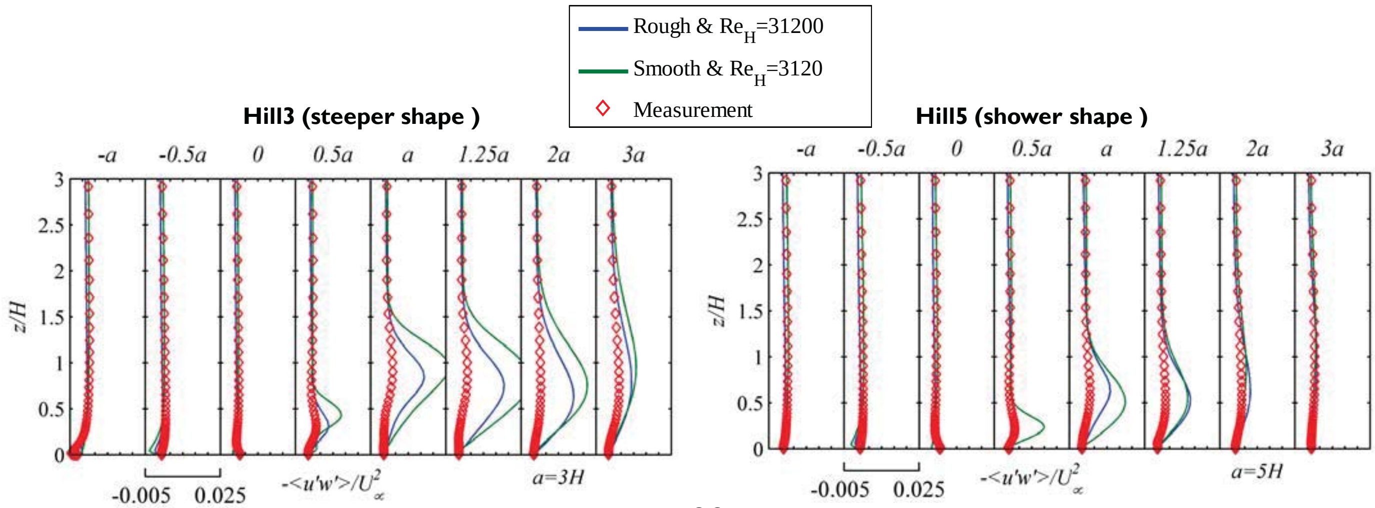
Results: Mean flow

- Mean velocity profiles compared with the wind-tunnel measurements (Kurshudhyan et al., 1981) at several locations.
- For a steeper hill-shape (Hill3), wall-modelled LES (also with roughness and higher Reynolds number case) gives better results of mean flows, where as in shallower hill (Hill5), the wall-resolved (smooth) LES results are better.
- The flow separation predicted by LES in the case of Hill3 is the most accurate (closer to measurements) prediction compared to all the previous studies done on the same hill geometry



Results: Reynolds shear stress

- Wall-modelled LES using a recycling method provides better perditions for the turbulence property.
- Many reasons: rough surface condition as well as higher Re_H (i.e. same as in wind-tunnel exp.), inflow boundary conditions, etc.

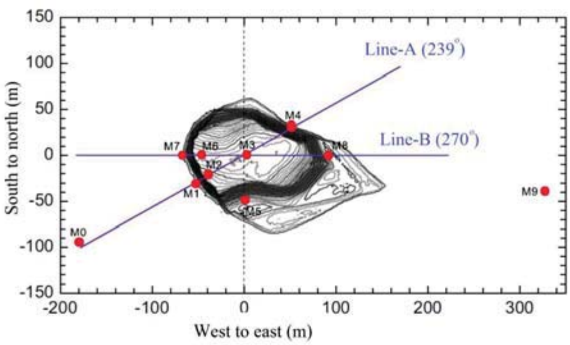


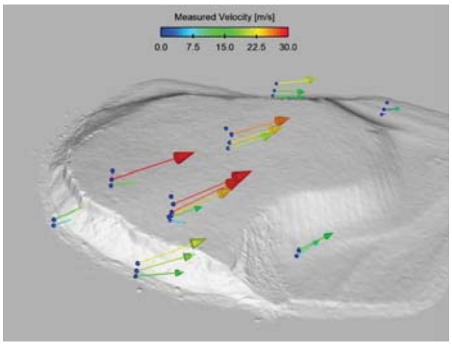
The Bolund hill

- The Bolund is a 12 m high, 250 m long and a 150 m wide costal hill located at near the city of Roskilde (Denmark).
- Objectives:
  - to reproduce the real atmospheric flows over the complex terrain
  - to validate our LES methodology over a real terrain for practical applications in wind energy
- The hill is small, but
  - More challenging topography - almost vertical slope and a cliff - complex 3D flow features - high number of measurement positions

The Bolund field experiment

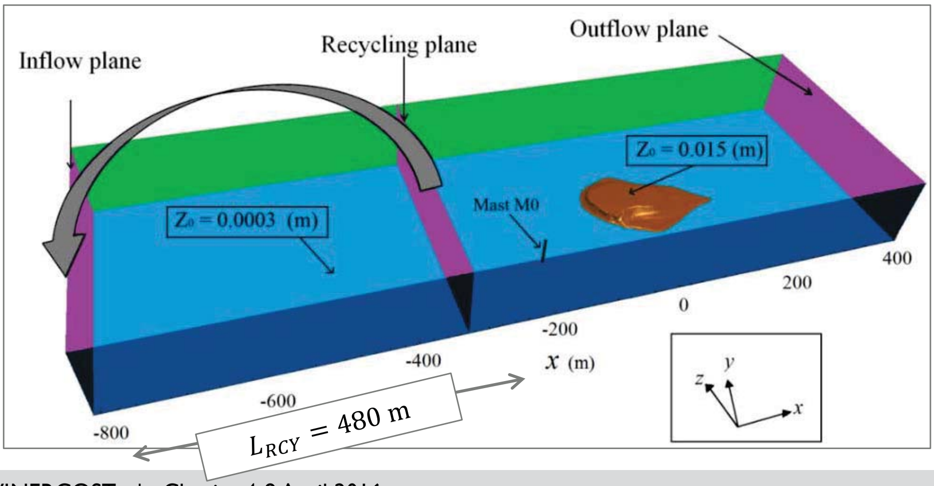
- The field campaign took place during a three month period from Dec 2007 to Feb 2008
- **23** sonic, **12** cup anemometers and **2** Lidars instruments
- High number of measurement positions at challenging locations
- Data on the mean flow and turbulence quantities for 4 different wind directions
- Aimed for mainly model validation over complex terrains for wind-energy application





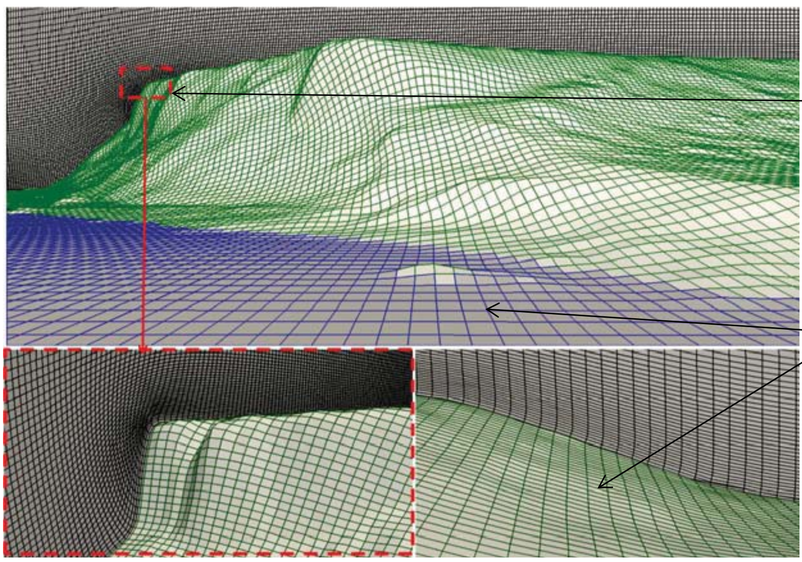
LES over the Bolund hill

- Computational domain: $1200 \times 400 \ \times 120 \text{ m}^3$
- The recycling length (L_{rcy}) is 4δ, (sufficiently enough)
- Periodic boundary conditions were used in the stream-wise direction
- Two different z_0 values $= 0.0003$ m (sea) and $z_0 = 0.015$ m (ground)



LES modelling: Grid resolution

- Grid generation is much more challenging on the Bolund due to its vertical slop
- Some guidelines were followed from the literature (Prospathopoulos et al., 2012, Diebold et al, 2013)
- Total grid: $940 \times 428 \ \times 100 \approx \mathbf{40} \times \mathbf{10^6}$ hexahedron type cells



Hill–surface grid
$\Delta x = 0.31 \text{ m} - 0.85 \text{ m}$
$\Delta y = 0.40 \text{ m} - 0.70 \text{ m}$

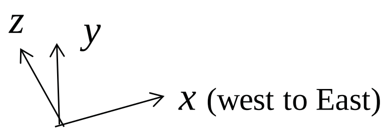
Elsewhere
$\Delta x = 0.85 \text{ m} - 4 \text{ m}$
$\Delta y = 0.70 \text{ m} - 4 \text{ m}$
$\Delta z = 0.15 \text{ m} - 5 \text{ m}$

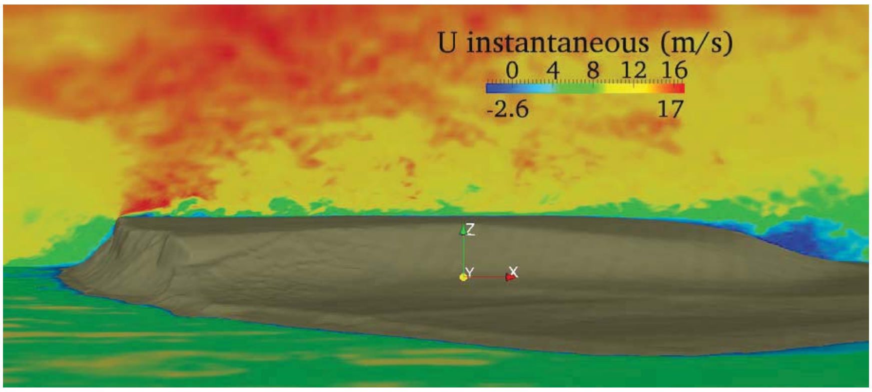
Some fact about CPU time:
- 40 days using 512 processors for 2700 sec of flow time on supercomputer

LES methodology

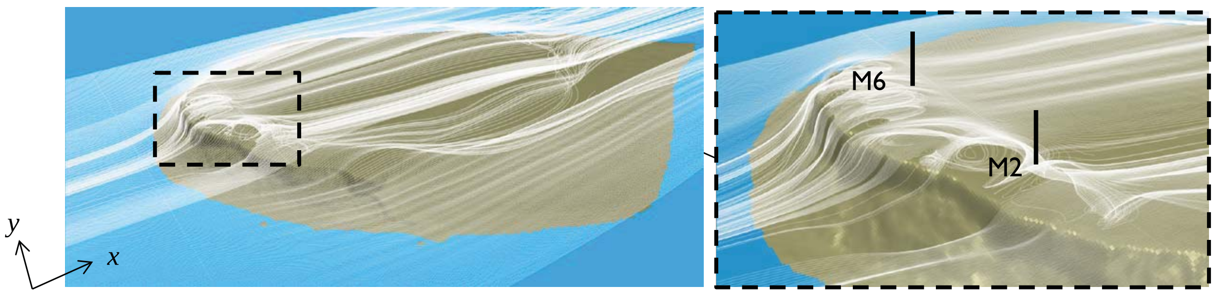
- We used our own OpenFOAM®-based numerical (LES) flow solver (Chaudhari, 2014; Vuorinen et al.,2015)
  - Projection method for pressure-velocity coupling
  - Fourth order RK scheme for the time-integration
  - Second order central difference scheme for spatial discretization
  - Automatic time-step by fixing the Courant number
- One-equation eddy viscosity sub-grid-scale model (Yoshizawa, 1993)
- Recycling (mapping) technique for the upstream boundary-layer flow
- The logarithmic wall function based on the aerodynamic roughness-length
- Neutral flow (no temperature equation) and no Coriolis forces

Results: Flow visualization





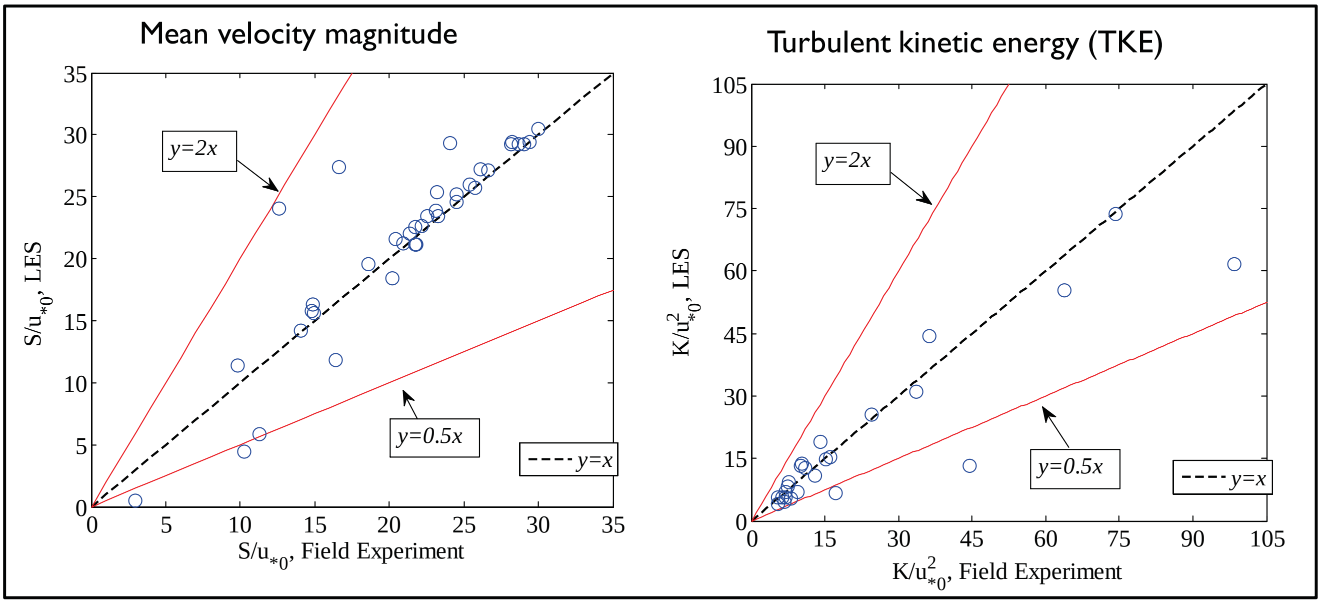
Instantaneous flow over the stream-wise plane showing the influence of the hill



10-min time averaged streamlines highlighting flow separations

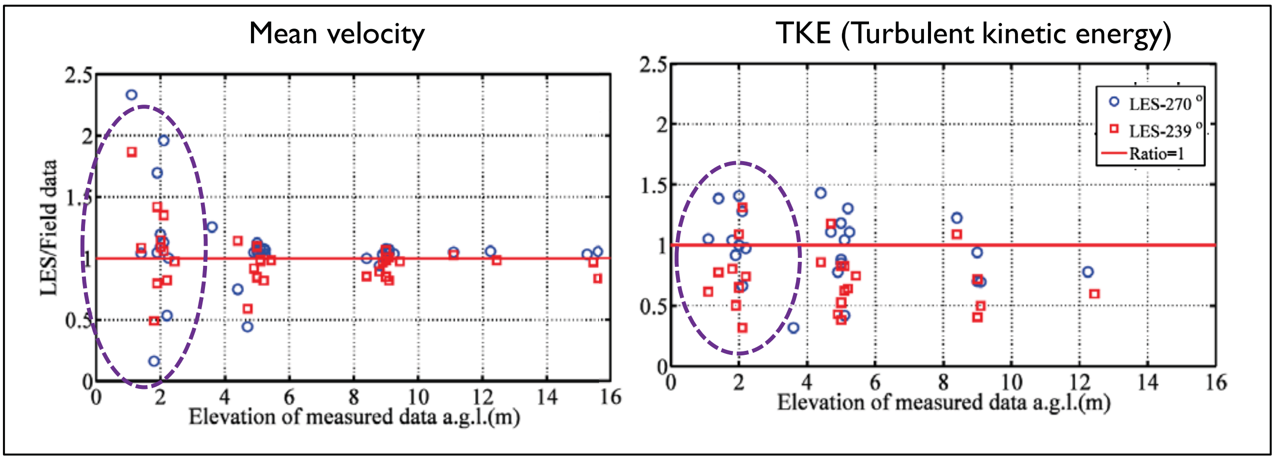
Results: Scatter plot

- 10-min time averaged results at all the anemometer positions
- Overall good (linear) fitting is observed in both cases: velocity and TKE



Results: Ratio with height

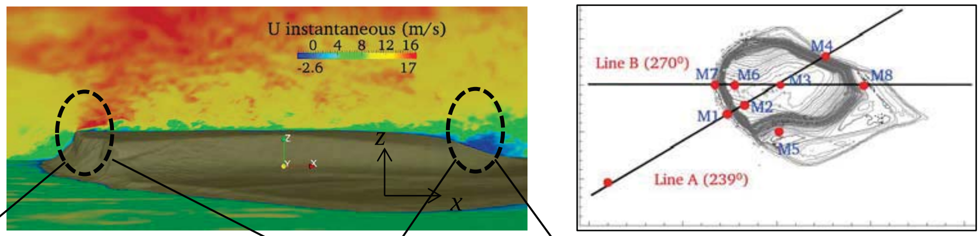
- 10-min time-averaged results on the ratio of LES to field data from two wind directions: 270° and 239°
- Velocity results are much scattered near the surface ($z_{agl} \leq 2$ m), but they are improved with the height
- TKE prediction is better near the surface compared to the velocity prediction

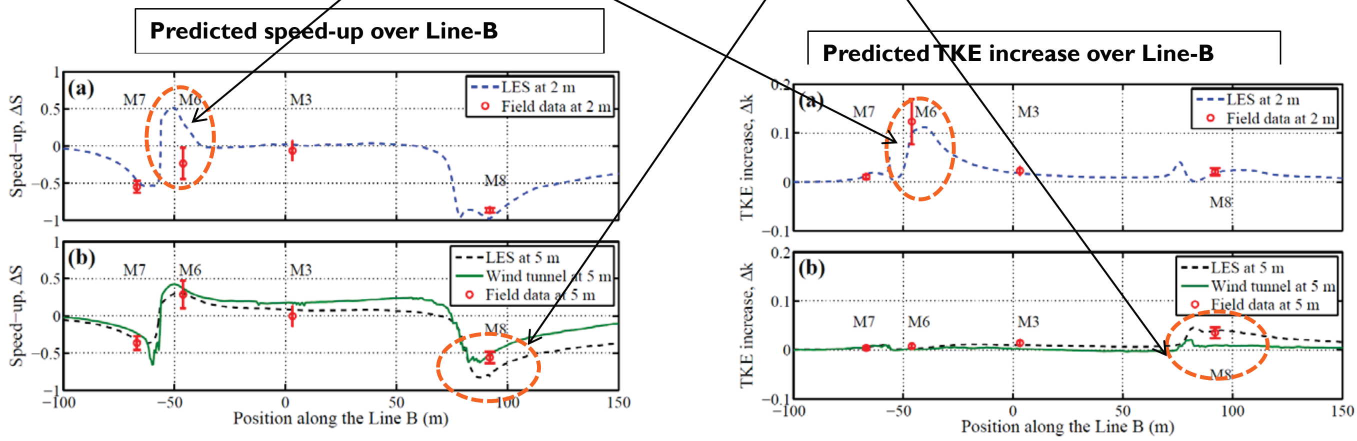


Results: Speed-up and TKE

- Results on velocity speed-up (ΔS) and TKE increase (Δk) compared with field (Berg et al. 2011) and laboratory (Conan 2012) experimental data

- Speed-up: $\Delta S = \frac{S - S_0}{S_0}$
- TKE increase: $\Delta k = \frac{k - k_0}{S_0^2}$





Model evaluation: Validation metric

- We use the following validation metrics to quantify the prediction accuracy:
  - Factor of Two (FAC2) => $0.5 \le \frac{P}{O} \le 2$; P is the predicted and O the observed value
  - Fractional Bias (FB)= $2\frac{\langle O\rangle - \langle P\rangle}{\langle O\rangle + \langle P\rangle}$
  - Normalized Mean Square Error (NMSE)= $2\frac{\langle (O-P)^2\rangle}{\langle O\rangle\langle P\rangle}$

Table Calculated values of the validation metrics from the LES results. The acceptance criteria for the model evaluation are adopted from Hanna and Chang (2012).

Validation metric	Present model value	Acceptance criteria	Satisfy ?
FAC2	0.9194	FAC2 $\ge$ 0.50	✓
FB	0.1130	$\lvert FB\rvert \le 0.3$	✓
NMSE	0.2180	NMSE $\le$ 3	✓

- The LES model passed all three validation-metric tests

Model evaluation: Simulation error

- Error (%)= $100(P - O)$ defined by Bechmann et al. (2011)
- The present LES gives **better results** than any wind-tunnel modeling !
- Present LES shows the **best results** for predicting the turbulence kinetic energy with the smallest error.
- In terms of TKE, the second best performing model has **75% higher error** than present LES-model error.

Model	Mean error R_S (best)	Mean error R_k (best)	Wind direction	Reference
RANS 2 eq.	15.1 (14.4)	47.0 (29.9)	270° and 239°	Bechmann et al. (2011)
RANS 1 eq.	17.2 (13.8)	44.7 (42.7)	270° and 239°	Bechmann et al. (2011)
Experiment	14.7 (13.3)	61.4 (59.4)	270° and 239°	Bechmann et al. (2011)
LES	17.3 (14.1)	48.0 (41.6)	270° and 239°	Bechmann et al. (2011)
Linearized	23.7 (20.6)	76.7 (71.4)	270° and 239°	Bechmann et al. (2011)
RANS 2 eq.	10.3	-	only 270°	Prospathopoulos et al. (2012)
Experiment	12.4	42.2	only 270°	Conan 2012
Experiment	13.9	47.9	only 270°	Yeow et al. (2013)
LES-EPFL	9.6 (7.1)	-	270° and 239°	Diebold et al. 2013
Present LES	**10.3 (9.7)**	**24.1 (19.3)**	270° and 239°	-

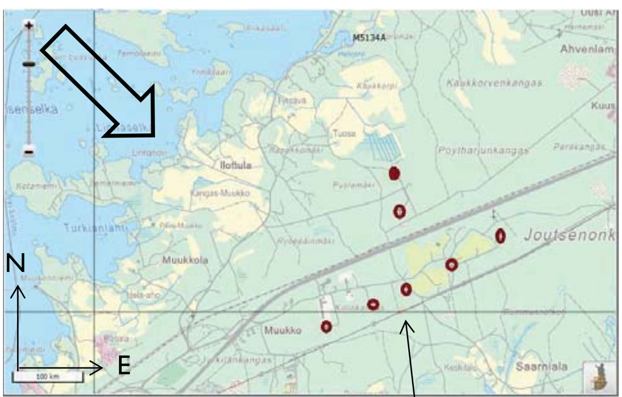
Wind-tunnel

Non-blind

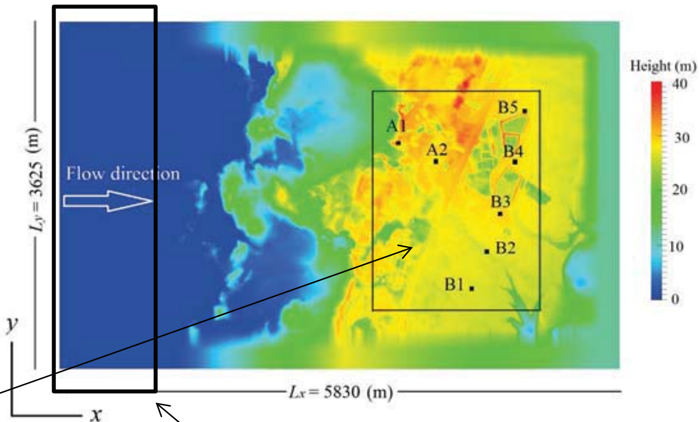
Demonstration over real-life wind farm

- The validated LES is further demonstrated to simulate the real wind condition over the existing Muukko wind-farm located near Lappeenranta (Finland).

Muukko wind-farm in reality



CFD domain: $5.8 \times 3.6 \times 0.3$ km^3
Grid: 104×10^6 millions
CPU time: 40 days using 1024 processors

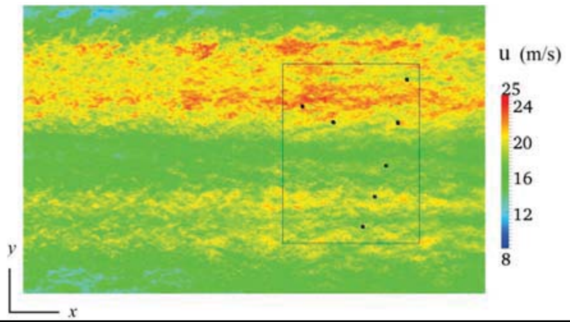


7 turbines are named A1,A2, B1-B5

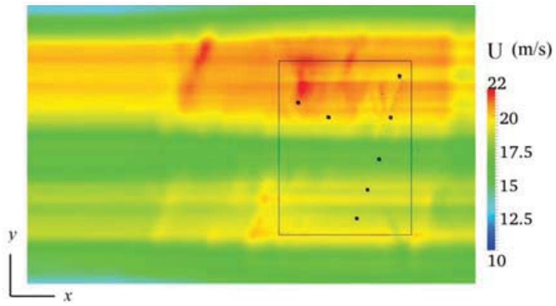
Recycling section

Preliminary results

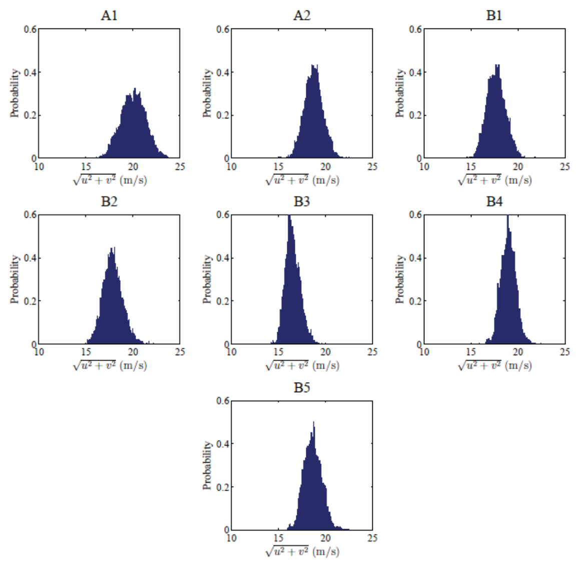
Instantaneous flow at 90 m height



30-min time averaged flow at 90 m height



Probability density function of the simulated wind at 90m height



Modelling of forest

- Building a wind farm in a forest has a huge benefit from the social acceptance point of view, as many people do not like heavy constructions near their neighborhoods
- Wind turbines installed within forested area suffer from high aerodynamic loads
  - Strong wind shear into velocity profile
  - Turbulence is increased (at its largest) on the top of the forest
  - Affect directly turbine life-time and its maintenance cost
- Explicit modeling of the forest canopy is more realistic and thus recommended
- The forest-resistance effect on the flow can be represented by adding the estimated drag force terms into the momentum equations (Dwyer et al., 1997; Shaw and Patton, 2003; Dupont and Brunet, 2008)

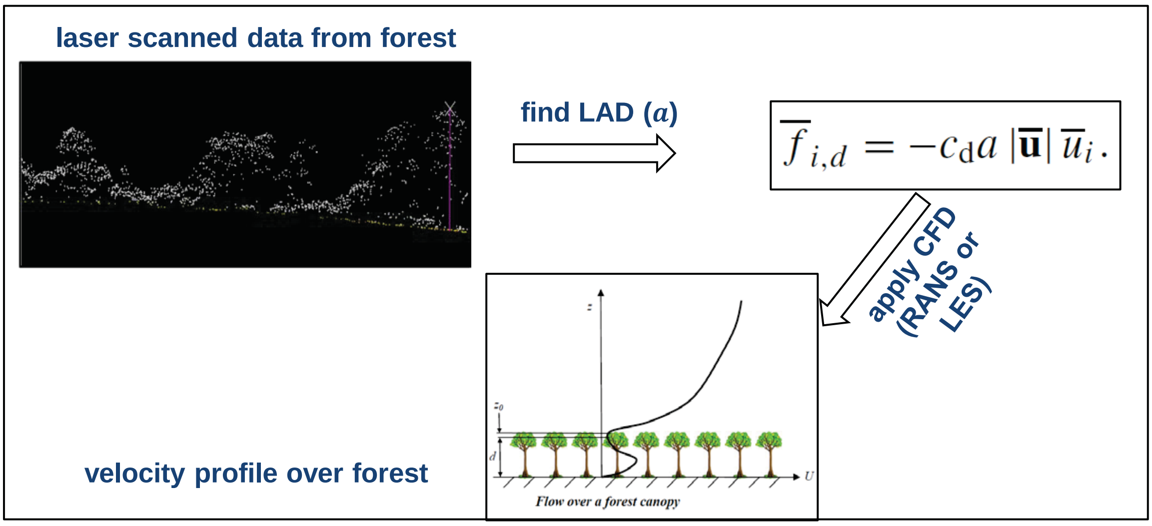
Filtered N-S equations = $\overline{f_{i,d}}$

$$\overline{f}_{i,d} = -c_d a \, |\overline{\mathbf{u}}| \, \overline{u}_i .$$

Where Cd is the drag coefficient
a is the Leaf Area Density (LAD) in (1/m)
$\boldsymbol{u_i}$ is the wind velocity

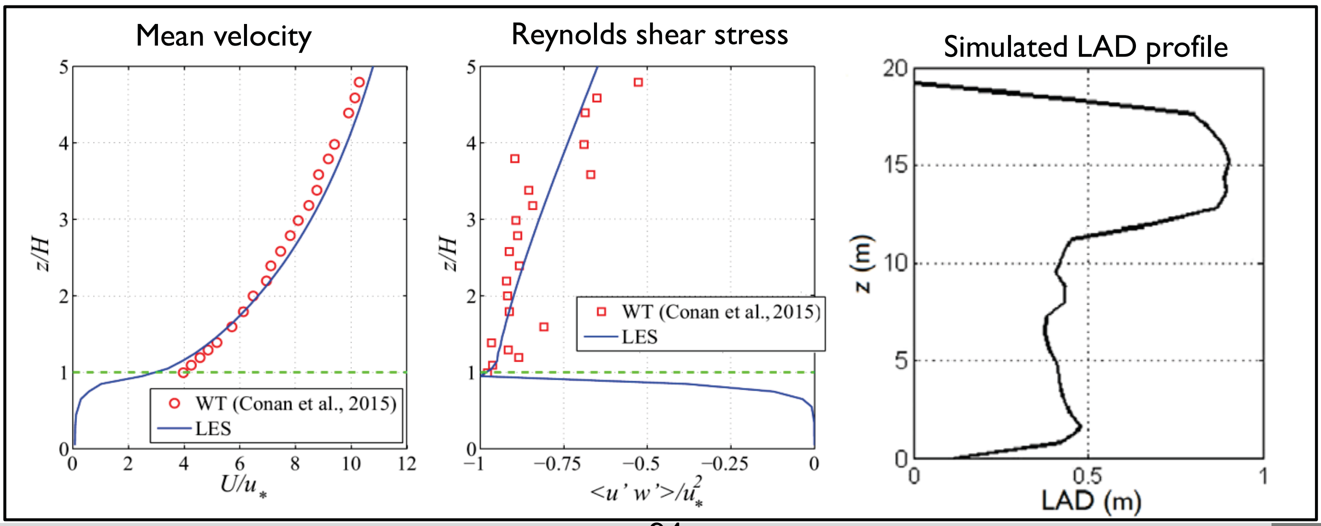
Adding forest into simulations

- The remote measurements of forest by laser scanning provide the necessary properties such as canopy height, trunk-layer height, average leaf-area index etc., of any real forest, which can then be input into CFD simulations
- See, Lalica and Mihailovic (2004) to learn on calculating heterogeneous LAD



Validation of the solver

- Standard OpenFOAM does not include canopy model
- We implanted it into OpenFOAM and carried out validation test case for homogeneous forest canopy over flat terrain
- LES-result comparison with the wind-tunnel experimental data by Conan et al. (2015)



Modelling of wind-turbine wakes

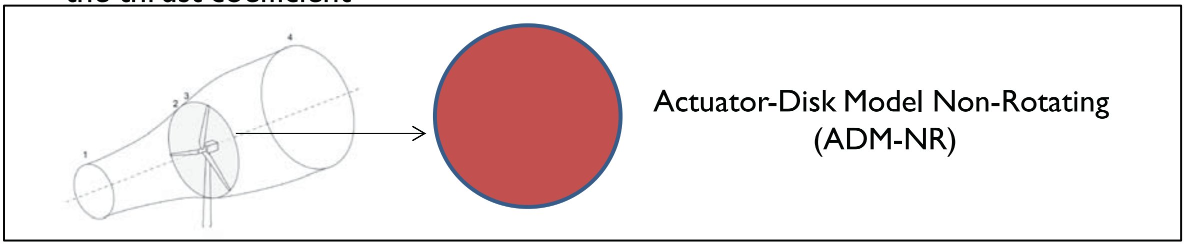
- Interactions of wind-turbine wakes should be taken into account while optimizing wind farms
  - For example, extraction in the wind power occurs when the first row turbines extract large amount of the wind momentum leaving less for the next rows
  - This extraction depends on the ABL turbulence (i.e. mainly on stability conditions), surface roughness and the distance between turbines (Emeis 2010)
- Therefore, in order to optimize energy production potential, a study of the interactions between meteorology, turbulence, terrain local orography, surface condition, and wind-farm layout and characteristics should be considered when designing a wind park.

Different modelling techniques

- Direct modelling of rotors (resolving turbine structure) is computationally expensive and certainly infeasible if used in combination with LES because that would require much small grid spacing near the structure
- Wall function that we use to avoid small grid sizes near terrain surface is not designed to model the turbulence near the turbine structures
- Instead, an efficient mathematical approach is used to replace rotating turbines with mathematical model, that is, source terms in Navier-Stokes equations
  - Most LES codes use the actuator disk (AD) and actuator line (AL) techniques
- These methods model turbines as local volume forces that extract momentum from the flow

Actuator-Disk Model (non-rotating)

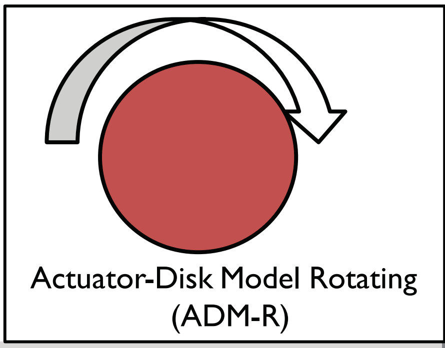
- The most straight forward approach to represent the wind-turbine forces in numerical models of flow through propellers and turbines
- It assumes the loads are distributed uniformly over the rotor disk and acting only in the axial direction
- Only 1D approximation of the turbine-induced thrust force and with out rotation
  - $F_x = \frac{1}{2}\rho u_0^2 A C_T$; A is the frontal area of the cells within the rotor region and C_T is the thrust coefficient



- Due to its simplicity and capability to deliver reasonable results with coarse grids, this model is still widely used in the context of both RANS and LES

Actuator-Disk Model (rotating)

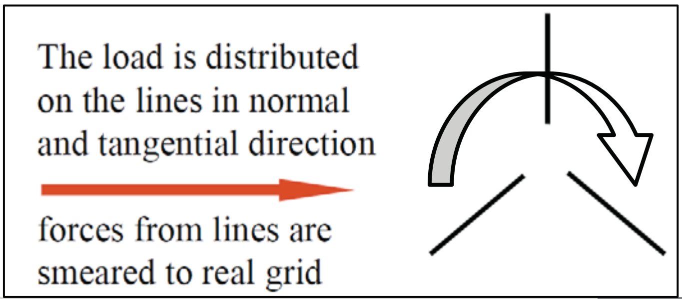
- In the rotating disk model (ADM-R), the lift and drag forces acting on the turbine blades are parametrized using the blade-element theory
- The load is distributed inside the disk area in normal and tangential directions
- The tangential forces account the turbine-induced flow rotation
- The ADM-R considers the effect of the non-uniform force distribution
- Gives more detailed information on the wake as compared to non-rotating disk model
- Refer to Wu and Porte´-Agel (2011) and Porte´-Agel et al. (2011) for more detail on the actuator models



Actuator-Line Model (ALM)

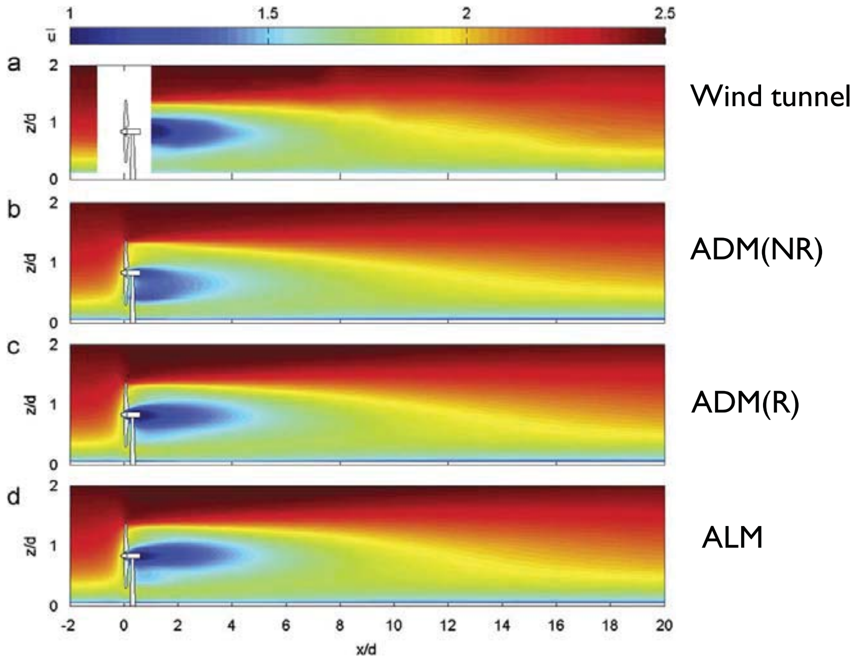
- The ALM uses Blade-Element Momentum (BEM) theory to calculate the turbine-induced forces (lift, drag and thrust) and distributes them along the three lines representing the blades
- Instead of merely averaging the forces over the disk, the approach takes their temporal variations into the account (Sørensen and Shen, 2002).
- Much more advanced: fully rotating, three dimensional and transient model
- As a result, it has the ability to capture important features of turbine wakes, such as tip vortices in the near-wake region
- Computationally more expensive !

  More reading:
  Sørensen and Shen (2002)
  Calaf et al. (2010)
  Porte´-Agel et al. (2011)



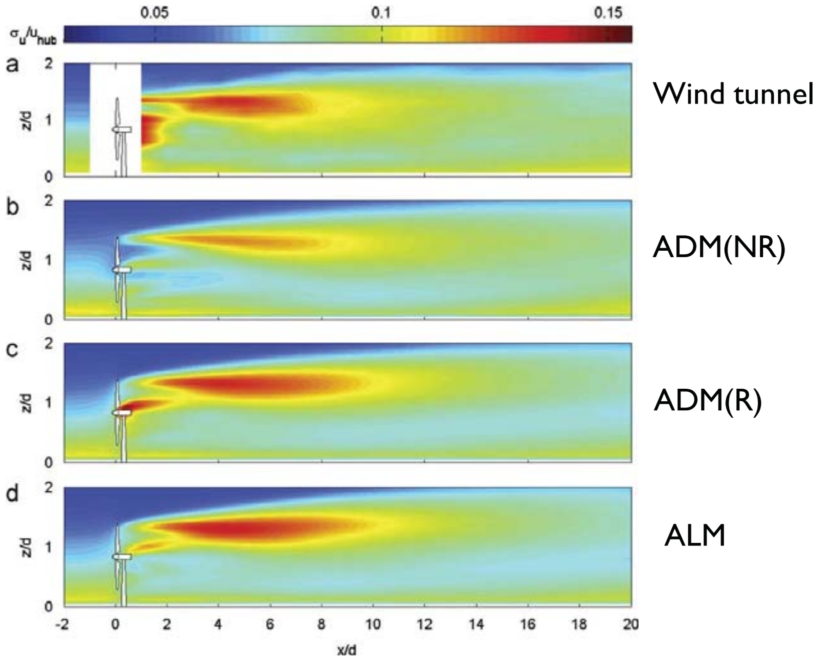
Actuator model comparison

- Time-averaged stream-wise velocity $\bar{u}$ (m/s). Figure is reproduced from Porte´-Agel et al. (2011).



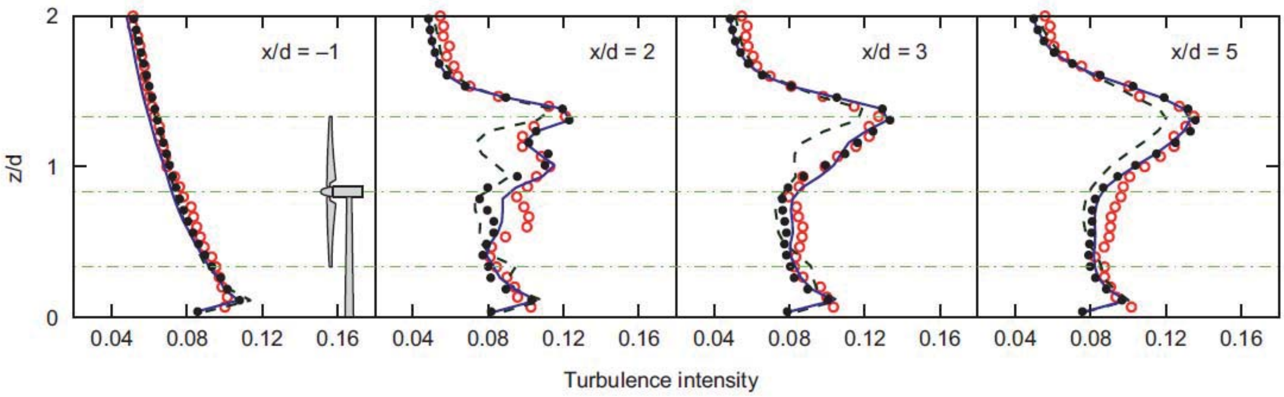
Actuator model comparison

- Stream-wise turbulence intensity $\sigma_u/\overline{u_{hub}}$. Figure is reproduced from Porte´-Agel et al. (2011).



Actuator model comparison

- Vertical profile of the stream-wise turbulence intensity $\sigma_u/\overline{u_{hub}}$. Figure is reproduced from Porte´-Agel et al. (2011).



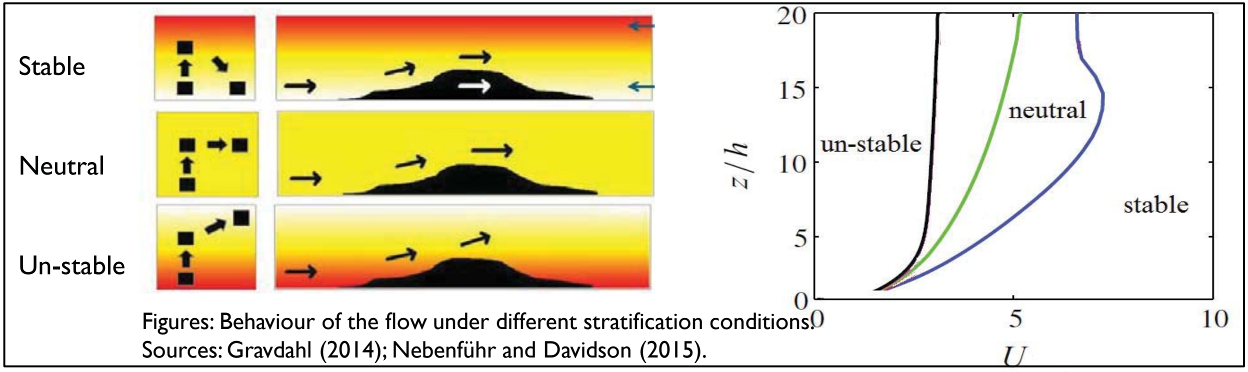
open (red) circles: measurements
dashed lines: ADM-NR
solid (blue) lines: ADM-R
closed (black) symbols: ALM

Importance of atmospheric stability

- Wind farms have strong influence on local wind and weather conditions, which in turn, affect optimal locations and altitudes of wind turbines in a wind farm
- The most common trend in the numerical simulations is to assume the atmospheric flow to be neutrally stratified
- The models are much simpler from the meteorological point of views
- The physical processes that are specific to the ABL have been ignored mostly for wind energy applications
  - the Coriolis force generated by the earth's rotation,
  - buoyancy forces, and
  - temperature equation
- In order to decrease the uncertainty of wind resource assessment, the models in wind energy sector should consider the full depth of the ABL taking into account the thermal stratification and the Earth's rotation

Atmospheric stability

- ABLs are usually classified into three types:
  - neutral, convective (un-stable), and stable
- Stably stratified ABL-conditions and thermal surface inversions, especially typical in winter-time, are a challenge to onshore wind energy production at high-latitudes.
- The boundary layer becomes stably stratified whenever the underlying surface is colder than the air.
- The characteristic size of the eddies becomes increasingly small with increasing atmospheric stability.



Figures: Behaviour of the flow under different stratification conditions.
Sources: Gravdahl (2014); Nebenführ and Davidson (2015).

Stable Vs unstable

- Chimney plume under stable and unstable conditions

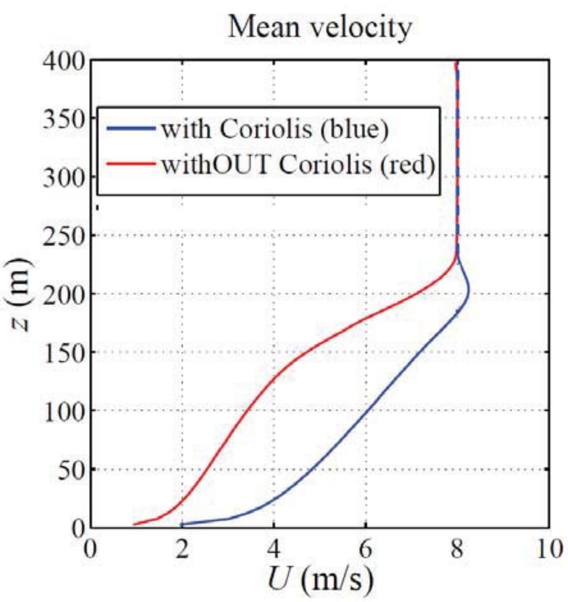
stable

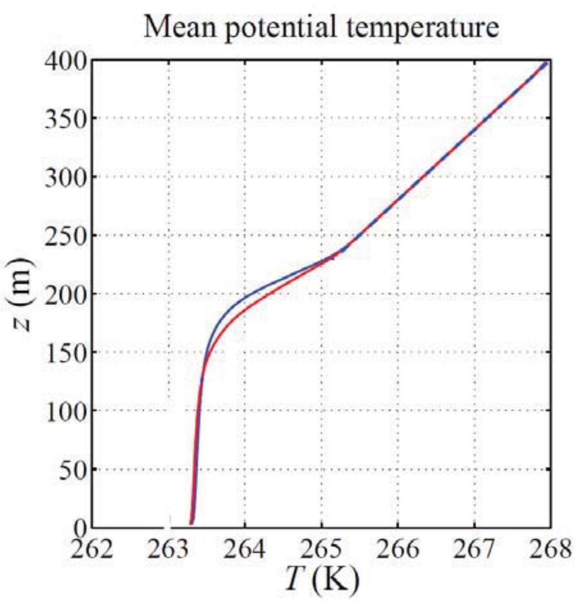
unstable

Figure Courtesy: Torben Mikkelsen, Thomas Ellermann, Koblitz, A. Bechmann, J. Berg, A. Sogachev

Effect of the Coriolis forces

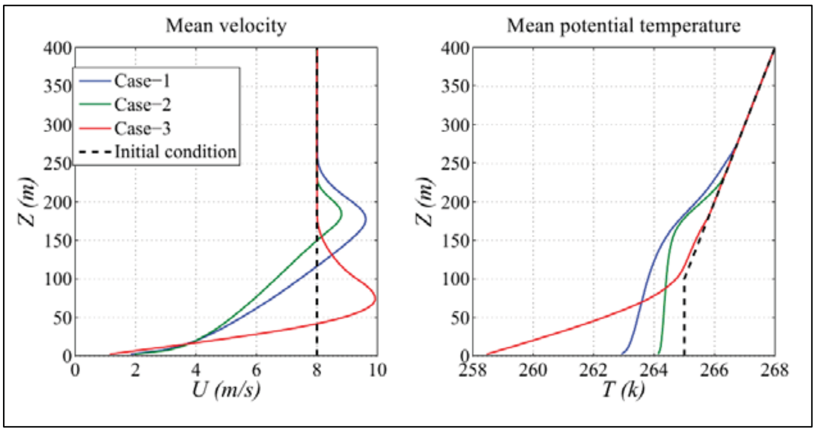
- The Coriolis forces generated by the Earth's rotation are important to reproduce the correct ABL





Dependence of surface temperature on ABL depth

Numerical results →

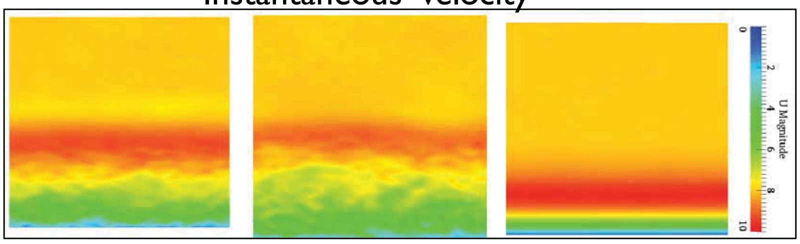


Quantitative comparison ↓

	Changes in cases, [only at the surface boundary]	Surf. Temp. (K)	BL-depth (m)	Increase in geostrophic wind
Case-1	cooling rate of 0.25 K/h	262.9	177.5	20.24 %
Case-2	temperature flux of -0.005 (K m/s)	264.1	182.5	10.16 %
Case-3	temperature flux of -0.01 (K m/s)	258.5	77.5	24.08 %

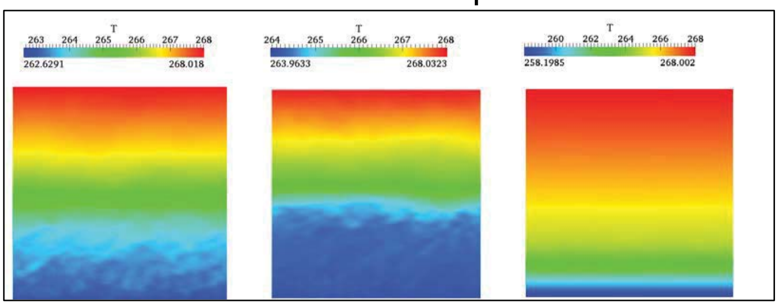
Qualitative comparison

Instantaneous velocity



Case-1 Case-2 Case-3

Instantaneous temperature



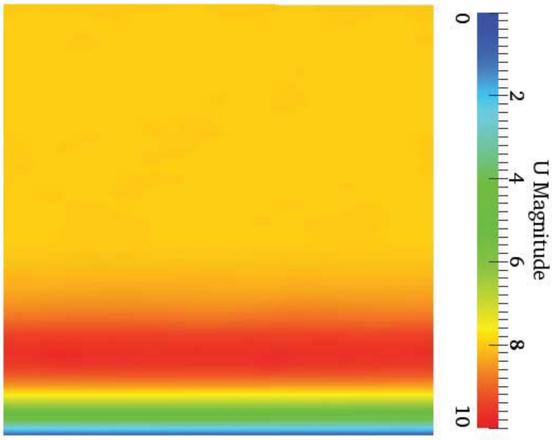
Case-1 Case-2 Case-3

- Eddies become increasingly smaller with increasing atmospheric stability
- With the same cell-size (5m) among all three cases, the velocity and temperature perturbations are not resolved in case-3 as the eddies are too small compared to the grid size
- Is it a kind of limit for LES in very strongly SBL flows?

Qualitative comparison

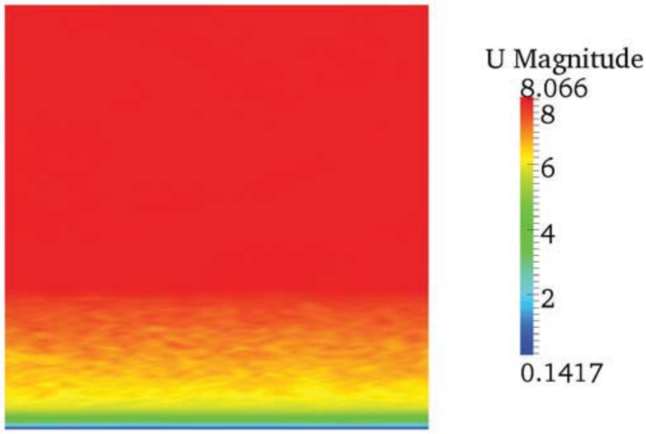
- Influence of grid resolution in Case-3 (strongly SBL)

Cell size: $\Delta x = \Delta y = \Delta z = 5 \text{ m}$ (isotropic)



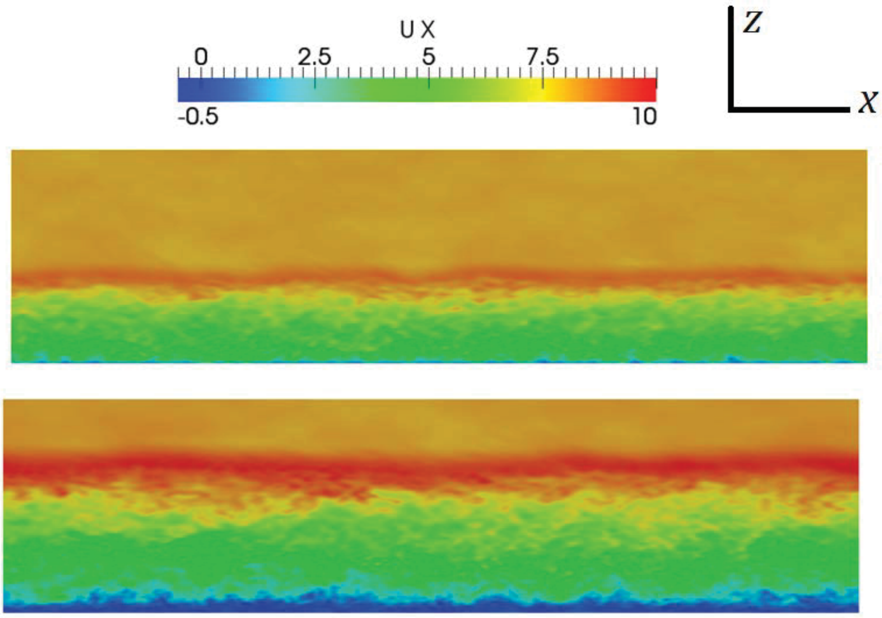
Case-3

Cell size: $\Delta x = \Delta y = 2.5 \text{ m}$, $\Delta z = 0.15 \text{ m to } 2.5 \text{ m}$



Case-3

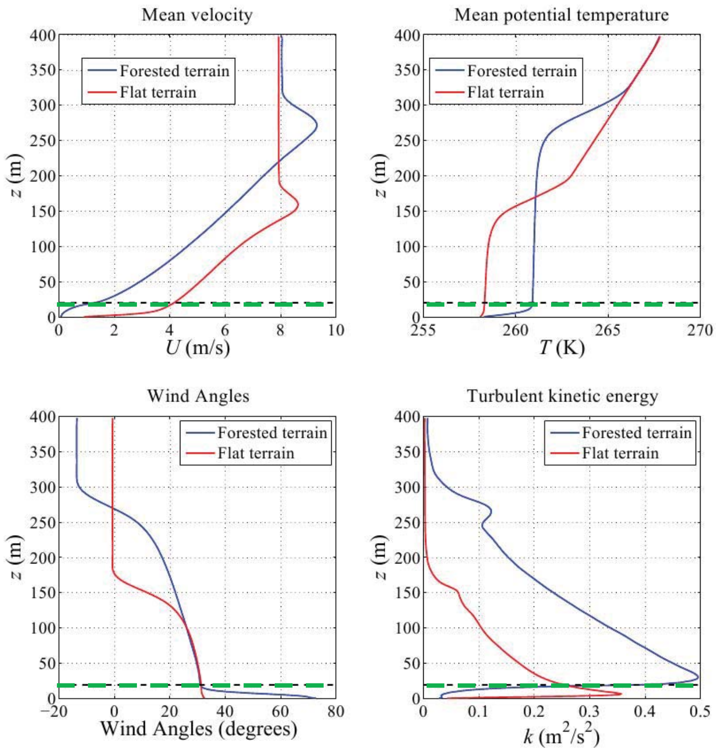
Flat vs forested terrains under SBL



Flat (non-forested) terrain

Forested terrain

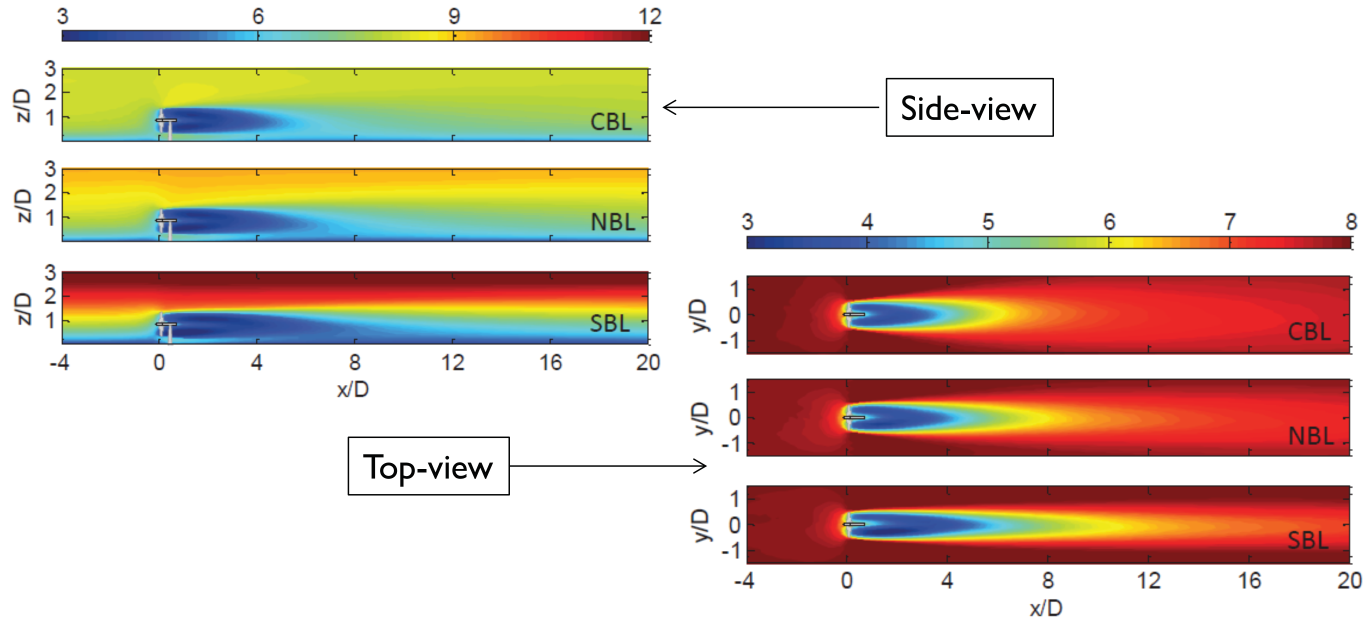
Flat vs forested terrains under SBL



- Forest influences the local stratification a lot
  - decrease the atmospheric stability
  - lift the BL height and the Low-Level Jet (LLJ) by 85%
  - increase the temperature within canopy region
- Forest increases the level of turbulent kinetic energy
  - the peak of the TKE profile is higher by 42% in the case with forest

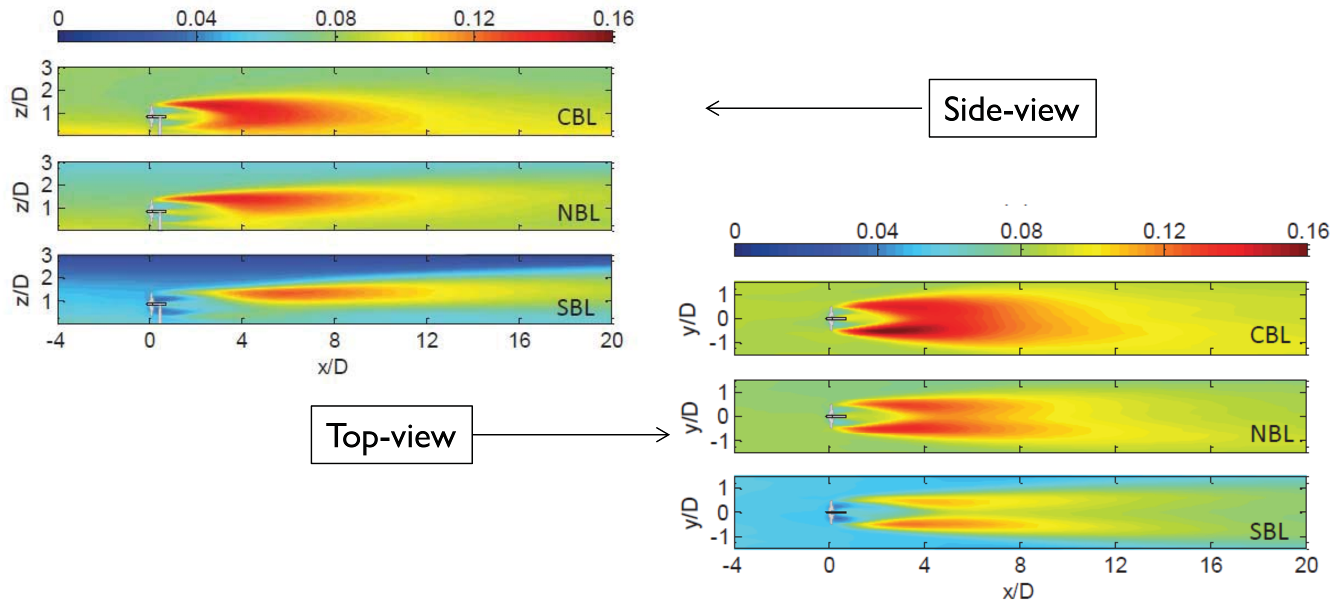
Effect of stratification

- Time-averaged stream-wise velocity $\bar{u}$ (m/s)
- Figures are reproduced from Akbar and Porte´-Agel et al. (2014)



Effect of stratification

- Turbulence intensity
- Figures are reproduced from Akbar and Porte´-Agel et al. (2014)



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1. INTRODUCTION

1.1 On&Off-Shore: installed wind power

1.2 On&Off-Shore technologies

CRIACIV
On- and Off-shore wind turbines:
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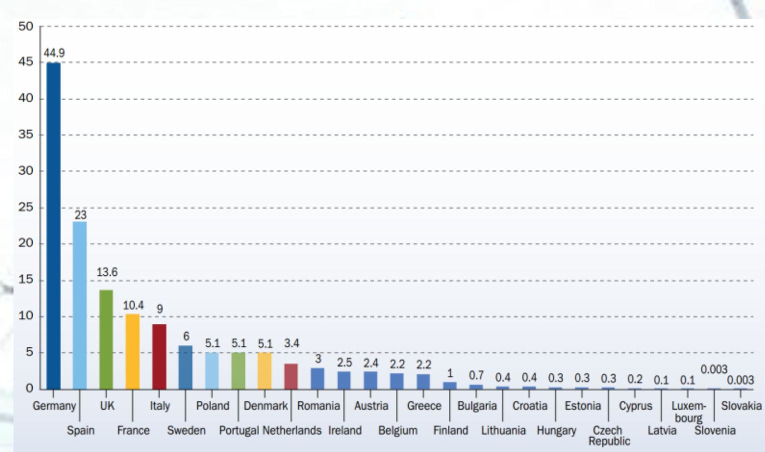
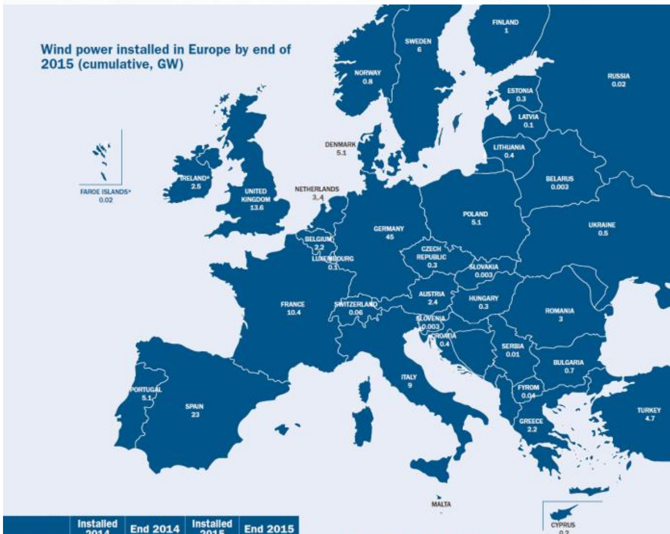
THE WIND ENERGY IN EUROPE



EU member state market shares for total installed capacity (GW). Total 141.6 GW [source: EWEA, 2016]

2nd Training School on "Advances in Wind Energy Technology II" – Chania, Greece, 4-8 April 2016

THE WIND ENERGY IN EUROPE



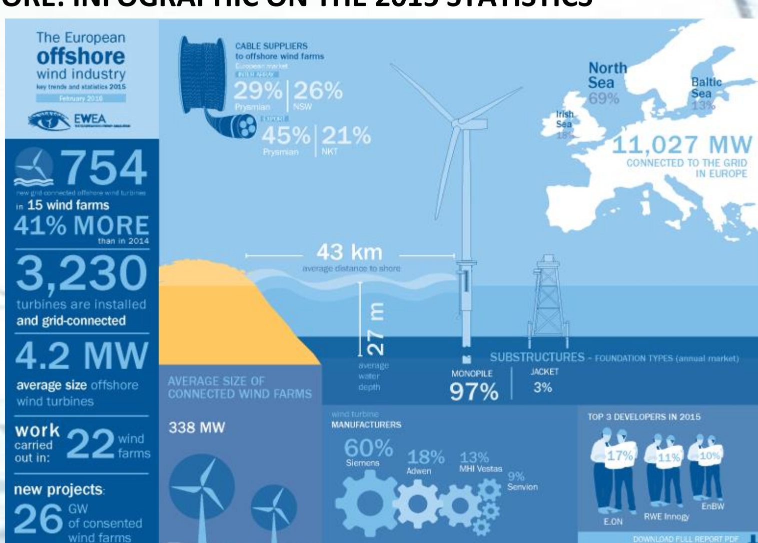
End 2008:

- GERMANY: 23,9 GW
- SPAIN: 3,2 GW
- ITALY:3,74 GW
- FRANCE: 3.40 GW
- UK: 3.2 GW

End 2015:

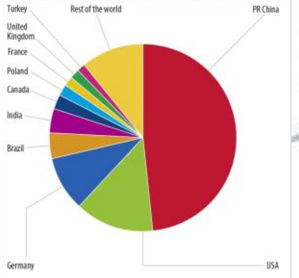
- GERMANY: 45 GW
- SPAIN: 23 GW
- ITALY: 9 GW
- FRANCE: 10.4 GW
- UK: 13.6 GW

OFFSHORE: INFOGRAPHIC ON THE 2015 STATISTICS



OFFSHORE: INSTALLED WIND POWER WORLDWIDE

TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2015

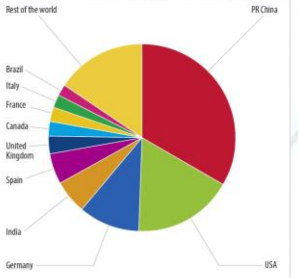


Country	MW	% Share
PR China**	30,500	48.4
USA	8,598	13.6
Germany	6,013	9.5
Brazil	2,754	4.4
India	2,623	4.2
Canada	1,506	2.4
Poland	1,266	2.0
France	1,073	1.7
United Kingdom	975	1.5
Turkey	956	1.5
Rest of the world	6,749	10.7
Total TOP 10	**56,264**	**89**
World Total	**63,013**	**100**

** *Provisional figure*

Source: GWEC

TOP 10 CUMULATIVE CAPACITY DEC 2015



Country	MW	% Share
PR China**	145,104	33.6
USA	74,471	17.2
Germany	44,947	10.4
India	25,088	5.8
Spain	23,025	5.3
United Kingdom	13,603	3.1
Canada	11,200	2.6
France	10,358	2.4
Italy	8,958	2.1
Brazil	8,715	2.0
Rest of the world	66,951	15.5
Total TOP 10	**365,468**	**84.5**
World Total	**432,419**	**100**

** *Provisional figure*

Source: GWEC

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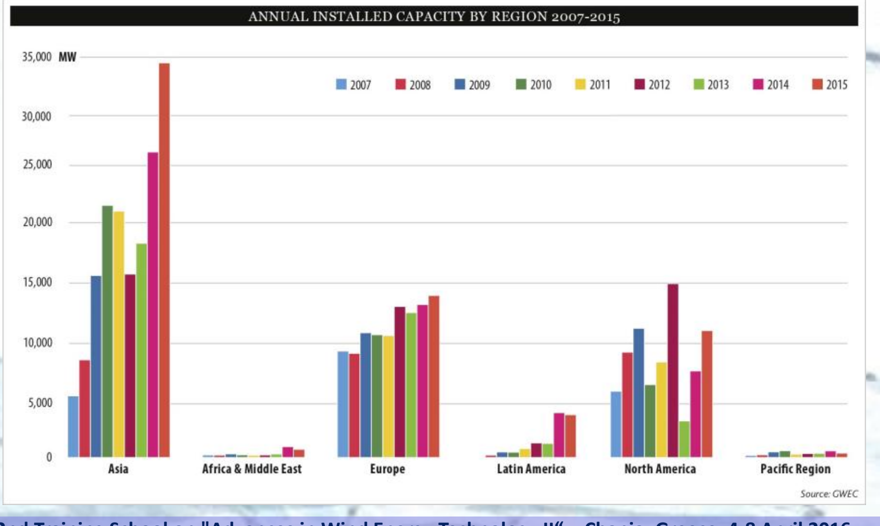
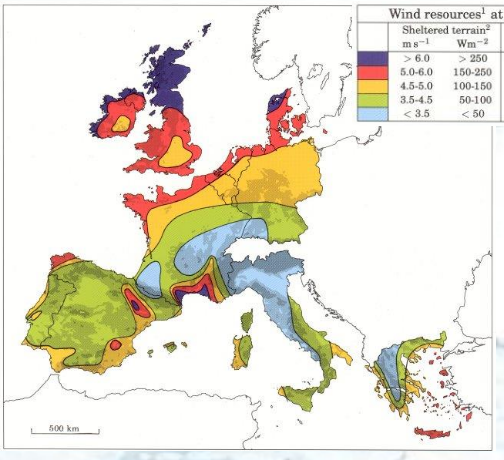
OFFSHORE: INSTALLED WIND POWER WORLDWIDE



POTENTIAL

The European onshore potential

Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(yellow)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
(light blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400



Minimum cost-effective wind speed = 4 m/s

Source: *European Wind Atlas*. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark.

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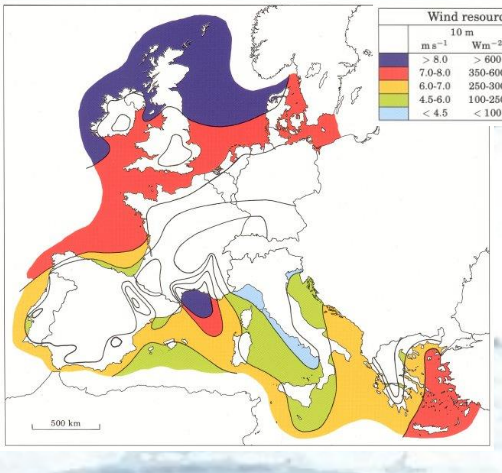
POTENTIAL

The European offshore potential

Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}	$m\,s^{-1}$	Wm^{-2}
(purple)	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
(red)	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
(yellow)	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
(green)	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
(light blue)	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300



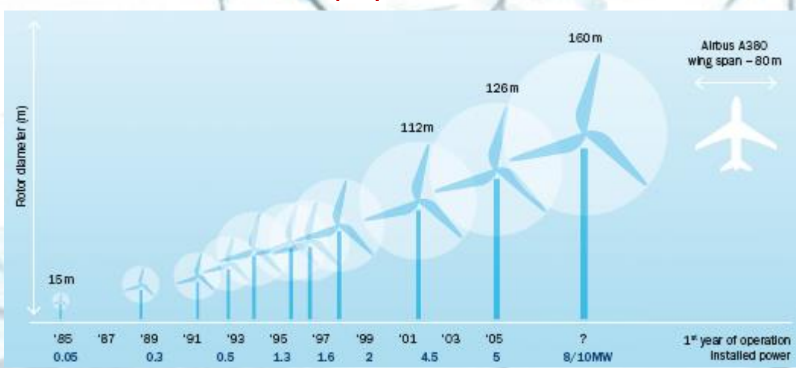
Minimum cost-effective wind speed = 4 m/s

Source: *European Wind Atlas*. Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark.

TECHNOLOGIES

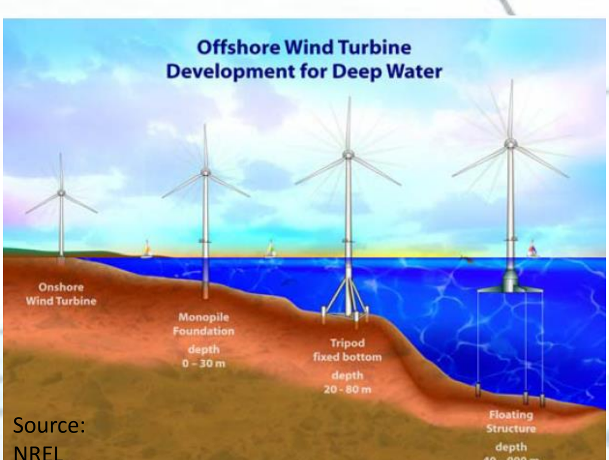
The technological challenge

A (offshore) wind turbine is a very sophisticated system, combination of components and sub-systems that have to be designed in an interdisciplinary and integrated manner. In addition, the size and complexity of wind turbines is increasing rapidly over time:



TECHNOLOGIES

From onshore to the deep ocean



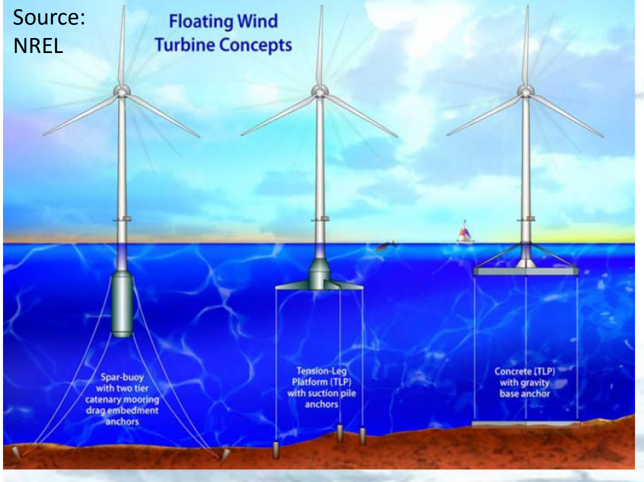
Source:
NREL

- The monopile subsctructure technology is limited to water depth up to 30m.
- w.d. > 30 m = deep water
- Fixed-bottom subsctructure technologies (e.g. tripod) are limited to water depth up to about 80m.
- For w.d. > 40 m floating supports necessary.

TECHNOLOGIES

Several types of floating systems

Source: NREL



The floating technology seems to be the leading solution as deep waters represent a promising resource for many countries, e.g. Italy, US.

This makes fundamental further investigations on the best technology to be adopted!

(See “Blue H” and “Hydro” prototypes)

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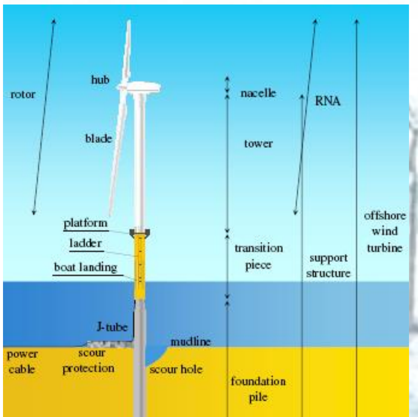
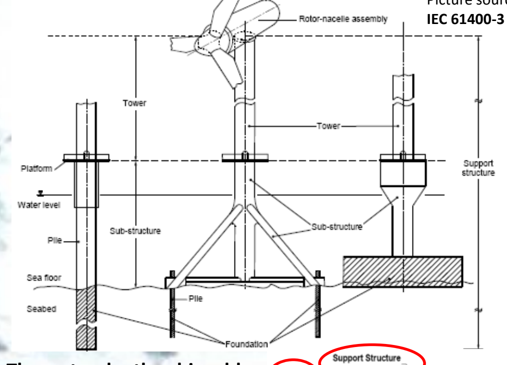
TECHNOLOGIES

OWT Nomenclature

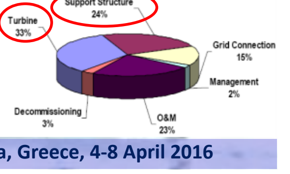


Picture source:
Jan Van Der Tempel, PhD thesis 2006

Picture source:
IEC 61400-3

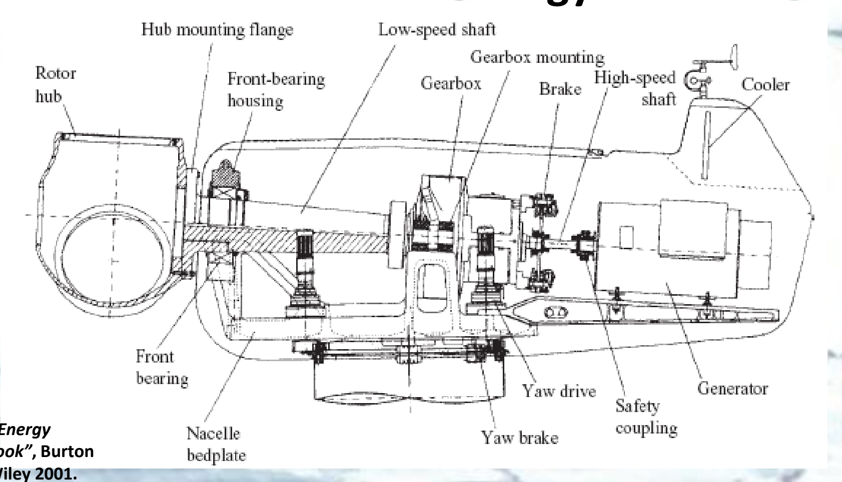


•The water depth achievable depends on the substructure type;
•Substructure is ca 25% of the whole cost!



TECHNOLOGIES

More terminology



Source: ***"Wind Energy Handbook"*, Burton et al. Wiley 2001.**

2. STATIC AND DYNAMIC ANALYSIS

2.1 Site-Classification (an example for Italy)

2.2 Design loads

2.3 Modelling for static and dynamic analysis

2.4 Basic rotor aerodynamics

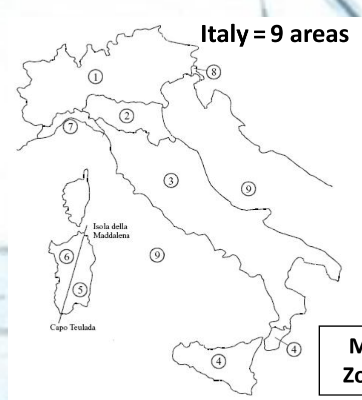
2.5 Vibrations Problems

D.M. 14.01.2008

WIND LOAD

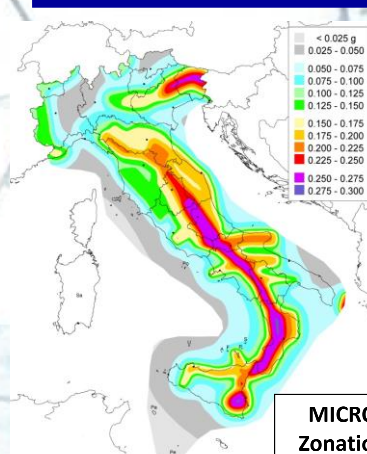
- Basic wind velocity V_b

Italy = 9 areas



MACRO Zonation

EARTHQUAKE LOAD



MICRO Zonation

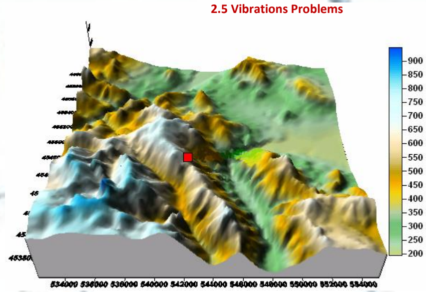
WIND REPORT

- The wind report is based on measurements on site and is based on a reconstruction of the wind velicity field "V_{WR}" in a given site, in particular:
  - Determination of mean wind speed "V_{ave}"
  - Determination of reference wind speed "V_{ref}"
  - Determination of characteristic turbulence intensity for each wind turbine (WT) position
- The design wind reference speed "V_d" is normally given by the wind report value (for all those Legislations which allow the bypassing of the normatives values).

WIND REPORT

WIND REPORT

- Study of the orographic situation of the planned wind farm.



- Measurement system

Mast / height	Sensor (type of installation)	Manufacturer and Type	Measurement height [m]	Serial number	Measurement period
(070)/50m	Anemometer (WS1) (installed on boom)	NRG #40 (calibrated)	50	25629	30.04.2007 to 17.09.2008

- Recorded quantities

Mast / height	Sensor	Slope / Offset	Measuring frequency [Hz]	Averaging period [s]	Recorded quantities
50m	WS1	0.7656 / 0.3544	0,5	600	Mean-, Min- and Max-value as well as standard deviation

Analyses of the measured data

DESIGN WIND SPEED

- The E-82 84/98m WTGS are designed for Class IIA of the IEC 61400, then it is strongly recommended that inside the energy yeld wind report, for the site, a special consideration about the reference wind speed at hub height would take place.

Class IIA (IEC 61400) $V_{m,IEC}$

↓

Check with Italian Code D.M. 14.01.2008 $V_{m,IT}$

Wind report speed V_{WR} → ↓ ← Design wind reference speed V_d

V_d to be checked with $V_{m,IT}$, $V_{m,IEC}$ and V_{WR}

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2.4 Basic rotor aerodynamics
2.5 Vibrations Problems

DESIGN LOADS

Loads sources

Extremely complex and multiphisic environment: *Aero + Hydro + Geo*

Offshore

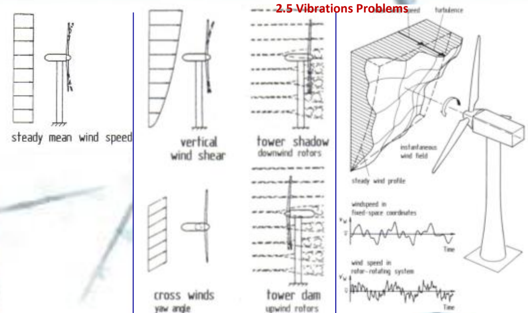
Onshore

- Aerodynamic
- Gravitational
- Inertial
- Operation & Control

Hydrodynamic
Waves
Current
Tides

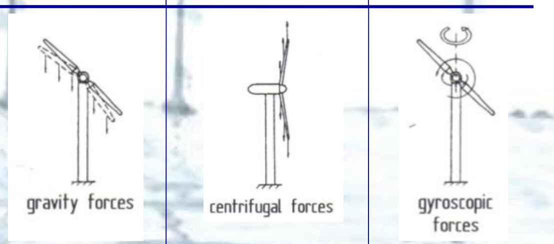
DESIGN LOADS

1. **Aerodynamic loads:**
   - Steady Uniform;
   - Steady Wind Shear
   - (Un)steady Hub Height Wind Velocity
   - Unsteady 3D Full Wind Field:



2. **Inertial loads:**
   - Gravitational;

   (produce 10^7cycles, relevant for FATIGUE!)
   - Centrifugal;
   - Gyroscopic;



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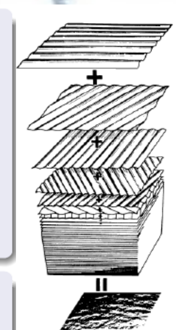
DESIGN LOADS

3. **Hydrodynamic loads:**
   - Waves
   - Currents;
   - Tides

Regular Waves: single harmonic wave:
- Linear Theory (Airy, 1842);
- Stokes' 5th order Theory (Stokes, 1847);

Irregular Waves: superposition of single (linear) waves, by using standard spectra:
- Pierson–Moskowitz (for open sea areas);
- JONSWAP ('68-'69 measurement program into the NS, for coastal wind generated seas);



Source: Pierson et al., 1955.

Morison's equation

$$q(t) = \frac{\pi}{4}\rho C_M D^2 \dot{v}(t) + \frac{1}{2}\rho C_D D v(t)\,|v(t)|$$

Unit-length force on slender cylinder!

4. **Control loads:**
   - Braking; Yawing;
   - Blade-pitch control
   - Loss of grid

A realistic sea is then represented by the superposition of different single-harmonic linear wave!

Drawback: only linear theory can be used!

DESIGN LOADS

Since WTs are sophisticated systems made up of many different components, which in turn are sensitive and exposed to different stress type, it makes sense to identify the:

Design Driver		
Component	Ultimate	Fatigue
Rotor Blades and Hub		•
Drive Train Low-Speed Shaft Gearbox High-Speed Shaft	 • (breaking)	 • •
Nacelle Bedplate Yaw Drive	 • (stiffness) • (breaking)	 •
Tower	• (stiffness, stability)	
Foundation	• (breaking)	

DESIGN LOADS

For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions that the wind turbine may experience, obtained by cobining:

- ***"Normal design situations and appropriate normal or extreme external conditions;***
- ***Fault design situations and appropriate external conditions;***
- ***Transportation, installation and maintenance design situations and appropriate external conditions".*** **IEC61400-1**

Ultimate Loads

- Rupture of Materials
- Structural Stability
- Deformations

Fatigue Loads

Controlling the *Accumulated Damage* during the design lifetime of a WT.
(See details in Annex G, IEC61400-1)

MODELLING FOR STATIC AND DINAMIC ANALYSYS

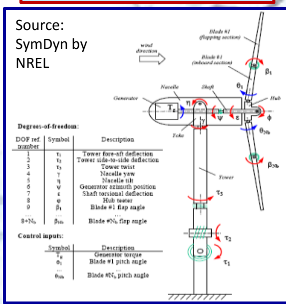
Time-domain simulations are required to calculate loads effects on wind turbines. The following scheme is usually adopted:

PREPROCESSING
- Create model;
- Generate wind, waves, earthquake
- Create Design Load Cases

SIMULATION
- Compute aerodynamic forces
- Compute reaction of elastic structure

POSTPROCESSING
- Determination of extreme loads (sectional forces, moments)
- Determination of fatigue loads

Source: SymDyn by NREL



Multybody simulation with many dof (e.g. 24 dof for 3 blades wind turbine) including both flexible and rigid elements

Used codes:
- Bladed by GH
- FAST by NREL
- etc.

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MODELING PROCEDURE

Wind Data (environmental conditions) → Load Case

Load Case → Wind Input; Aerodynamic Model; Aeroelastic Model; Control System

Wind Input
- Hub Heigh steady
- 3D Full Field

Aerodynamic Model

Aeroelastic Model

Control System

Structural Loading
- load TH
- load spectra
- extreme load

Structural Stresses, Deformations ↔ Component design and manufacturing techniques

Maximum Stresses and stiffness requirements

Safety Factors

Design verifications: strenght & fatigue

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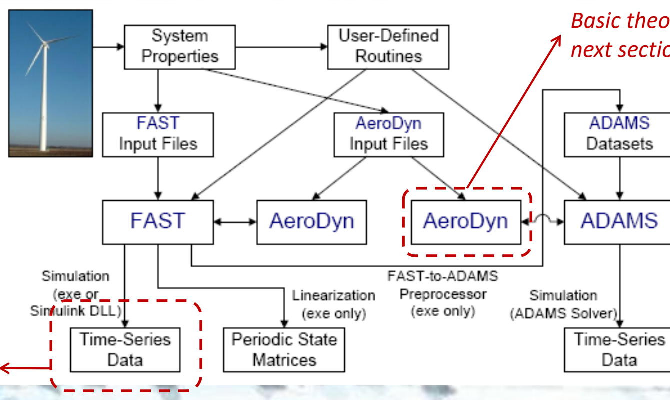
FLOWCHART FOR SOME WT DESIGN CODES BY NREL:

FAST is adopts a combined modal and multibody dynamics formulation.



Basic theory in the next section!

Extraction of internal forces for tower design!!

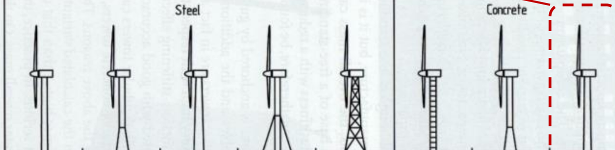
Three main phases

1. **User provides Input Files for solvers: Aerodyn and FAST**
2. **Runing FAST (with callings to Aerodyn)**
3. **Output TD series**

NWTC Design Codes (FAST by Jason Jonkman).
http://wind.nrel.gov/designcodes/simulators/fast

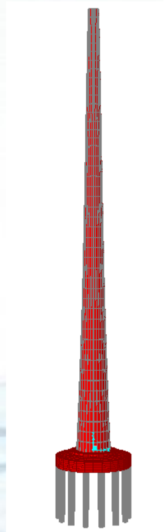
TOWER TYPES COMPARISON

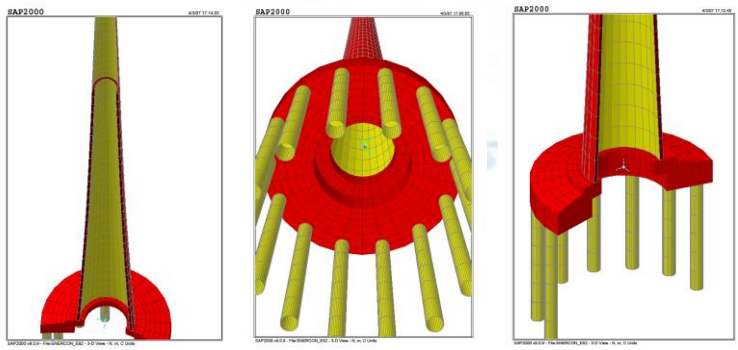
A FE model is showed in the next slide!



Wind Turbine		Steel					Concrete		
Rotor: 3 blade Diameter: 60 m Rotor speed: 23 rpm Towerhead mass: 180 t Hub height: 50 m Tower height: 46.6 m		cylindrical	cylindrical with conical base	conical	cylindrical with guys	lattice	prefabricated prestressed	reinforced	prestressed
1st bending eigenfrequency	Hz	0.567	0.577	0.570	0.551	0.60	0.65	0.941	0.947
Multiple of rated rotor speed	P	1.48	1.51	1.49	1.44	1.57	1.70	2.45	2.47
Upper diameter	m	3.5	3.5	3.5	2.5	3.5	3.5	3.5	3.5
Lower diameter	m	3.5	7.1	4.4	2.5	11.6	3.5	8.4	5.5
Wall thickness	mm	55 +15 staged	25/15 staged	30/15 staged	20/15 staged	16/10	520/250 staged	300	300
Mass									
- Tower structure	t	150	120	111	40	110	465	485	477
- Equipment	t	22	22.5	22.8	20	22.5	21	22.5	22.5
Total mass	t	172	142.5	133.8	60+guys	ca. 120	486	507.5	499.5
Appr. cost relation	%	100	90	85	95	70	60	75	75

CONCRETE TYPE TOW.- NUMERICAL MODELS





FE models of Enercon E82 Hybrid Tower on deep foundation:

- Tower Height = 83.30 m
- Concrete segment length = 57.39 m
- Concrete segment thickness = 30 cm
- Steel segment length = 25.91 m
- Steel segment thickness = 25 mm approx.

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BASIC ROTOR AERODYNAMICS

Axial momentum

Mass Flow Rate conservation

$$\rho A_\infty U_\infty = \rho A_d U_d = \rho A_w U_w$$

Velocity at the Disc

$$U_d = U_\infty(1-a)$$

Axial velocity induction factor

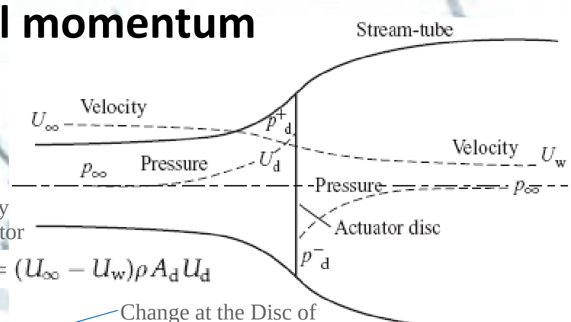
Rate of change of momentum $= (U_\infty - U_w)\rho A_d U_d$

Momentum balance

$$(p_d^+ - p_d^-)A_d = (U_\infty - U_w)\rho A_d U_\infty(1-a)$$

Easily computed by Bernoulli's theorem!

Change at the Disc of the momentum rate!



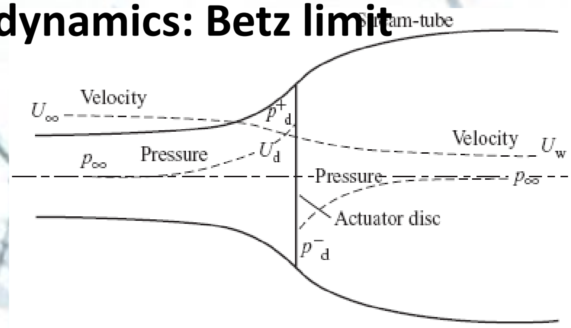
Thus , the Wake velocity is

$$U_w = (1-2a)U_\infty$$

Source: *"Wind Energy Handbook"*, Burton et al. Wiley 2001.

BASIC ROTOR AERODYNAMICS

Rotor Aerodynamics: Betz limit



Resultant Force applied at the Disc

$$F = (p_d^+ - p_d^-)A_d = 2\rho A_d U_\infty^2 a(1-a)$$

$$\text{Power} = FU_d = 2\rho A_d U_\infty^3 a(1-a)^2$$

Power Coefficient

$$\text{Def: } C_P = \frac{\text{Power extracted}}{\text{Power available}}$$

$$C_P = \frac{\text{Power}}{\frac{1}{2}\rho U_\infty^3 A_d} = 4a(1-a)^2$$

Betz limit: ideal value of the maximum Power Coefficient

Maximum energy exploitation

$$\frac{dC_P}{da} = 4(1-a)(1-3a) = 0$$

$$a = \frac{1}{3}$$

$$C_{P_{max}} = \frac{16}{27} = 0.593$$

Source: ***"Wind Energy Handbook"*, Burton et al. Wiley 2001.**

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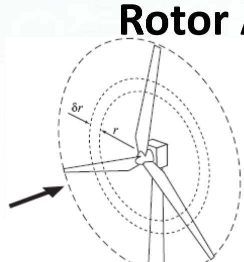
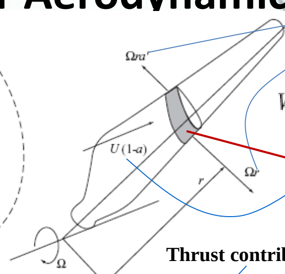
BASIC ROTOR AERODYNAMICS

Rotor Aerodynamics, Lift and Drag





Tangential velocity induction factor

$$W = \sqrt{U_\infty^2(1-a)^2 + \Omega^2 r^2(1+a')^2}$$

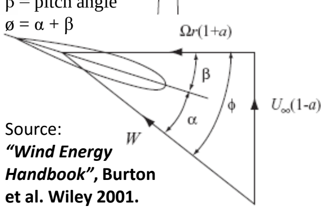
On a span-wise element of lngth δr the DRAG and LIFT forces are:

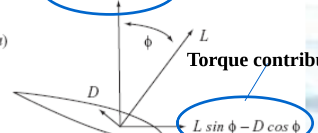
$$\delta D = \frac{1}{2}\rho W^2 c C_d r \delta r$$

$$\delta L = \frac{1}{2}\rho W^2 c C \delta r$$

Thrust contribution

α = angle of attack
β = pitch angle
ø = α + β





Torque contribution

Source: ***"Wind Energy Handbook"*, Burton et al. Wiley 2001.**

BASIC ROTOR AERODYNAMICS

BEM theory: Momentum th. + Drag and Lift

- MOMENTUM

Change of axial mom. Rate:

$$\delta T = 4\pi\rho U_\infty^2 a\ 1-a\ r\delta r$$

Change of ang. mom. rate:

$$\delta M = 4\pi\rho U_\infty\ a'\ \Omega r\ \ 1-a\ r^2\delta r$$

- DRAG AND LIFT

Thrust contribution:

$$\delta T = \frac{1}{2}\rho W^2 N_b\, c\ C_L\ \cos\phi + C_D\ \sin\phi\ \delta r$$

Torque contribution:

$$\delta M = \frac{1}{2}\rho W^2 N_b\, c\ C_L\ \sin\phi - C_D\ \sin\phi\ r\delta r$$

Equating the above equations leads to a set of equations which can be iteratively solved for the induced velocity factors a and a' and forces on each blade element.

NOTE: the above plain BEM needs corrections accounting for tip and hub losses. See leteratue!!

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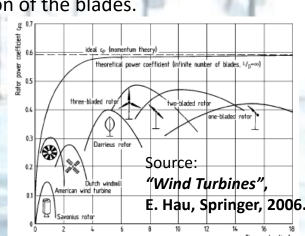
BASIC ROTOR AERODYNAMICS

Rotor performance curve

The BEM allows to compute the total developed torque M, and thus the Power extracted $P = M^*\Omega$, as functions of the Tip Speed Ratio: $\lambda = \frac{U_{tip}}{U_\infty} = \frac{\Omega R}{U_\infty}$

The main parameters dominating the extractible power are:
- number of rotor blades;
- chord length distribution of the blades;
- aerodynamic airfoil characteristics;
- twist variation of the blades.

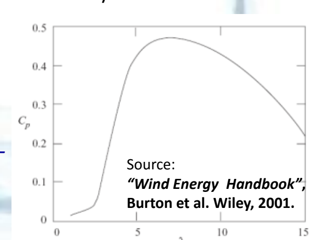
Power coefficients of wind rotors of different designs



Source: *"Wind Turbines"*, E. Hau, Springer, 2006.

The maximum power coefficient occurs at a tip speed ratio for which the axial flow induction factor a, which in general varies with radius, approximates most closely to the Betz limit value of 1/3.

A typical performance curve for a modern, high-speed wind turbine



Source: *"Wind Energy Handbook"*, Burton et al. Wiley, 2001.

VIBRATIONS PROBLEMS

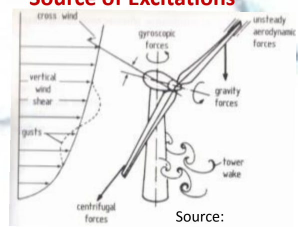
Wind Turbines are made up of slender components which make the system highly prone to VIBRATION PROBLEMS

Aims:
Verify the Dynamic Stability and the Absence of Resonance!

The ROTOR-TOWER system is exposed to self excitation!!

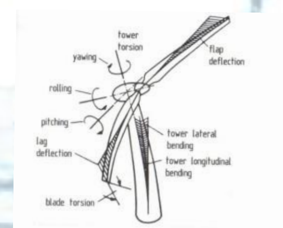
The primary risk is that the 1st natural bending frequency (meant with the tower head mass!) may resonate with the exciting rotor forces!

Source of Excitations



Source: ***"Wind Turbines"***, **E. Hau, Springer 2006.**

DOF excitable



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VIBRATIONS PROBLEMS

The rotor exciting frequencies occur at

- **1P**
- **N_bP**

where P is the rotor rotational frequency and N_b is the number of blades.

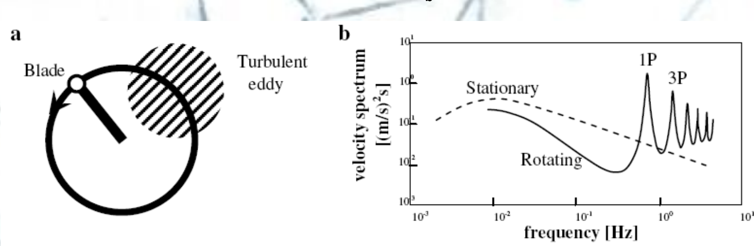


Figure 2.40 a) Blade passing through a turbulent eddy
b) Stationary and rotationally sampled turbulence spectrum

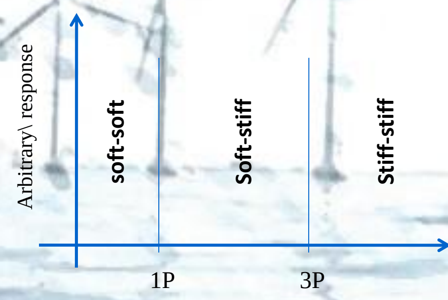
Picture source:
Jan Van Der Tempel, PhD thesis 2006

VIBRATIONS PROBLEMS

Once the rotor exciting frequencies 1P and 3P are known, under any circumstances, the support tower must be designed having the first natural bending freq. close to the critical ones!

As a consequence, only three possibility remain available:

1. **stiff-stiff structure: a very stiff structure with its first natural frequency above 3P;**
2. **soft-stiff structure: when the first natural frequency falls between 1P and 3P;**
3. **soft-soft structure: if a very soft structure with its first natural frequency below 1P.**



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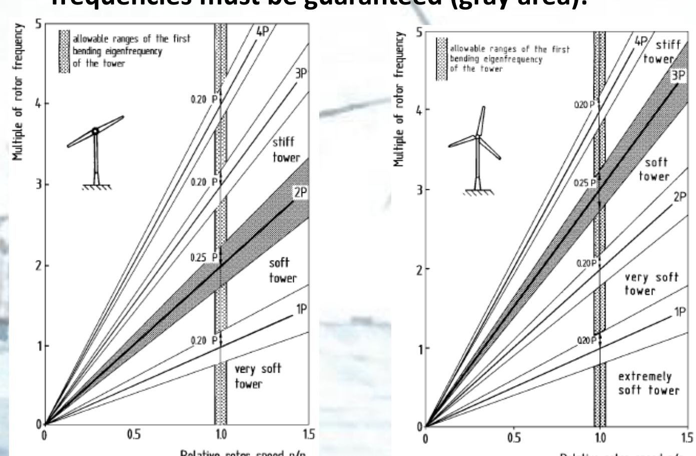
VIBRATIONS PROBLEMS

Moreover, a certain distance from the resonating frequencies must be guaranteed (gray area):

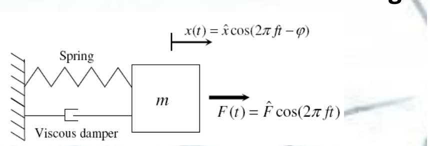


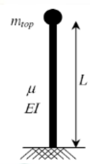
Source: *"Wind Turbines"*, E. Hau, Springer 2006.

VIBRATIONS PROBLEMS

The position of the tower first natural bending frequency characterize the design!

Idealized System

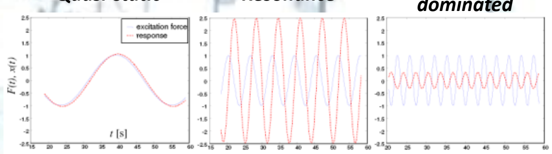




WT simplified 1 DOF model

System Response

Quasi-static ***Resonance*** ***Inertia-dominated***



Approximation for the first natural bending frequency

$$f_{nat}^2 \cong \frac{3.04}{4\pi^2}\frac{EI}{(m_{top}+0.227\mu L)L^3}$$

Pictures source:
Jan Van Der Tempel, PhD thesis 2006

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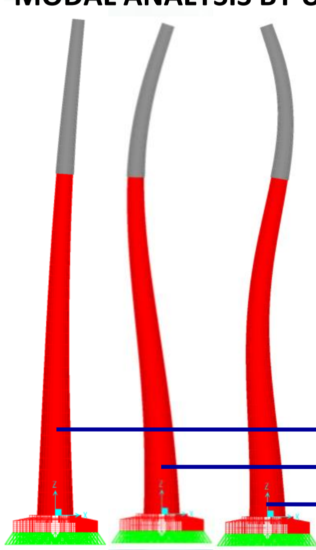
MODAL ANALYSIS BY USING FE



The dynamical features of the tower can be better captured by a proper FE model.
In a first and more approximate model, frame elements can be used. Further aspects, like local buckling, local stress concentration (doors, etc.) can be investigated by employing adequate shell elements.

On the left, the first three mode shapes obtained with a FE model with shell elements

- The model can capture the real mass distribution of an hybrid concrete-steel tower ENERCON E82 (83.3 m height).
- Of course, the modal analysis is carried out with the tower head mass (Rotor + nacell!)

1st natural bending frequency
2nd natural bending frequency
3rd natural bending frequency

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WHAT DIBt STATES ABOUT VIBRATIONS

$$\frac{f_R}{f_{0,1}} \leq 0{,}95$$

$$\frac{f_{R,m}}{f_{0,n}} \leq 0{,}95 \quad \text{oder} \quad \frac{f_{R,m}}{f_{0,n}} \geq 1{,}05$$

Where:

- $\boldsymbol{f}_{R}$: Rotational frequency of the rotor in the normal operating range;
- $\boldsymbol{f}_{0,1}$ first natural frequency of the tower;
- $\boldsymbol{f}_{R,m}$ blade passing frequency for a m blades rotor;
- $\boldsymbol{f}_{0,n}$ eigenfrequency of the tower.

The number **n** of the natural frequencies to be determined must be at least large enough so that the highest calculated natural frequency is at least 20% higher than the blade passing frequency!

3. DESIGN AND VERIFICATION

3.1 IEC 61400

3.2 Euro Codes / DM 2008

3.3 Towered support

3.4 Foundations

3.5 Soil-structure Interaction

(with the contribution of Ing. M. L. Pecora)

The IEC 61400-1 (2005)

International Electrotechnical Commission

IEC 61400-1:2005 WIND TURBINES
Part 1: **Design requirements**

- This part of IEC 61400 specifies essential design requirements to ensure the engineering integrity of wind turbines.
- Wind turbines are subject to environmental and electrical conditions. Wind conditions are the primary external conditions affecting structural integrity.

The IEC 61400-1 (2005)

IEC **International Electrotechnical Commission**

IEC 61400-1:2005 WIND TURBINES
Part 1: **Design requirements**

- This standard is concerned with all subsystems of wind turbines such as control and protection mechanism, internal electrical systems, mechanical systems and support structures.

- This standard requires the use of a structural dynamics model to predict design loads: wind + other environmental conditions.

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WIND TURBINE CLASSES

- **Wind turbine classes are defined in terms of wind speed and turbulence parameters of the installation site.**

NORMAL Safety Class

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

SPECIAL Safety Class

- **A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class.**

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WIND CONDITIONS

NORMAL wind conditions

- **Frequently conditions loads**
- **NWP (Normal Wind Profile model)**

$$V(z) = V_{hub}\,(z/z_{hub})^{0.2}$$

V_{hub} = wind speed at hub height

z_{hub} = hub height of the wind turbine

EXTREME wind conditions

- **1 or 50-year recurrence period**
- **EWM (Extreme Wind speed Model)**

$$V_{e50}(z) = 1.4V_{ref}\,(z/z_{hub})^{0.11}$$

$$V_{e1}(z) = 0.8V_{e50}\,(z)$$

V_{ref} = reference wind speed

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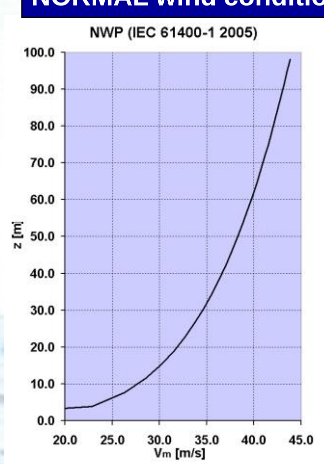
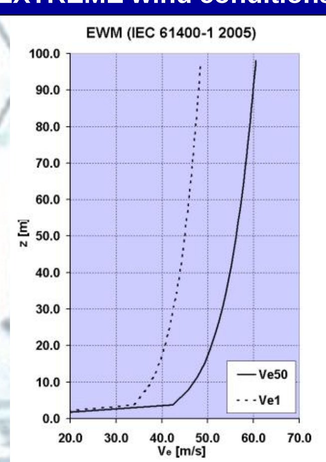
WIND CONDITIONS

NORMAL wind conditions



EXTREME wind conditions



ENVIRONMENTAL CONDITIONS

- **Environmental conditions other than wind can effect the integrity and safety of wind turbines, moreover combinations of climatic conditions may increase their effects.**
  - **Temperature**
  - **Humidity**
  - **Air density**
  - **Solar radiation**
  - **Rain, hail, snow and ice**
  - **Chemically active substances**
  - **Mechanically active particles**
  - **Salinity**
  - **Lightning**
  - **Earthquakes**

The earthquake loading shall be superimposed with wind loading

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DESIGN LOAD CASES

- **For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions: normal, extreme and failure or damage to the machine.**

- **For each design load case:**

Type of analysis

U = ultimate limit state — **F = fatigue failure**

Partial safety factors (for U):

- **N** Normal
- **A** Abnormal
- **T** Transport and erection

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DESIGN LOAD CASES

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N

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DESIGN LOAD CASES

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year recurrence period		U	N
	6.2	EWM 50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM 1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM 1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM V_{maint} to be stated by the manufacturer		U	T
	8.2	EWM 1-year recurrence period		U	A

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PARTIAL SAFETY FACTORS

- **The type of design situation, N, A, or T, determines the partial safety factor γ_f to be applied to the ultimate loads.**

Unfavourable loads			Favourable loads
Type of design situation			All design situations
N	A	T	
1.35	1.1	1.5	0.9

- **The partial safety factor for fatigue loads shall be 1.0 (N, A).**

- "Use of the partial safety factors for loads for normal and abnormal design situations requires that the load calculation model is validated by load measurements. These measurements shall be made on a wind turbine that is similar to the wind turbine design under consideration with respect to aerodynamics, control and dynamic response".

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WIND LOAD - EC1/DM2008

Site identification

- **Basic wind velocity V_b**

$V_b = f$(altitude; zone)

Italy = 9 areas

Defining wind profile

- **Terrain Roughness class**
- **Exposure parameters**

→ $k_r \quad z_0 \quad z_{min}$

- **Height above ground: z**
- **Orography factor: C_t**

$$V_m(z) = k_r C_t \ln(z/z_0) V_R(T_R)$$

$$V_R(T_R) = \alpha_R V_b \qquad \alpha_R = f(T_R)$$

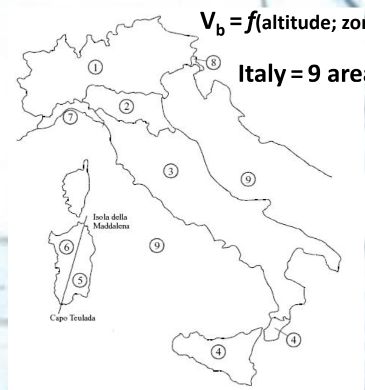
WIND LOAD - EC1/DM2008

Site identification

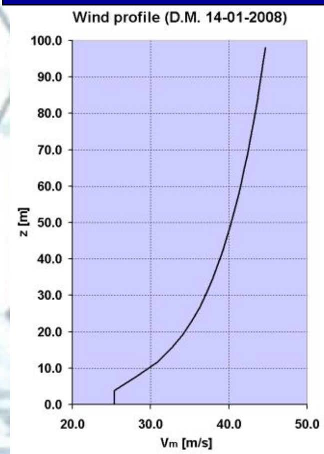
- **Basic wind velocity V_b**

$V_b = f$(altitude; zone)

Italy = 9 areas



Defining wind profile



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WIND LOAD - Normative framework

- **In Italy it is possible to design with a different reference speed if more reliable data, for the specific site, is available based on a measurement campaign.**

Class IIA (IEC 61400) $V_{m,IEC}$ → Design wind speed V_d

↓

Check with Italian Code D.M. 14.01.2008 $V_{m,IT}$ → Wind report speed V_{WR} ↓ **OK if $V_d \geq V_{WR}$**

If $V_d \geq V_{m,IT}$ ↓ **OK**

If $V_d < V_{m,IT}$ ↓ **NO**

No Wind report available

WIND LOAD - Normative framework

- Consider a site in "**Zone 3**" set at **770 m** above sea level with **roughness class "D"** and **C_t=1**, gives the following values for the average wind speed at hub height of the E-82 WTGS (84.3m):

	$V_m(84.3)$ [m/s]
D.M. 14.01.2008	43.68
UNI EN 1991-1-4	43.68
IEC 61400 (class IIA)	42.50

⬇

$V_d \geq 43.68$ m/s

\+ **$V_d \geq V_{WR}$**

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EARTHQUAKE LOAD - EC8/DM2008

- **For the definition of the seismic action, the new Italian Code (D.M. 14.01.2008) has many differences compared to Euro Codes and old Italian Codes.**

	UNI EN 1998-1	D.M. 14.01.2008
ULS	ULS (T_R = 475)	SLV (T_R = 475)
		SLC (T_R = 975)
SLS	DLS (T_R = 95)	SLO (T_R = 30)
		SLD (T_R = 50)
Ground Types	A B C D E S_1 S_2	
Spectral parameters	a_g (National Annex)	a_g, F_0, T_C^*
Site map	MICRO zonation	MICRO zonation

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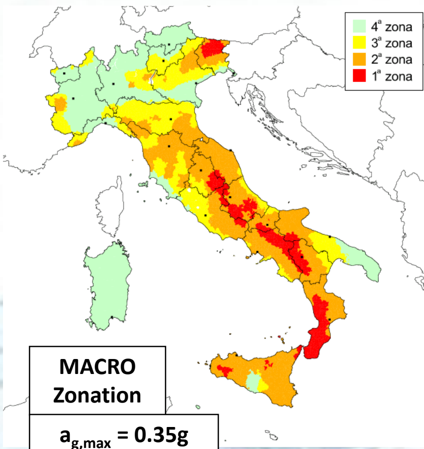
EARTHQUAKE LOAD - EC8/DM2008

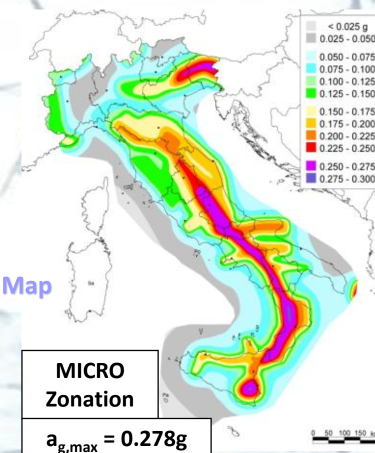
Old Italian Codes | **D.M. 14.01.2008**



MACRO Zonation

$a_{g,max}$ = 0.35g

Site Map



MICRO Zonation

$a_{g,max}$ = 0.278g

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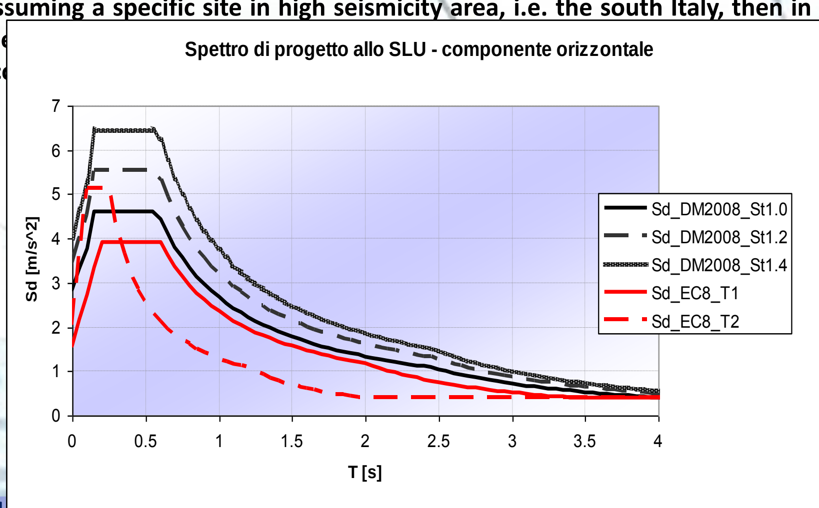
EARTHQUAKE LOAD - EC8/DM2008

- Assuming a specific site in high seismicity area, i.e. the south Italy, then in the ac



THE ENERCON E-82

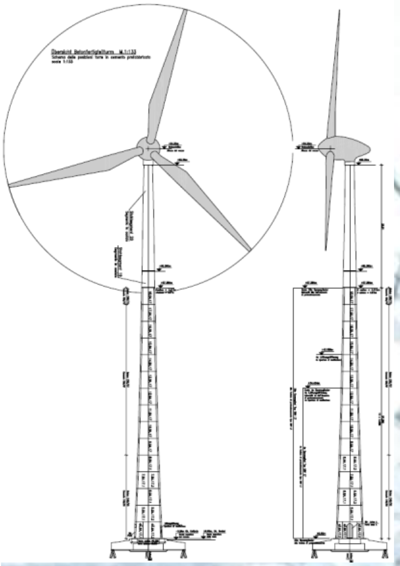
ROTOR
Rated power: 2.000kW
Rotor diameter : 82m
Hub height: 78 - 138m

TOWER
In Italy E-82 are supported by mixed steel-prestressed R.C. towers (hub heights of 84m and 98m)

FOUNDATIONS
The foundations are made by means of monolithic concrete block.
The circular can be built in 3 different configurations:

- **Direct foundations without buoyancy (d = 14.2m);**
- **Direct foundations with buoyancy (d = 16.8m);**
- **Piled foundations (12-16 piles ø=1-1.2m, d=15.6-15.8m)**

THE ENERCON E-82



STEEL PART:
2 segments: 3m + 22.910m (84m WTG)
2 segments: 3m + 25.232m (98m WTG)
Top diameter: 2.00 m

CONCRETE PART:
<u>84m WTG</u>
15 segments, up to 57.390m
3 preassembled half segments
Outer base diameter: 6.369m
<u>98m WTG</u>
18 segments, up to 68.838m
6 preassembled half segments
Outer base diameter: 7.500m

THE ENERCON E-82

- **Concrete tower is prestressed with 32 or 36 strands, dipending on the performance requirements, anchored below the foundation crown (bottom) and at the base of the first steel segment (top).**
- **Segments are built with high strength concrete, from C45/55 up to C70/85.**
- **Concrete thickness is constant for all segments (30 cm), excepting the upper one, varying from 30 cm to 36 cm.**
- **The material qualification follows the common rules as for the usual building construction, even if the production is prefabricated (and in quality control).**

DESIGN AND VERIFICATION

- **The design and verification of the E-82 wind turbines structures have been made according to the new Italian Code (D.M. 14.01.2008) and the Euro Codes.**
- **The criterion adopted was first to meet the requirements of Italian Code, following the Eurocodes requirements when the first lacks of information.**

Towered support design

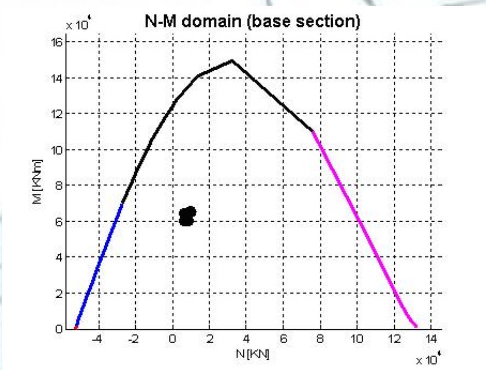
Foundations design

- **Main actions on the towered support and on the foundations:**
- **DEAD WEIGHT - ROTOR - WIND - EARTHQUAKE - TEMPERATURE**

CONCRETE AT ULS

Stresses induced by Normal and Bending actions

- **The resistance domain of each of the sections examined is traced with reference to actual coordinate couples N-M obtained from the results.**



- **Main loads:**
  WIND and/or EARTHQUAKE
- **Verification:**
  CONCRETE and PRESTRESSING STRANDS

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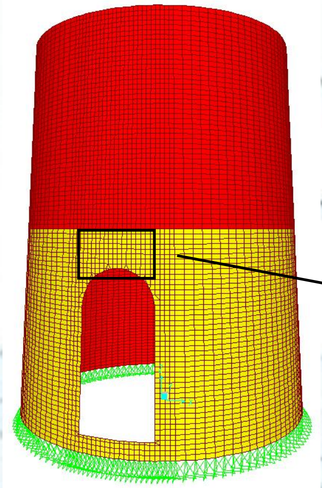
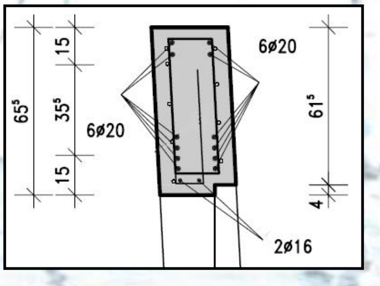
CONCRETE AT ULS – (base segment)



- **For the first segment a FEM model with shell elements has been built.**
- **This detailed analysis allowed the design of minimum steel reinforcement to insert in the lintel of the door.**



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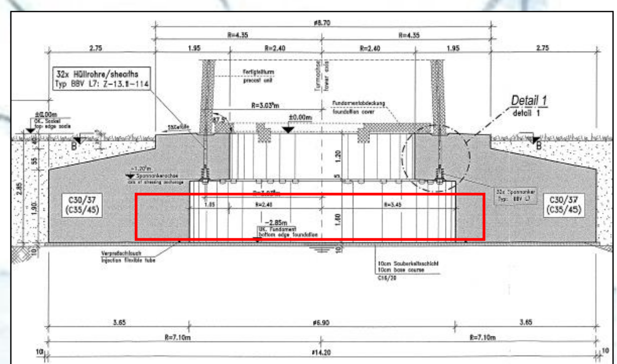
FOUNDATIONS

The foundations are made by means of a monolithic concrete block, built in 3 different configurations:

- **Direct foundations without buoyancy** (diameter = 14.2 m);



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FOUNDATIONS MODELING

FE - Model

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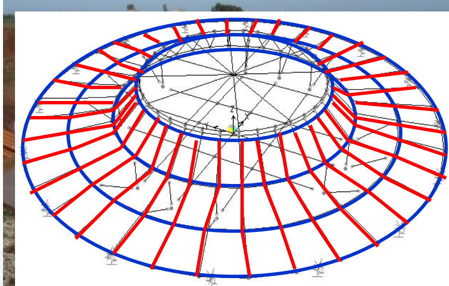
FOUNDATIONS MODELING

FE - Model

- Frame elements – 3D frame



RING   RADIAL

Actions

- The foundations actions must meet the following conditions according to D.M. 14.01.2008:

$E_{Ed} = R_{Ed}$ (overhanging elements)

$E_{Ed} \leq E_E(q=1)$

$E_{Ed} \leq \gamma_{Rd}\ E_E$

γ_{Rd} = 1 CD"B"
= 1.3 CD"A"

VERIFICATION

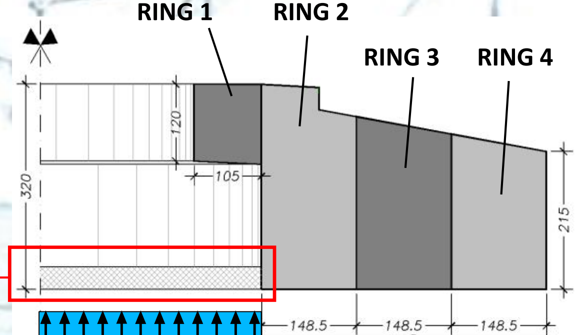
- For the foundations with buoyancy:

Concrete slab verification → Hydrostatic thrust

↓

- Calculation according to the shell theory

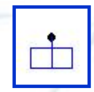
Concrete slab



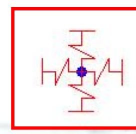
SOIL-STRUCTURE INTERACTION

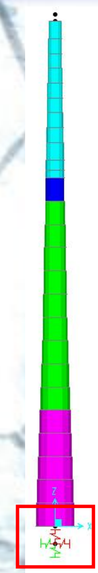
Base Constraints

- **Rigid bond** → **JOINT FULL RESTRAINT**



- **Elastic bond** → **JOINT SPRINGS**





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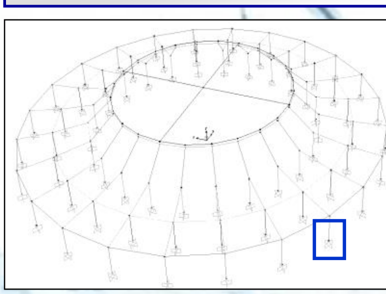
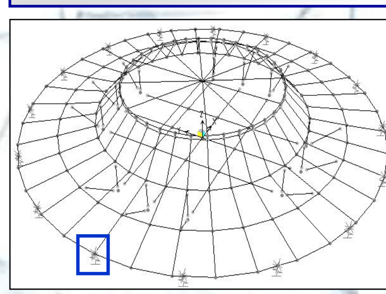
SOIL-STRUCTURE INTERACTION

Basic Constraints

Direct foundations	Piled foundations





The Winkler bed springs	12-16 piled = 12-16 joint springs
K_{vert} = 3000 – 21000 kN/m^3	$K_{vert} = K_{piled}$ = 1.85*10^7 kN/m

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4. CONSTRUCTION & ERECTION

The construction phase, for such a tower, are quite different from the ones of a steel tower.

The prestressing system leads to a different approach to the construction process.

The foundation system is provided by the manufacturer which has to continuously check the respect of the tolerances and the well execution before to install the tower. It contains the active devices for the prestressing system.

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Construction & Erection

In order to increase the bearing capacity of the whole foundation, the same can be installed over a group of piles having a specified length in dependence of the soil properties.

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Construction & Erection

The foundation block is built around the internal shuttering

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Construction & Erection

The foundation block is built around the internal shuttering

Then the external shuttering is placed

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Construction & Erection

The foundation block is built around the internal shuttering

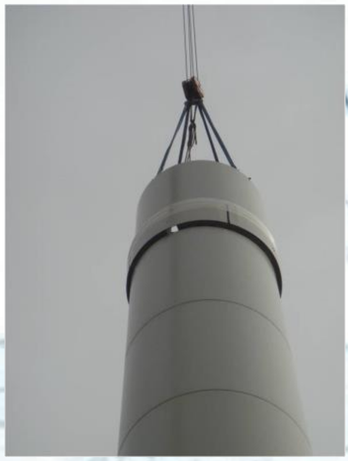
Then the external shuttering is placed

The block is ready for the embankment and the following erection

Construction & Erection

Segments are then installed by placing between them a layer of special mortar with an high tensile strength.

Construction & Erection



During the erection phase no prestressing forces are acting on the tower. The tower self sustains only by the own dead weight and the special mortar which is able to absorb traction forces.

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After the erection of the first 3m steel segment, prestressing cables are inserted from the top of the tower.

The first steel segment include at its base the special devices for the anchorage of cables.

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Construction & Erection

Finally cables can be prestressed and the tower reaches the required configuration able to receive the last steel segment and the rotor.

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The second and final steel segment is joined by means of a bolted connection.

A flange on the top allows to install the machine.

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Construction & Erection

After installing the machine house, the generator has to be erected in front of it.

Construction & Erection

Before the erection the rotor has to be assembled at ground.

Construction & Erection

At the end of the process the rotor can be installed in front of the generator by means of a 105 m tall crane.

Monitoring & Testing Techniques: Checking large structures by using coherent radar

By the courtesy of M. Pieraccini, M. Fratini and F. Parrini, DET, Univ. of Florence

INTRODUCTION

1. The estimation of dynamic characteristics of LARGE structures is based on the measurement of the oscillations induced by artificial or natural (wind, vehicular traffic, etc.) excitations on the structure itself. Traditionally, the mostly employed technique is based on the use of a set of accelerometers placed on the structure. They are only able to detect the acceleration at given points in one or more directions.
2. However, in a lot of situations, this method can result in a complex implementation as it is necessary to install the sensors directly on the structure, often in unreachable places, and then to collect the information using a transmission cabled network.
3. All of these operations can become very complex especially in the case of structures with limited accessibility (for example towers or chimneys). Furthermore in some cases, the structures need to be put out of service.
4. The interferometric sensor, developed in a collaboration between IDS and DET, overcomes many of these problems of the conventional sensors.

Interferometric radar:

electromagnetic sensor for measuring the static and dynamic deformations of large structures (bridges, towers, buildings..)

Università di Firenze, Dip.to di Elettronica

IDS SpA

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Interferometric radar:

The prototype of interferometric sensor employed for structural monitoring and tests (see Fig. 1) is a portable device (weight 12 Kg) which is temporarily installed, over a tripod, near the structure under test.

The compact overall size and the decomposability of the main components are important features that enables the instrument to be a true portable equipment.

Its physical aspect is very similar to a camcorder but it is able to record the scenario and to measure the radial displacements of all the objects lying/ standing in its view cone.

Fig. 1 - Prototipo Sensore Interferometrico (*IDS S.p.A*)

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Interferometric radar:

The instrument is power supplied by a battery pack which enables the user to operate continuously for a maximum of 5 – 6 hours. The system is controlled by software installed in a PC whose hard disk is used to store all the acquired data. The instrument is connected to the notebook through a USB 2.0 link.

System performances depend on the selected configuration but on the operating conditions too. However, generally speaking, the instrument can be used to measure displacements of objects within a maximum distance of 2km, with an high accuracy (less than 0.1 mm) and a selectable sampling frequency between 10Hz and 100Hz.

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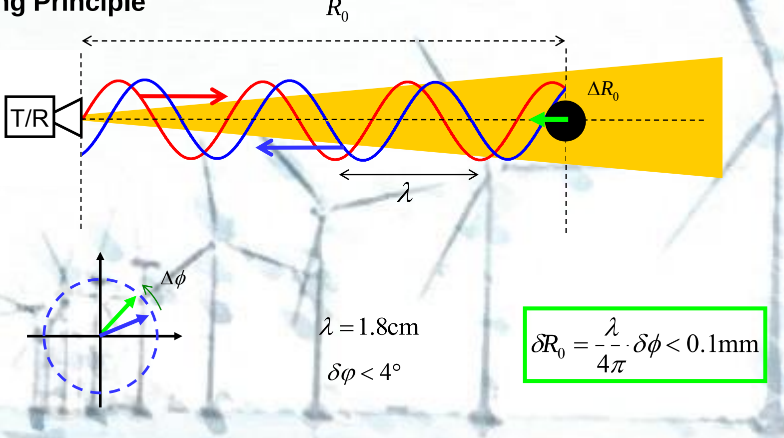
Working Principle



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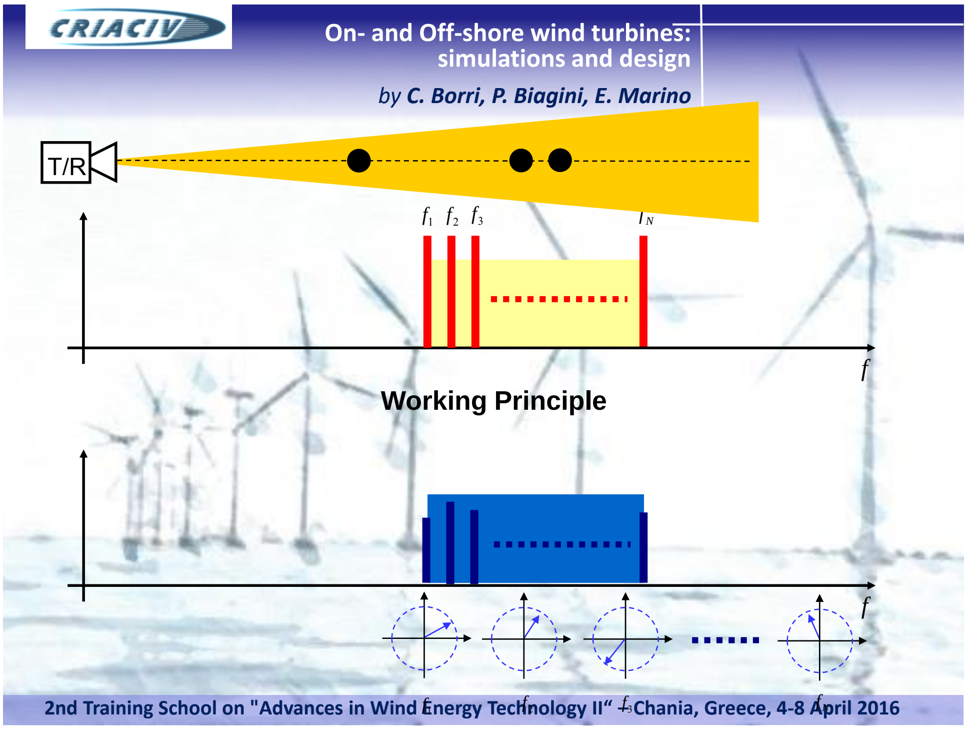
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T/R
f1 f2 f3
fN
f
Working Principle
f
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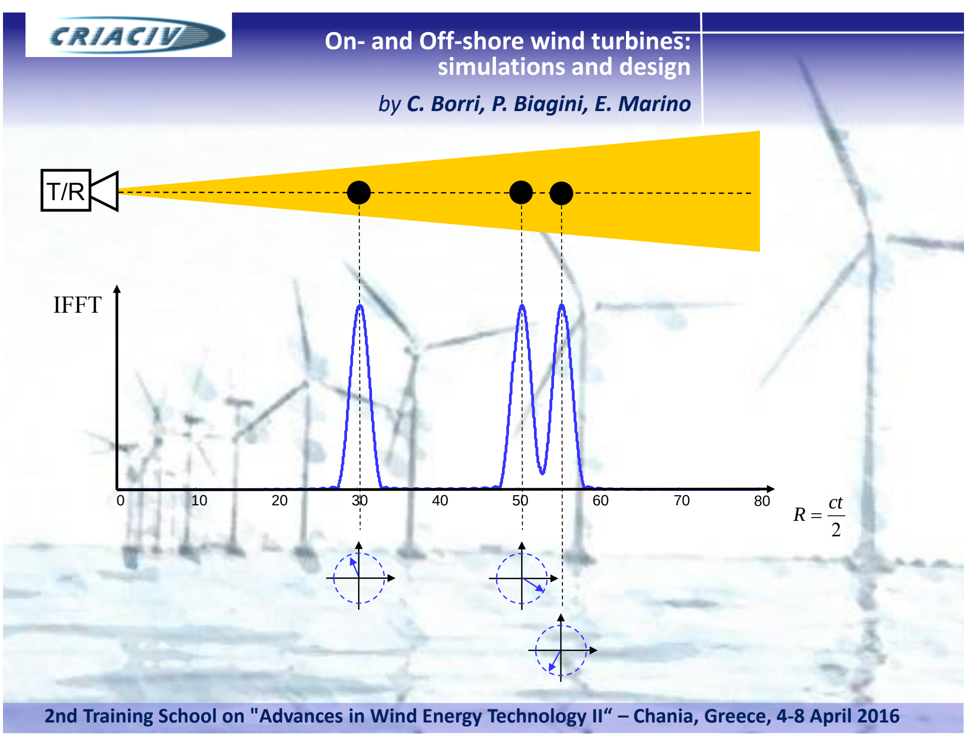
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T/R
IFFT
0
10
20
30
40
50
60
70
80
R = ct/2
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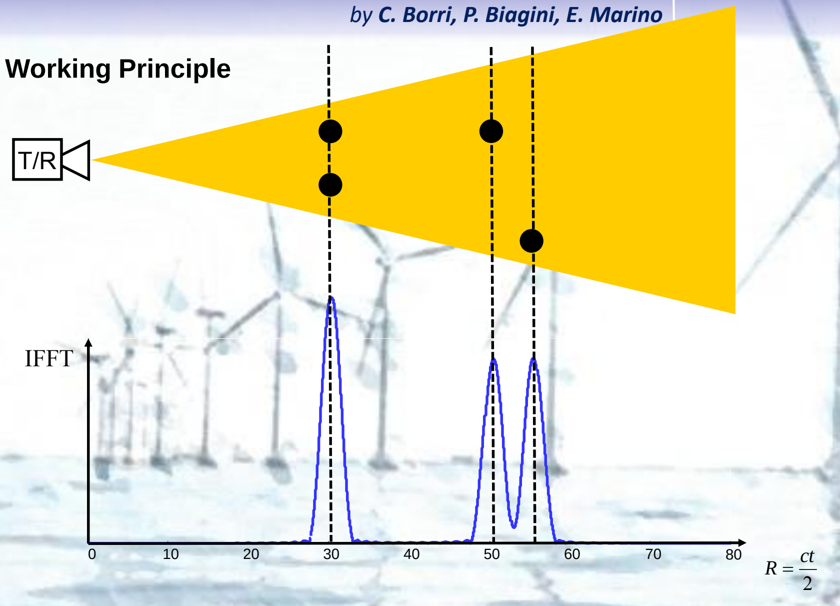
Working Principle



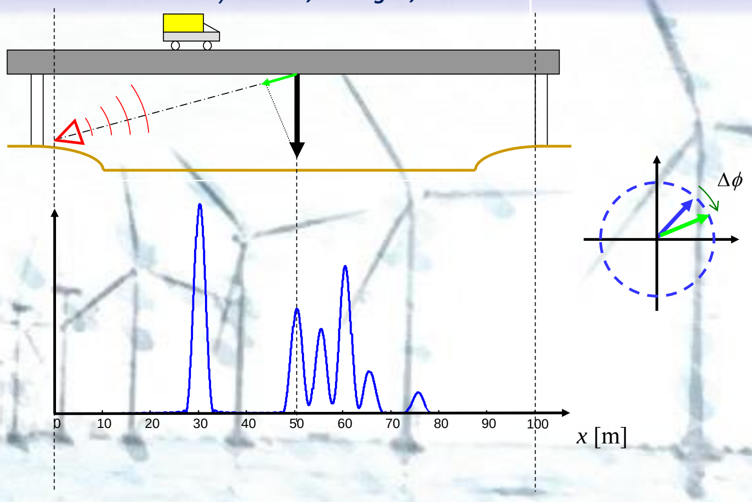
Sampling time: 50ms
Number of frequencies: 1000 → Commutation time: **50μs**

Operation distance: up to 2Km

Range resolution: **40cm**

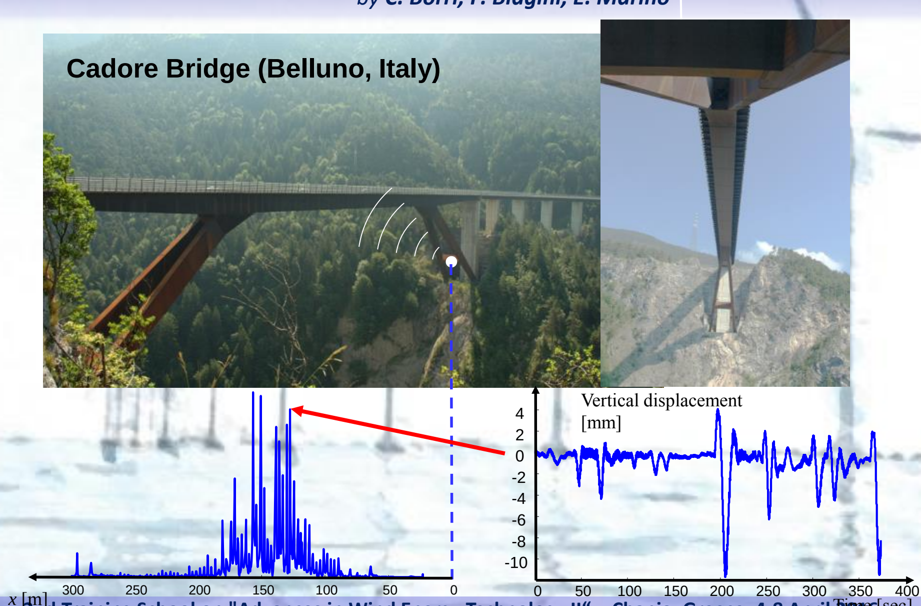
Sampling frequency: **10-100Hz**

The instrumentation



Measurement set-up for horizontal structures (bridges)

On- and Off-shore wind turbines:
simulations and design
by C. Borri, P. Biagini, E. Marino



2nd Training School on "Advances in Wind Energy Technology II" – Chania, Greece, 4-8 April 2016

Final dynamic check-up (Collaudo dinamico) of the wind farms of in Southern Italy (2008)

Dynamic identification tests via

experimental radar interferometric sensor

On- and Off-shore wind turbines:
simulations and design
by C. Borri, P. Biagini, E. Marino

MEASUREMENTS ON 2MW WIND TURBINES

OF 84/98M HEIGHT (ROTOR DIAMETER: 82M)

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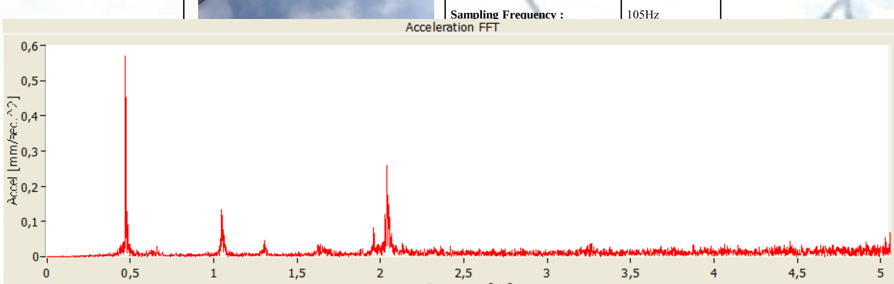
SERRACAPRIOLA – TOWER 5

Serracapriola – Tower 5 / Torre 5		
Fig. 3-5 - Interferometer View / Vista dall'interferometro 	Interferometer Distance : Distanza Interferometro :	8m
	Sampling Frequency : Frequenza di campionamento :	105Hz
	Starting Date and Time : Data e Ora avvio misura :	01/04/2008 10:07
	Wind Conditions : Condizioni del vento :	Slight Wind Vento debole
	Turbine Conditions : Condizioni della Turbina :	Free Rotor Rotore Libero
	Oscillation Frequencies : Frequenze di Oscillazione :	0,47Hz 1,05Hz 1,31Hz 1,96Hz 2,04Hz
Fig. 3-6 – Acceleration Spectrum / Spettro accelerazione		
Note : The shown acceleration spectrum is related to a tower section at an altitude of 36,5m		

On- and Off-shore wind turbines:
simulations and design
by C. Borri, P. Biagini, E. Marino

SERRACAPRIOLA – TOWER 5

Serracapriola – Tower 5 / Torre 5
Fig. 3-5 - Interferometer View / Vista dall'interferometro
Interferometer Distance : Distanza Interferometro : 8m
Sampling Frequency : 105Hz



2,04Hz

Fig. 3-6 – Acceleration Spectrum / Spettro accelerazione
Note : The shown acceleration spectrum is related to a tower section at an altitude of 36,5m

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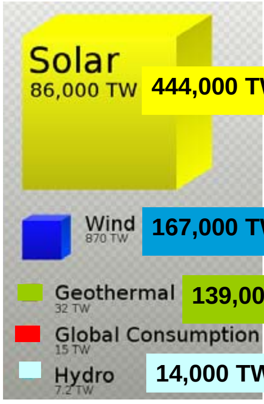
Design of supporting structures of Onshore Wind turbines

M.Veljkovic, TUD

Content

- General introduction
- Basics of a tower loaded by the wind
- Design of HAWT tower
  - Regulations
  - Failure modes
  - Design validations
- Numerical examples
- Questions

AVAILABLE RENEWABLE RESOURCES

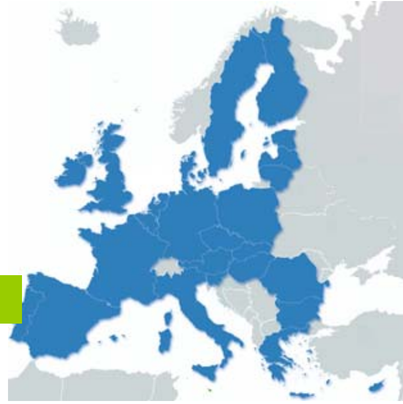


444,000 TWh

167,000 TWh

139,000 TWh

14,000 TWh

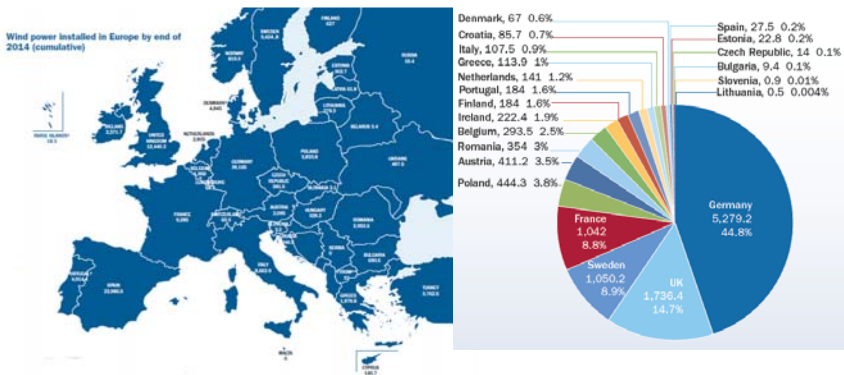


In 2012 (IEA) estimated:
155,505 TWh global consumption

EU (EWEA2014): wind energy 10% of el. consumption

http://en.wikipedia.org/wiki/World_energy_consumption

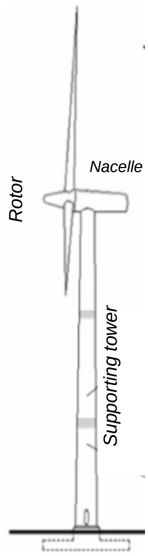
EU MARKET, CUMULATIVE AND 2014 INSTALLATION



http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA-Annual-Statistics-2014.pdf

MOSTLY USED WIND ENERGY CONVERTERS

- On/off-shore horizontal axis wind turbines (HAWT)
- Approximately 2 to 5 MW rated power.
- Typical layout:
  - The rotor
  - The nacelle
  - The supporting tower
- Three blade rotors ≈ 100 m diameter
- Hub heights: 80-100 m



TYPES OF TOWER STRUCTURES

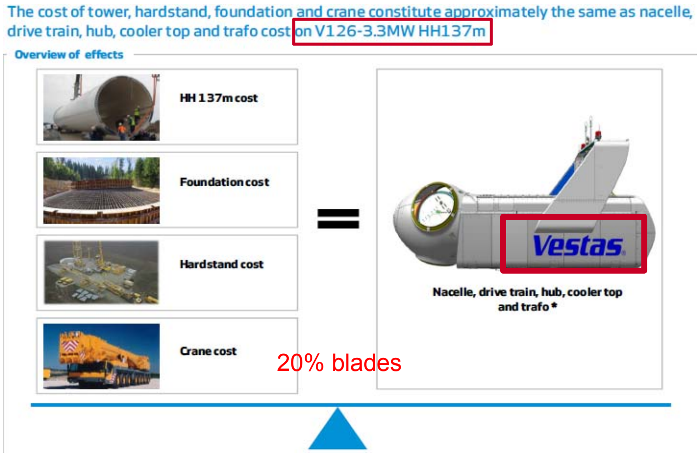
Steel Tubular

Hybrid Steel-Concrete

Concrete

Steel Lattice

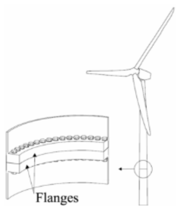
ILLUSTRATIVE OVERVIEW OF COST BREAK DOWN ON HIGHER TOWERS



•Total cost per MW	•€1.5 - 2 million	•€2.5 – 3.5 million

SUMMARY OF CURRENT LIMITATIONS

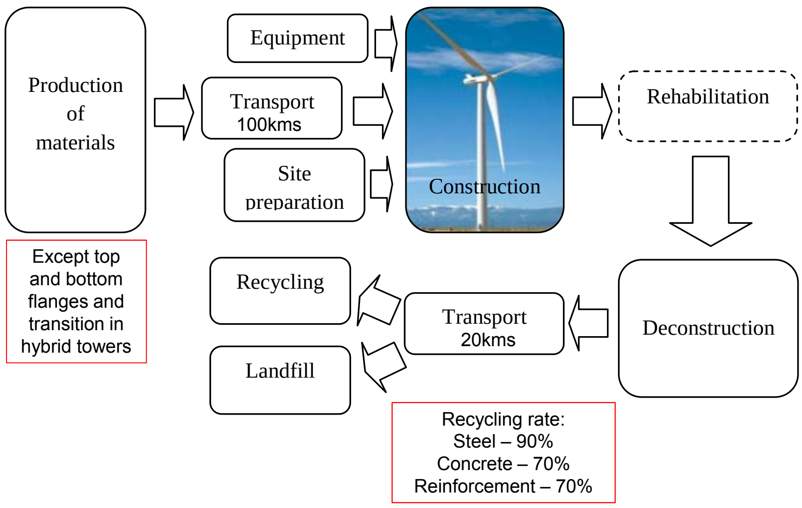
- Limited heights of current steel tubular towers (80 – 100 m)
- Transportation
  - Max. shell diameter: 4 – 4.5 m
- Cost effectiveness
  - Fatigue endurance due to transversal welding is the common design criterion – no use of HSS.
  - Connections with thick flanges.
  - Expensive rolling process.
- Lifting technology
  - Rather thick tower shell – difficulties for lifting heavy segments to large heights.



ECONOMICS OF WIND POWER

Element	On-shore Cost as % of total	Offshore Cost as % of total
•Turbine	•33%	•21%
•Blades	•22%	•15%
•Tower	•20%	•13%
•Foundation	•9%	•21%
•Grid connection	•6%	•21%
•Design & Management	•10%	•9%
		2010
•Total cost per MW	•€1.5 - 2 million	•€2.5 – 3.5 million

COMPARATIVE LIFE CYCLE ASSESSMENT: LCA



Analysis of environmental indicators – 1st scenario

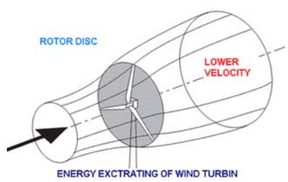
Environonmental category	Concrete tower	Steel tower WFC	Steel tower FrC	Hybrid tower WFC	Hybrid tower FrC
ADP fossil [MJ]	(150)				(80/100)
AP [kg SO2-Eq.]	(150)				(80/100)
EP [kg PO4-Eq.]					(80/100/150)
GWP [kg CO2-Eq.]			(80/100/150)		
ODP [kg R11-Eq.]	(80/100/150)				
POCP [kg Ethane-Eq.]	(80/100/150)				

Indicator
Abiotic Depletion (ADP fossil)
Acidification Potential (AP)
Eutrophication Potential (EP)
Global Warming Potential (GWP)
Ozone Layer Depletion Potential (ODP)
Photochemical Ozone Creation Potential (POCP)

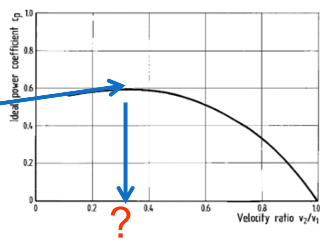
		Tower Height and Rated Power of Wind turbine					
		80m/2MW		100m/3.6MW		150m/5MW	
	Lifetime (years)	20	40	20	40	20	40
Steel towers and steel segments in hybrid towers	WFC	x		x		x	
	FrC	x	x	x	x	x	x
Concrete towers and concrete segments of hybrid towers	CT	x	x	x	x	x	x

THEORETICAL MAXIMUM OF WIND ENERGY EXTRACTION

- How much mechanical energy can be extracted from the free-stream airflow by an energy converter?
  - To transform the entire kinetic energy contained in the wind the wind velocity must be reduced to zero when passing the energy converter!
  - Reduced velocity, means at the same time a widening of the cross-section, as the same mass flow must pass through it.
  - There must be a Theoretical Maximum for the energy that can be converted from wind!



The ratio between the mechanical power extracted by the converter and that of the undisturbed air stream is called the “power coefficient” c_p:



POWER COEFFICIENT

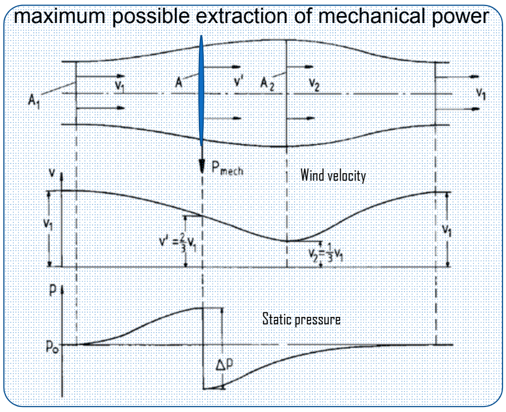
$$c_p = \frac{P}{P_o} = \frac{\text{mechanical power output of the converter}}{\text{power of the free-air stream}} = \frac{\frac{1}{4}\varrho A\left(v_1^2 - v_2^2\right)\left(v_1 + v_2\right)}{\frac{1}{2}\varrho A v_1^3}$$

$$c_p = \frac{P}{P_o} = \frac{1}{2}\left|1 - \left(\frac{v_2}{v_1}\right)^2\right|\left|1 + \frac{v_2}{v_1}\right|$$

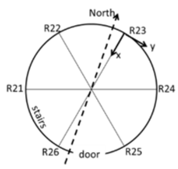
The maximum "ideal power coefficient" c_p is obtained for $v_2/v_1 = 1/3$

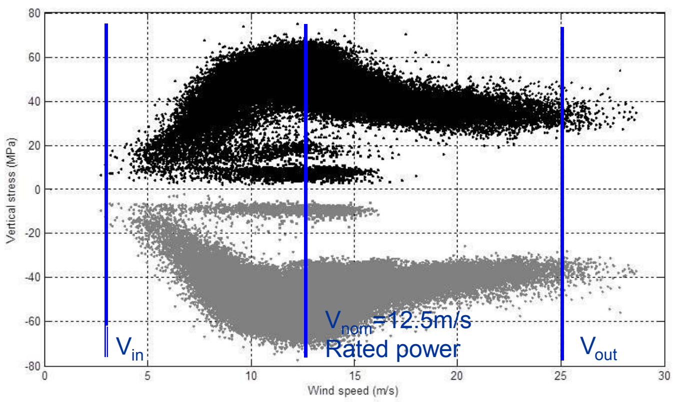
$$c_p = \frac{16}{27} = 0{,}593$$

$$v' = \frac{2}{3}v_1 \qquad v_2 = \frac{1}{3}v_1$$



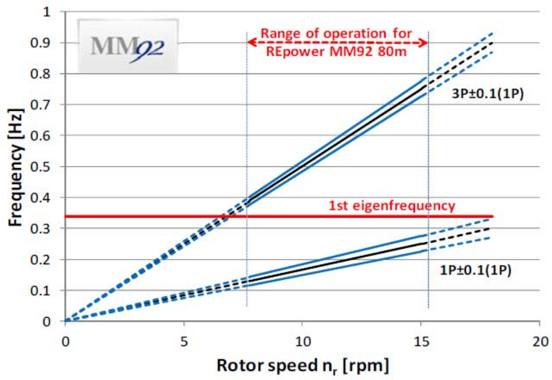
LIMITING ROTOR THRUST AND STRESSES IN THE TOWER





Measured maximum vertical stresses *versus* mean wind speed

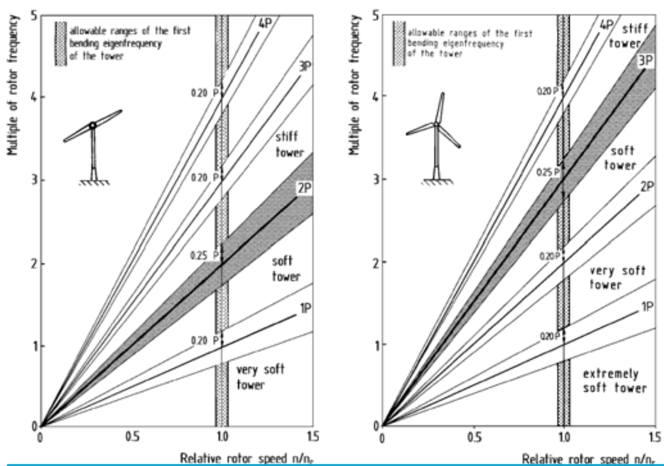
A COMMERCIAL WIND TURBINE



Rated power	2,05 MW
Rotor Diameter	92,5 m
Hub Heights	80,0 m (max 100m)
Power Control	Pitch (electrical)
Rotor Speed	7.8 - 15,0 rpm (+12,5%)
V_{in}	3m/s
V_{out}	24.9m/s
V_{nom}	12.5 m/s
Mass Hub+Rotor	66+40.7=106.7 Ton

CAMPBELL DIAGRAM FOR A TOWER RESONANCE EXCITED BY A ROTOR

Erich Hau
© Springer-Verlag Berlin Heidelberg 2006
Printed in Germany
Wind Turbines
Fundamentals, Technologies, Application, Economics



$$m\ddot{x} + kx = 0 \qquad x(t) = A\cos(\omega_0 t) + B\sin(\omega_0 t);\ \omega_0 = \sqrt{\frac{k}{m}}$$

MEASUREMENTS ON 5MW WT: h=67m, l_b=58m

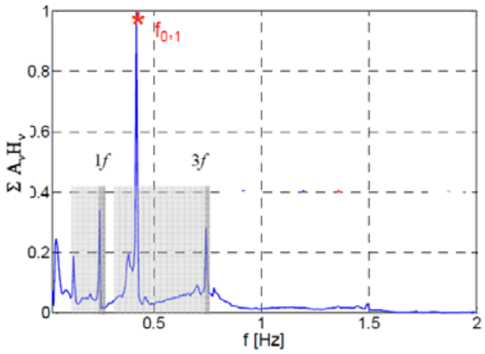
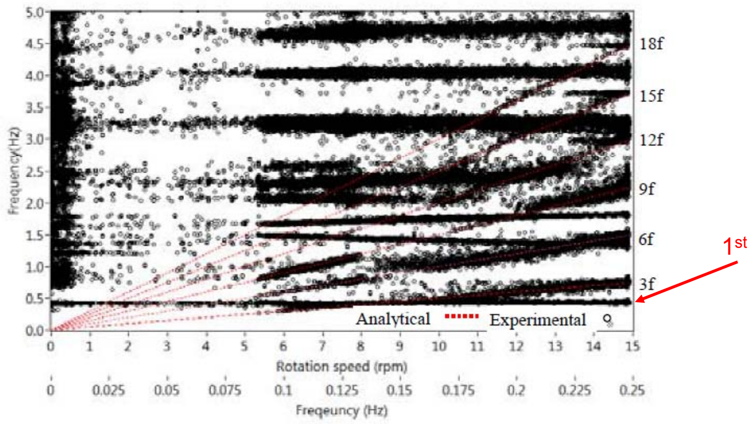


Figure 14 Frequency spectrum based on strain measurement

Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
Porto, Portugal, 30 June - 2 July 2014
A. Cunha, E. Caetano, P. Ribeiro, G. Müller (eds.)
ISSN: 2311-9020; ISBN: 978-972-752-165-4

EIGEN FREQUENCIES ESTIMATED BY DYNAMIC RESPONSES ALONG MWD



Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
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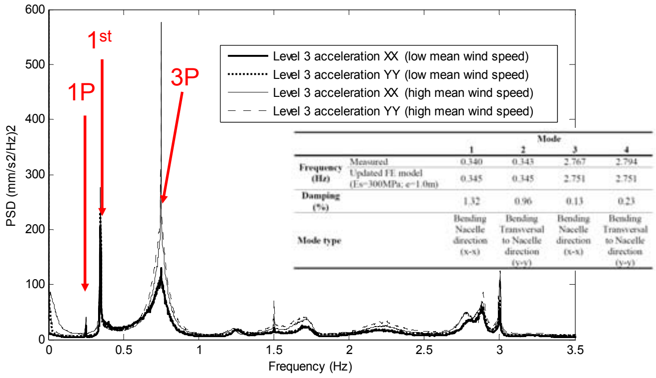
POWER SPECTRAL DENSITIES OF THE ACCELERATION



		Mode 1	Mode 2	Mode 3	Mode 4
Frequency (Hz)	Measured	0.340	0.343	2.767	2.794
	Updated FE model (Es=300MPa; e=1.0m)	0.345	0.345	2.751	2.751
Damping (%)		1.32	0.96	0.13	0.23
Mode type		Bending Nacelle direction (x-x)	Bending Transversal to Nacelle direction (y-y)	Bending Nacelle direction (x-x)	Bending Transversal to Nacelle direction (y-y)

C. Rebelo, M. Veljkovic, R. Matos and L. Simões da Silva, *Structural Monitoring of a Wind Turbine Steel Tower – Part II: monitoring results*. Wind and Structures, An Int'l Journal Vol. 15, No. 4, 301-311, 2012

DESIGN OF HAWT TOWERS

- Designs and guidlines
- Wind tower structural safety and loading
- Wind towers structural design
- Design Load Situations
- Type of Analysis
- Influence of dynamic characteristics of tower and foundation
- Safety Factors (IEC61400-1)
- Failure modes
- Structural Pre-design of Towers
- Fatigue details

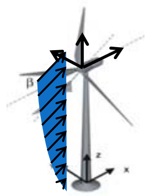
GUIDELINES FOR DESIGN OF WIND TURBINES

- Who creates standards and guidelines for Wind Energy equipment?
  - ISO/IEC
  - CEN/Cenelec
  - National standardization organizations (e.g. Danish standard DS472, DIN)
  - Certification companies (GL, DNV, Riso, ECN-CIWI etc)
- Some guidlines:
  - Det Norske Veritas & Wind Energy Department at Risø National Laboratory , Copenhagen, Denmark, 2002
  - Guideline for the Certification of Wind Turbines
  - Germanischer Lloyd WindEnergie GmbH (GL Wind), Hamburg, Germany, 2010

STRUCTURAL RELIABILITY FRAMEWORK IN IEC 61400-1 AND EN1990

- Choose wind turbine class depending on site conditions
- The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation.
- Wind turbine classes are defined in terms of wind speed and turbulence parameters.
- **V_{ref} is the reference wind speed: extreme 10 min average wind speed** at the hub-height with a **50 year return period**, air density 1.225 kg/m3
- I_{ref} is the reference turbulence intensity: expected value of hub-height turbulence intensity (**coefficient of variation of wind speed**) at a 10 min average wind speed of 15 m/s

	Wind Turbine Class		
	I	II	III
V_{ref}	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	



WIND TOWERS STRUCTURAL DESIGN

- The structural design of a wind turbine support structure must provide adequate **strength and stiffness**:
  - to withstand extreme loads from the highest wind speeds which may occur;
  - to guarantee fatigue strength/life;
  - To provide adequate dynamic behaviour and control of deflections by avoiding resonance situations through well balanced natural frequencies in relation to rotation frequency ranges; the vibrational behaviour of a wind turbine can be kept under control only when the stiffness and mass parameters of all its components are carefully matched.

DESIGN LOAD SITUATIONS

- For design purposes, the life of a wind turbine is represented by a set of design situations covering the most significant conditions that the wind turbine may experience.
- The load cases are determined from the combination of operational modes or other design situations with the external conditions giving three main design load cases:
  - **normal operation** and appropriate normal or extreme wind conditions
  - **fault situations** and appropriate wind conditions
  - **transportation, installation and maintenance** and appropriate wind conditions

TYPE OF ANALYSIS

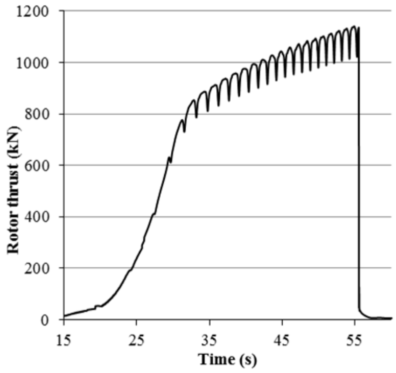
- Ultimate Limit State (**U**) – Strength, Stability, Blade tip Deflection
  - Normal (**N**) – situation occurring frequently during lifetime
  - Abnormal (**A**) – situation occurring rarely during lifetime (severe faults)
  - Transport and Construction (**T**)
- Fatigue Limit State (**F**) – Fatigue strength of material and structural details

DESIGN LOAD CASES AND TYPE OF ANALYSIS (IEC61400-1)

DLC	Situation	Type of Analysis	Safety Factor
1.x	power production	U or F	N
2.x	power production plus occurrence of fault	U or F	N or A
3.x	start up of wind turbine	U or F	N
4.x	normal shut down	U or F	N
5.x	emergency shut down	U or F	N
6.x	parked wind turbine	U or F	N or A
7.x	parked wind turbine and fault conditions	U	N or A
8.x	transport, assembly, maintenance and repair	U	N or A or T

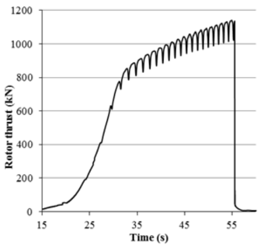
SHUT DOWN EVENT OF THE TURBINE

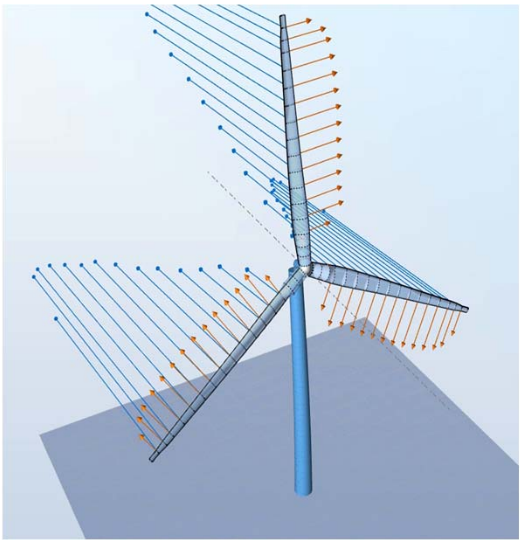
- The turbine is stopped at high wind speeds and for maintanance reasons.
- Shut down is operated by turning the blades – pitch control.
- Simulation is made in software ASHES.



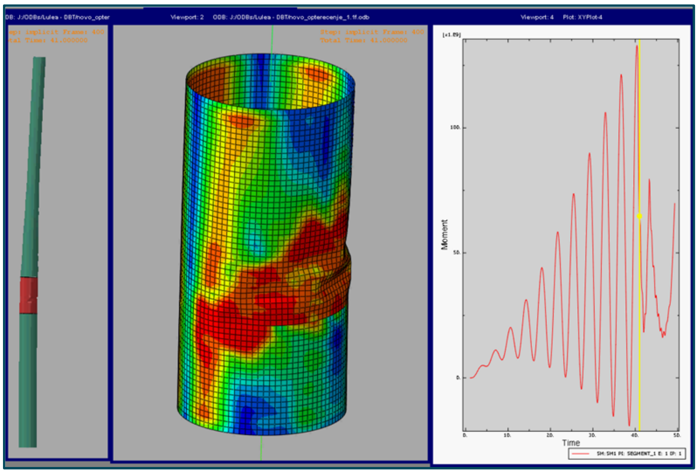
SHUT DOWN SIMULATION

- Blades are turned by 90˚ at steady state load.
- Deformations are scaled x20.





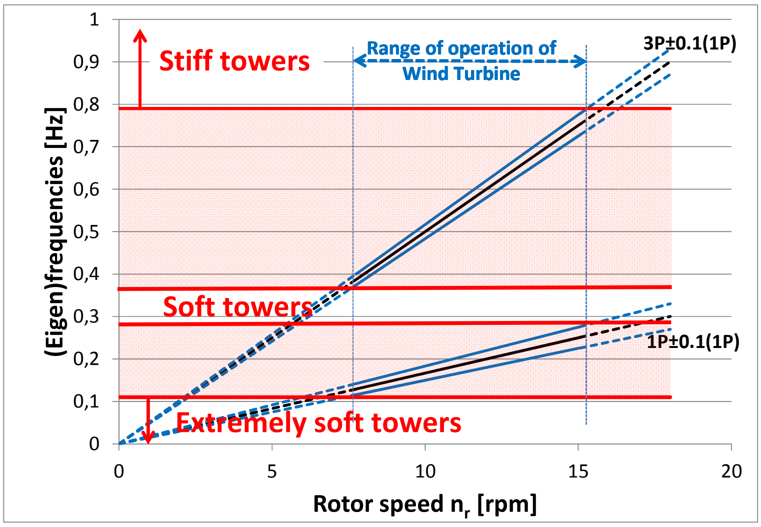
BUCKLING – DUE TO INCREASED DYNAMIC LOADING



INFLUENCE OF DYNAMIC CHARACTERISTICS OF TOWER AND FOUNDATION

- The most important design requirement concerning vibrations of the turbine as a whole is to prevent the exciting rotor forces from resonating with the natural tower bending frequencies.
- The natural frequencies of the tower must include tower head mass and soil-structure interaction.
- The cyclic exciting forces of the rotor have basically two sources:
  - "**mass imbalances**" of moving parts, mainly the rotor with blades
  - "**aerodynamic imbalances**" that result from the asymmetrical air flow against the rotor, mostly the tower shadow effect and the vertical wind shear
- The second type of forces is the critical one, since it cannot be avoided.
- **The first frequencies of excitation** is usually called 1 *P* (per revolution) and corresponds to the rotor angular speed. It is the only one present in one-bladed turbines and it is the basic frequency of excitation for all other turbines. Higher harmonics appear for multi-blade turbines as 2 *P*, 3 *P*, *etc*.

INFLUENCE OF DYNAMIC CHARACTERISTICS OF TOWER AND FOUNDATION



SAFETY VERIFICATION CONCEPT (IEC61400-1)

Type of Analysis	Safety verification format
Strength	Action effect ≤ Resistance effect $\gamma_f F_k \leq \frac{1}{\gamma_n \gamma_m} f_k$
Stability	Components shall not buckle under the design load $\gamma_f F_k$
Blade tip Deflection	No mechanical interference between blade and tower will occur $\gamma_n \gamma_m \gamma_f \delta(F_k) \leq$ allowable clearence
Fatigue	Miner Rule applies $D = \sum_{i,j} \frac{n_{ij}}{N(\gamma_n \gamma_m \gamma_f S_i)} \leq 1.0$ n_{ij} is the expected number of lifetime load cycles in the j^{th} wind speed and the i^{th} load bin; S_i is the centre value for the i^{th} load bin

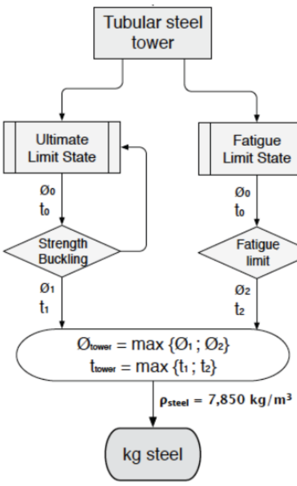
SAFETY FACTORS (IEC61400-1)

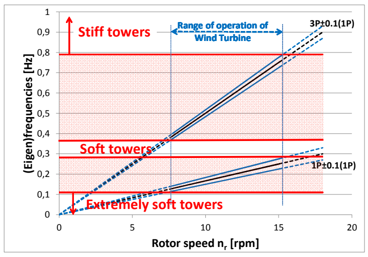
Type of Analysis	γ_f					γ_n	γ_m (*)
	Unfavourable effect				Favourable effect		
	N	A	T	F	-		
Strength	1.35	1.1	1.5		0.9	1.0	Ductile components and 1 out of several bolts ≥ 1.0
Stability	1.35	1.1	1.5		0.9	1.0	≥ 1.2
Deflection	1.35	1.1	1.5		0.9	1.0	Elastic properties ≥ 1.1
Fatigue	–	–	–	1.0	–	1.15	Welded and structural steel ≥ 1.1

FAILURE MODES

- Dominant action - bending due to operation of the turbine.
- Local buckling of the shell
- Buckling around the door opening
- Resistance of the connections
- Fatigue of the weld regions (the shell and the connections)

STRUCTURAL PRE-DESIGN OF TOWERS





FATIGUE DETAILS

EN 1993-1-9 : 2005 (E)

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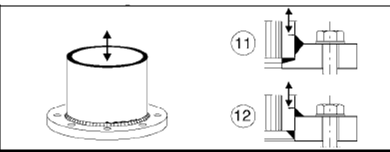
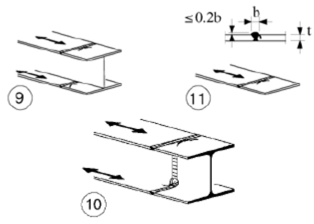
71		11) Tube socket joint with 80% full penetration butt welds.	11) Weld toe ground. Δσ computed in tube.
40		12) Tube socket joint with fillet welds.	12) Δσ computed in tube.

Page 22

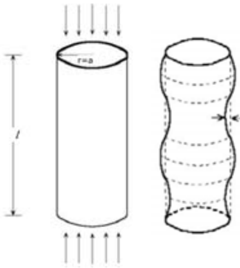
80	size effect for t>25mm: $k_s=(25/t)^{0,2}$		9) Transverse splices in welded plate girders without cope hole. 10) Full cross-section butt welds of rolled sections with cope holes. 11) Transverse splices in plates, flats, rolled sections or plate girders.	- The height of the weld convexity to be not greater than 20% of the weld width, with smooth transition to the plate surface. - Weld not ground flush - Weld run-on and run-off pieces to be used and subsequently removed, plate edges to be ground flush in direction of stress. - Welded from both sides; checked by NDT. Detail 10: The height of the weld convexity to be not greater than 10% of the weld width, with smooth transition to the plate surface.

BUCKLING OF A CYLINDRICAL SHELL

- Axial compression

$$D\frac{d^4v}{dx^4}+N_x\frac{d^2w}{dx^2}+Eh\frac{w}{a^2}=0$$

$$D=\frac{Eh^3}{12\left(1-\mu^2\right)} \qquad w=-A\sin\frac{m\pi x}{l}$$



The critical stress:

$$\sigma_{cr}=\frac{N_{cr}}{h}=D\left(\frac{m^2\pi^2}{hl^2}+\frac{E}{a^2D}\frac{l^2}{m^2\pi^2}\right)$$

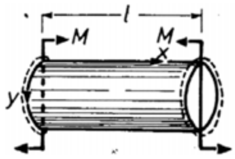
- Bending moment

Flügge:

$$\left(\sigma_{cr,x}\right)^M\approx1.33\left(\sigma_{cr,x}\right)^{N_x}$$

Brazier:

$$M_{cr}=\frac{0.99}{\left(1-\nu^2\right)}Eh^2a$$

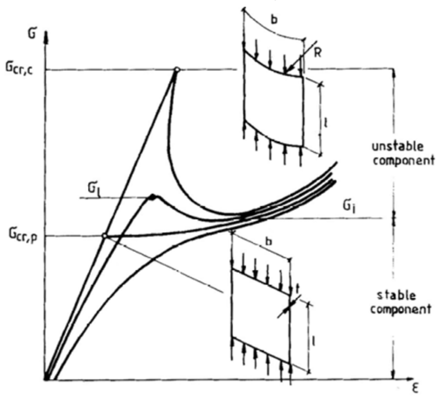


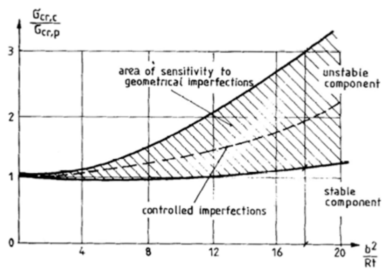
SENSITIVITY TO IMPERFECTIONS AND POST-CRITICAL RESISTANCE

- Cylindrical shells are more sensitive to imperfections due to unfavourable influence of spatiality

$$\sigma_{cr,p}=\frac{\pi^2E}{3\left(1-\mu^2\right)}\left(\frac{t}{b}\right)^2$$

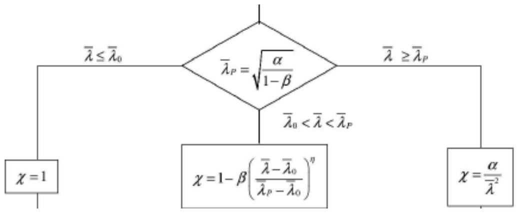
$$\sigma_{cr,c}=\underbrace{\frac{\pi^2E}{3\left(1-\mu^2\right)}\left(\frac{t}{b}\right)^2}_{\text{Stable component}}+\underbrace{\frac{E}{4\pi^2}\left(\frac{b}{r}\right)^2}_{\text{Unstable component}}$$

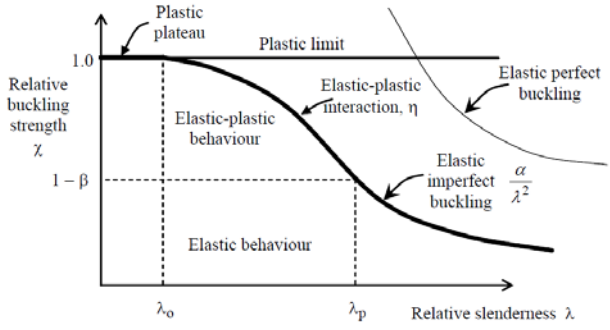




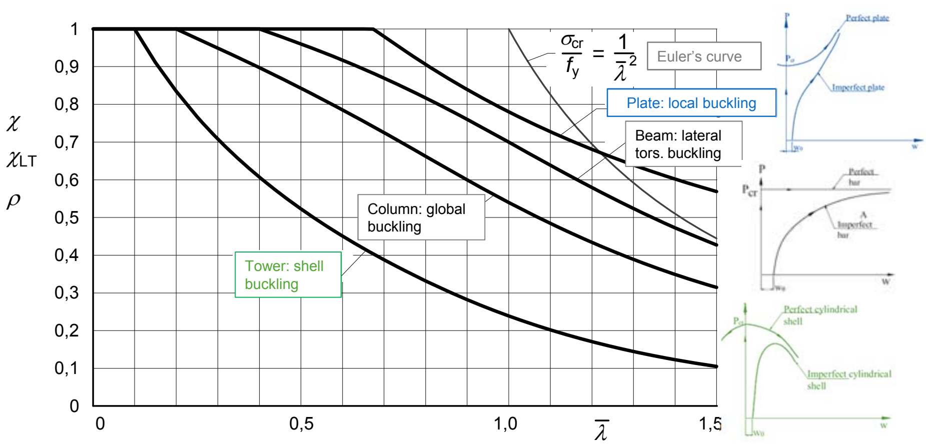
IMPERFECT SHELL BUCKLING

- Elastic behaviour
- Elastic-plastic behaviour
- Parameters: α, β, λ_0, η





RELATIVE STRENGTH FOR VARIOUS STABILITY PHENOMENA



CONTENTS OF EC3 PART 1-6

ULTIMATE LIMIT STATES IN EC3 PART 1-6

- ***Plastic limit state (LS1)***
  - the capacity of the structure to resist the actions is exhausted by **yielding of the material**.
- *Cyclic plasticity limit state* (LS2)
  - relatively *low number* of repeated cycles of loading and unloading produce yielding in tension and compression at the same point.
- ***Buckling limit state (LS3)***
  - **loss of stability** under compressive membrane or shear membrane stresses in the shell wall
- ***Fatigue limit state (LS4)***
  - low stress ranges in large number of cycles leading to **cracking** of the structure components (welds, bolts,...)

APPLICATION TO WEC TOWERS

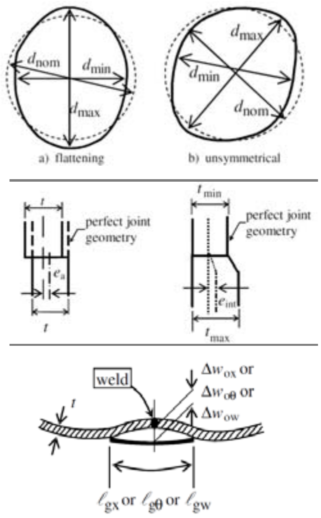
- Generally in in a WEC tower, **the Buckling limit state (LS3)** is the governing (compared to the Plastic limit state (LS1))
- *Cyclic plasticity limit state* (LS2)
  - The nature of the loads arising from operation of the turbine are highly cyclic.
  - Low cycle fatigue is rarely present in steel tubular towers for wind energy converters.
- **Fatigue limit state** (LS4)
  - Welded joints in the shell (longitudinal and transversal) and in connections have low design class: 71 – 80 according to EC3 Part 1-9.
  - The fatigue endurance is most often the governing one for the design.
  - This gives **limitation** of use of **H**igh **S**trength **S**teels for **the cylindrical shell.**

TYPES OF ANALYSES IN EC3 PART 1-6

- Several types of analysis can be conducted following the structure complexity and regarding the failure mode that is considered:
  - **L**inear elastic **A**nalysis (LA)
  - **L**inear elastic **B**ifurcation **A**nalysis (LBA)
  - **M**aterially **N**onlinear **A**nalysis (MNA)
  - **G**eometrically and **M**aterially **N**onlinear **A**nalysis (GMNA)
  - **G**eometrically and **M**aterially **N**onlinear **A**nalysis with **I**mperfections included (GMNIA)

IMPERFECTIONS

- Imperfections are depend on **Fabrication Tolerance Quality Class.**
- Three types of geometrical imperfections:
  - Out-of-roundness
    - deviation from circularity
  - Eccencitries
    - deviations from a continious middle surface
  - Local dimples
    - local normal deviations from nominal middle surface



PLASTIC LIMIT STATE (LS1)

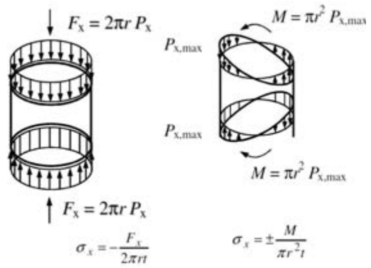
- Strength of the structure when stability is not important.
- Two potential failure modes:
  - **Tensile rupture** or **compressive yield**,
  - Plastic collapse mechanism involving **bending**.
- Where holes for fasteners are present additional check need to be carried out taking into account the **net cross section**.

PLASTIC LIMIT STATE (LS1)

- Types of analyses / calculation of stresses:
  - Equations – Annex A
  - **Linear Analysis of stresses** (LA)
    - elastic bending theory

$$\sigma_{x,Ed} = \frac{N_{Ed}}{A} + \frac{M_{Ed}}{W_{el}}$$

    - underestimated resistance for bending
  - **Materially Nonlinear Analysis** (MNA)
    - plastic resistance
    - better estimation of true resistance to bending loads



PLASTIC LIMIT STATE (LS1)

- In wind towers the most important are the membrane stresses.
- Three components of membrane forces/stresses:
  - Meridional (longitudinal) - *x*

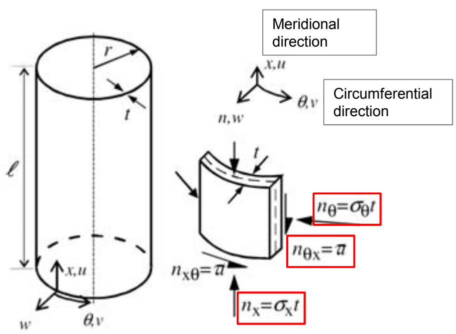
$$\sigma_{x,Ed} = \frac{n_{x,Ed}}{t} \pm \cancel{\frac{m_{x,Ed}}{(t^2/4)}}$$

  - Circumferential (tangential) - θ

$$\sigma_{\theta,Ed} = \frac{n_{\theta,Ed}}{t} \pm \cancel{\frac{m_{\theta,Ed}}{(t^2/4)}}$$

  - Shear (in plane)

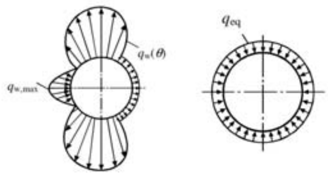
$$\tau_{x\theta,Ed} = \frac{n_{x\theta,Ed}}{t} \pm \cancel{\frac{m_{x\theta,Ed}}{(t^2/4)}}$$



- Surface stresses may be important in the connection zone!

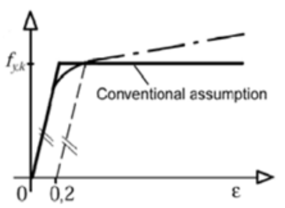
PLASTIC LIMIT STATE (LS1)

- $\sigma_{eq,Ed} = \sqrt{\sigma_{x,Ed}^2 + \sigma_{\theta,Ed}^2 - \sigma_{x,Ed} \cdot \sigma_{\theta,Ed} + 3\left(\tau_{x,\theta,Ed}^2 + \tau_{xn,Ed}^2 + \tau_{\theta n,Ed}^2\right)}$
- In towers the circumferential and shear stresses are practically negligible, but need to be checked!
  - Bending moments in the tower are dominant compared to shear and torsion.
  - Influence of local wind pressure on the tower wall is small compared to load due to operation of the turbine.
- \ $\sigma_{eq,Ed} \leq f_{eq,Rd} = f_{yd} = f_{yk} / \gamma_{M0}$

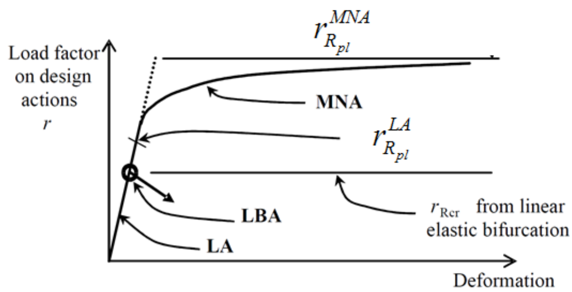


PLASTIC LIMIT STATE (LS1)

- Materially Nonlinear Analysis (MNA)
  - idealised elastic-plastic material behaviour
  - load amplification factor for design loads is obtained



MATERIAL MODEL



BUCKLING LIMIT STATE (LS3)

- Verification of local buckling resistance of the shell in steel tubular tower.
- Three design approaches:
  - Stress limitation
    - analogy to uniform member in compression in EC3 Part 1-1.
  - MNA+LBA
    - analogy to the general method in EC3 Part 1-1 6.4.3.
  - GMNIA
    - Geometrically and Materially Nonlinear Analysis with Imperfections included

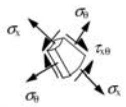
Application in WEC towers:

- Stress limitation, MNA+LBA: Verification of the shell
- MNA+LBA, GMNIA: Verification of door oppenings

BUCKLING STRESS LIMITATION (LS3)

- Linear Analysis (LA) or Annex A is used to calculate the membrane stresses in the shell, same as for the LS1.
- The design check is made with regards to design resistances taking into account buckling strength:
  - For individual stress components:

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



Membrane stresses

  - Interaction of components:

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

$$k_x = 1{,}0 + \chi_x^2 \qquad k_i = (\chi_x \chi_\theta)^2 \qquad k_\theta = 1{,}0 + \chi_\theta^2 \qquad k_\tau = 1{,}5 + 0{,}5\,\chi_\tau^2$$

DESIGN RESISTANCES (LS3)

- Design resistances for stress components are obtained using **buckling reduction factors c** taking into account:
  - **Imperfections** depending on the Fabrication Tolerance Quality Class
  - **Boundary Conditions** of the cylindrical shell

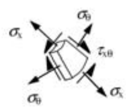
$$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_{M1}, \quad \sigma_{\theta,Rd} = \sigma_{\theta,Rk}/\gamma_{M1}, \quad \tau_{x\theta,Rd} = \tau_{x\theta,Rk}/\gamma_{M1}$$

$$\sigma_{x,Rk} = \chi_x \, f_{yk}, \quad \sigma_{\theta,Rk} = \chi_\theta \, f_{yk}, \quad \tau_{x\theta,Rk} = \chi_\tau \, f_{yk} \, / \sqrt{3}$$

- The partial safety factor may be defined in the National Annex. The recommended value is: $\gamma_{M1} = 1{,}1$.
- Yield strength depends on the steel grade, and on the thickness of the shell as well.

BUCKLING REDUCTION FACTORS (LS3)

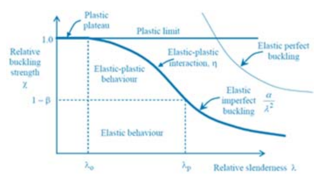
- For each stress component buckling reduction factors are obtained separately.
- The buckling reduction factors are determined as a function of the relative slenderness of the shell:



$$\chi = 1 \qquad \text{when} \qquad \bar{\lambda} \le \bar{\lambda}_0$$

$$\chi = 1 - \beta\left(\frac{\bar{\lambda} - \bar{\lambda}_0}{\bar{\lambda}_p - \bar{\lambda}_0}\right)^{\eta} \qquad \text{when} \qquad \bar{\lambda}_0 < \bar{\lambda} < \bar{\lambda}_p$$

$$\chi = \frac{\alpha}{\bar{\lambda}^2} \qquad \text{when} \qquad \bar{\lambda}_p \le \bar{\lambda}$$



α	is	the elastic imperfection reduction factor	Annex D
β	is	the plastic range factor	
η	is	the interaction exponent	
$\bar{\lambda}_0$	is	the squash limit relative slenderness	

plastic limit relative slenderness

$$\bar{\lambda}_p = \sqrt{\frac{\alpha}{1-\beta}}$$

RELATIVE SLENDERNESS OF THE SHELL (LS3)

- The relative shell slenderness parameters for different stress components:
  - Meridional $\bar{\lambda}_x = \sqrt{f_{yk} / \sigma_{x,Rcr}}$
  - Circumferential $\bar{\lambda}_\theta = \sqrt{f_{yk} / \sigma_{\theta,Rcr}}$
  - Shear $\bar{\lambda}_\tau = \sqrt{\left(f_{yk} / \sqrt{3}\right) / \tau_{x\theta,Rcr}}$
- Elastic critical buckling stresses can be obtained using:
  - appropriate expressions in Annex D,
  - LBA under buckling relevant action.

CRITICAL MERIDIONAL BUCKLING STRESS– ANNEX D

- The elastic critical meridional buckling stress: $\sigma_{x,Rcr} = 0{,}605 E C_x \frac{t}{r}$
- The parameter Cx depends on effect of boundary conditions and dimensionless length parameter w:

$$C_x = 1{,}36 - \frac{1{,}83}{\omega} + \frac{2{,}07}{\omega^2} \quad \text{short cylinders} \quad \omega \leq 1{,}7$$

$$C_x = 1{,}0 \quad \text{medium-length cylinders} \quad 1{,}7 \leq \omega \leq 0{,}5\frac{r}{t}$$

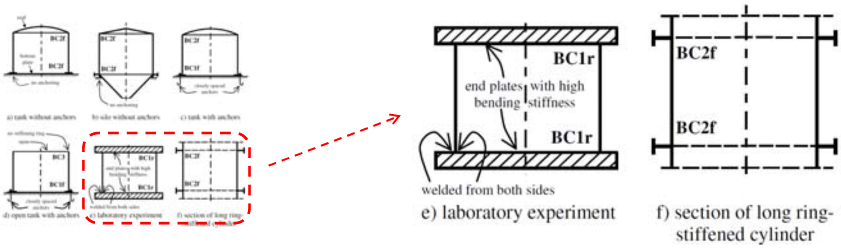
$$C_x = C_{x,N} = 1 + \frac{0{,}2}{C_{xb}}\left[1 - 2\omega\frac{t}{r}\right] \geq 0{,}60 \quad \text{long cylinders} \quad \omega > 0{,}5\frac{r}{t}$$

$$\omega = \frac{\ell}{r}\sqrt{\frac{r}{t}} = \frac{\ell}{\sqrt{rt}}$$ dimensioneless length parameter

EFFECT OF BOUNDARY CONDITIONS – ANNEX D

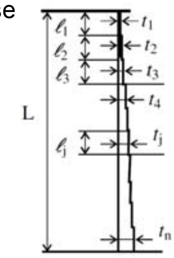
- The parameter C_{xb} depends on effect of boundary conditions:

Case	Cylinder end	Boundary condition	C_{xb}
1	end 1 end 2	BC 1 BC 1	6
2	end 1 end 2	BC 1 BC 2	3
3	end 1 end 2	BC 2 BC 2	1



EQUIVALENT LENGTH – ANNEX D

- Steel tubular towers for WEC are long cylinders with stepwise variable wall thickness.
- Each cylindrical section j of length l_j, for buckling in the meridional direction should be treated as an:
  - equivalent cylinder of overall length $l = L$,
  - with uniform wall thickness $t = t_j$
- Considering the connections in tower:
  - The ring flange connection - L should be the length of the assembling segment.
  - The friction connection - L should be the length of the whole tower.
- For long equivalent cylinders the parameter Cxb should be conservatively taken as $C_{xb} = 1$!



MERIDIONAL BUCKLING PARAMETERS – ANNEX D

- Meridional elastic imperfection reduction factor:

$$\alpha_x = \frac{0,62}{1+1,91(\Delta w_k / t)^{1,44}}$$

- Characteristic imperfection amplitude Dwk depends on the fabrication quality parameter Q:

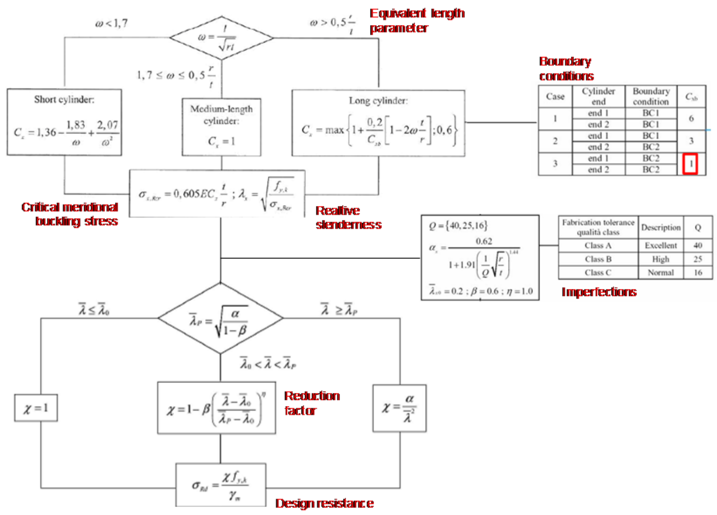
$$\Delta w_k = \frac{1}{Q}\sqrt{\frac{r}{t}} \cdot t$$

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

- Other parameters should be taken as:

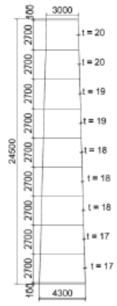
$\bar{\lambda}_{x0} = 0,20$ $\beta = 0,60$ $\eta = 1,0$

FLOWCHART FOR DESIGN CHECK USING BUCKLING STRESS LIMITATION



NUMERICAL EXAMPLE

The design exemple is given for the conical segment of a wind tower 100 m height. The segment consists of 9 sections with variable thicknesses. The complete procedure is shown only for the lowest section with thickness t = 17 mm. The segment is made of steel S355. Calcuation of ultimate design forces and moments is not shown here.



Tower segment geometry:

h=24500 mm

r_1 =1500 mm

r_2=2150 mm

β=1.572°

L=24500 mm

f_y=355 MPa

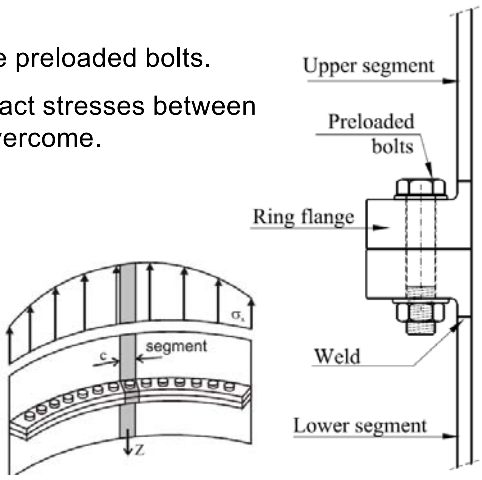
Note: Special design rules are given in Annex D.4 of EC3 Paert 1-6 for the trucated conical shells. However, the incination angle β in the case shown here is rather small β=1.572° that the segment is considered as cylindrical.

COMPONENTS OF THE CONNECTION

- The load is transfered by the preloaded bolts.
- At the design loads the contact stresses between the flanges should not be overcome.

- Single section of the connection comprising one bolt in tension can be considered for the design.

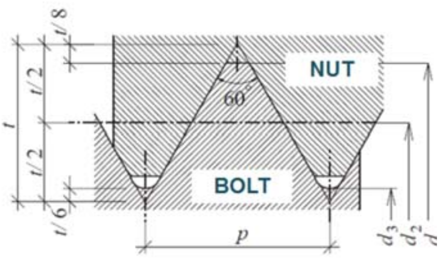
$$A_s = \frac{\pi}{4}\left(\frac{d_2 + d_3}{2}\right)^2$$



TENSILE STRESS AREA OF THE BOLT

- Fracture of the bolt in tension always appear in the threaded zone of the bolt due reduced cross sectional area.
- The area of the bolt cross-section in the threaded zone is called the tensile stress area - A_s.

$$A_s = \frac{\pi}{4}\left(\frac{d_2 + d_3}{2}\right)^2$$



d nominal bolt diameter
d_2 average diameter of the tread
d_3 diameter of the core of the shank
p pitch (p=1.75 mm for M12
t depth of the tread

MATERIAL PROPERTIES OF BOLTS

- Two most important material properties are:
  - Yield strength – f_y
  - Ultimate strength - f_u

Bolt grade	4.6	5.6	6.8	8.8	10.9
f_{yb}, MPa	240	300	480	640	900
f_{ub}, MPa	400	500	600	800	1000
Material and treatment	low or medium carbon steel, fully or partially annealed			medium carbon alloy steel, quenched and tempered	

PRELOADING OF THE BOLTS

- $F_{p,C} = 0{,}7 f_{ub} A_s$ force according to EC3 Part 1-8:
- There are several tightening methods predicted in EN 1090-2:
  - Torque method
  - Combined method
  - Direct tension indicator (DTI) method
  - HRC tightening method
- The first two metods are based on a torque moment M_r applied with a torque wrench.

Manual torque wrench

PRELOADING OF THE BOLTS

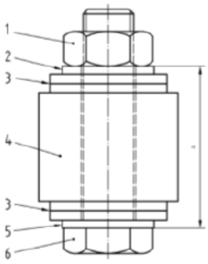
- The torque moment may be specified in to ways:
  a) Based on km factors supplied by the manufacturer:

  $$M_r = k_m \, d \, F_{p,C}$$

  a) Based on a calibration procedure predicted in Annex H of EN 1090-2.

  $$M_r = M_{test}$$

- **The torque method** comprise at least of the two steps:
  - Application of torque moment equal to $0.75M_r$
  - Application of torque moment equal to $1.10M_r$



Calibrated force, mesuring device – load cell

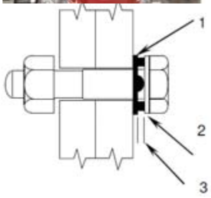
PRELOADING OF THE BOLTS

- **The combined method** comprises two steps:
  - Application of torque moment equal to $0.75M_r$
  - Additional nut rotation with an angle given by the following table

Total nominal thickness "*t*" of parts to be connected (including all packs and washers)	Further rotation to be applied, during the second step of tightening	
d = bolt diameter	Degrees	Part turn
$t < 2d$	60	1/6
$2d \le t < 6d$	90	1/4
$6d \le t \le 10d$	120	1/3

- Direct tension indicator method indicator washers have protrusions that flaten at the proper preloading force.

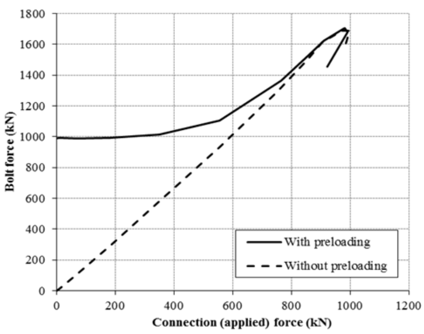
1: Indicator washer
2: Bolt face washer
3: Gap



BOLT FORCE VARIATION

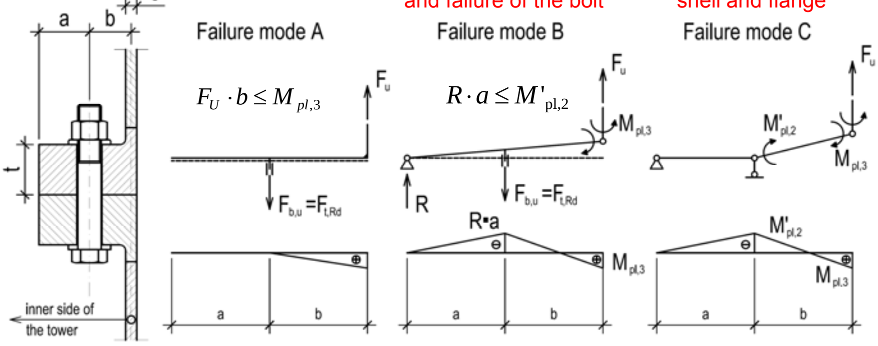
- Due to presence of the preloading the variation of the bolt force in function of the applied load is nonlinear.
- The force in the bolt increases only after the contact stresses between the flanges is overcome by the outer load.

- Ultimate resistance of the connection would be the same even without the preloading of the bolts.
- Bolts need to be preloaded for two reasons:
  - Fatigue endurance
  - Serviceability



FAILURE MODES

Failure of the bolt	Plastic hinge in the shell and failure of the bolt	Plastic hinges in the shell and flange
Failure mode A	Failure mode B	Failure mode C

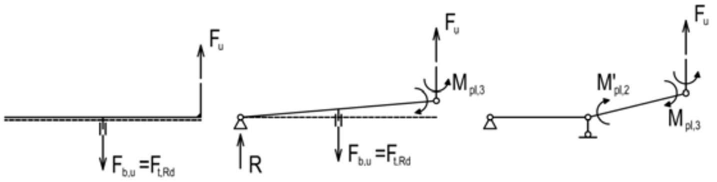


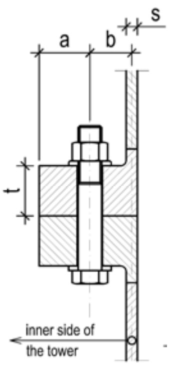
$$F_U = F_{t,Rd} = \frac{0.9 \cdot A_s \cdot f_{ub}}{\gamma_{M2}}$$

$$F_U = \frac{F_{t,Rd} \cdot a + M_{pl,3}}{a + b'}$$

$$F_U = \frac{M'_{pl,2} + M_{pl,3}}{b}$$

FAILURE MODES





R	– is the reaction force at the flange edge,
a	– is the distance from the bolt axis to the flange edge,
b	– is the distance from the bolt axis to the shell mid plane,
t	– is the flange thickness,
s	– is the shell thickness,
c	– is the segment width,
$c' = c - d_B$	– is the segment width reduced by the bolt hole diameter,
d_H	– is the bolt hole diameterer,
d_W	– is the washer diameterer,
b'_D	– is the distance between bolt axis and plastic hinge in the shell or flange,
b'_E	– is the distance between mid-washer and plastic hinge in the shell or flange

FAILURE MODES

- $M_{pl,3}$ - is the bending resistance of the shell or of the flange, considering the M-N and M-V interaction respectively.
- It is iteratively derived from:

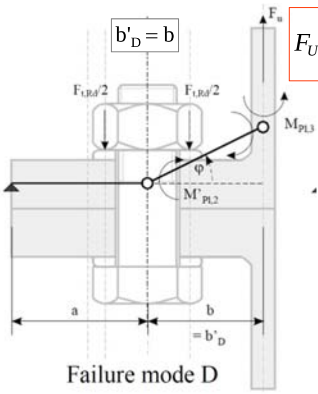
$$M_{pl,3} = \min \left\{ \frac{M_{pl,N,shell} = \left[1 - \left(\frac{N}{N_{pl,shell}}\right)^2\right] \cdot M_{pl,shell} = \left[1 - \left(\frac{F_U}{c \cdot s \cdot f_{yd,shell}}\right)^2\right] \cdot \frac{c \cdot s^2}{4} \cdot f_{yd,shell}}{M_{pl,V,flange} = \left[\sqrt{1 - \left(\frac{V}{V_{pl,flange}}\right)^2}\right] \cdot M_{pl,flange} = \left[\sqrt{1 - \left(\frac{F_U}{c \cdot t \cdot f_{yd,flange}}\right)^2}\right] \cdot \frac{c \cdot t^2}{4} \cdot f_{yd,flange}} \right\}$$

$M_{pl,2} = \frac{c \cdot t^2}{4} \cdot f_{yd}$ - is the full bending resistance of the flange

$M'_{pl,2} = \frac{c' \cdot t^2}{4} \cdot f_{yd}$ - is the reduced bending resistance of the flange at the bolt axis

FAILURE MODES

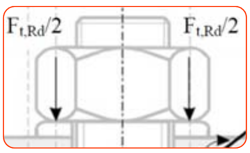
- (Seidel, 2001) introduced two new failure modes D and E that can be used instead of failure mode C.



Failure mode D

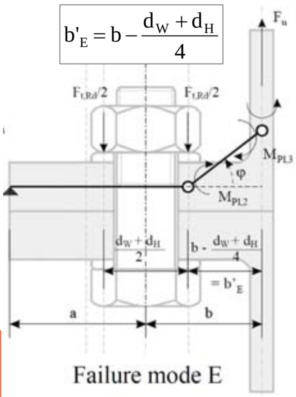
$$F_U = \frac{M'_{pl,2} + \Delta M_{pl,2} + M_{pl,3}}{b'_D}$$

$$\Delta M_{pl,2} = \frac{F_{t,Rd}}{2} \cdot \frac{d_W + d_H}{4}$$



$$F_U = \frac{M_{pl,2} + M_{pl,3}}{b'_E}$$

$$b'_E = b - \frac{d_W + d_H}{4}$$

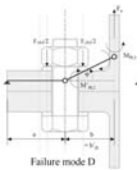


Failure mode E

FAILURE MODES

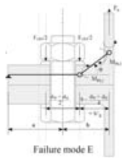
- For failure modes D and E, following conditions must be satisfied:

The minimum bending moment of the flange is not exceeded at the bolt axis:



$$\left(\frac{F_{t,Rd}}{2} - F_{U,D}\right) \cdot \left(\frac{d_W + d_H}{4}\right) \leq M_{pl,2} - M'_{pl,2}$$

The reaction force R, must act on the flange: $r = \frac{M'_{pl,2} + \Delta M_{pl,2}}{F_{t,Rd} - F_U} \leq a$ (1)



The full bending moment of the flange is not exceeded at mid-washer:

$$\left(\frac{F_{t,Rd}}{2} - F_{U,E}\right) \cdot \left(\frac{d_W + d_H}{4}\right) \geq M_{pl,2} - M'_{pl,2}$$

The reaction force R, must act on the flange: $r = \frac{M'_{pl,2} + 2 \cdot \Delta M_{pl,2}}{F_{t,Rd} - F_U} - \frac{d_W + d_H}{4} \leq a$ (2)

- If those requirments (1 and 2) are not fulfilled than the failure mode C must be used!

DESIGN CHECK

- Meridionial stress in the shell due to design value of actions on tower must satifsy the minimum design resistance for all failure modes:

$$\sigma_{ult,ED} = \frac{M_{Ed}}{W_{el}} - \frac{N_{Ed}}{A} \leq \sigma_{ult,Rd}$$

$$\sigma_{ult,Rd} = \frac{F_U}{c \cdot s}$$

M_{Ed} - is the design bending moment in the tower at the connection cross-section,

N_{Ed} - is the axial compressive force in the tower at the connection cross-section.

W_{el} - is the elastic section modulus of the shell at the connection cross-section,

A - is the area of the cross-section of the shell.

$$F_U = \min\{F_{U,A}; F_{U,B}; F_{U,C}\}$$

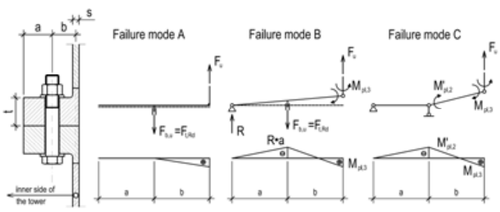
or

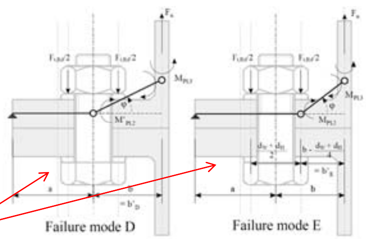
$$F_U = \min\{F_{U,A}; F_{U,B}; F_{U,D}; F_{U,E}\}$$

If the requirments are fullfiled!

COMPARISON TO FEA RESULTS

Failure modes by Petersen. Failure modes by Seidel.





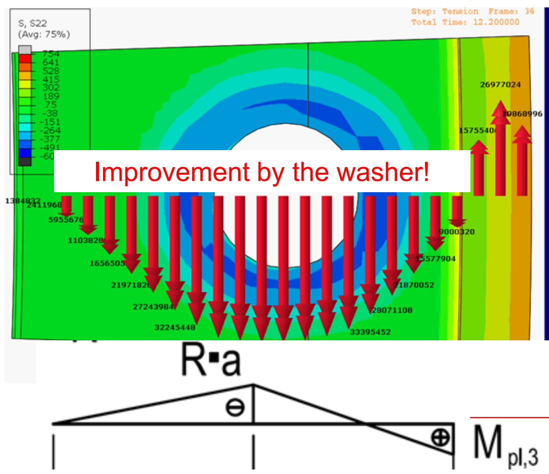
1679 kN | 979 kN | 617 kN

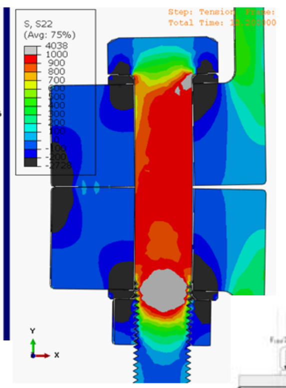
1009 kN | 1811 kN

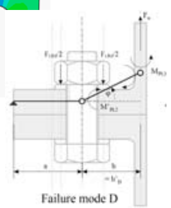
$F_{ult,FEA}$ = 983 kN

Verification of analytical failure modes!

ANALYTICAL VS. FEA RESULTS



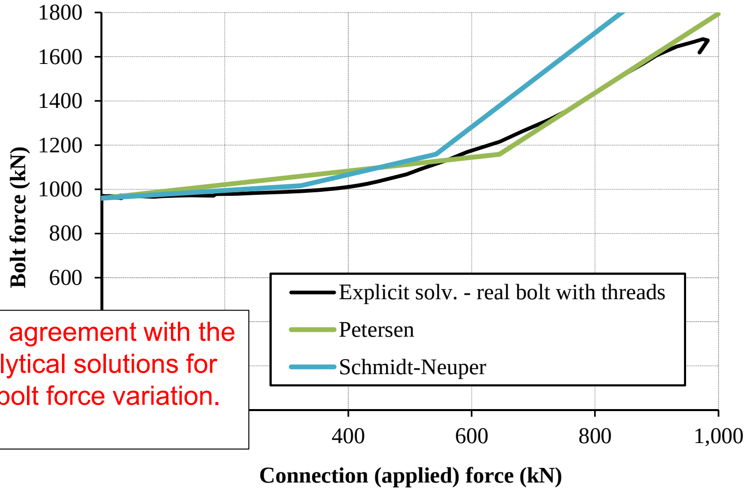




Good agreement with Seidel's assumption?

Failure mode B (Petersen)!

ANALYTICAL VS. FEA RESULTS

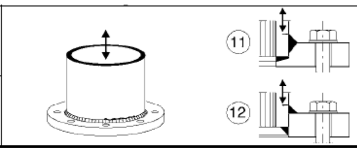
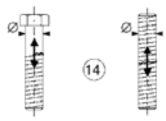


Good agreement with the analytical solutions for the bolt force variation.

FATIGUE – RING FLANGE CONNECTION

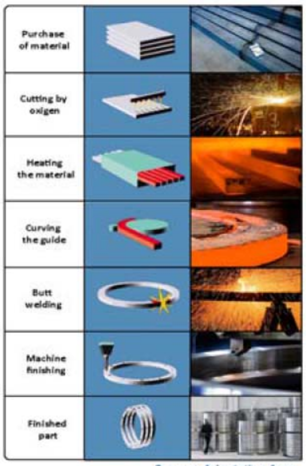
- Two fatigue failures are possible in the case of ring flange connection:
  - Weld zone between the shell and the flange (detail class 71) – mostly dominant,
  - Bolt fatigue endurance (detail class 50) – due to preloading this criterion is rarely dominant, utilisation factor is approximately 40%!

EN 1993-1-9 : 2005 (E)

71			11) Tube socket joint with 80% full penetration butt welds.	11) Weld toe ground. Δσ computed in tube.
40			12) Tube socket joint with fillet welds.	12) Δσ computed in tube.
50	size effect for $t > 30$mm: $k_s=(30/t)^{0.25}$		14) Bolts and rods with rolled or cut threads in tension. For large diameters (anchor bolts) the size effect has to be taken into account with k_s.	14) Δσ to be calculated using the tensile stress area of the bolt. Bending and tension resulting from prying effects and bending stresses from other sources must be taken into account. For preloaded bolts, the reduction of the stress range may be taken into account.

FABRICATION

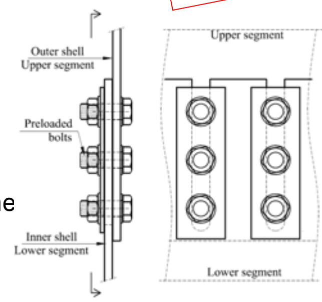
- Fabrication process of ring flanges is quite expensive.
- Approximate cost of the connection is 30k€
- High tolerances need to be achieved in order to have proper alignment of two adjoining flanges.



Source: Adaptation from www.barranquesa.com

FRICTION CONNECTION

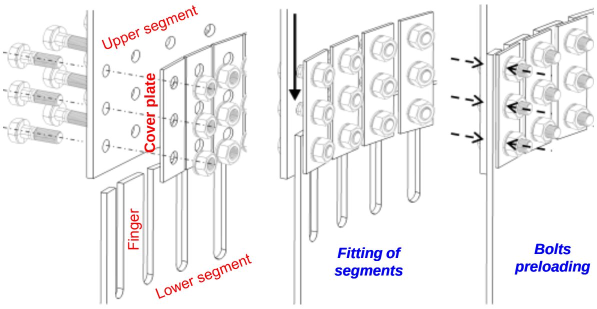
RESEARCH



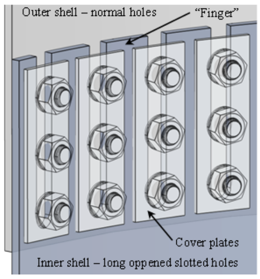
- Single lap joint
- Preloaded bolts – friction connection
- Long open slotted holes
- Competitive alternative to the ring flange conne
  - No additional thick flanges
  - Number of bolts is not limited
  - No welding – higher fatigue endurance
  - Possibility of adjustment of tower geometry during execution
- This type of the connection is still under research.
- Approximately 80 % saving of in the cost compared to classical ring flange connection is expected.

ASSEMBLING

RESEARCH



Feasibility test – HISTWIN



1. Bolts are pre-installed in the upper segment.
2. They easily slide on the top of the lower segment.
3. Bolts are tightened from the inside of the tower.

SLIP RESISTANCE ACC. EN 1993-1-8

RESEARCH

- Failure modes of a friction connection (Category C - slip-resistant at ULS):
  - **Slip resistance - $F_{s,Rd}$** (in general the governing one)
  - Bearing of the bolts due to contact pressure – $F_{b,Rd}$
  - Resistance of the net cross section – $N_{net,Rd}$

$$F_{s,Rd} = \frac{k_s \, n \, \mu}{\gamma_{M3}} F_{p,C}$$

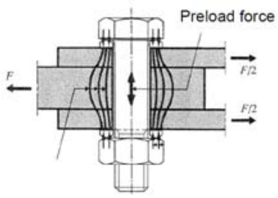
$F_{p,C} = 0,7 \, f_{ub} \, A_s$

μ – slip factor (Table 18 of EN 1090-2);

n – number of contact surfaces;

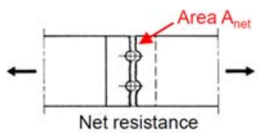
k_s – parameter (k_s = 1.0 for normalized holes;
k_s = 0.63 for slotted long holes);

γ_{M3} – partial safety factor taken as γ_{M3} = 1.25.



$$F_{b,Rd} = \frac{k_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t}{\gamma_{M2}}$$

$$N_{net,Rd} = \frac{0.9 \cdot A_{net} \cdot f_u}{\gamma_{M0}}$$



Net resistance

APPLICATION TO WIND TURBINE TOWERS

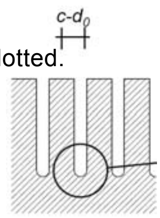
RESEARCH

- In the case of friction connection with long slotted holes some differences occurs compared to EC3 Part 1-8.

1. **Design slip resistance** $Z_{s,Rd}$ of one bolt row of the friction connection (segment model) can be determined as:

$$Z_{s,Rd} = \frac{n_s \cdot \mu \cdot k_s \cdot F_{p,C}}{\gamma_{M3}}$$

with n_s = number of bolts in rows;
μ = slip factor;
k_s = reduction factor for long slotted holes (k_s =0.63);
$F_{p,C}$ = characteristic preload force in bolts;
γ_{M3} = partial safety factor taken as γ_{M3} = 1.25.



2. Bearing resistance does not develop because the holes are slotted.
3. Resistance of the net cross section can be determined as:

$$Z_{net,el,Rd} = (c - d_o) \cdot s \cdot \frac{f_{y,shell}}{\gamma_{M0}}$$

with c = segment width = distance between two bolt rows;
d_0 = diameter of the hole;
s = shell thickness;
$f_{y,shell}$ = characteristic yield strength of shell material;
γ_{M0} = partial safety factor taken as γ_{M0} = 1.00.

SLIP FACTOR

- The friction surfaces and corresponding values of slip factors predicted in EN 1090-2, are described in the table:

Table 18 — Classifications that may be assumed for friction surfaces

Surface treatment	Class	Slip factor μ
Surfaces blasted with shot or grit with loose rust removed, not pitted.	A	0,50
Surfaces blasted with shot or grit: a) spray-metallized with a aluminium or zinc based product; b) with alkali-zinc silicate paint with a thickness of 50 μm to 80 μm	B	0,40
Surfaces cleaned by wire-brushing or flame cleaning, with loose rust removed	C	0,30
Surfaces as rolled	D	0,20

- In wind towers in general the surfaces are blasted and painted by alkali-zinc silicate paint (m = 0.40 to 0.50).
- For other surface treatment – the slip factor may be obtained through experimental tests, in accordance with the normalized procedure described in Annex G of EN 1090, Part 2.

DESIGN CHECK

- Meridionial stress in the shell due to design value of actions on tower must satifsy the minimum design resistance for all failure modes:

$$\sigma_{c,ED} = \frac{M_{Ed}}{W_{el}} + \frac{N_{Ed}}{A} \leq \sigma_{s,Rd} = \frac{Z_{s,Rd}}{c \cdot s} \qquad \sigma_{t,Ed} = \frac{M_{Ed}}{W_{el}} - \frac{N_{Ed}}{A} \leq \sigma_{net,Rd} = \frac{Z_{net,el,Rd}}{c \cdot s}$$

M_{Ed} - is the design bending moment in the tower at the connection cross-section,

N_{Ed} - is the axial compressive force in the tower at the connection cross-section.

W_{el} - is the elastic section modulus of the shell at the connection cross-section,

A - is the area of the cross-section of the shell.

FRICTION CONNECTION

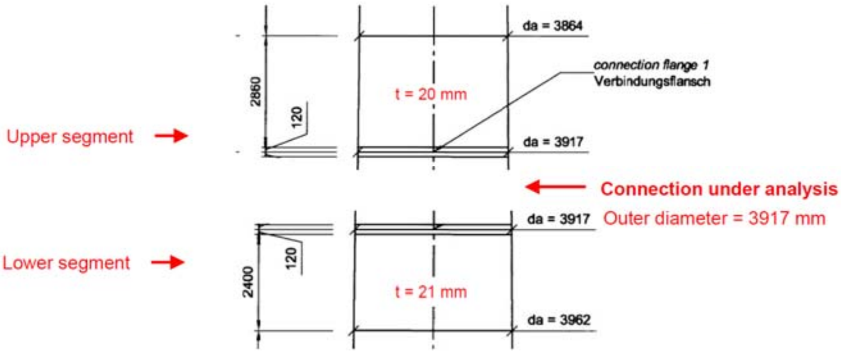
Hand calculation of the resistance at the Ultimate Limit State (ULS) of a connection between two segments of a wind tower, considering two equivalent configurations:

The tower considered in this example has a height of 80 m and it supports a three blade turbine with a diameter of 92.5 m and a nominal output of 2 MW.

- For design purpose it is assumed that the resistance of the three dimensional connection detail, which is loaded mostly in bending, can be described by the resistance of a segment with a single bolt (or a single bolt row in the case of friction connection configuration).
- The segment width *c* is equivalent to the arc length between two bolt holes or bolt rows in the tension zone of the shell.

FRICTION CONNECTION

Tower geometry at level of the connection under analysis



Connection at level 1 (connection between first and second tower segment)

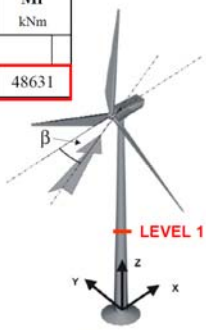
FRICTION CONNECTION –SOLVED EXAMPLE

Design internal forces due to extreme load cases, provided by a turbine producer, are given in a following table, at the cross-section of the flange 1:

	Height mm	Fx kN	Fy kN	Fz kN	Fr kN	Mx kNm	My kNm	Mz kNm	Mr kNm
Flange 1	21770	-886	27	-2443	886	1129	-48617	-1368	48631

- The effects of shear stresses on the resistance of the flanges are neglected and only the load components inducing longitudinal stresses in the shell (bending moment M_r and axial force F_z) are considered.

- The resistance will be verified in the tensile part of the tubular shell (the most unfavourable for connection design).



Coordinate system for the design loads

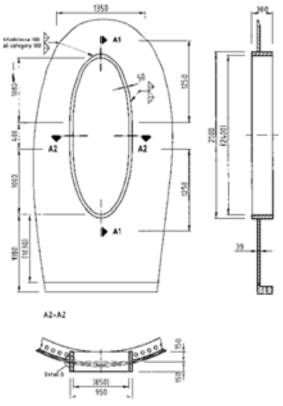
DOOR OPPENINGS

- Openings in the tower shell are very important for the design.
- Openings are made for two reasons:
  - for the door at the lower segment of the tower which is used for maintanace,
  - for ventilation.

OPPENINGS IN TOWER SHELL

- According to EC3 Part 1-6, an opening in the shell may be neglected in the modelling provided it's largest dimension is smaller than:

$$0,5\sqrt{rt} = 0,5\sqrt{2000 \cdot 20} = 100\text{mm}$$



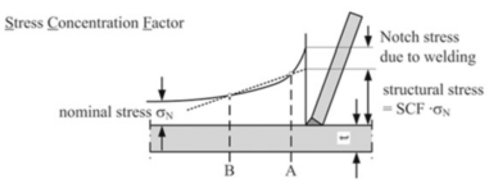
FAILURE MODES

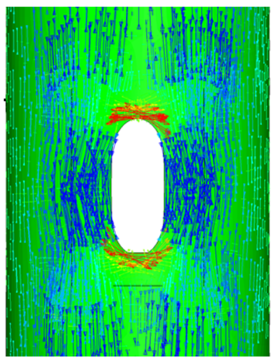
- Several failure modes can develop in the area of opening:
  - Ultimate limit state:
    - Buckling of the shell adjecent to the opening due to increased stresses and disturbed boundary conditions
    - Compressive plastic yielding in the areas of stress concentration.
    - Tensile rapture due to occurance of maximum principal stresses mostly above the opening
  - Fatigue limit state:
    - Crack failure due to reduced fatique endurance in the zone of stress concentration.

STRESS CONCENTRATIONS

- Stresses in the shell are increased around the door openning:
  - Meridional stresses are increased due to redistribution around the opening,
  - Stresses in other directions are also increased because of the disturbance of directions of principal stresses

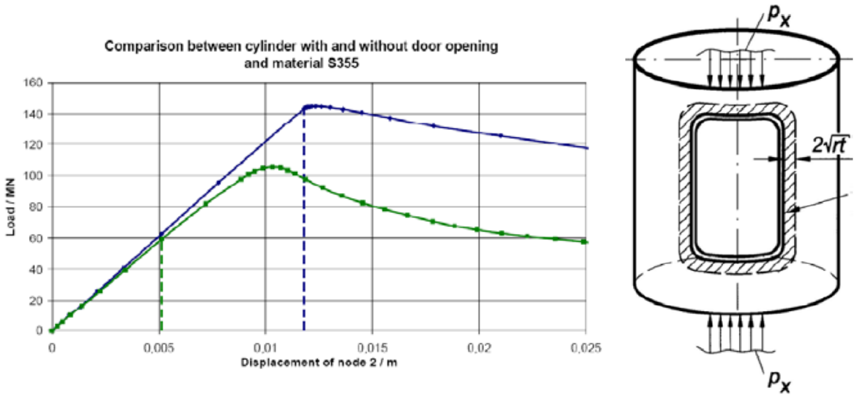
$$SCF = \frac{\sigma_{structural}}{\sigma_{nominal}}$$





STRESS CONCENTRATIONS

- It is supposed that stress cncentrations are located around the perimiter of the opening at distance of: $2\sqrt{rt}$



STIFFENING

- Stiffening of the door openning can be done either by:
  - Introducing thicker plates in the area of the oppening
  - Usage of edge-stiffeners around the oppening

BUCKLING STRESS LIMITATION

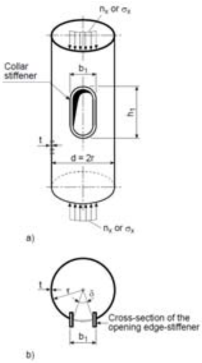
- In the area of circumferentially edge-stiffened openings without longitudinal stiffeners, simplified buckling design can be undertaken.
- Instead of critical meridional buckling stress, the reduced critical meridional buckling stress can be used:

$\sigma_{xS,R,d} = C_1 \cdot \sigma_{xS,R,d\text{-DIN}}$

$C_1 = A_1 - B_1 \cdot (r/t)$

A_1 and B_1 according to Table 6.6.1

δ opening angle along the girth



	S 235		S 355	
	A_1	B_1	A_1	B_1
$\delta = 20°$	1.00	0.0019	0.95	0.0021
$\delta = 30°$	0.90	0.0019	0.85	0.0021
$\delta = 60°$	0.75	0.0022	0.70	0.0024
Intermediate values may be interpolated linearly. Extrapolation is not permissible.				

$r = 2000\text{mm}$

$t = 20\text{mm}$

$0{,}81$ to $0{,}48$ $\quad$ $0{,}74$ to $0{,}46$

CONCLUDING QUESTIONS

- What is power coefficient of the wind converter?
- Which codes/standards and guidelines are used in design of towers for WT?
- What are the three most challeging limitations for tower heights?
- Why the design load tables prepared by the WT producer are necessary for design of towers?
- Which load scenarios should be used in predesign of WT towers?
- What is the detail class for fatique for the transversal weld between the tubular tower sections?
- How can we increase the detail class?

CONCLUDING QUESTIONS

- How are the various imperfections introduced into the buckling resistance model for the column?
- Why can we use the effective width concept for the plate?
- Do we choose the equivalent imperfection level for a plate according to EN 1993-1-5?
- Why are the cylindrical shells more sensitive to imperfections?

CONCLUDING QUESTIONS

- What are the four limit states covered by the EC3 Part 1-6?
- Which limit states are the most important for the wind turbine tower?
- What does the GMNA stands for?
- What are the geometrical imperfections in towers dependent on?
- Which stress components are the most important in a wind turbine tower?
- Which analysis type (design approach) is most conservative for the plastic limit state?
- How does the boundary conditions of the shell reflect it's critical buckling stress?
- What is the level of magnitude of the design circumferential buckling strenght?

CONCLUDING QUESTIONS

- How often are friction connections used in wind turbine towers?
- Is number of bolts in a friction connection limited?
- Where are the „fingers“ located, in the outside or the inside segment of the tower?
- Which failure mode is the most important for the friction connection?
- What is the approximate value of the slip factor for a blasted and zinc coated friction surface?

NUMERICAL EXAMPLES:

- Stability
- Connection
- Fatigue

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SYSTEMS LAB

Sustainable siting of an offshore wind park. A case study in Chania, Crete.

Mary Christoforaki
Professor Theocharis Tsoutsos, Lab Director

Introduction

- **Greek national targets of 2020 make the installation of big wind farms essential**
- **The offshore wind farms, in areas with promising energy potential, without legislation barriers and without creating conflicts with the nearby community**
- **The installation of wind farms has caused tension in the local community, basically due to the property conditions, to the reduced perception and information about the operation of wind farms**

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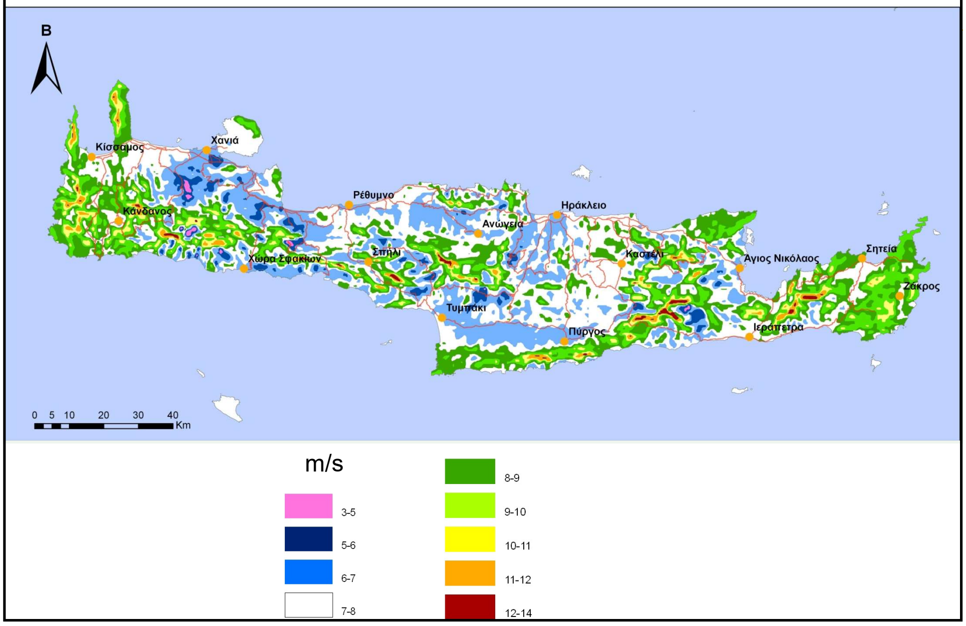
WIND ENERGY STATUS IN THE ISLAND OF CRETE, GREECE

WIND POTENTIAL



Legally Available WP Siting Areas

LEGEND

- Exclusion Zones
- Legally available areas for the installation of WPs

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METHODOLOGY

Methodology 1/3

- This project aims for the define areas with significant wind potential and characteristics (based primarily on RES legislation and on the Special Framework for Spatial Planning and Sustainable Development) that allow installing offshore wind farms around the province of Chania.
- The methodology is based on the use of GIS with application of ArcGIS 10.1
- The issue under scrutiny is the installation of an offshore wind park based on legal limits, with particular sensitivity of ecological and economic resources of the island. It will also be considered the visual, acoustic and aesthetic disturbance of the coastal's and marine area's residents/users

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Methodology 2/3

- 3 steps have been followed:
  - The exception of unsuitable areas (due to geological restrictions, visual and acoustical disturb, safety and of course due to environmental conditions)
  - Valuation of environmental impacts on birdlife, Special Protection Areas and Sites of Community Importance
  - Valuation of wind potential and needs of electricity in Chania

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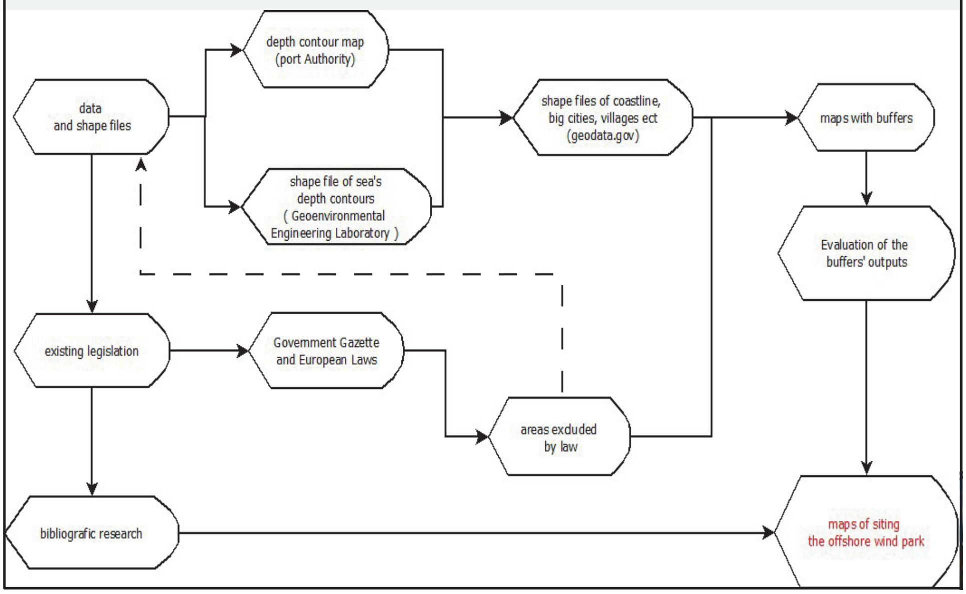
Methodology 3/3



Data_ Shapefiles 1/3

- Data were collected through the free data base of geodata.gov.gr.
- Specifically, data included by this source(following the legislative restrictions):
  - Settlements: The Settlements of the country as used by EL.STAT.(Hellenic Statistical Authority), for census purposes
  - Wildlife sanctuaries: the boundaries of the Wildlife Sancturaries established in accordance with the provisions of forest law and were demarcated based on the data of Forest Services.
  - National forests: the boundaries of the core and peripheral zone of National Forests as established and demarcated based on the data of the Forest Services; included in Natura 2000.

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Data_ Shapefiles 2/3

- Natura network and protected areas: The Natura 2000 Network is a European Ecological Network of sites which host natural habitat types and habitats of species that are important at a European level. Today Greece has designated 202 Special Protection Areas (SPAs) and 241 Sites of Community Importance (SCI), two of which are still under consideration.
- Archaeological sites and Ancient Monuments Positions: shows the locations of ancient theaters, conservatories and churches according to the list of the cultural association 'Diazoma'. Extra archaeological sites have been digitized for the needs of the study based on the culture ministry's data. ("Ministry of Culture and Sport")

Data_ Shapefiles 3/3

- additional data were used by the Laboratory of Geoenvironmental Engineering, TUC. The shape file concerns the depths' contours around the area of Crete.
- data were collected from CRES which concerns the maximum, mean and minimum electrical power per habitant, concluding 30 houses from a random municipality.
- Chania has 150.387 inhabitants (Greek Statistical Authority) and the maximum power demand is almost 52 MW; per resident is about 0,9-1,8 kW/inhabitant

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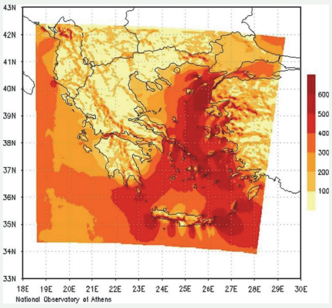
Data_ Wind potential

The existing wind potential for an offshore wind park close to the region of Chania was based on data from the National Observatory of Athens.



Wind potential (in W/m^2) at 50m (Kotroni et al., 2014)

- The wind potential is presented by an energy scale by 100 to 600 W/m^{D}
- in Chania, the wind potential is 300 to 600 W/O^{0}, the strongest value appears in the West.
- In order to support the objective of the current study, a typical year (20 years of observation) based only on the wind flow over Greece and the surrounding maritime areas has been defined.

Nature conditions

- The island accommodate 1.750 species of plants, from which 9% of them are endemic species of Crete. It consists a station of the migrating birds, which explains the amount of 350 different kinds of birds, that have been observed
- At the region of Chania has also been observed sea meadows and coral reefs, which protect the underwater flora of the area. These areas, called ‘Poseidonias meadows’, are in the red list of the International Union for the Conservation of Nature (IUCN), as they have been reduced due to human activity.
- These special areas have the benefit of increasing the biodiversity of the coastal zone, binding the CO_2, harboring endemic species of fish and protecting against coastal erosion. These zones are Special Protection Areas (SPA) for the avifauna.

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Human Impact

- **Visual impact and the social acceptance of the installation of a wind farm close to the coast: The zone of visibility, where the turbines could be visible but assimilate by the landscape extents over the distance of ~x10 the height of the wind turbine.**
- **The subjective factor brings remarkable restrictions not only on visual evaluation but also on the acoustic impacts; these distributions could not have been the result of a simple simulation software.**
- **The current methodology overestimates the distribution of the coastal users and situates the turbines at a distance of the coast much >x10 their own height.**

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Identification of the Legally Available Siting Areas

Identification of the Legally Available Siting Areas

Law 2464/3.12.2008, article10

Areas where the siting of wind farms according to the Specific Plan for Spatial Planning and Sustainable Development for RES is not permitted in:

- **Archeological Sites**
- **Areas within the limits of cities or villages**
- **Areas with organized development of productive activities in the tertiary sector, in thematic parks and marinas**
- **Coasts**
- **quarry areas**
- **natural conservation areas**
- **Ramsar wetlands**
- **national parks and declared monuments of nature and aesthetic forests**
- **bird Protection Areas**

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Identification of the Legally Available Siting Areas

Law 2464/3.12.2008, Annex II

Minimum distances must be applied from:

- **Areas of environmental interest**
- **Areas and elements of cultural heritage**
- **Areas of residential activities**
- **Networks of technical structure and special uses**
- **Zones of productive activities**

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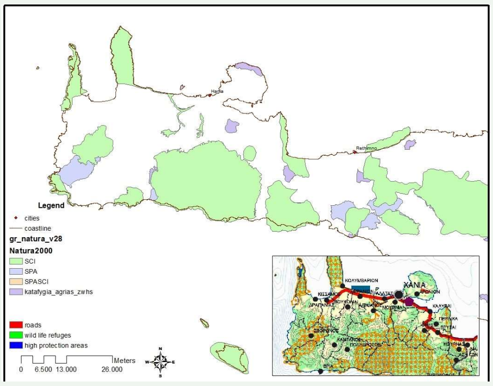
Result _ Natural Landscape



Map of protected areas and wildlife shelters

- **Enormous spaces of land, covered by special protection areas and sites of community importance. Obviously, the range of this site type spreads into the sea, which means that concern some sea species too.**
- **In Poseidonia areas any activity is prohibited.**

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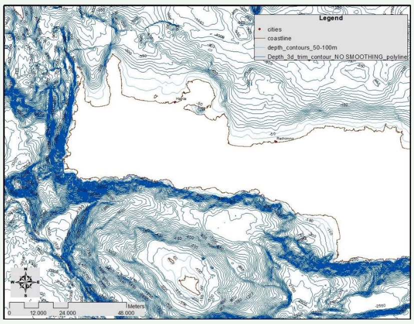
Result _ Natural Landscape



Contours of depth around Chania

- **The map of contours around Chania indicates that in a short distance of the coastline, appear contours up to 600m.**
- **Especially, on the south and the west coast, the relief is intense. On the west coast, in a distance of 1.200-1.500m, there are depths between 600 and 1.000m.**

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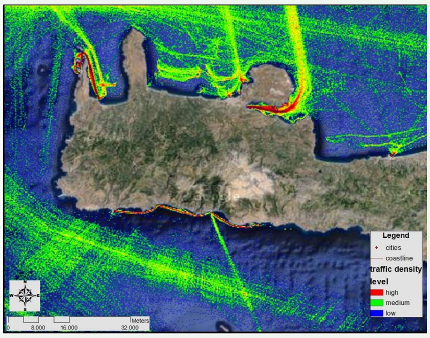
Result _ Human Activity



Map of marine traffic ("Live Ships Map - AIS - Vessel Traffic and Positions - AIS Marine Traffic," n.d.)

- **The density of ships' movement is high at the north site where the port of Souda and the old harbor are situated, and on the south where small ships connect some tourist attractions like the Samaria gorge, Sfakia and Paleochora. Medium and low activity movements can change if there is a serious problem or danger.**
- **The military installations are not depicted on the maps therefore there is not complete information about the activity developed in the area.**

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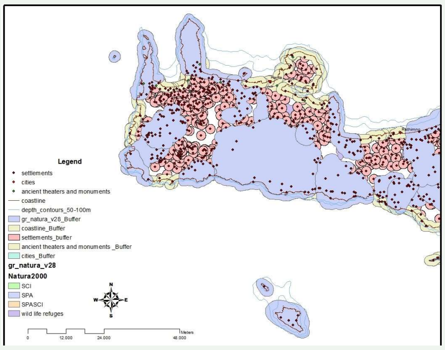
Result_ Exclusion Steps



Map of exclusion, distances institutionalized by law

The elements of contours will be introduced according to their values. Initially those with value smaller than (50) m settlements, ancients theaters and monuments, cities and coastline.
Then, the first available areas will be defined according to present law regulations and due to the distance by the coast, the settlements and cities (1.500m). Additional areas referred in the legislation, are overlapped by the above.
Some areas in south and west to be excluded due to morphology of depth contours and distances set by the legislation, although the wind potential is considerable evidence for siting offshore wind farm.

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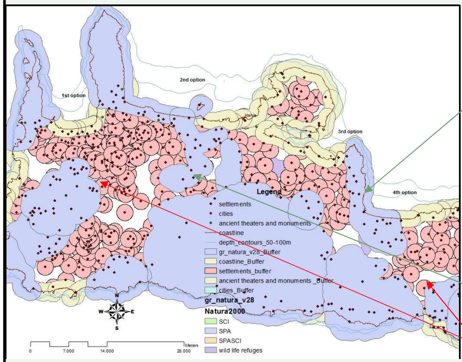
Result_ Exclusion Steps



Regions capable of siting turbines

3rd option: The area that seems available on east site of Chania can should be blocked because of the intense coastal activity and the establishment of military installations of NATO
The establishment of an offshore wind farm affects specific pieces of flora and fauna. Underwater disturbance needs to be assessed primarily and subsequently the aerial nuisance. The study on the siting will take place with strict exclusion limits of these areas by keeping a minimum distance of 1.500m from the surroundings.
2nd option: Due to environmental constraints and mainly due to the existence of underwater meadows, important for biodiversity of Chania Bay, the siting scenario in the available area. An additional reason is the productive tertiary activities (shaped tourist areas) that implies the visual impact on users.
Options 1 and 4: restrictions shoreline coincide with the NATURA2000 regions. Also, in some cases the distances define exclusion areas overlap and therefore have been omitted.

Result_ Exploitation Steps

Type of VESTAS V80-2.0 MW	
Diameter	80 m
Area swept	5027m^2
Nominal revolutions	16,7 rpm
Number of blades	3
Tower height	80m

Scenarios

Wind turbine 's characteristics

	Scenario	
	1st option	4th option
Wind speed at50m	6-7m/s	5-6m/s
Wind speed at 80m	6,5-7,6m/s	5,4-6,5m/s
Wind potential at 50m	300-400W/m^2	200-300W/m^2
Free surface	11,1km^2	21,8km^2
1st scenario	86 turbines	157 turbines
	172 MW	314 MW
2nd scenario	26 turbines	26 turbines
	52MW	52MW

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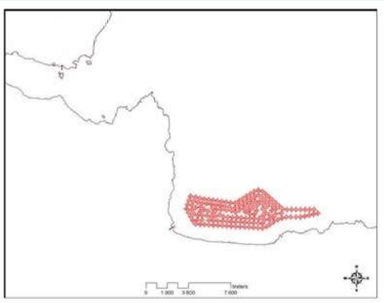
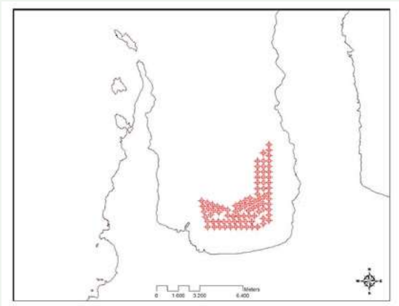
Result_ Exploitation Steps

Scenario 1: installation at a distance of 400m between them and the coverage of all available surface. The maximum carrying capacity of sustainable regions is determined, in other words the maximum wind power (MW) that can be installed in them is estimated.



Map of siting the WP, at the 1st option ,scenario 1



Map of siting the WP, at the 2nd option, scenario 1

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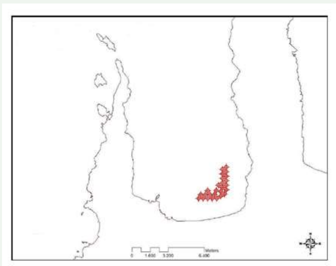
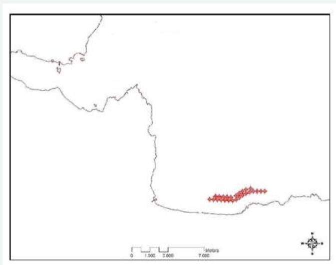
Result_ Exploitation Steps

Scenario 2: installation of VESTAS V80-2.0 MW wind turbines in a row with a distance of 400m between them, based on the maximum power demand per capita for a random region of Greece multiplied by the number of county residents. This calculation is not absolutely correct because the consumption varies.



Map 8:Map of siting the WP, at the 1st option, scenario 2



Map 9:Map of siting the WP, at the 2nd option, scenario 2

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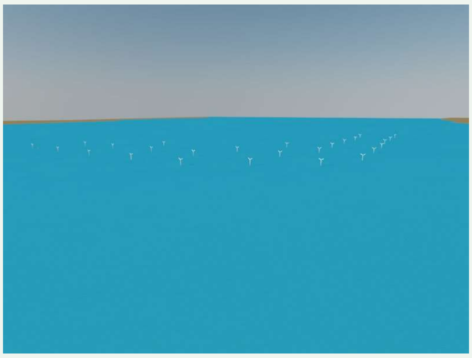
Result_ Exploitation Steps

- The wind direction is at a greater rate of the North, West and Northwest, so the wind turbines are placed vertically in the same direction, even If the mechanism allows them to rotate when the wind direction changes.
- Indicatively, the 3D render of the 2nd Scenario for 1st option is presented to understand the size and extent of WP. For the 3D rendering creation it has been used SketchUp2015 software.



3D render of the 2nd Scenario and 1st option

Conclusion 1/4

- The issue of sustainable siting of an offshore wind farm follows in each case of study, different approximate reasoning that relate the particular characteristics of each country in which it was performed. Current legislation and spatial planning resulting from climatic, geomorphological, social and culture and elements is different for each country.
- In any case, the decisions on area exclusions are associated with usage of GIS software, however there is variety in the analysis method chosen each time. The analysis process is determined by the evaluation of exclusion criteria and the weight given to each of them .

Conclusion 2/4

- In the present study, largely environmental constraints examined legislation and not economic criteria of the WP installation.
- The optimal location was evaluated based on the remaining surface, although this is the best aesthetic distribution of wind installations. Nevertheless it has been implemented in a way that affects as little as possible the natural and human environment.
- The visual impact is considered negligible, because the distance from the coast is almost 20 times the height of the wind turbines. Therefore, the visual impact is not an actual issue.
- The acoustic disturbance can be avoided by keeping sufficient distance from the shore

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Conclusion 3/4

- The dynamic data structure of this study may be renewed and enriched with further information depending on possible change of land use planning or changing exclusion areas.
- the areas with the strongest wind potential are not appropriate for installing WP due to their big depth in a very short distance from the coast
- two suitable locations were found, with less wind potential but sufficient space, to cover a large part of the Chania regions‵ needs. Furthermore, areas deemed suitable are considered closer to possible interconnection point either with the island's network or with what is proposed for linking the island with the rest of Greece (north coast).

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Conclusion 4/4

The two options of sustainable installation of a WP have not been studied in the sense of capacity therefore criterion of the wind potential is introduced. The first area is considered ideal having strongest wind potential, whereas the second region has a greater carrying capacity. With the installation of turbines type VESTAS V802.0MW, which by today's standards are considered small, it is possible to cover both areas with wind turbines which correspond to approximately 490MW,increasing by 24,7% the total installed wind power of Greece (compared with the elements at the end of 2010).

Conventional forms of storage are not considered efficient due to the size of the energy. Therefore, the study on the creation of hybrid storage stations should be performed immediately before the possible authorization of a large RES installation. This will help to lower production costs by reducing the consumption of expensive fossil fuel and maximizing the penetration of the available RES in each isolated system.

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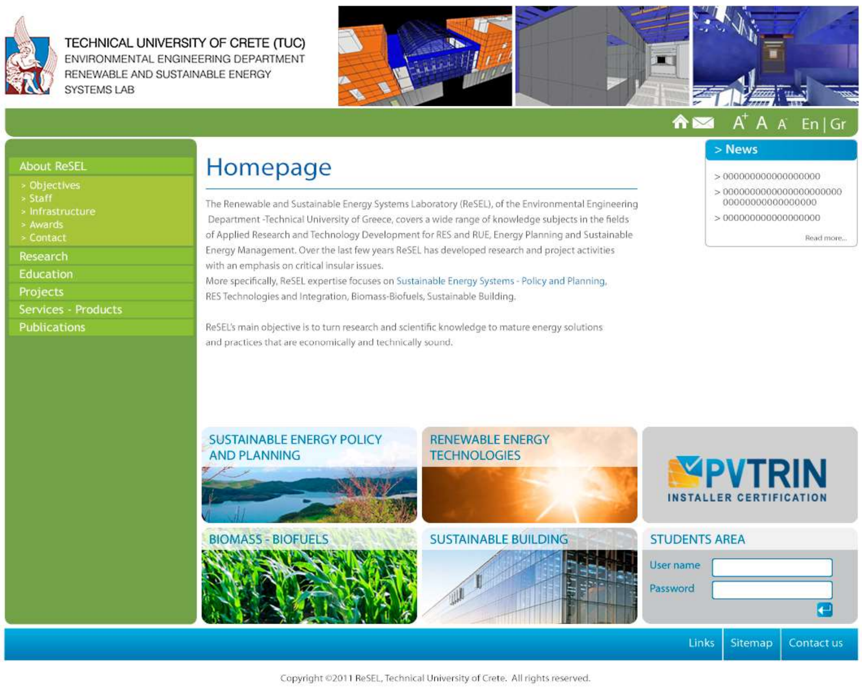

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TU 1304 – WINERCOST
Advances in Wind Energy Technology II
Chania, 4 - 8 April 2016

Piezocomposites for energy harvesting

Georgios E. Stavroulakis, Ioannis Fournianakis,
Panagiotis Koutsianitis, Georgios Tairidis
Institute for Computational Mechanics and Optimization www.comeco.tuc.gr
School of Production Engineering and Management,
Technical University of Crete, Greece

ABSTRACT

Every vibrating structure can be used for energy harvesting. Usually small ammount of energy can be gathered.
A model smart beam with embedded piezoelectric components are studied, in order to investigate the maximum amount of energy that can be produced. They can be used in submerged offshore structures subjected to external wave forces.

The various quantities used are defined below:

f_I = Inertia force (N)
f_D = Drag force (N)
L = Beam length (m)
A = Cross-sectional area (m^2)
ρ = Mass density of the beam(kg/m^3)
Y = Elastic Modulus
V = Volume of the beam (m^3)

SMART MATERIALS - PIEZOELECTRICS

Piezoelectric materials have the ability to produce electric charge when subjected to mechanical stresses or vibration and are widely used for the formation of sensors and actuators in smart composite structures for static and dynamic analysis and control as well as for mechanical energy harvesting from vibrations.

The design of the harvester, which is based on the usage of piezoelectric elements, is performed in such a way as to be able to obtain the maximum amount of energy. The geometric characteristics of the structure play a significant role in the overall results. Usage of structural optimization can optimize the performance.

Modal analysis within a finite element model is used.

$$\{X\} = \sum_{i=1}^{N} \Phi_i \eta_i(t) = [\Phi]\{\eta\}$$

$$\{\ddot{\eta}\} + \left[\Omega^2\right]\{\eta\} = [\Phi]^T \{F_m\} - [\Phi]^T \{F_{el}\}$$

$$E = \frac{1}{2} Y \left(\frac{\Delta\varphi}{L}\right) V_{vol}$$

$$\Delta\varphi = \left(\varphi_i^j - \varphi_{i+1}^j\right)\frac{h}{2}$$

TWO MODEL HARVESTERS

For the design of the offshore energy harvester let us consider a beam vertically positioned and fixed at the bottom end.

- The total height (*H*) = 3.0m and
- width (*W*) = 0.30m placed on submerged structure at 3.0m depth.

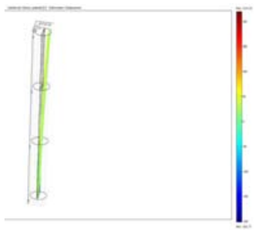
The piezoelectric materials have the form of thin plates that are placed longwise in each model. The piezoelectric material selected is PZT-4 with the following properties: Crystal symmetry class, uniaxial and density7500 kg/m3. More specifically, for the first model piezoelectric material is placed on the outer side of the beam, while for the second model inside the beam.

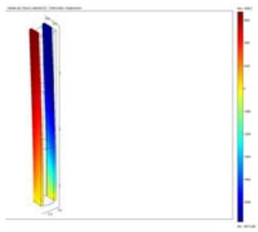
The force applied along the surface of the beam *f(z, t)*, by the wave phenomenon is given by the Morison equation:

$$f(z, t) = f_I(z, t) + f_D(z, t)$$

FEM ANALYSIS OF TWO HARVESTERS

the vertical displacement and the total electric potential of each structure





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RESULTS

A parametric investigation shows how the system changes under the addition of an extra mass at different positions of the cantilever.

Element of extra mass	Node of max energy	Amount of max energy (J)	Element of extra mass	Node of max energy	Amount of max energy (J)
1	1	1562.80	17	1	1149.20
2	1	1562.80	18	1	1052.10
3	1	1571.60	19	1	957.84
4	1	1582.10	20	1	868.25
5	1	1596.20	21	1	784.51
6	1	1612.30	22	1	707.24
7	1	1627.50	23	1	636.60
8	1	1638.40	24	1	572.49
9	1	1640.80	25	1	514.61
10	1	1630.80	26	1	462.56
11	1	1605.00	27	1	415.89
12	1	1561.90	28	1	374.10
13	1	1501.80	29	1	336.75
14	1	1426.70	30	1	303.39
15	1	1340.20	31	1	273.59
16	1	1246.40	32	1	246.98

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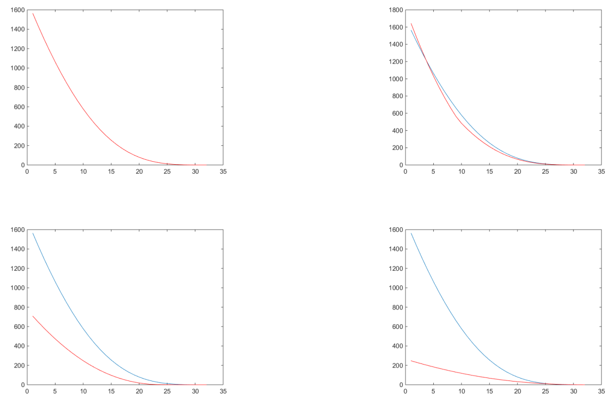
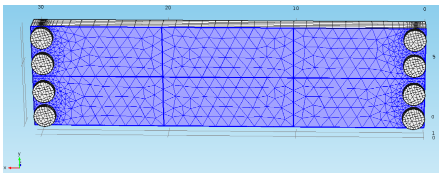
RESULTS

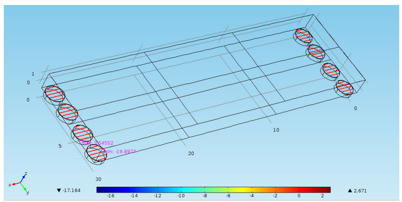
In the following figures the fluctuation of energy at each element before (blue line) and after (red line) the adding of the extra mass are shown.



OTHER APPLICATIONS AND REFERENCES

PZT harvesters placed at the support of a bridge (Vassiliki Kokkinou, Diploma Thesis, TU Crete, 2015)





Optimal shape design of a PZT plate (for micro-senror or harvesting applications)

REFERENCES

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WINERCOST Action

2nd Training School: “Advances in Wind Energy Techology II”

Chania, Crete, April 2016

Agent Cooperatives for Effective Demand-Side Management

Georgios Chalkiadakis

Associate Professor

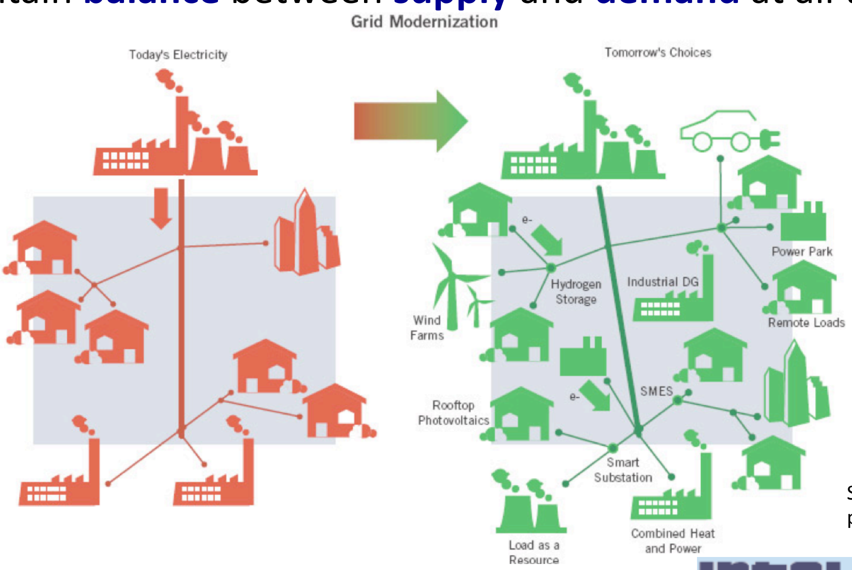
School of Electronics and Computer Engineering

Technical University of Crete

Transition to a Smart Electricity Grid

- Information exchange, more (intermittent) sources, distributed energy generation, renewables, electric vehicles
- Maintain **balance** between **supply** and **demand** at all times

Generation follows demand



Alter demand patterns to follow generation (Demand Side Management)

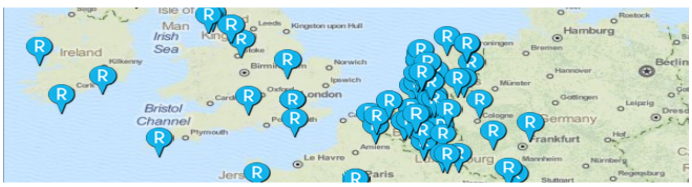
Source: powerelectronics.com

Demand-Side Management (DSM)

- Simple "peak-trimming" demand reduction schemes: not pro-active; can be "gamed"; too late => not enough
- Need for pro-active demand-side management
- Must guarantee smooth business operation and certain levels of people's comfort: demand shifting
- Effective DSM requires statistical forecasting methods, machine learning, artificial intelligence, game theory, optimization, decision theory

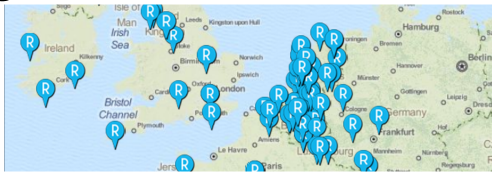
Demand-Side Management (DSM)

- Actors must coordinate with each other
- Need for effective **large-scale** demand-side management
  - One actor alone is not sufficient to make a difference
- Coordination via Cooperation:
- Intelligent agent cooperatives for large-scale DSM
- More than *2,500* real-world REScoops in Europe with *>300.000* members, *billions of euros* work-cycles



RESCoops: Activities

- Might have own production units
- Buy “green” power from others
- Sell electricity to members and to the Grid
- Implement *demand-side management* schemes
- H2020 CSA project: RESCOOP plus



Programme co-funded by the EUROPEAN UNION

RESCOOP.EU plus

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RESCoops focusing on Power Production

- Virtual Power Plants (VPPs)
  - Many small producers, act as a single large entity
    - considered as a single plant from the Grid’s perspective
    - USA: 840 distribution systems and 65 G&Ts coops
  - Achieve cost efficient integration of distributed energy resources (DERs)
  - Tackle uncertainties related to production estimates
  - Can end up with better sales deals

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RESCoops implementing Demand-Side Management Schemes

- Mainly: Demand reduction *"on request"* for peak-trimming
- Provide "negawatts" to the Grid
- Vision: Pro-active Demand-Side Management
  - Strike joint deals with the Grid
- Requires: incentives to contributors…
  - Economic (better prices/reduced bills), or
  - Social (e.g., status, "likes", growing network, etc.)

How can we do this properly?

Intelligent Agent Solutions for Effective RESCoops

- **Cooperative game theory** and **mechanism design** to the rescue
  - The mathemetics for incentivizing efficiency and coordination
- => mechanisms ("games") incentivising demand reduction, consumption shifting, or production predictions accuracy
  - Negotiations: exchange of information regarding contributors' (stated) preferences, costs, constraints, etc.
  - Commitments: actors will act as collectively agreed, or else…:
  - *Penalties, Exclusions, Negative incentives*

Intelligent Agents for Reliable RESCoop Production

- Reliability of supply: *future production estimates must be as accurate as possible*

1. Cooperative members state their production forecasts
2. Member receive payments that are "proportional" to their accuracy
   - They are better off by being truthful and accurate
   - Achieved via "scoring rules"

Intelligent Agents for Effective RESCoop Consumption Reduction

- Cooperative interaction with the Grid:
  1. Estimate collective reducable amount
  2. Place bid in the market
  3. Redistribute achieved revenues to coop participants
- Incentive compatibility
  - Participants must not be able to "game" the scheme

Intelligent Agents for Effective RESCoop Consumption Reduction

- Solution:
  - Choose participants with *some probability*
  - If an actor over-consumes energy only to show large reductions,…
  - …it will in the long run suffer monetary losses
- Simulations: cooperative participation => higher daily revenue than when acting alone

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A Novel Paradigm: Cooperative Demand Shifting

- Idea: Shift consumption to intervals when:
  - renewable production is high, i.e. excess of renewable energy
  - electricity demand is lower
- Avoid the formation of large peaks in demand:
  - Increase Grid reliability
  - No need to turn on (conventional) emergency generators
- Monetary incentive: offer better prices for large-scale electricity consumption shifting
  - i.e., large enough to reduce Grid's costs

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Cooperative Demand Shifting: what we achieve [Akasiadis & Chalkiadakis, '13,'14,'16]

- We propose methods for selecting teams (coalitions) of participants to shift demand
- We provide incentives to participating agents to be truthful and accurate
- Cooperative formation allows the incorporation of agents with initially forbidding shifting costs
  - **Reward sharing** between members internally to the cooperative
  - Inspired by group buying schemes
- An incentive compatible "Win-Win" mechanism:
  - Individually rational : Agents do not lose from participation
  - Truthful: Private preferences are truthfully revealed
  - Weakly budget balanced: Profits are shared proportionally to the contribution

Demand Shifting: The scheme

- Agents state their:
  - Reduction capacities during peak intervals
  - Shifting costs, for shifting to non-peak intervals
  - Confidence factors, regarding willingness to act as stated
- Coop selects agents based on their "shifting potential"
- Shifted consumption is charged with *lower prices*
- Bills scaled according to accuracy between cooperative stated and final actions (use of CRPS scoring rule)
- Charges are redistributed among members
  - Most profited agents might grant some profit to negative gain ones
  - Most profited agents are still most profited
  - Agents with negative gain can contribute without losses
  - Accurate members achieve more gains than the inaccurate ones

Simulations: (the hard-to-get) Datasets

- Dataset A: Industrial consumers from India
  - 4968 agents based on real power consumption data
  - Reduction capacities estimated based on the variance of baseline consumption
- Dataset B: Municipality of Crete (Kissamos)
  - 7954 simulated agents based on real power consumption data
  - 7 contract types
  - Reduction capacities based on real proportionate values
- Shifting costs follow beta distributions
  - no real data available
- Stated uncertainty estimated given consumer type, follows another beta distribution
  - no real data for this aspect either

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Simulation results (daily averages)

- India 4968 participants (Industrial) :
  - Gains: 930 Euros
  - Shifted amount: 24 MWh
  - Peak demand trimmed: 98%
  - Average shifting coalition size : 50 actors per time interval
- Kissamos: 7954 participants (7 contract types):
  - Gains: 195 Euros
  - Shifted amount: 2.5 MWh
  - Peak demand trimmed: 95%
  - Average shifting coalition size: 250 actors per time interval

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The future: Prosumer RESCoops

- A prosumer both produces and consumes energy
  - Examples: houses with PVs, wind turbines, electricity storage infrastructure, industries with power generators
- Optimize wrt both selling price and buying price
- Collectively seek "bargains" in the wholesale market
- Need for careful planning, many factors & constraints
  - User comfort
  - Renewable production forecasts
  - Future demand predictions
- Cooperative consumption shifting can affect the prices

The future: crypto-currency for Prosumer RESCoops

- Coordination and reward sharing with a crypto-currency approach
- Distributed consensus, no need for
  - Centralized cooperative managers
  - Other third-party mediators
- Idea: Mine currency (generate money!) given prosumers production and demand reduction/shifting actions
- The cooperative generates its own coins and distributes them wrt
  - Proportionality of contribution
  - Accuracy
- "Coopcoins" can be traded back for other currencies (economic)
- Coopcoins indicate engagement and contributor efficiency (social) & help create a "job market" for efficient cooperative members

Prosumers and Prosumer Coops: The future is here

- Ongoing research – already achieved promising results:
  - ✓ Can compute optimal buy/sell/store decisions of (standalone) prosumers for participating in day-ahead power markets

  When prosumers are in a coop:
  - ✓ Increased prosumer profits due to rescheduling consumption when prices are better
  - ✓ Electricity price stability: Cooperatives help reduce large price fluctuations which the cooperative can help to reduce
  - ✓ Simulations show we can reduce energy "imports" from polluting energy sources

Conclusions

- Intelligent agents and multiagent systems technologies are essential for
  - Grid reliability
  - Efficient use of renewable energy
- Demand side management with intelligent agents can
  - help keep the demand curve flat at all times
  - improve users' comfort
  - achieve bill reductions

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3. Charilaos Akasiadis and Georgios Chalkiadakis: **Agent Cooperatives for Effective Power Consumption Shifting**. In Proc. of the 27th AAAI Conference on Artificial Intelligence (AAAI-2013), Bellevue, WA, USA, July 2013.
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Thank you!

Contact info:

Georgios Chalkiadakis
gehalk@intelligence.tuc.gr
http://www.intelligence.tuc.gr/~gehalk

InteLLigence Lab
School of Electronic and Computer Engineering
Technical University of Crete, Chania, Greece

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Lecture

Life Cycle Environmental Impact of Wind Energy Projects

Dr. **Ruben Paul Borg**[a]

[a] Faculty for the Built Environment, *University of Malta, Malta*
ruben.p.borg@um.edu.mt

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- **PART B**: LCA: Comparative Life Cycle Assessment: Structural Design & Life Cycle Assessment
- **PART C**: Environmental Impacts of Wind Energy Projects
- **PART D**: Challenges in the Implementation of Wind Energy Projects: Case Study Malta

A Review of Life Cycle Impact Analysis of Wind Turbines

PART A

A Review of Life Cycle Impact Analysis

of Wind Turbines

Outline

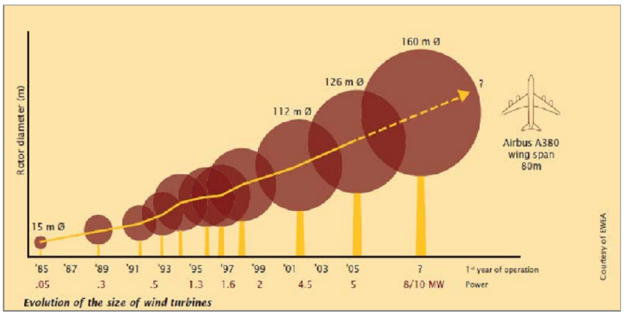
1. Introduction
2. LCA Methodology (the standard for LCA)
3. LCA for Wind Turbines
4. Comparison of Results
5. Discussion
6. Conclusions

Introduction

Wind turbine growth led to the following developments:

- Use of new composite materials and new design adaptations for blades
- Increase in blades sizes to increase the swept area and energy yields
- Use of new advanced gear boxes and geared drive solutions
- More use of direct-drive generators

However
- Increasing sizes require bigger generator diameters
- Increased blade sizes may cause higher fatigue
- Higher towers create new practical O&M challenges



Evolution of the size of wind turbines

Introduction

Management Considerations:

- Wind farms and turbines are now remotely monitored.
- Technical problems are detected earlier and failures are easier to predict.

This reduces cost and increases the returns

Challenge:

Bigger turbines cause more logistical and construction challenges and are associated to higher costs.

Introduction

The trend to off-shore farms creates a new set of challenges:

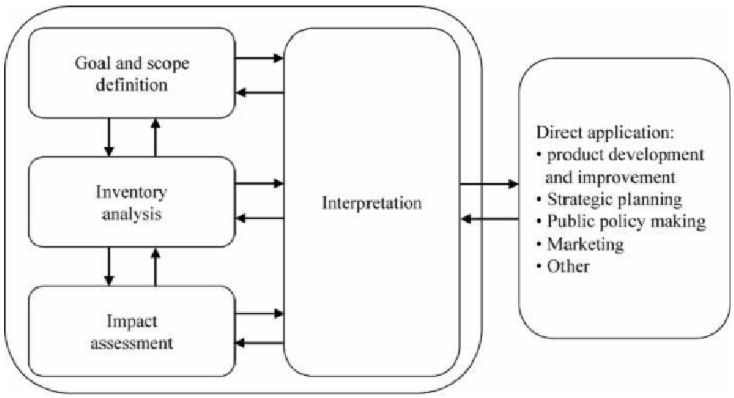
- systems must be more reliable and adapted to marine conditions
- logistics and installation is much more difficult
- grid related challenges

This increases the cost

- Therefore a very detailed analysis and comprehensive assessments must be carried out towards energy yield, investments and environmental issues.
- Addressing the entire system including manufacturing and installation processes.

This is easily achievable through a LCA

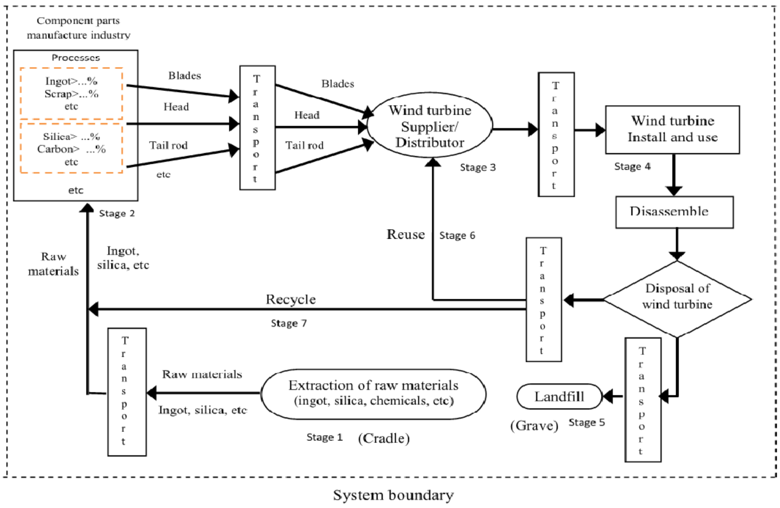
Life Cycle Analysis (LCA)



Life Cycle Analysis (LCA)

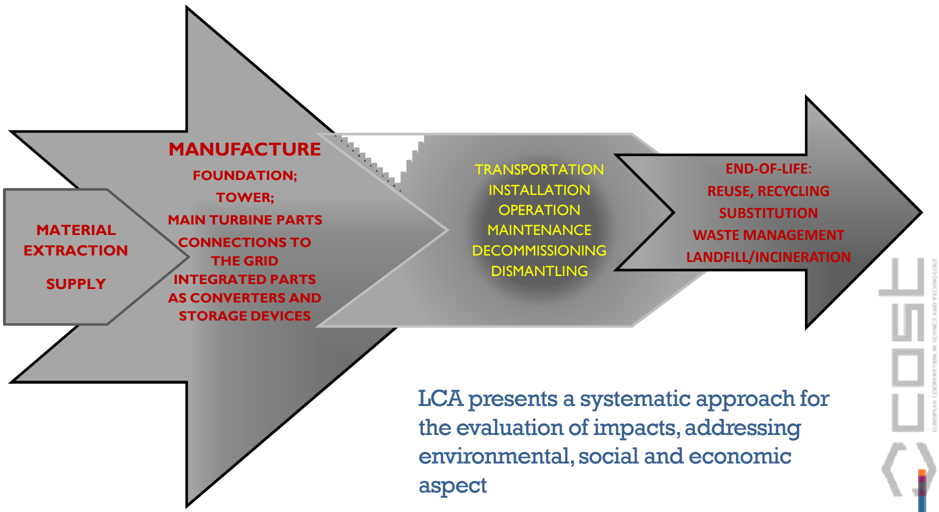
- Renewable Energy (RE) sources, such as wind energy, are preferred over non-renewable sources, primarily due to the potential reduction in greenhouse gas (GHG) emissions.
- Large scale Wind Turbines (WTs) present significant challenges as discussed in this paper. Meanwhile, recent developments in micro-generation 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. Near-zero energy buildings relying on the energy produced on site have been demonstrated and developed for different climatic regions.
- A life cycle assessment (LCA) allows for environmental impact evaluation during the whole life cycle stages from production, to operation, generation of energy on site, disposal and reuse or appropriate waste (end-of-life) management.
- LCA leads to a comprehensive evaluation of performance of a technology.

LCA for Wind Turbines



Reference: Uddin, 2014, Energy, emissions and environmental impact analysis of wind turbine using LCA techniques.

LCA for Wind Turbines



LCA presents a systematic approach for the evaluation of impacts, addressing environmental, social and economic aspect

LCA: Comparative Analysis 1/2

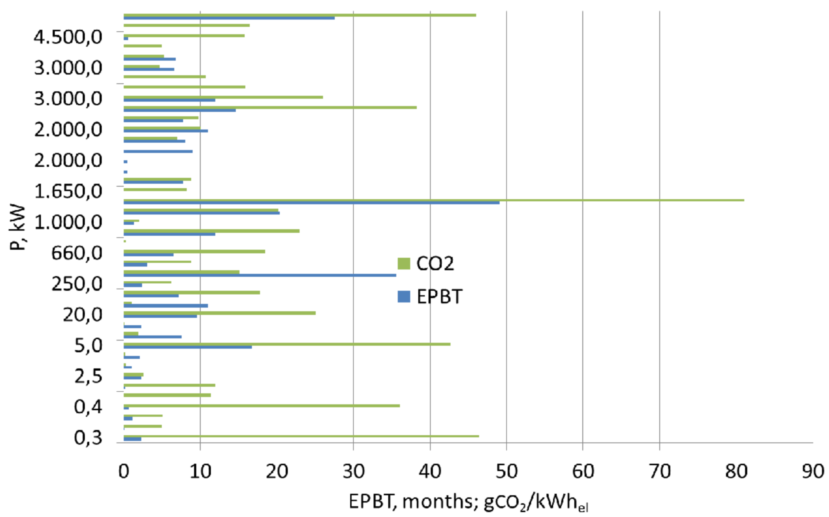
Ref., date	Technology	C_p	Size, kW	A, m^2	Site	LFT, yrs	EPB-T, mths	Energy intensity	CO_2 intensity
[14], 2013	N/A	0.2	0.4 2.5 5 20	1.08 19.6 31.9 70.9	Thailand, *On*	20	1.2-0.7 2.3-1.0 7.6-2.1 11-2.3	29.75-3.59 2.89-0.24 3.62-0.19 2.15-0.09	36.06-5.11 2.59-0.29 1.94-0.15 1.09-0.057
[17], 2009	*H*	0.33-0.34	850 3000	2123.72 6361.74	Australia, *On*	20 / 30	12	N/A	23-26
[7], 2002, [10], 2004	N/A		S; M; L	1.77-283.5; 707-3217	Brasil/ Germany	N/A	6-49	0.09-0.77	2-81
[11], 2012	N/A	0.18; 0.22; 0.31; 0.43 *Off*	S; M; L	N/A	*On* *Off*	15-30	N/A		16-12
[18], 2014	*V*; *H*;	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, *On*	20	0.43-0.53	N/A	
[19], 2012	N/A		>1000	N/A	Various regions: USA, EU, East sites	N/A	1.3-20.4-49	N/A	2-20.2-46.4-81-168-185
[20], 2009	*V*; *H*; 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

LCA: Comparative Analysis 2/2

[24], 2010		0.29 0.45	100× 3000	N/A	China; *On;Off*	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; *On;* *Off*	20	9; 6.6 6.8	 0.098 0.102	 4.64 5.23
[27], 2013	N/A	0.34	141500	N/A	Brasil; *On*		N/A		7.1
[28], 2009	Scenario 2000-2030	0.375	60×5000		Scandinavia; *Off*	25	N/A		16.5+/- 1.3
[29], 2009	Off-grid; Batteries	0.17	0.4	1.08	Canada; *On*	20	N/A		11.43
[30], 2013	N/A		330 500 810 2050 3020	876 1560 2198 5281 5281	Turkey	20	35.6 14.6	 N/A	 15.1-38.3
[31], 2013		0.2	25×2000		Denmark; *On*	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, *On;* *Off*	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.

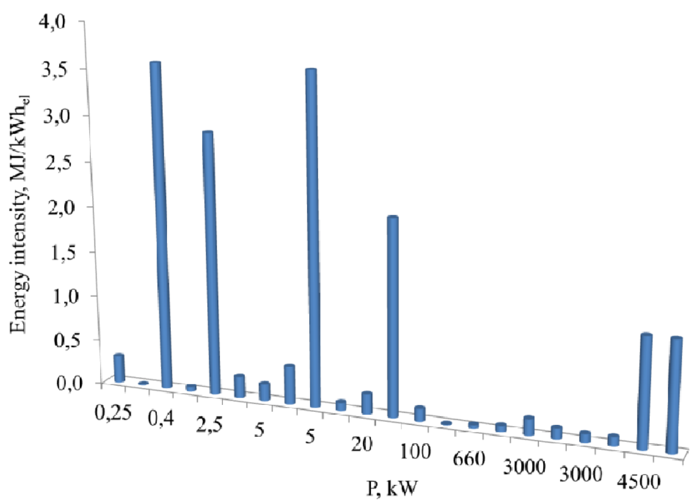
Key Environmental Indicators: Review 2002-2015

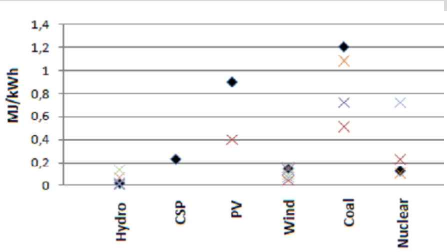


Comparative Analysis

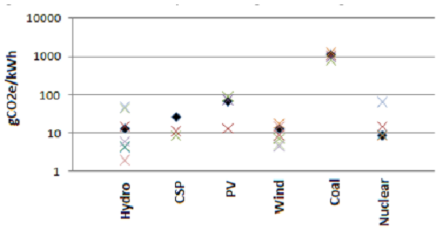
- Factors Considered: Type, Capacity Factor, Location, Lifetime, EPBT, Energy Intensity, CO_2 Intensity.
- A wide scatter can be observed in Energy, Intensity, CO_2 Intensity and EPBT.
- CO_2 is likely to be higher for smaller wind turbines than large scale WT.
- Though larger wind turbines may produce more output, the EPBT tends to be lower for smaller scale WT.

Key Environmental Indicators: Review 2002-2015





Benchmark comparison for energy input



Benchmark comparison for greenhouse gas emissions

Ref: Aden. Muller. 2010, Comparative Life-cycle Assessment of Non-fossil Electricity Generation Technologies China 2030 scenario analysis.

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LCA Review

		Fixed cost at construction	Annual fixed cost	Variable cost cost	Lifetime	**Levelized cost**
Technology	CF	$2010/KW	$2010/KW	$2010/MWh	Years	**$/Kwh**
coal	57%	$ 3,006	$ 33	$ 4	40	**0.056**
nuclear	90%	$ 4,668	$ 118	$ 4	50	**0.061**
hydro	41%	$ 3,076	$ 13	$ -	100	**0.063**
Wind onshore	44%	$ 2,438	$ 28	$ -	20	**0.067**
solar CSP	43%	$ 4,190	$ 66	$ -	25	**0.114**
Wind average	32%	$ 4,207	$ 41	$ -	20	**0.164**
Wind offshore	27%	$ 5,975	$ 53	$ -	20	**0.261**
solar PV	19%	$ 5,300	$ 47	$ -	30	**0.285**

Source: EIA (2010); O'Donnel (2009)

Normalized cost of various technologies

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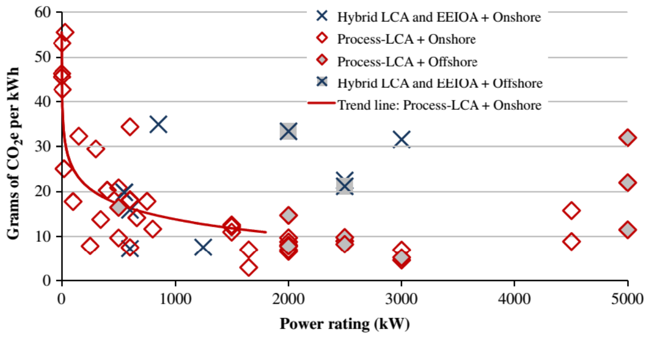
LCA Review



EEIOA: environmentally extended input output analysis.

Ref:Arvesen, 2012, Assessing the life cycle environmental impacts of wind power - a review of present knowledge and research needs

LCA Review

Life cycle phase	Coverage	Agreement	Quality	Remarks
Production of components	******	****	****	Complete coverage (Scope, assumptions and methodologies section). Uncertainty about emissions embodied in materials. Detailed material compositions are often not known. Toxic emissions from manufacturing are poorly understood; issues of mineral resource pressures are not well understood (Impact category coverage section). Studies assuming European energy systems dominate. Few studies of very large wind turbines and offshore wind turbines in deep waters and/or far from shore (Scope, assumptions and methodologies section).
Transportation to site, on-site construction	****	***	***	Coverage is variable (Scope, assumptions and methodologies section). Onshore: not important according to most studies (results of [34] disagree; the Contribution analysis section). Offshore: possibly important; modeling appears simplistic; NO_x from fuel oil-burning may be significant. Few studies of wind turbines in deep waters and/or far from shore (Scope, assumptions and methodologies section).
Operation and maintenance	****	***	***	Coverage is variable (Scope, assumptions and methodologies section). Offshore transportation and on-site activities: modeling appears simplistic; NO_x from fuel oil-burning may be significant. Empirical basis for assumptions about replacement of parts seems to be lacking. Few studies of wind turbines in deep waters and/or far from shore (Scope, assumptions and methodologies section).
End-of-life	***	****	**	Scarcely assessed in detail (Scope, assumptions and methodologies section). Future waste handling practices for rotor blades are unknown. Assessments using the avoided burden method are often lacking in transparency and may be inconsistent.

- Basic drawbacks in stage inputs and outputs.
- Judgments re. research coverage - life cycle phases - existing studies.

Ref:Arvesen, 2012, Assessing the life cycle environmental impacts of wind power - a review of present knowledge and research needs

LCA Review

	Input transparency	Output transparency
Quantitative	Necessary for replicability of study and recalculation of study with new information	Reporting granularity. Required for reinterpreting results.
Qualitative	Use for assessment of a study's completeness and a record of modeling parameters and assumptions	

Drawbacks in quantitative and qualitative aspects of assessments and reports.

Ref: Price A Kendall, 2012, Wind Power as a Case Study. Improving life cycle assessment reporting to better enable meta analysis

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Conclusions 1/2

1. Increase in size of WTs and rated power requires further assessment to determine whether it covers and compensates for the embodies energy requirements.

2. Variability of a number of LCA studies lead to difficulties in the comparison of results due to distinct assumptions and boundaries.

3. LCA studies differ from very simple to very detailed ones, going into different aspects, based on assumptions, published results and scenarios or refered to up to date actual data resulting in challenging uncertainty levels.

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Conclusions 2/2

4. Economies of scale play a vital role in energy intensity and system outputs.

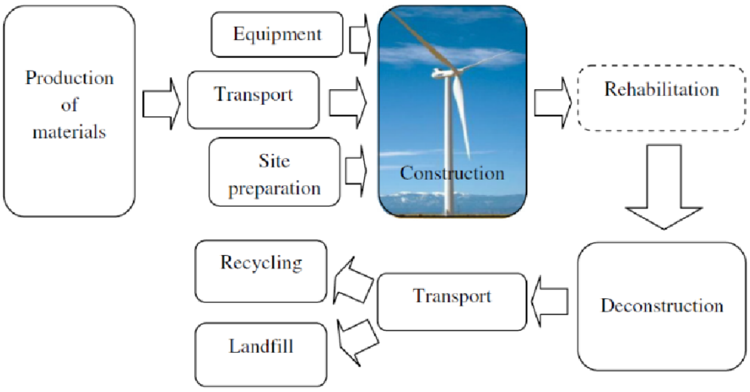
5. Small to Medium-scale units are not adequately covered in literature. This justifies the LCA Review analysis.

LCA: Comparative Life Cycle Assessment: Structural Design & Life Cycle Assessment

PART B

LCA: Comparative Life Cycle Assessment: Structural Design & Life Cycle Assessment

Comparative Life Cycle Assessment



- Rebelo C et al. Comparative life cycle assessment of tubular wind towers and foundations – Part 1: Structural design. Eng Struct (2014), http://dx.doi.org/10.1016/j.engstruct.2014.02.040
- Gervásio H et al. Comparative life cycle assessment of tubular wind towers and foundations – Part 2: Life cycle analysis. Eng Struct (2014), http://dx.doi.org/10.1016/j.engstruct.2014.02.041

Introduction

- Design of tubular towers and respective onshore foundations.
- Solutions based on steel, concrete and hybrid steel-concrete tubular towers supporting multi-megawatt turbines of 2, 3.6 and 5 MW power with hub heights of 80, 100 and 150 m respectively.
- Life cycle analysis of the designed case studies performed – determination of environmental impact.
- Two different scenarios concerning the lifetime of the towers were established.

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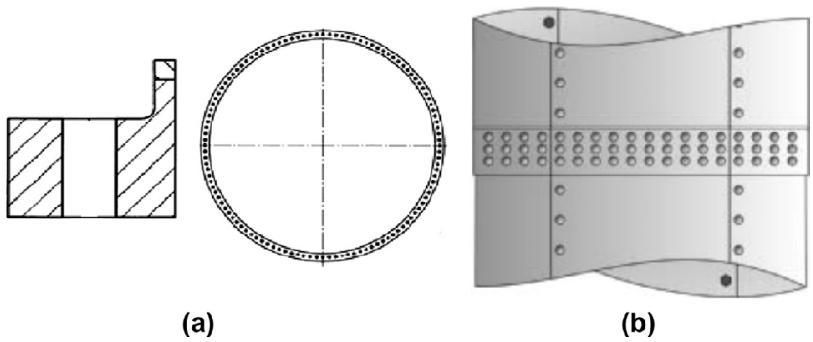
Comparative Life Cycle Assessment



Type of connections used in steel tubular towers; (a) welded flange connection (WFC); (b) friction connection (FrC).

Comparative Life Cycle Assessment

Scenarios for life-cycle analysis of towers.

		Tower height and rated power of wind turbine								
		80 m/2 MW			100 m/3.6 MW			150 m/5 MW		
	Lifetime (years)	20	40a	40b	20	40a	40b	20	40a	40b
Steel towers and steel segments in hybrid towers	WFC	x	–	–	x	–	–	x	–	–
	FrC	x	x	x	x	x	x	x	x	x
Concrete towers and concrete segments of hybrid towers	CT	x	x	x	x	x	x	x	x	x

Scenario 1: the structure is dismantled and materials are recycled after the lifespan of 20 years.

Scenario 2: after the initial period of 20 years, the structures are refurbished, mainly by surface rehabilitation and reused for another period of 20 years (scenario 40a).

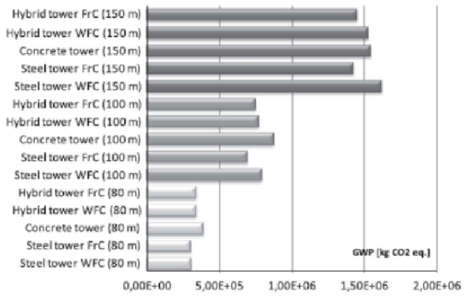
Scenario 3: after the initial period of 20 years, the structures are deconstructed, rehabilitated and reused in another place for another period of 20 years (scenario 40b).

[In both cases, after the total period of 40 years the structures are then demolished and sent to their final destination according to Scenario 1].

Comparative Life Cycle Assessment

Environmental indicators for LCA.

Indicator	Unit
Abiotic Depletion (ADP fossil)	MJ
Acidification Potential (AP)	kg SO_2-Equiv.
Eutrophication Potential (EP)	kg Phosphate-Equiv.
Global Warming Potential (GWP)	kg CO_2-Equiv.
Ozone Layer Depletion Potential (ODP)	kg R11-Equiv.
Photochemical Ozone Creation Potential (POCP)	kg Ethene-Equiv.



Comparative Life Cycle Assessment

Bill of main materials for each scenario.

Scenario		Steel S355 (ton)	Bolts (ton)	Concrete C40/50 (m^3)	Tendons (tons)	Concrete C25/30 (m^3)	Steel rebars (tons)
Steel tower (80 m)	WFC20	122.7	4.65	–	–	359.0	30.5
	FrC20	122.7	1.25				
	FrC40	122.7	1.25				
Steel tower (100 m)	WFC20	414.0	6.99	–	–	729.3	53.0
	FrC20	333.5	1.61				
	FrC40	384.7	1.66				
Steel tower (150 m)	WFC20	1025.0	21.43	–	–	981.9	65.38
	FrC20	871.9	4.24				
	FrC40	987.6	4.27				
Hybrid tower (80 m)	WFC20	44.0	2.62	233.3	16.9	373.6/295.9[a]	37.2/29.8[a]
	FrC20	44.0	0.68				
	FrC40	44.0	0.68				
Hybrid tower (100 m)	WFC20	136.4	3.71	488.3	25.1	831.4/700.4[a]	83.5/70.9[a]
	FrC20	120.7	0.88				
	FrC40	129.6	0.89				
Hybrid tower (150 m)	WFC20	342.5	9.41	1187.5	59.3	1324.0/1035.4[a]	101.3/81.1[a]
	FrC20	284.1	1.41				
	FrC40	334.8	1.42				
Concrete (80 m)		–	–	322.2	21.6	458.9/299.7[a]	56.74/37.9[a]
Concrete (100 m)		–	–	790.9	39.6	1058.6/646.6[a]	119.7/75.3[a]
Concrete (150 m)		–	–	1778.9	74.2	1664.1/957.1[a]	140.7/86.4[a]

[a] No seismic risk.

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Comparative Life Cycle Assessment

Environmental indicators for the towers with 80 m (1st scenario).

Environmental category	Concrete	Steel			Hybrid		
	CT	WFC	FrC	Δ (%)	WFC	FrC	Δ (%)
ADP fossil (MJ)	**3.49E+06**	3.53E+06	3.48E+06	−1.4	2.74E+06	**2.72E+06**	−1.1
AP (kg SO_2-Eq.)	**8.00E+02**	8.55E+02	8.43E+02	−1.4	7.42E+02	**7.35E+02**	−0.9
EP (kg PO_4-Eq.)	1.12E+02	1.03E+02	**1.02E+02**	−1.1	1.00E+02	**9.94E+01**	−0.6
GWP (kg CO_2-Eq.)	3.86E+05	3.04E+05	**3.01E+05**	−1.3	3.40E+05	3.38E+05	−0.6
ODP (kg R11-Eq.)	**1.12E−03**	6.41E−03	6.24E−03	−2.6	2.97E−03	2.87E−03	−3.2
POCP (kg Ethene-Eq.)	**8.10E+01**	1.27E+02	1.25E+02	−1.5	8.82E+01	8.71E+01	−1.2

Note: Minimum values for each category are in bold.

Environmental indicators for the towers with 100 m (1st scenario).

Environmental category	Concrete	Steel			Hybrid		
	CT	WFC	FrC	Δ	WFC	FrC	Δ
ADP fossil (MJ)	6.83E+06	9.08E+06	7.79E+06	−14.1	6.34E+06	**6.07E+06**	−4.4
AP (kg SO_2-Eq.)	1.72E+03	2.34E+03	1.99E+03	−14.9	1.73E+03	**1.66E+03**	−4.3
EP (kg PO_4-Eq.)	2.48E+02	2.77E+02	2.39E+02	−13.7	2.31E+02	**2.23E+02**	−3.5
GWP (kg CO_2-Eq.)	8.75E+05	7.93E+05	**6.92E+05**	−12.6	7.70E+05	7.48E+05	−2.8
ODP (kg R11-Eq.)	**2.29E−03**	2.05E−02	1.65E−02	−19.7	8.13E−03	7.26E−03	−10.8
POCP (kg Ethene-Eq.)	**1.68E+02**	3.65E+02	3.04E+02	−16.8	2.13E+02	2.00E+02	−6.1

Note: Minimum values for each category are in bold.

Environmental indicators for the towers with 150 m (1st scenario).

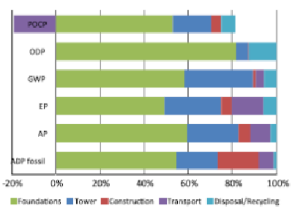
Environmental category	Concrete	Steel			Hybrid		
	CT	WFC	FrC	Δ (%)	WFC	FrC	Δ (%)
ADP fossil (MJ)	**1.09E+07**	1.97E+07	1.72E+07	−12.9	1.29E+07	1.19E+07	−7.7
AP (kg SO_2-Eq.)	**2.88E+03**	5.11E+03	**4.42E+03**	−13.4	3.51E+03	3.24E+03	−7.6
EP (kg PO_4-Eq.)	**4.39E+02**	5.88E+02	5.14E+02	−12.6	4.72E+02	**4.43E+02**	−6.1
GWP (kg CO_2-Eq.)	1.55E+06	1.62E+06	**1.42E+06**	−12.2	1.53E+06	1.45E+06	−5.0
ODP (kg R11-Eq.)	**3.12E−03**	5.00E−02	**4.20E−02**	−16.0	1.88E−02	1.57E−02	−16.6
POCP (kg Ethene-Eq.)	**2.64E+02**	8.39E+02	7.19E+02	−14.3	4.46E+02	3.99E+02	−10.4

Note: Minimum values for each category are in bold.

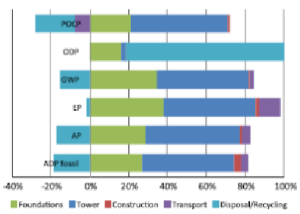
Comparative Life Cycle Assessment

Influence of seismic design for concrete and hybrid towers.

Environmental category	80 m 2.0 MW			100 m 3.6 MW			150 m 5.0 MW		
	Concrete	Hybrid		Concrete	Hybrid		Concrete	Hybrid	
	CT (%)	WFC (%)	FrC (%)	CT (%)	WFC (%)	FrC (%)	CT (%)	WFC (%)	FrC (%)
ADP fossil (MJ)	−15	−8	−9	−19	−6	−6	−18	−6	−6
AP (kg SO_2-Eq.)	−19	−9	−9	−21	−6	−7	−19	−6	−7
EP (kg PO_4-Eq.)	−18	−9	−9	−20	−7	−7	−18	−7	−7
GWP (kg CO_2-Eq.)	−19	−10	−10	−21	−7	−8	−19	−8	−8
ODP (kg R11-Eq.)	−24	−4	−4	−28	−2	−2	−25	−2	−2
POCP (kg Ethene-Eq.)	−19	−7	−7	−22	−5	−5	−19	−4	−5

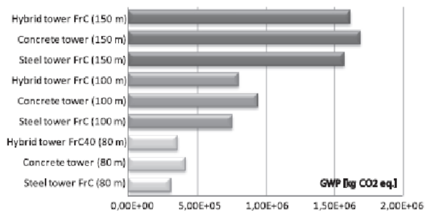


(a) concrete tower (100 m)

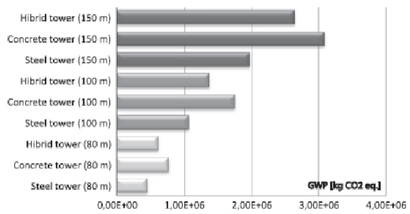


(b) hybrid tower (100 m)

Comparative Life Cycle Assessment



LCA of Wind Turbines (Scenario 2)



LCA of Wind Turbines (Scenario 3)

Environmental indicators for the three tower heights (3rd scenario).

Environmental category	80 m 2.0 MW			100 m 3.6 MW			150 m 5.0 MW		
	Steel	Concrete	Hybrid	Steel	Concrete	Hybrid	Steel	Concrete	Hybrid
ADP fossil (MJ)	5.15E+06	6.99E+06	**4.78E+06**	1.14E+07	1.37E+07	**1.05E+07**	2.32E+07	2.18E+07	**2.03E+07**
AP (kg SO_2-Eq.)	**1.19E+03**	1.60E+03	1.29E+03	**2.84E+03**	3.44E+03	2.86E+03	5.79E+03	5.76E+03	**5.54E+03**
EP (kg PO_4-Eq.)	**1.50E+02**	2.24E+02	1.79E+02	**3.54E+02**	4.97E+02	3.97E+02	**6.95E+02**	8.78E+02	7.84E+02
GWP (kg CO_2-Eq.)	**4.59E+05**	7.72E+05	6.25E+05	**1.06E+06**	1.75E+06	1.37E+06	**1.97E+06**	3.09E+06	2.64E+06
ODP (kg R11-Eq.)	6.74E−03	**2.25E−03**	3.68E−03	1.97E−02	**4.58E−03**	9.28E−03	4.85E−02	**6.25E−03**	2.05E−02
POCP (kg Ethene-Eq.)	1.60E+02	1.62E+02	**1.42E+02**	4.03E+02	3.35E+02	**3.19E+02**	8.86E+02	**5.28E+02**	6.28E+02

Note: Minimum values for each category are in bold.

Conclusions

Life cycle analysis of the designed case studies performed – determination of environmental impact.

Two different scenarios:

- The first scenario considers 20 years lifetime and two different construction methods for the connection of the steel segments, the first based in current technology using flange connections and the second using newly developed friction connections. Assuming equal importance for all environmental categories in this scenario, it may be concluded that for heights up to 100 m hybrid towers with friction connections are the most efficient solution. For higher heights, the concrete tower becomes more efficient.

- The second scenario considers an increased total lifetime of 40 years, assuming the reuse of the tower after 20 years of operation. In this case, the use of friction connections in steel towers enhances the possibility of dismantling and reusing the tower - much better performance in relation to the environmental category of global warming.

Environmental Impacts of Wind Energy Projects

PART C

Environmental Impacts of Wind Energy Projects

Outline

- Introduction
- Analysis of Effects of Wind-Powered Electricity Generation
- Ecological Effects of Wind Energy Development
- Impact of Wind-Energy Development on Humans
- Planning for and Regulating Wind-Energy Development
- Conclusions

Introduction

Guidance for reviewing Wind-Energy proposals

- Environmental benefits of Wind Energy
- Ecological Impacts
- Impacts on Humans
- Analysing Adverse and Beneficial Impacts in Contexts
- Framework for reviewing Wind Energy Proposals

Introduction

- Generating Electricity from Wind Energy
- Analytical Framework Development
- Temporal and Spatial Scales of Analysis
- Cumulative Environmental Effects

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Analysis of Effects of Wind-Powered Electricity Generation

1. Estimating Environmental Benefits of Generating Electricity from Wind Energy

- Atmospheric Emissions – Factors affecting potential emissions reductions by Wind Energy
- Life Cycle Costs
- Life Cycle Assessment
- Drivers of Wind Energy Development
- Technological, Economic, Regulatory and Policy Changes.
- Effects and Benefits in Context of Change.

Analysis of Effects of Wind-Powered Electricity Generation

2. Quantifying Wind Energy Benefits

- Wind Energy Potential
- Development projections: Wind Powered Generation – meeting projected Electricity demands.
- Factors that limit wind energy
- Air Quality Improvements
- Emissions Displacement

3. Global Wind Energy Developments

Ecological Effects of Wind Energy Development

1. Effect on Birds and Bats
    1. Bird Species prone to collision with wind turbines
    2. Trubine design and bird and bat fatality
    3. Site Characteristics and bird and bat fatalities
    4. Temporal pattern of bird and bat fatalities
2. Ecosystem structure alterations
    1. Habitat Alteration, Birds and bats
    2. Habitat alteration, terrestrial mammals, amphibians, reptiles, fish and aquatic organisms

Impact of Wind-Energy Development on Humans

1. Aesthetic Impacts
    1. Aesthetic issues
    2. Assessment of visual impacts of wind energy projects
    3. Project visibility, appearance and landscape context
    4. Scenic Resource values and sensitivity levels
    5. Mitigation techniques
    6. Guidelines for protecting scenic resources; Planning and Siting Guidelines, evaluation of aesthetic impacts
2. Cultural Impacts
    1. Recreation Impacts
    2. Historic, Sacred and Archaeological sites

Impact of Wind-Energy Development on Humans

3. Human Health and Well-Being
   1. Noise levels (Assessment, Impact, Mitigation)
   2. Shadow flicker (Assessment, Impact, Mitigation)
4. Economic and Fiscal Impacts
   1. Lease and Easement Arrangements
   2. Property values
   3. Employment and Secondary Economic Effects
   4. Public Revenue and Costs
5. Electromagnetic Interference

   Television, Radio, Fixed Radio Links, Cellular phones, Radar, Recreation Impacts.

Planning for and Regulating Wind-Energy Development

1. Wind Energy Planning and Regulation Guidelines
2. Regulation of Wind Energy Development
   1. Land Ownership
   2. Information required for review
   3. Public Participation in review
   4. Advantages and disadvantages – balance
   5. Long-term project-Permit Compliance
   6. Proactive Planning and Evaluation of Cumulative Effects
   7. Quality of Review
3. Framework for Reviewing Wind Energy Proposals

PART D

Challenges in the Implementation

of Wind Energy Projects:

Case Study Malta

Contents

- Introduction to non-technical issues
- Wind power in the built environment
- Acceptance issues
- Stakeholders
- Critical Issues
- Non-Technical Issues
- Case Study: Malta

Introduction on non-technical issues

Building and maintenance

Architecture

History and heritage

Environmental effects

Societal acceptance

Life Cycle Analysis

Market acceptance

Community acceptance

Legislation / policy

Planning

Permission procedures

Tourism

Safety

Economics & financial support

Business models

Wind Power in the Built Environment

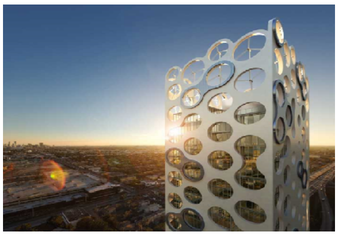
Offshore

Near-shore

On land (usually rural)

Wind Power in the Built Environment

Infrastructures



Integrated

Near dwellings

Urban

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Wind Power in the Built Environment

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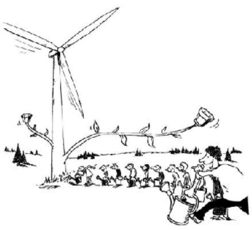
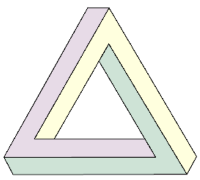
Wind Power in the Built Environment

Acceptance issues

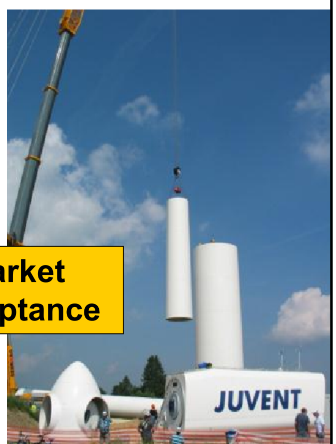


Socio-political acceptance



Community acceptance

Market acceptance



Wüstenhagen et al. (2007), IEA Wind Task 28

Acceptance issues

Well-being
- Standard of living
- Quality of life
- Health, lights, noise & shadow flicker
- Valuation of ecosystems

Policy & Strategies
- National framework
- Incentive programs
- Spatial planning

Procedural design
- Regulatory requirements
- Fair and transparent processes
- The role of public engagement
- Respect of cultural history / local context

Distributional justice
- Ownership models
- Regional welfare
- Creation of win-win-situations

Implementation strategies
- Visualization
- Social marketing / communication
- Checklists / guidelines
- Practical application of scientific results

Stakeholders – Urban Wind-Energy Projects

Neighbours

Heritage protection

Media

Politicians

Health authority

Police

Environmental NGO

Building Authority

Architects

Tourism agency

Investors / banks

Science

Urban planners

What would they say?

Stakeholders – Municipality

european energy award

Mobility
Public transport, parking, public spaces pedestrians, bicycles

Planning / development
Principles, energy planning, construction controlling

Internal organisation
Education, controlling, supply

Energiestadt
european energy award

Communal buildings
Analysis, renovation, maintenance

Communication
Cooperations, events, marketing, encouragement

Provision, waste
Electricity, heat, renewables, water, waste

Critical Issues

- Movement / rotation + flickering / technical element

https://www.youtube.com/watch?v=MbIe0iUteIQ

- Visual Impact on Buildings – Audible
- Threat for birds & bats
- Several Permissions needed

Non-Acceptance

Acceptance

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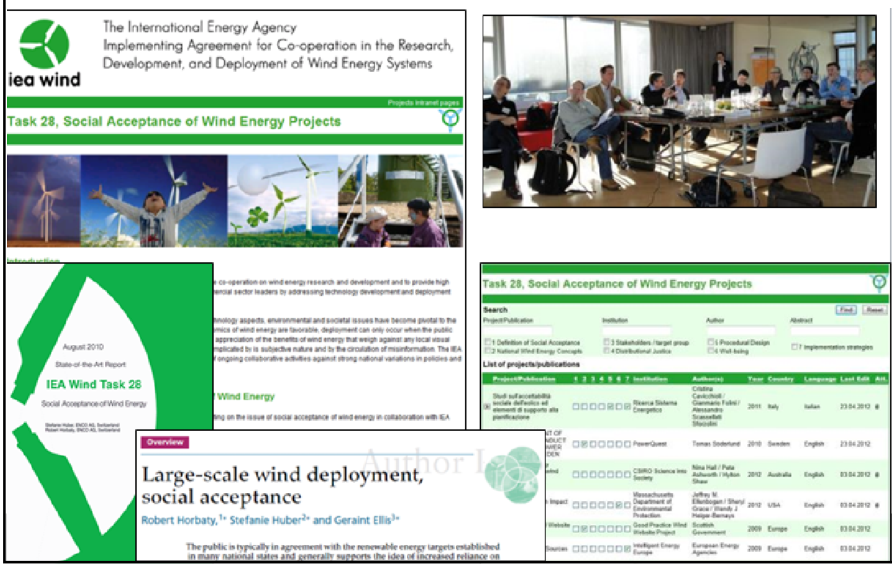
Work of IEA Wind Task 28

www.socialacceptance.org



Non-Technical Issues

- Various issues need to be taken into account
- Efficient turbines at the right places with enough wind resources – implementation requires more
- There is no receipe for acceptance – but attention to people and their needs is a good first step.
- Stakeholder Involvement
- Critical Issues - Acceptance

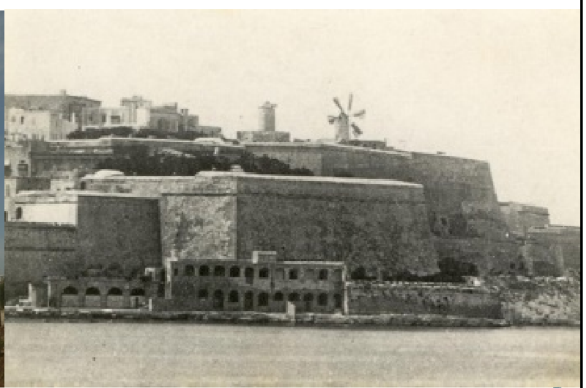
Case Study - Malta

Case Study Malta:

- Historic Context of Wind Energy Structures: Stone Masonry Windmills & Water Pumps.
- Implementation of Wind Energy projects in Malta
- Grid Connected Micro-Wind Turbine Projects
- Guidelines for Micro-Wind Turbines

History of Wind Energy in Malta

- Ta' Kola Windmill (Gozo) with surrounding open space.
- Windmills perched on the high Bastions of Valletta



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Stone Masonry Windmills

- Corn Grinding mills for the Production of flour. The first Corn grinding mills were driven by animals.
- Construction of Windmills: 16th century.
- Windmills constructed in stone masonry in the 16th Century in Malta after the arrival of the Knights of the Order of St John in 1530. (c. 37 windmills)
- The first were constructed in Senglea in the Grand Harbour in 1532 by Grand Master L'Isle Adam (1530-1534) and at Fort St Elmo in 1582.
- Grand Master Nicolas Cotoner (1663-1680): 10 windmills.
- Grand Master Gregorio Carafa (1680-1690): 10 windmills.
- Grand Master Ramon Perellos y Rocafull (1697-1720): 3 / 4 windmills.
- Grand Master Manoel de Vilhena (1722-1736): 8 / 9 Windmills.

Stone Masonry Windmills

- New windmills constructed in stone masonry in the 19th Century in Malta during the British Period (c. 38 windmills).
- Increase in animal driven grinding mills which could be operated for longer periods. c.1860 .
- Increased competition led to operational difficulties for the windmills.
- Introduction of steam driven grinding mills led to a sharp decline in the operation of windmills.
- Introduction of fuel operating grinding mills in the mid 20th century.

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Stone Masonry Windmills

Stone Masonry Windmills

- Windmills constructed on high ground and open space close to the villages.
- Exposed ground, high on the bastions in the Cities.
- Stone masonry structures, consisting of three or more storeys: Two storey base with a rectangular plan and a cylindrical structure on top supporting the 6 sails.
- Rectangular, Circular or Octagonal base stone masonry structure.
- External Timber structure to support the sails.
- Internal Timber structure and mechanism, grinding stone.

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Water pumps

- Chicago windmill (Raddiena) Water pumps: micro-scale.
- Have been used for irrigation in rural Malta: 20th Century.
- 300 windmills were listed across Malta and Gozo in 2001. Farmers replaced the windmill with electric water pumps: deteriorating windmill steel structures.
- Ministry for Resources and Rural Affairs – University of Malta project: upgrading the rotor design structure's aerodynamics to improve water-pumping efficiency and maintain the original visual appearance of a multi-bladed rotor.
- Grid-connected turbine producing electricity: clean energy

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Water pumps


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Grid-Connected Micro-Wind Turbine Systems [A]

Ref.	Location	Location	Manufacturer	Axis	Power (kW)	Year of Installation	Remarks
1	University Horizontal Axis	Msida	Fortis	Horizontal	1.5	2003	Urban Area
2	University Vertical Axis	Msida	Enervolt	Vertical	3	2010	Urban Area
3	Xrobb il-ghagin Horizontal Axis	Xrobb il-Ghagin	Proven	Horizontal	6	2008	Non-Urban
4	Xrobb il-ghagin Vertical Axis	Xrobb il-Ghagin	Aeolos	Vertical	6	2008	Non-Urban pending Tech. Issues
5	Enemalta - Vendome, Ramlet il-Qortin	Mgarr	Proven	Horizontal	2.5	2008	Non-Urban
6	Cirkewwa Ferry Terminal	Cirkewwa	n/a	Horizontal	15	2012	Non-Urban
7	Wasteserv (Luqa)	Luqa	Proven	Horizontal	2.5	n/a	Non-Urban
8	Wasteserv (Hal Far)	Hal Far	Proven	Horizontal	2.5	2008	Non-Urban
9	Wasteserv (Mrieħel)	Mrieħel civic amenity		Horizontal	1	2008	Urban

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Grid-Connected Micro-Wind Turbine Systems [B]

Ref.	Location	Location	Type	Axis	Power (kW)	Year of Installation	Remarks
11	Naxxar – Solar Solutions – Tal-Balal	Naxxar	Fortis	Horizontal	n/a	n/a	Non-Urban
12	Balzan – San Anton	Balzan	n/a	Vertical	n/a	n/a	Urban
13	Pembroke Primary School – Vertical Axis	Pembroke	Helix	Vertical	2/ 4.5	n/a	Urban
14	Wasteserv	Mriehel	Helix	Vertical	2 /4.5	n/a	Urban
15	Chicago Wind Turbine	n/a	UM	Horizontal	n/a	n/a	Under Design Phase
16	Smart City – Lamp Posts	Smart City	n/a	Vertical	<1	n/a	-
17	Ta'Qali - Parks	Ta' Qali	Recowatt	Vertical	≈0.3	n/a	Non-Urban
18	Naxxar GS Roundabout	Naxxar	Bergey	Horizontal	≈0.3	n/a	Urban
19	Gozo Econotechnique	Gozo		Vertical	n/a	n/a	Non-Urban

Summary:
Urban Wind Turbine = 2 HAWT and 5 VAWT
Non-Urban Turbine = 5 HAWT and 3 VAWT

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Guidelines: Micro Wind Turbines

- Approved planning guidance for micro wind turbines, with an energy generating capacity of up to 20kW. Intended to promote renewable energy and cleaner resources of energy production (MEPA, Malta)
- Main issues for wind turbines: visual impact, noise, vibrations and potential effects on local ecology; Cumulative impact of multiple turbine installations, especially in urban areas. Potential impact that the turbines may have on the surrounding environment as well as other possible causes of nuisance to surrounding receptors.
- Guidelines favour installation of micro wind turbines in industrial areas, on the roofs of large buildings or within the curtilage of large buildings surrounded by large grounds situated in ODZ areas (hospitals, schools and other infrastructural facilities).
- Guidance on the potentially acceptable locations, size, efficiency and feasibility aspects. Due to the lack of information, the policy adopts a precautionary approach in urban areas due to lack of information on potential amenity impacts such as visual, noise and vibrations.

Guidelines: Micro Wind Turbines

- MEPA proposed partnership with public agencies, research institutions and NGOs to fund and carry out research to assess the potential impacts – particularly visual, noise and vibrations – of this infrastructure on residential buildings and townscapes.
- Results of these studies are envisaged to be a determining factor in any possible wider dissemination of micro wind technology in urban areas.
- The guidance calls for the need of a sensitive siting as a key element in reducing the visual impact, improve the general perception related to this technology and make them more acceptable to the public.
- Turbines are ideally located high up to take advantage of the prevailing winds; the policy proposes maximum overall height limitations for turbines as a mitigation measure against visual impact; tower mounted turbines not recommended within the grounds of historic buildings because of their conservation value.
- Larger wind turbines assessed within government's Proposal for an Energy Policy of 2009, other supporting documents published by the Malta Resources Authority (MRA), and all relevant studies necessary to inform decisions on any future applications for such development. (outside the scope of the Micro Turbine guidance).

Wind Energy in Malta

- Planning Guidance for Micro-Wind Turbines
- Studies for the impact of off-shore / on-shore wind farms.
- Concerns regarding the Feasibility in the Maltese Islands.
- Current trend of increased promotion of PV Farms to reach 2020 targets.

Environmental, Social and Planning Aspects

WINERCOST - TU1304 Horizon 2020 COST: Work Group 3

Social, Environmental and Planning Aspects

- WG3A: Non-technical issues of WET (Wind Energy Technology) including societal acceptance, European energy policy and municipalities-researchers-industries dialogue.
- WG3B: Societal acceptance, European BWT (Built Environment Wind Energy Technology) policy and other non-technical BWT issues.

Environmental, Social and Planning Aspects

- Work Group 3: Initiating a social debate on the use of BWT with municipality authorities in the presence of the rest of the stakeholders.
- Work Group 3: psychologists, sociologists, urbanists together with engineers and other scientists will for first time collaborate towards a societally accepted strategy, in dialogue with the municipality authorities and the industry, on a successful urban habitat integration of BWT.
- Feedback from experts from international energy fora on this subject along with energy economics.

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Thank you

Ruben Paul Borg

ruben.p.borg@um.edu.mt

University of Malta

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International Training School
Crete 04-08.04.2016

Lecture

Life Cycle Environmental Impact of Wind Energy Projects

Dr. Ruben Paul Borg[a]

[a] Faculty for the Built Environment, *University of Malta, Malta*

ruben.p.borg@um.edu.mt

UNIVERSITY OF MALTA
L-Università ta' Malta

TU 1304 – WINERCOST
Advances in Wind Energy Technology II
Chania, 4 - 8 April 2016

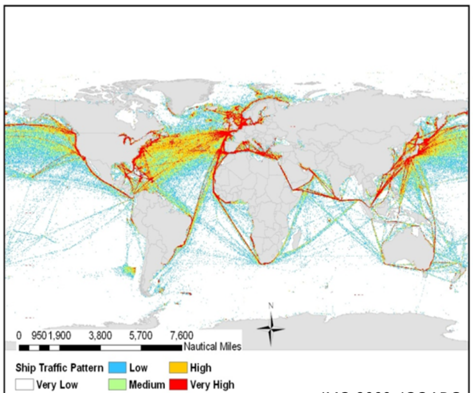
Sustainable Ports through smart energy systems

Spiros Papaefthimiou
Assistant Professor
School of Production Engineering and Management
Technical University of Crete, Greece
spiros@dpem.tuc.gr

Carbon efficiency of transport modes

- Transportation: an important source of CO_2 emissions.
- Due to globalization and increased worldwide trade, transportation has significantly increased CO_2 emissions in the last two decades.
- Sea transport is the least environmentally damaging modes of transport.

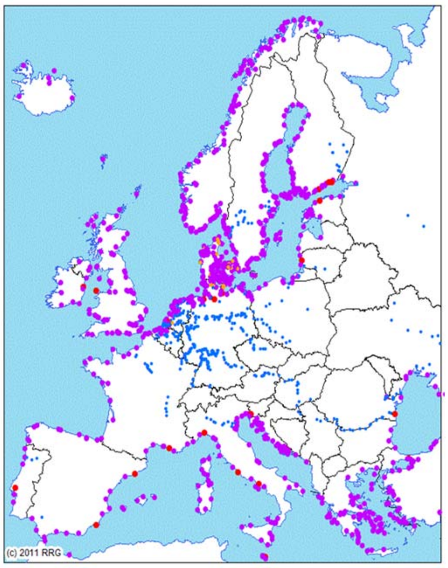
Global shipping: general issues



IMO 2009; ICOADS

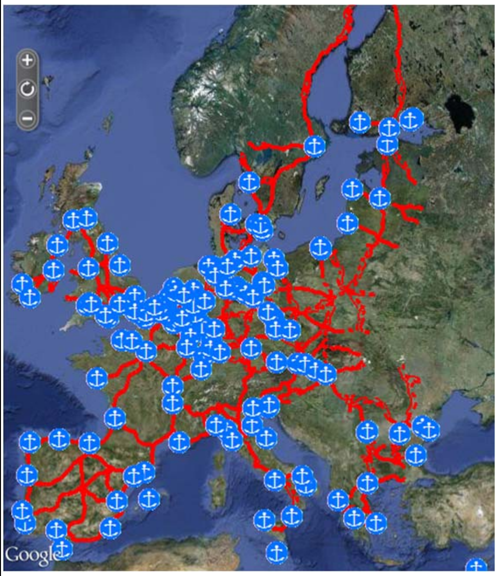
- Shipping is characterized by a complicated structure due to its globally oriented status.
- 90% of world trade is handled through maritime sector, with an annually increasing volume rate of 4%.
- The inclusion of shipping in the emissions market is inevitable, as it is responsible for 3-5% of global CO_2 emissions.
- For the next 15 years, an increase of 75% of emissions due to shipping is anticipated, due to the parallel growth of world trade.
- Till the deadline set by the Kyoto Protocol (i.e. 2050), maritime sector will be responsible for 15% of total emitted CO_2 amount.

Ports: economy – environment



- More than **8 billion tonnes of cargo** are handled globally each year.
- Sea trade grew at **5% per annum** and is expected to grow at ~2-3% per annum for the next years.
- **74% of goods** entering or leaving Europe go by sea, due to the lower cost, increased speed and obtained energy savings. More than **3.5 billion tonnes** of cargo are handled in the EU ports, annually.
- Ports also generate employment; **1.5 million workers** are employed in EU ports.
- Ports concentrate shipping traffic and ship exhaust emissions and their environmental effects have raised significant concerns regarding the induced costs and negative effects on local air quality.

Ports: economy – environment



- 90% of trade between Europe and the rest of the world is transported by sea, due to the lower cost, increased speed and obtained energy savings.
- More than 3.5 billion tonnes of cargo are handled in the European ports, annually.
- The effective and efficient operation of ports is an indicative factor of both competitiveness and attractiveness of a country to foreign investments.
- Ports concentrate shipping traffic and ship exhaust emissions and their environmental effects have raised significant concerns regarding the induced costs and negative effects on local air quality.
- Emissions from ships (even docked or maneuvering in port) are transported in the atmosphere over hundreds of kilometers, thus contributing to air quality problems on land, even if they are emitted at sea.
- On average, every ship remains at berth about 100 days per year.

Ports in the future: gas networks

"The importance of Eastern Mediterranean gas fields for Greece and the EU", Pytheas Limited, 2012

- East-Med gas pipeline could carry the already discovered and the about to be discovered natural gas from the Eastern Mediterranean to Europe through Greece and Italy.
- LNG bunkering areas could be created in adjacent ports, as East-Med provides stable, regular, repetitive and high frequency routes with fuel intensive engine utilization.

Ports in the future: Energy transmission networks

"European grid study 2030-2050", Greenpeace, Energynautics GmbH.

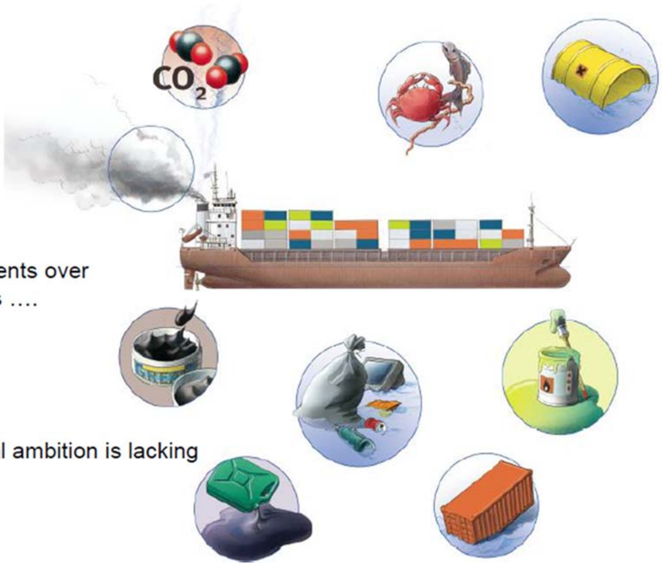
- Port authorities could ameliorate their carbon footprint by improving their energy mix through renewables.
- In order to promote and enhance renewable energy use in ports, the supporting transmission networks should be developed.
- Large ports are typically located on important nodal points in these smart grids - networks and apart from consumers they can act as green energy providers stabilizing loads.
- Funds will be necessary to realize such a goal.

Environmental issues in ports: top 10 priorities

	1996	2004	2009	2013
1	Port development (water)	Garbage / Port waste	Noise	Air quality
2	Water quality	Dredging operations	Air quality	Garbage / Port waste
3	Dredging disposal	Dredging disposal	Garbage / Port waste	Energy consumption
4	Dredging operations	Dust	Dredging operations	Noise
5	Dust	Noise	Dredging disposal	Ship waste
6	Port development (land)	Air quality	Relationship with local community	Relationship with local community
7	Contaminated land	Hazardous cargo	Energy consumption	Dredging operations
8	Habitat loss	Bunkering	Dust	Dust
9	Traffic volume	Port development (land)	Port development (water)	Port development (land)
10	Industrial effluent	Ship discharge (bilge)	Port development (land)	Water quality

"ESPO Port performance dashboard", European Sea Ports Organization, May 2013.

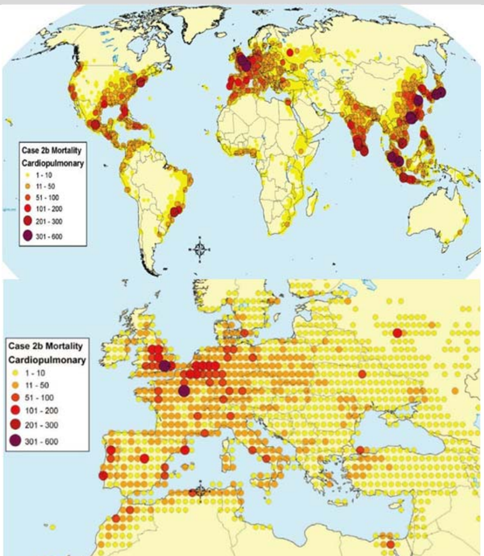
Emissions from ships



Some improvements over the past decades ….

… but real ambition is lacking

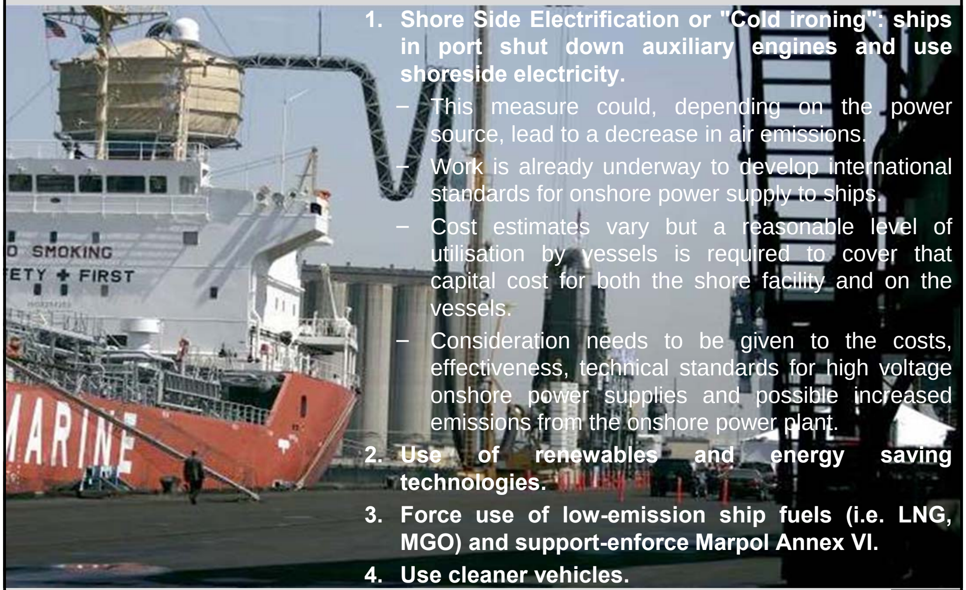
Air pollution in ports and induced health effects



J. Corbett et.al., Transportation Research Part D 14 (2009) 593

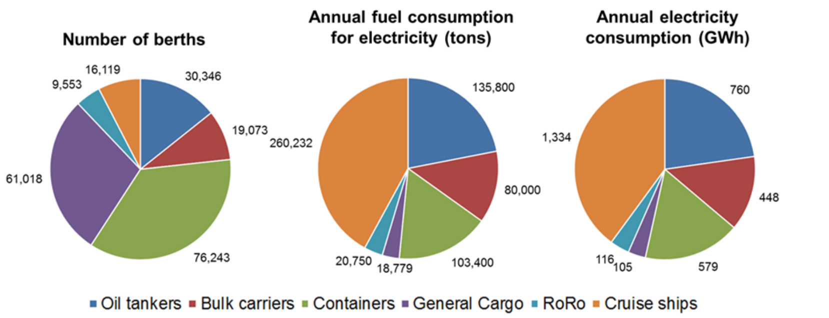
- Emissions from the international maritime transport sector today account for 3% of global GHG emissions and 4% of EU GHG emissions.
- The most important air emissions contributing to climate change and public health effects, are: **Carbon oxides** (CO, CO_2), **Sulphur and Nitrogen oxides** (SO_x, NO_x) and **Particulate Matter** (PM).
- Vessels are the dominant air pollutant source in ports. Ocean going vessels contribute approximately 36% of the NO_x, 60% of the PM, and 90% of the SO_x.
- Recent studies show that PM emissions related to shipping could be responsible for about 60,000 deaths worldwide each year.
- The vast majority of these deaths occur near large ports of Europe and Asia.

Technical solutions for improved air quality in ports



1. **Shore Side Electrification or "Cold ironing": ships in port shut down auxiliary engines and use shoreside electricity.**
   - This measure could, depending on the power source, lead to a decrease in air emissions.
   - Work is already underway to develop international standards for onshore power supply to ships.
   - Cost estimates vary but a reasonable level of utilisation by vessels is required to cover that capital cost for both the shore facility and on the vessels.
   - Consideration needs to be given to the costs, effectiveness, technical standards for high voltage onshore power supplies and possible increased emissions from the onshore power plant.
2. **Use of renewables and energy saving technologies.**
3. **Force use of low-emission ship fuels (i.e. LNG, MGO) and support-enforce Marpol Annex VI.**
4. **Use cleaner vehicles.**

Shore Side Electrification

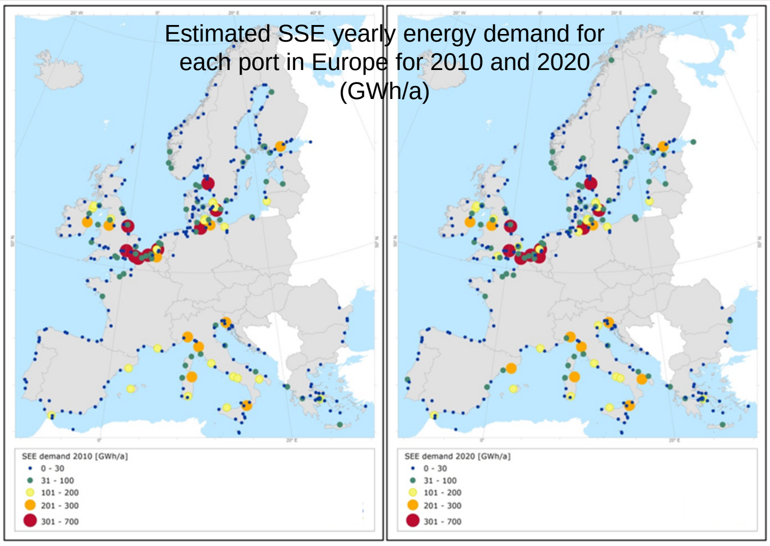


If all seagoing ships in European harbours would use SSE by 2020 for covering their energy demand at berth, they would consume 3,342 GWh annually (or 3,543 GWh if we also consider inland shipping), which is approximately 0.1% of the electricity consumption in Europe as a whole in 2012.
Cruise ships correspond to an excessive energy demand due to their hotelling activities while staying in port , as their annual electricity consumption in ports (i.e. 1,334 GWh) represents 39.9% of the total.

R. Winkel, U. Weddige, D. Johnsen, V. Hoen, S. Papaefthimiou, "Shore Side Electricity in Europe: Potential and environmental benefits" Energy Policy 88 (2016) 584–593.

SSE: study for EU ports

Estimated SSE yearly energy demand for each port in Europe for 2010 and 2020 (GWh/a)



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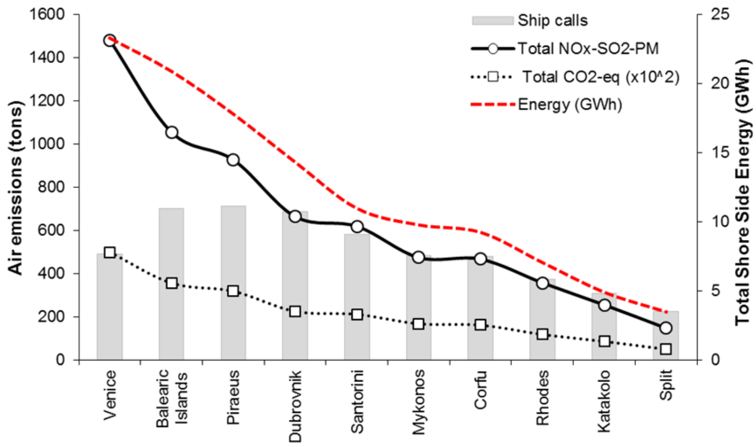
SSE: study for EU ports

Annual emissions to air and electricity consumption of various EU ports for cruise ships at berth.



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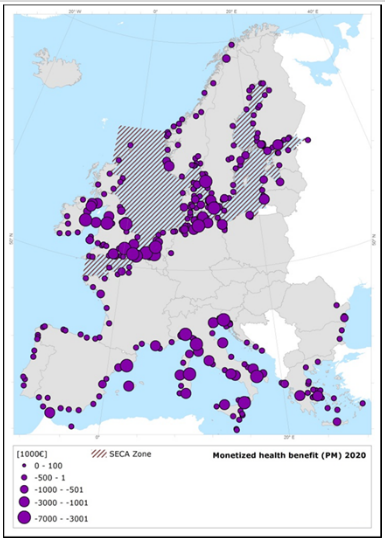
SSE: study for EU ports



Monetized health benefit (for PM) by using SSE instead of burning fuels while ships are at berth in 2020.

The total anticipated health benefits by using SSE in EU ports were estimated to 2.63 and 2.94 billion € for 2010 and 2020 respectively.

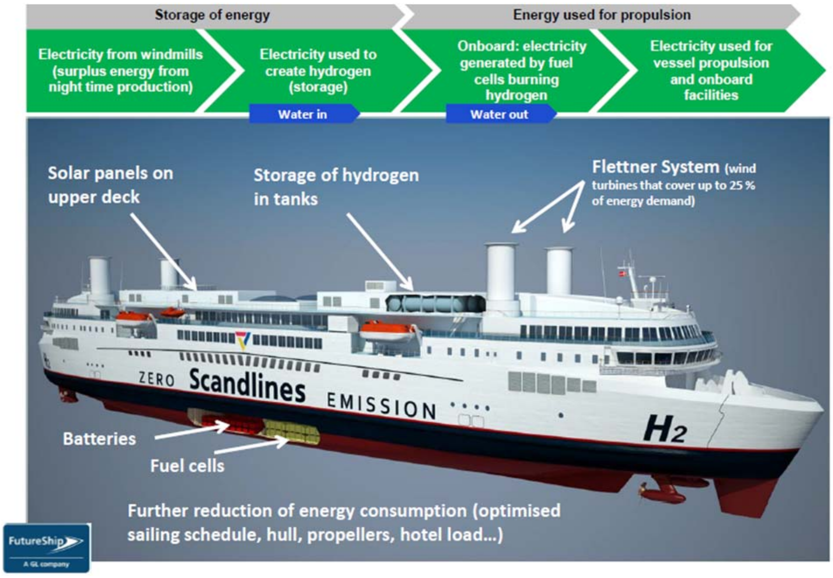
The potential for reduction of carbon emissions reaches the 800,000 tonnes of CO_2.

Energy Policy 88 (2016) 584–593

Technical solutions: hybrid vessels

- The world's largest hybrid ferry – 2.7 MWh battery bank / capacity for 364 cars
- The system equals approx. 600 hybrid cars and can propel the 8.800 tons vessels for 30 minutes
- Reduce CO_2 emissions with up to 15 % (approx. 10,000 tons CO_2 yearly)
- Large international recognition for this industry leading concept
- Gain fundamental knowledge of use of batteries in operations

Technical solutions: future green ships



Technical solutions

Port of Hamburg

Technical solutions: AGVs

Automated Guided Vehicles (AGV) are heavy duty vehicles for the automated transportation of containers within ports.

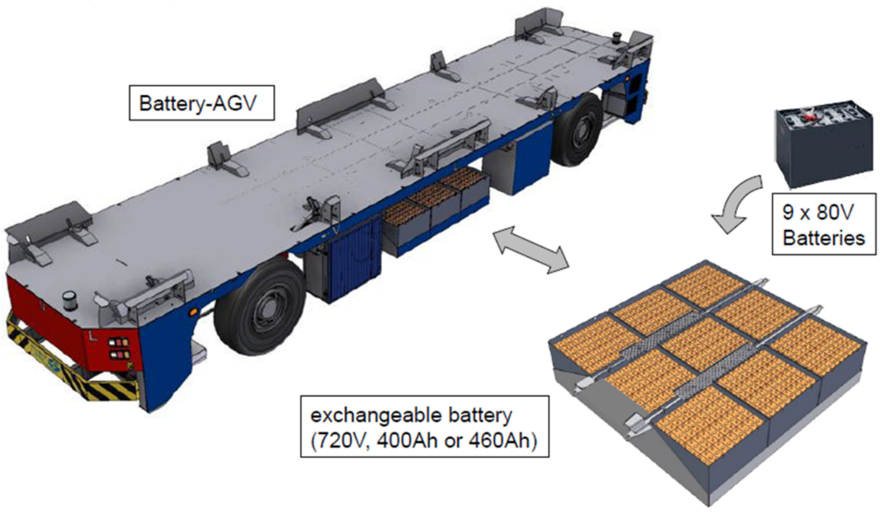
AGVs are guided by a navigation and a fleet management system.

High availability with up to 7,000 operating hours per year and vehicle, 24/7 operation.

Port of Hamburg

Technical solutions: AGVs

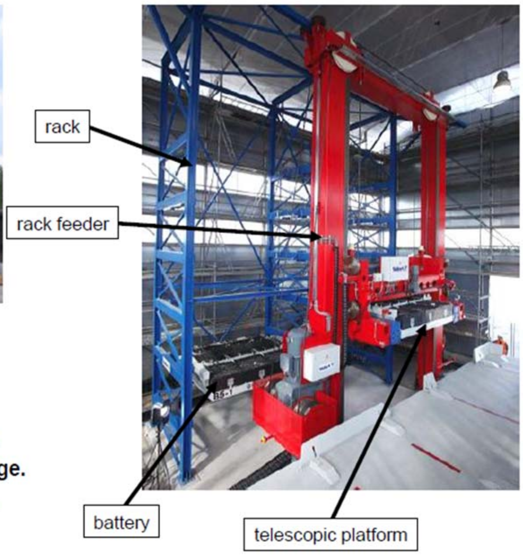
- Battery concept



Port of Hamburg

Technical solutions: AGVs

- Battery exchange & charging is fully automatic
- Decoupling of driving and charging.
- **No reduction of vehicle performance, only short downtime for battery change.**
- Station is integrated in existing software system.



Port of Hamburg

Technical solutions: solar, wind, biofuels

Port of Shoreham

Technical solutions: marine tidal energy

Port of Cherbourg

We should be optimists as there a lot that care…

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Wind energy technology reconsideration to enhance the concept of smart cities

EDITORS:
Charalambos Baniotopoulos
Claudio Borri
Bert Blocken
Hassan Hemida
Milan Veljkovic
Tommaso Morbiato
Ruben Paul Borg
Stefanie Huber
Evangelos Efthymiou
Georgios E. Stavroulakis

ΕΚΔΟΣΕΙΣ ΠΟΛΥΤΕΧΝΕΙΟΥ ΚΡΗΤΗΣ

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