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EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Università
degli Studi
della Campania
Luigi Vanvitelli

ADVANCES IN WIND ENERGY TECHNOLOGY

Editors
Charalampos Baniotopoulos, Claudio Borri, Bert Blocken, Hemida Hassan,
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3rd International Training School Naples, 23rd April – 28th April 2017
Wind Energy Technology to enhance the concept of Smart Cities

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Universita’ degli Studi della Campania *Luigi Vanvitelli*
Naples, Italy

COST (European Cooperation in Science and Technology) is a pan-European intergovernmental framework. Its mission is to enable break-through scientific and technological developments leading to new concepts and products and thereby contribute to strengthening Europe's research and innovation capacities.
It allows researchers, engineers and scholars to jointly develop their own ideas and new initiatives across all scientific disciplines through trans-European coordination of nationally funded research activities. Through its networks (called COST Actions) it promotes trans-disciplinary, original approaches and topics and addressing societal questions. It fosters better access and integration of less research intensive countries' researchers to the knowledge hubs of the European Research Area.
COST is implemented through the COST Association, an International not-for-profit Association under Belgian Law, whose members are the COST Member Countries. The production of this publication was supported by COST: www.cost.esf.org

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May 2017

COST Action TU1304 WINERCOST

Wind Energy Technology to enhance the concept of Smart Cities

Charalampos Baniotopoulos	University of Birmingham, UK	Action Chair
Claudio Borri	University of Florence, Italy	Action Vice Chair
Blocken Bert	University of Eindhoven, NL	WG1 Chair
Hemida Hassan	University of Birmingham, UK	WG1 Vice Chair
Milan Veljkovic	Luleo University, Sweden	WG2 Chair
Tommaso Morbiato	University of Padova, Italy	WG2 Vice Chair
Ruben Paul Borg	University of Malta, Malta	WG3 Chair
Neveen Hamza	University of Newcastle, UK	WG3 Vice Chair
Evangelos Efthymiou	University of Thessaloniki, Greece	Dissemination

Contents

TU1304 WINERCOST ACTION
3rd TRAINING SCHOOL
“ADVANCES IN WIND ENERGY TECHNOLOGY III”

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 3rd WINERCOST Training School on the *Advances in Wind Energy Technology III* is the third 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 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 (i) 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 (ii) 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

The TU1304 chair acknowledges with grateful thanks the valuable support of the staff of the COST Office and in particular, Dr. Mickael Pero, Science Officer.

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Wind energy technology reconsideration to enhance the concept of smart cities

Charalampos Baniotopoulos

TU 1304 –WINERCOST
Advances in Wind Energy Technology

COST is supported by the EU Framework Programme Horizon 2020

Wind energy technology reconsideration to enhance the concept of smart cities

C. Baniotopoulos[a]

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UNIVERSITY OF BIRMINGHAM

Wind Energy Technology Reconsideration to Enhance the Concept of Smart Cities

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 **45 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

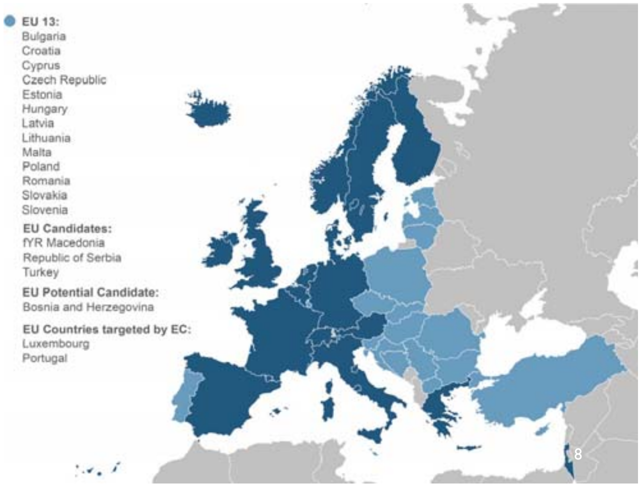
Originated from:

- Horizon 2020
- COST Member Countries

with the aim to:

- **encourage and enable researchers from less research-intensive countries across the COST Member Countries to set up or join COST Actions and get more intensively involved in all COST activities**

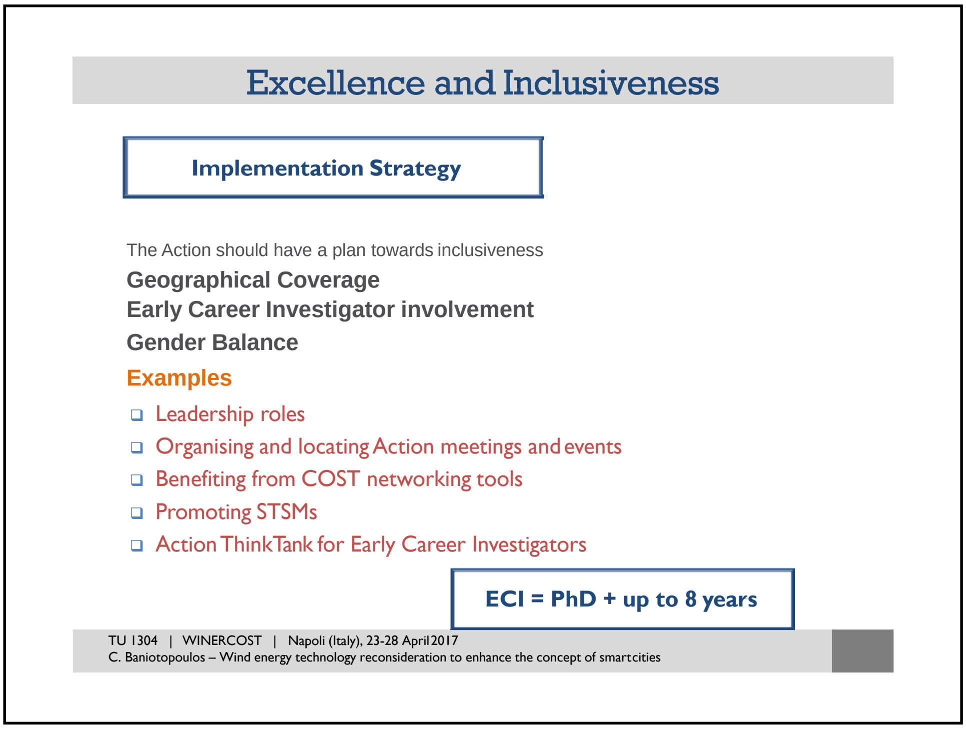
COST Inclusiveness Target Countries


EU 13:
Bulgaria
Croatia
Cyprus
Czech Republic
Estonia
Hungary
Latvia
Lithuania
Malta
Poland
Romania
Slovakia
Slovenia

EU Candidates:
fYR Macedonia
Republic of Serbia
Turkey

EU Potential Candidate:
Bosnia and Herzegovina

EU Countries targeted by EC:
Luxembourg
Portugal



Excellence and Inclusiveness

Implementation Strategy

The Action should have a plan towards inclusiveness

Geographical Coverage

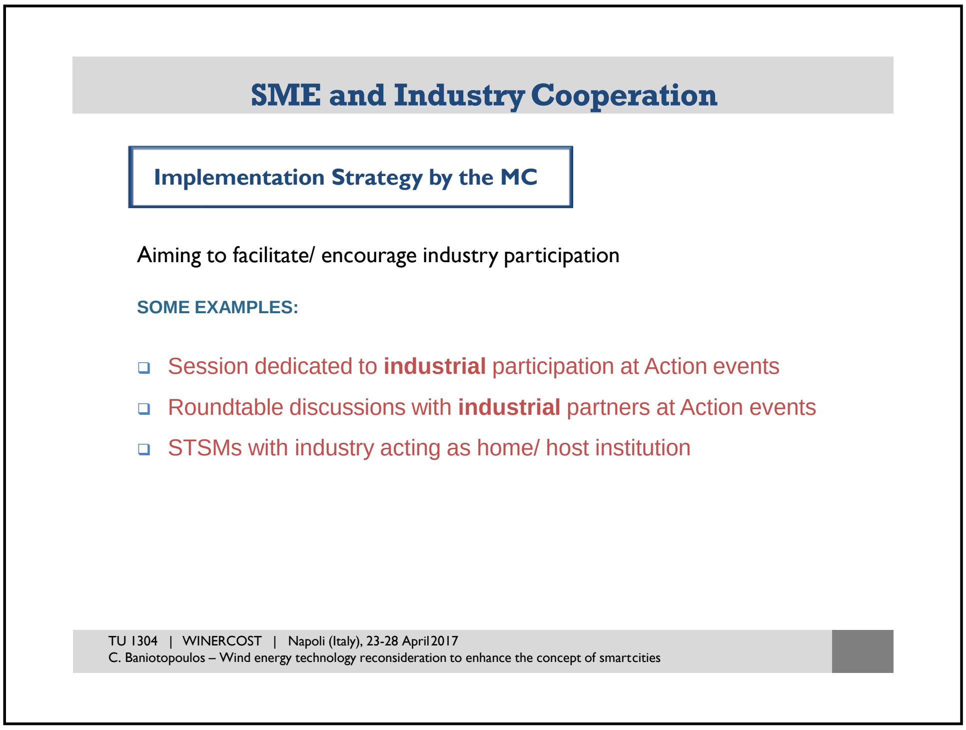
Early Career Investigator involvement

Gender Balance

Examples

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

ECI = PhD + up to 8 years



SME and Industry Cooperation

Implementation Strategy by the MC

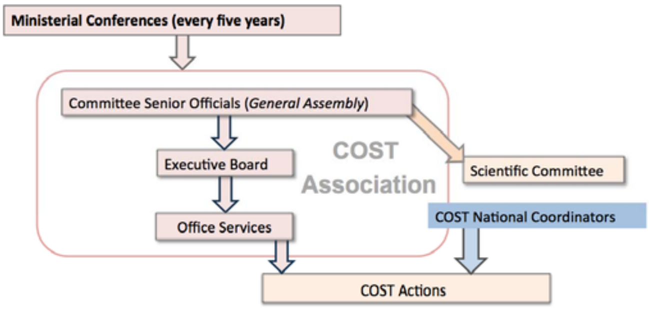
Aiming to facilitate/ encourage industry participation

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


Ministerial Conferences (every five years)

Committee Senior Officials (*General Assembly*)

Executive Board

Office Services

COST Association

Scientific Committee

COST National Coordinators

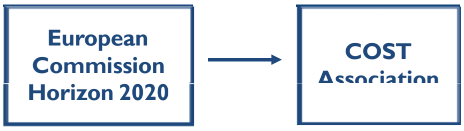
COST Actions

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

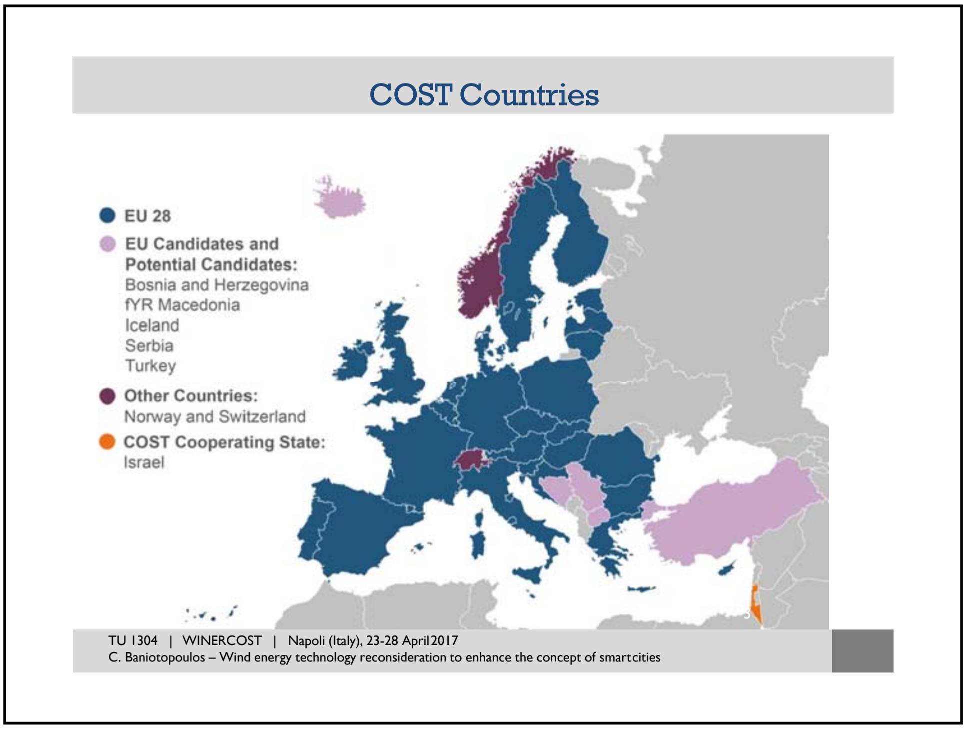
COST Budget in H2020

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"


European Commission Horizon 2020

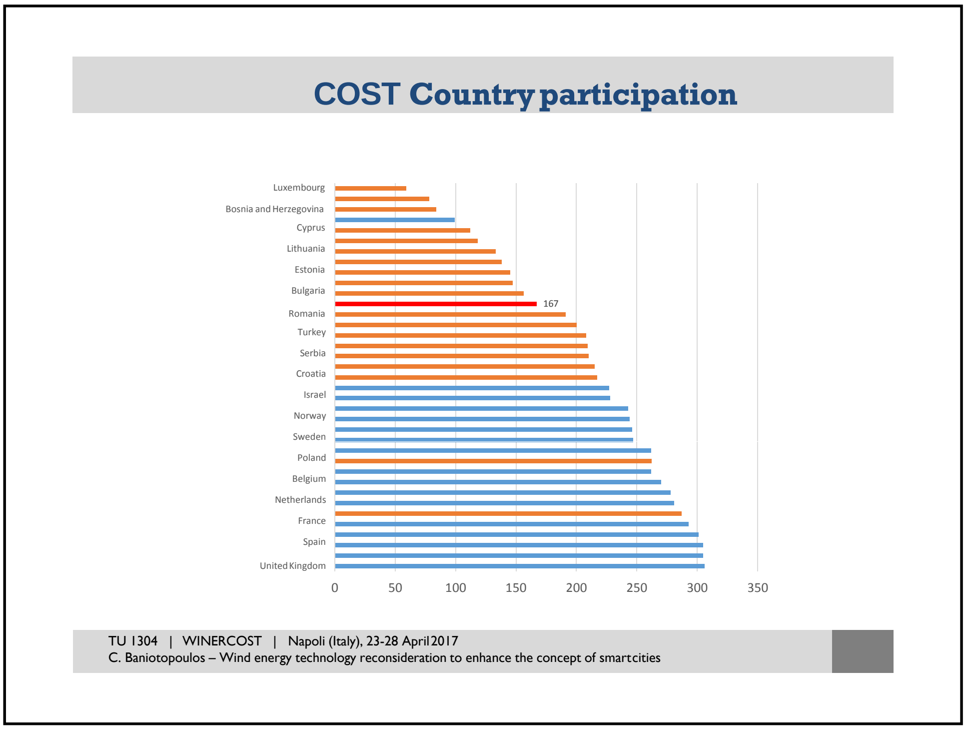
COST Association



COST Countries

- EU 28
- EU Candidates and Potential Candidates:
  Bosnia and Herzegovina
  fYR Macedonia
  Iceland
  Serbia
  Turkey
- Other Countries:
  Norway and Switzerland
- COST Cooperating State:
  Israel

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
C. Baniotopoulos – Wind energy technology reconsideration to enhance the concept of smart cities



COST Country participation

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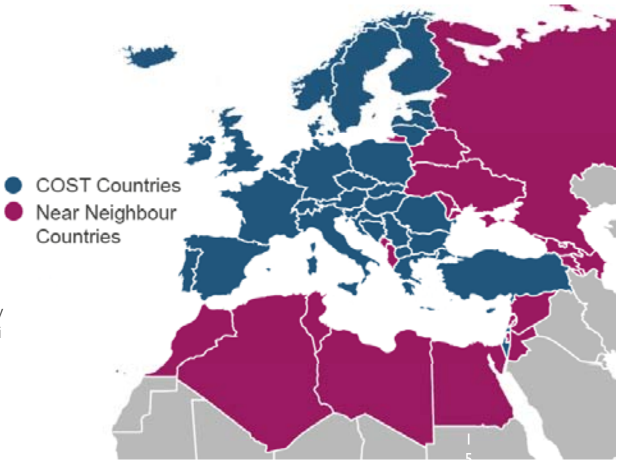
C. Baniotopoulos – Wind energy technology reconsideration to enhance the concept of smart cities

COST Near Neighbour Countries

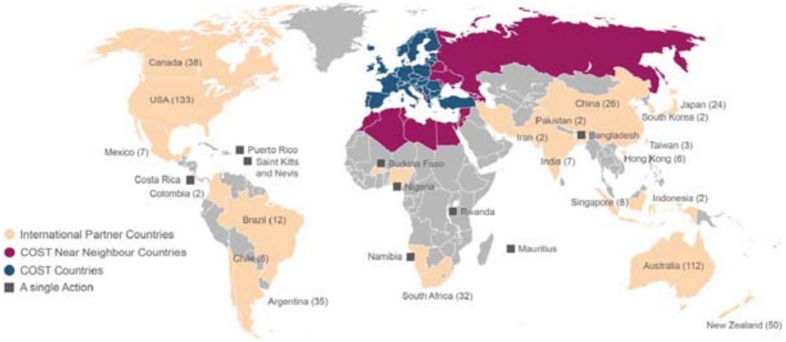
231 participations in running COST Actions across 17 countries

- Albania (19)
- Algeria (6)
- Armenia (10)
- Azerbaijan (5)
- Belarus (5)
- Egypt (10)
- Georgia (4)
- Jordan (2)
- Lebanon (4)
- Moldova (5)
- Montenegro (15)
- Morocco (16)
- Palestinian Authority
- Syrian Arab Republi
- Russia (58)
- Tunisia (16)
- Ukraine (50)



International Partner Countries

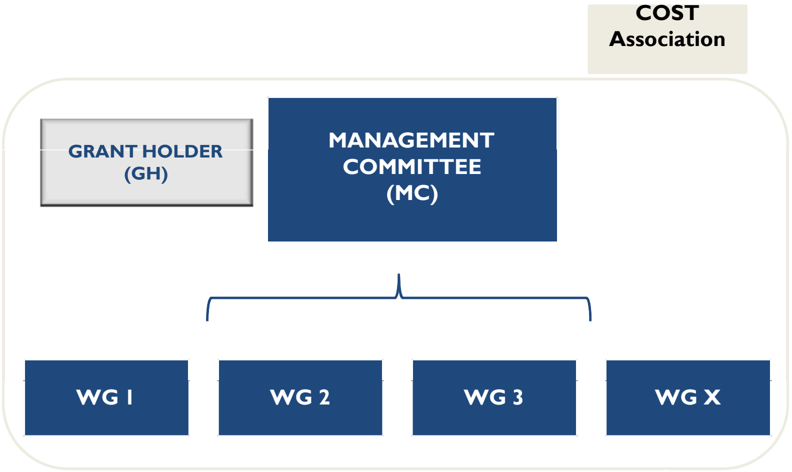
519 participations in running Actions across 29 countries



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 areas 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 anAction

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

Management Committee

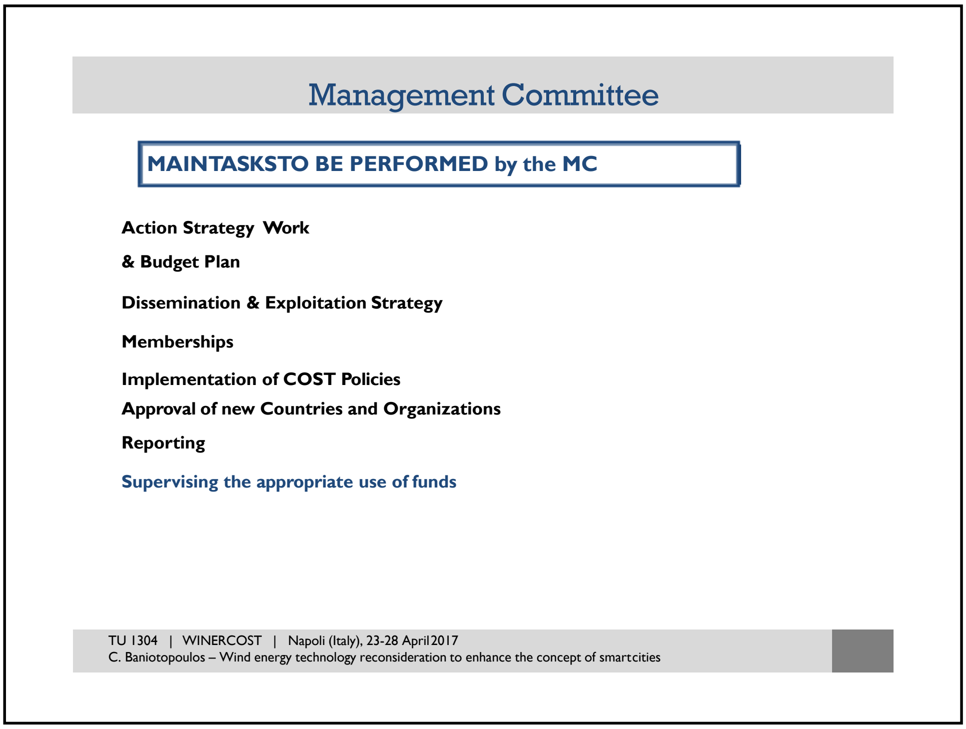
KEY ROLES in order to ORGANISETHEWORK

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

MAINTASKSTO BE PERFORMED by the MC

Action Strategy Work

& Budget Plan

Dissemination & Exploitation Strategy

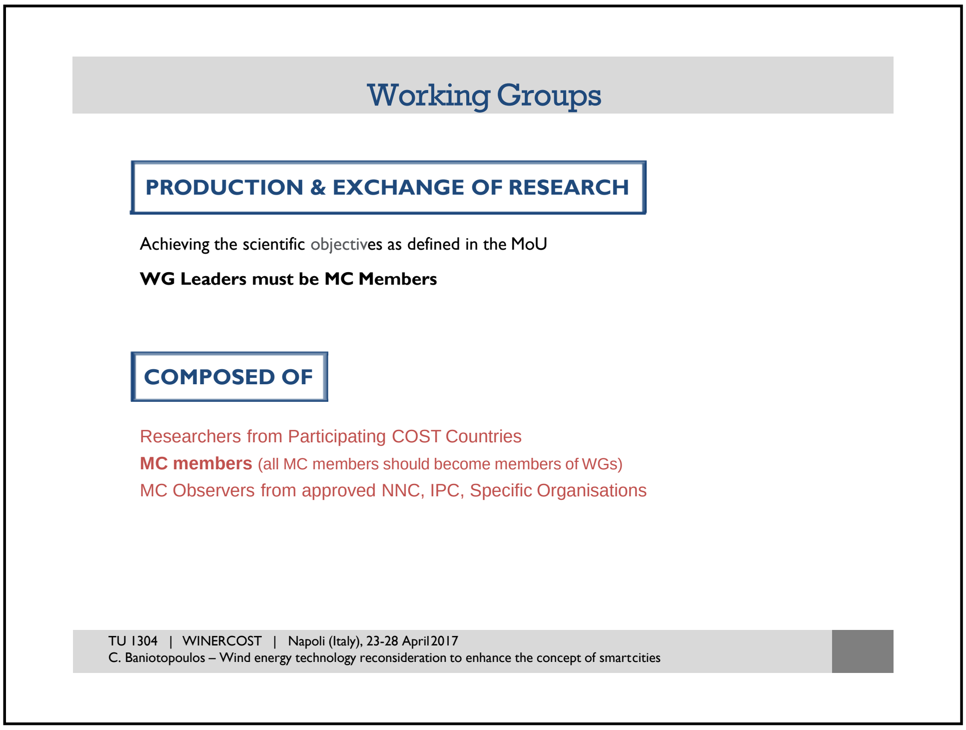
Memberships

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

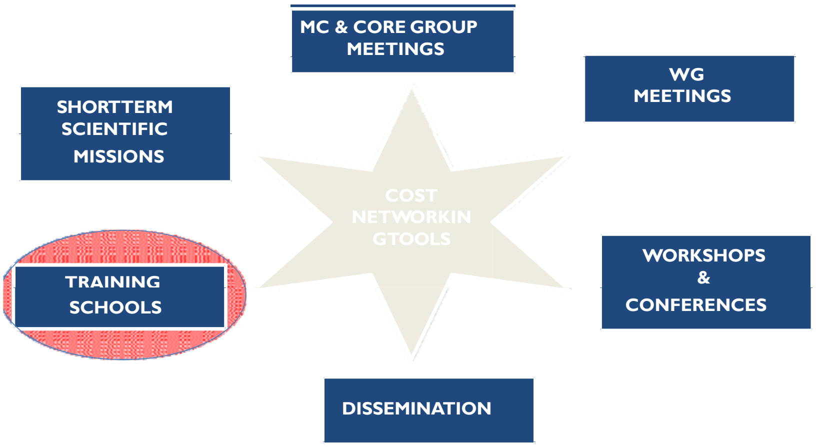
COMPOSED OF

Researchers from Participating COST Countries

MC members (all MC members should become members of WGs)

MC Observers from approved NNC, IPC, Specific Organisations

COST Networking Tools



COST Networking Tools: Training School

TRAINING SCHOOLS

Provide intensive training on a subject that contributes to the aim of the Action

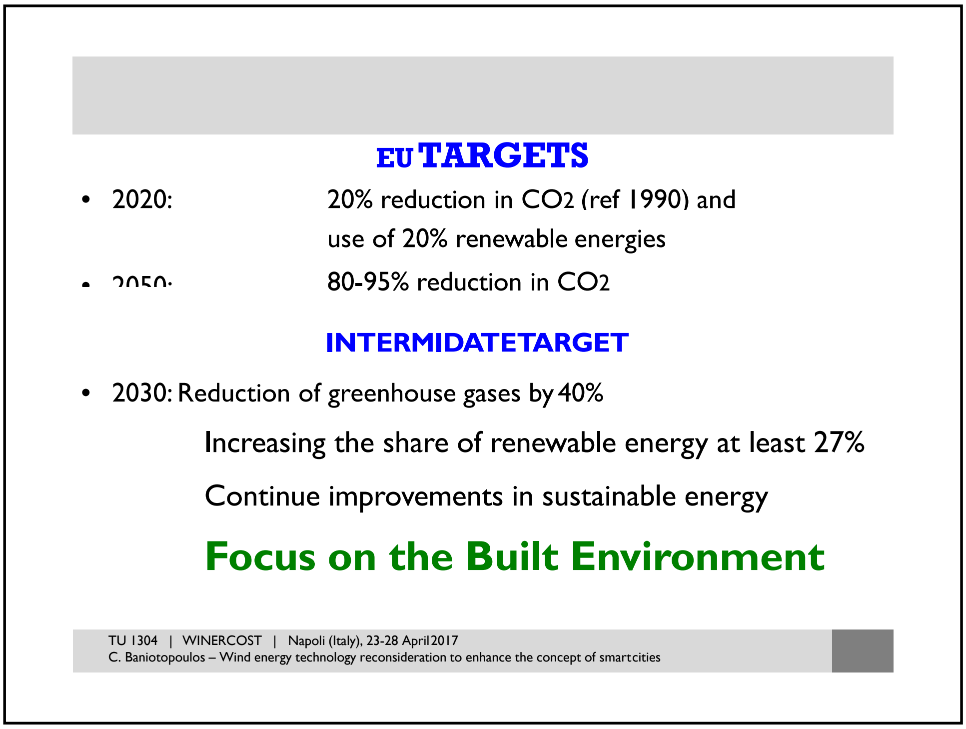
SETTING THE FRAMEWORK

- **Sustainable energy** is energy obtained from non- exhaustible resources.

By definition, ***sustainable energy*** *serves the* *needs of the present without compromising the ability of future* generations to meet their needs.

Technologies that promote **sustainable energy** include **renewable energy sources**, such as wind energy, and also technologies designed to **improve energy efficiency**.

- Sustainable technologies are <u>currently</u> economically competitive (or close to).
- Sustainable energy costs have fallen in recent years,and continue to fall.
- Increasingly, effective government policies support investor confidence and these markets are expanding.
- Considerable progress is being made in the **energy transition** from fossil fuels to ecologically sustainable systems, to the point where projects support **100% renewable energy**.



EU TARGETS

- 2020: 20% reduction in CO2 (ref 1990) and use of 20% renewable energies
- 2050: 80-95% reduction in CO2

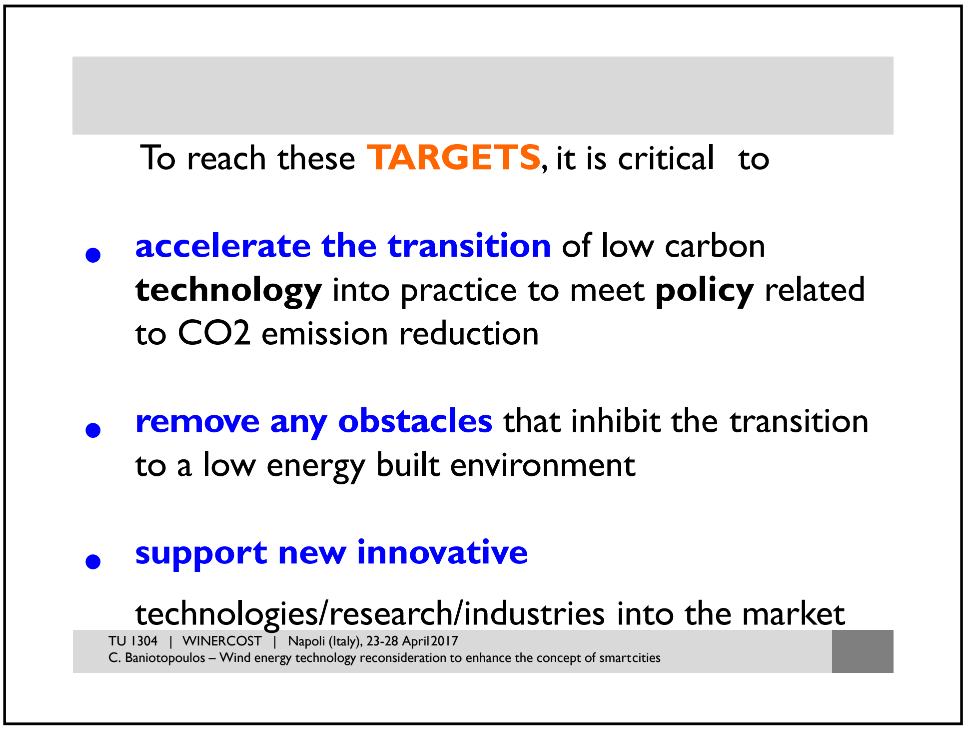
INTERMIDATETARGET

- 2030: Reduction of greenhouse gases by 40%

Increasing the share of renewable energy at least 27%

Continue improvements in sustainable energy

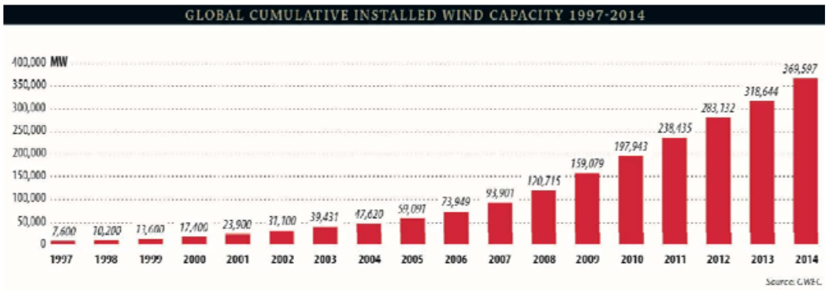
Focus on the Built Environment



To reach these **TARGETS**, it is critical to

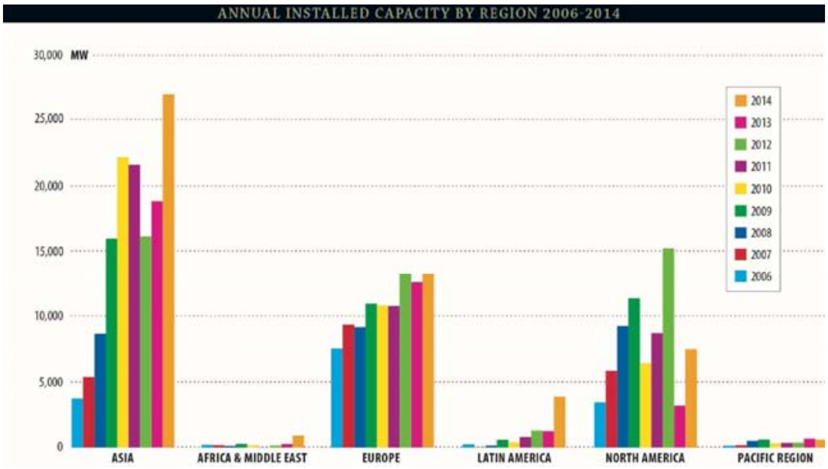
- **accelerate the transition** of low carbon **technology** into practice to meet **policy** related to CO2 emission reduction
- **remove any obstacles** that inhibit the transition to a low energy built environment
- **support new innovative** technologies/research/industries into the market

WIND ENERGY HARVESTING



Source: GWEC

ONSHORE & OFFSHORE AEOLIAN PARKS



Significant potential from small and medium size wind turbines

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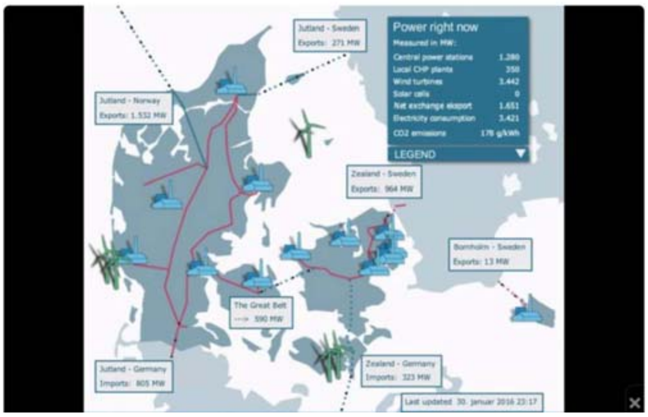
Good practice examples

Denmark did it again: Wind power generation surpassed national demand, 6th night in a row: 100.6% at 23:17 !!!



WIND POWER GENERATES 140% OF DENMARK'S ELECTRICITY DEMANDS

Wind farms outstrip nuclear power

By Roger Harrabin
BBC environment analyst

22 October 2014 | Business

The UK's wind farms generated more power than its nuclear power stations on Tuesday, the National Grid says.

Wind made up 14.2% of all generation and nuclear offered 13.2%.

It follows another milestone on Saturday, when wind generated a record amount of power - 6,372 MW, according to National Grid.

This formed nearly 20% of the the UK's electricity

Wind energy harvested by large onshore and offshore Aeolian parks is nowadays thriving,

however,

Sustainability Features of Smart Cities

could be enhanced by revisiting

Wind Energy Technology to be used in the built fabric.

There, SMALL WIND ENERGY is dominating the area!

Several definitions of small wind turbines:
The most important international standardisation body, International Electrotechnical Commission (IEC) defines SWTs in standard IEC 61400-2 as having a rotor swept area of less than 200 m2, equating to a rated power of approximately 50 kW.

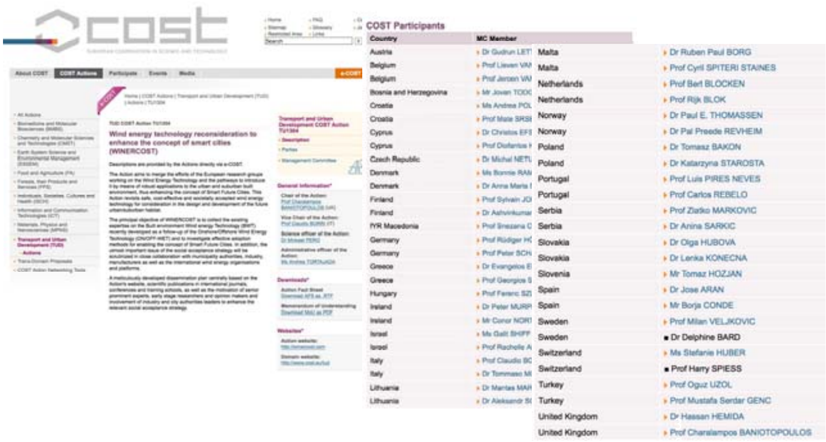
The discrepancy of the upper capacity limit of small wind ranges between 15 kW to 100 kW for the five largest small wind countries.

15kW-100kW

Our Action (TU1304 COST Action)

WINERCOST

TU1304 WINERCOST ACTION



COST Participants

Country	MC Member
Austria	Dr Gudrun LET
Belgium	Prof Lieven VAN
Belgium	Prof Jeroen VAN
Bosnia and Herzegovina	Mr Jovan TODO
Croatia	Ms Andrea POL
Croatia	Prof Mate SRSI
Cyprus	Dr Christos EFS
Cyprus	Prof Diofantos H
Czech Republic	Dr Michal NETU
Denmark	Ms Bonnie RAM
Denmark	Dr Anna Maria I
Finland	Prof Sylvain JO
Finland	Dr Ashvinkumar
fYR Macedonia	Prof Snezana C
Germany	Prof Rüdiger HO
Germany	Prof Peter SCH
Greece	Dr Evangelos E
Greece	Prof Georgios S
Hungary	Prof Ferenc SZ
Ireland	Dr Peter MURP
Ireland	Mr Conor NORT
Israel	Ms Galit SHIFF
Israel	Prof Rachelle A
Italy	Prof Claudio BO
Italy	Dr Tommaso M
Lithuania	Dr Mantas MA
Lithuania	Dr Aleksandr S
Malta	Dr Ruben Paul BORG
Malta	Prof Cyril SPITERI STAINES
Netherlands	Prof Bert BLOCKEN
Netherlands	Prof Rijk BLOK
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Poland	Dr Tomasz BAKON
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Portugal	Prof Luis PIRES NEVES
Portugal	Prof Carlos REBELO
Serbia	Prof Zlatko MARKOVIC
Serbia	Dr Anina SARKIC
Slovakia	Dr Olga HUBOVA
Slovakia	Dr Lenka KONECNA
Slovenia	Mr Tomaz HOZJAN
Spain	Dr Jose ARAN
Spain	Mr Borja CONDE
Sweden	Prof Milan VELJKOVIC
Sweden	Dr Delphine BARD
Switzerland	Ms Stefanie HUBER
Switzerland	Prof Harry SPIESS
Turkey	Prof Oguz UZOL
Turkey	Prof Mustafa Serdar GENC
United Kingdom	Dr Hassan HEMIDA
United Kingdom	Prof Charalampos BANIOTOPOULOS

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.***

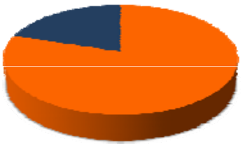
- **WINERCOST**

collects the existing expertise on the WET & Built environment Wind energy Technology (BWT)

and

investigates effective adoption methods for enabling the concept of Smart Future Cities.

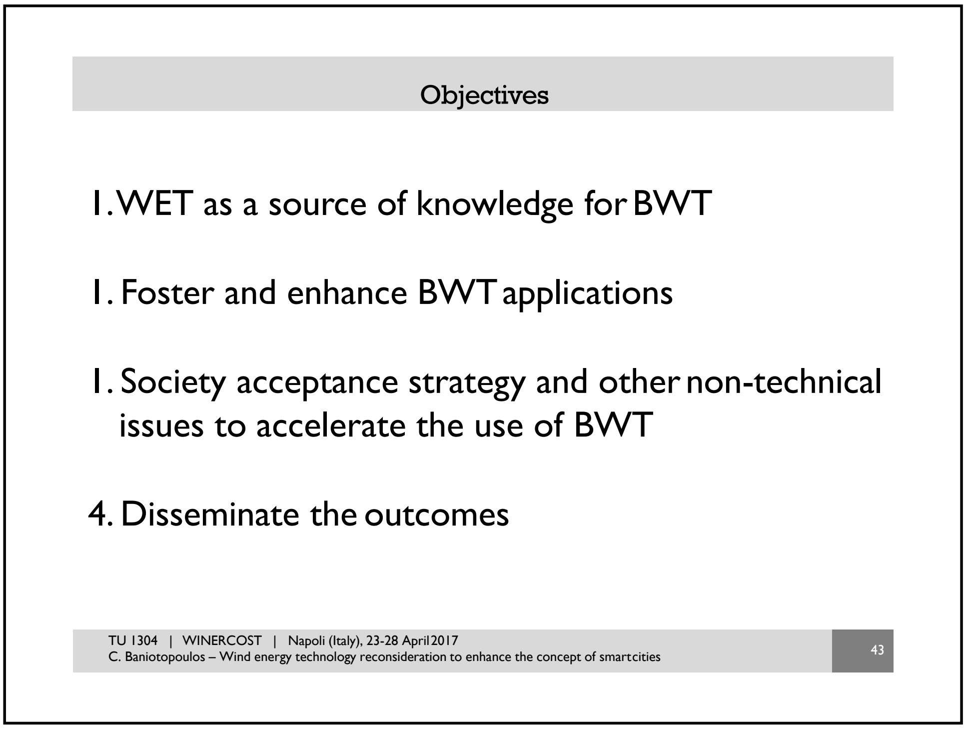
Social acceptance strategy



The objective of *Future Smart Cities* (HORIZON

20% of renewable energy

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



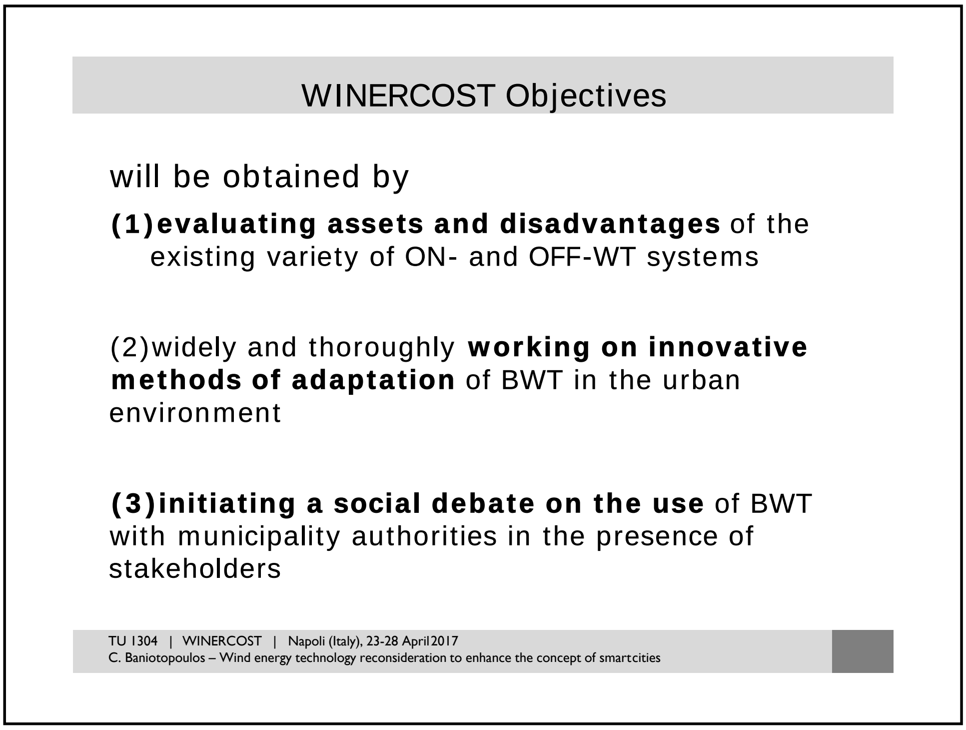
Objectives

1. WET as a source of knowledge for BWT

1. Foster and enhance BWT applications

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

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

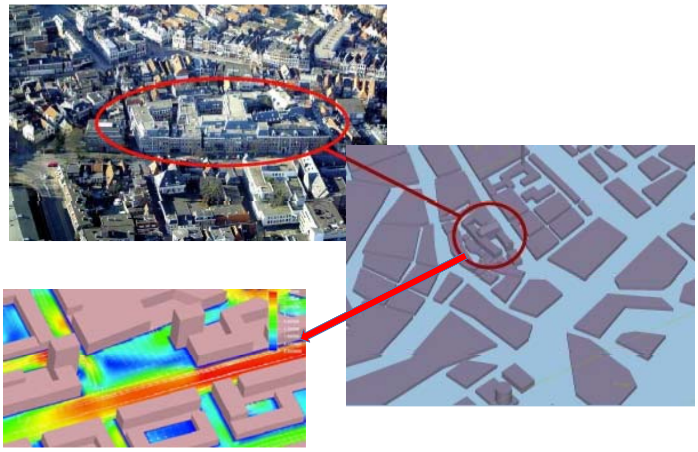
- **Technological implementation** difficulties
- **Non-technical negative effects** (e.g. noise, production/installation costs, logistics, reliability, integrity, system robustness, aesthetic problems)
- **European energy policy**
- **Society acceptance issues**

3 Working Groups

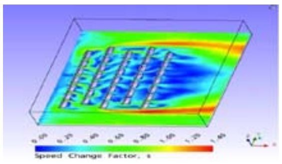
- **WG1A**: Wind simulation, characterization etc. issues (CFD, Maps, etc) with reference to theoretical, experimental and numerical research approaches
- **WG2A**: ON- and OFFSHORE WT projects and the respective accumulated expertise
- **WG3A**: Non-technical issues of WT including social acceptance,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

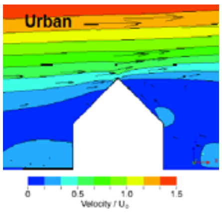
- **WG1B**: Built environment Wind Energy Technology (BWT) advances
- **WG2B:** Built environment Wind energy (BWT) pilot projects and good practice examples
- **WG3B:** Social acceptance, European BWT policy and other non-technical BWT issues.

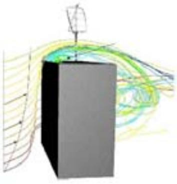
Urban scale approach

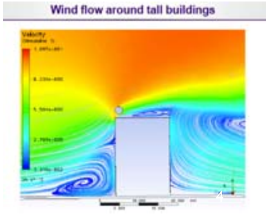


Building scale









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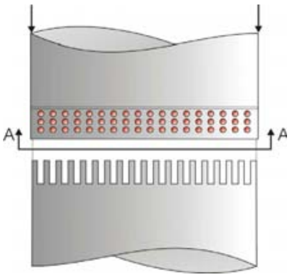

REPOWER 5M assembled in 2004, Germany New
proposal

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%
•Total cost per MW	•€1.5 - 2 million •300-400 k€	•€2.5 – 3.5 million 325-455 k€

Innovative wind harvesting projects


Experimental setup on Venice link motorway

---

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Society acceptance

iea wind

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

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) .

Training Policy

STSMs | **Training**

Training Schools (Malta 2015, Chania 2016, Napoli 2017)

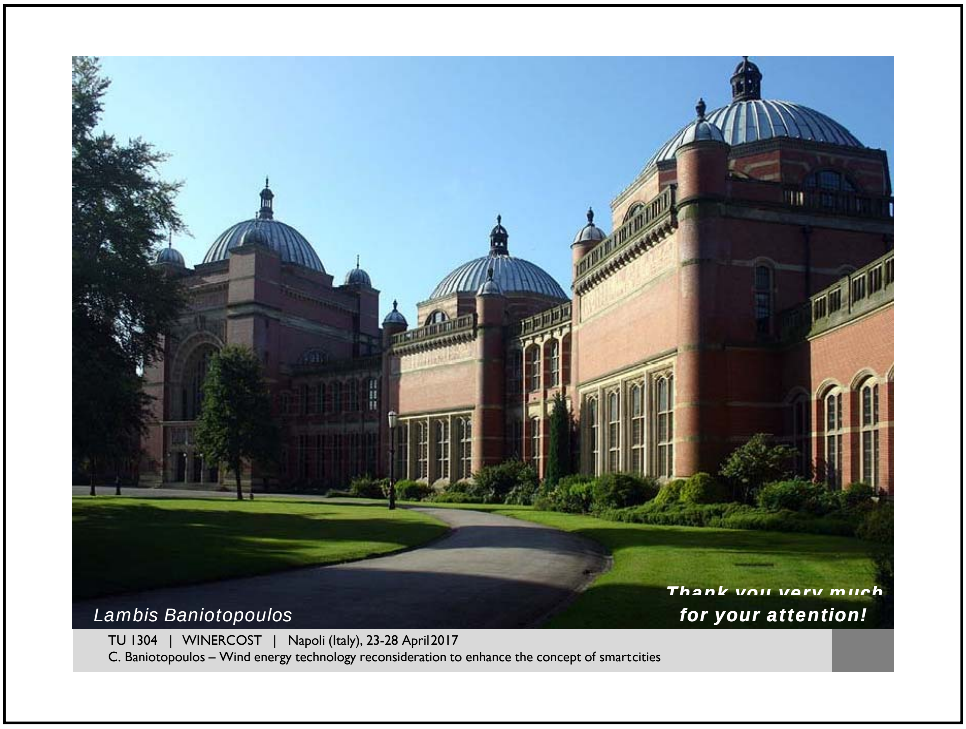
Gender Balance Strategy
(Encouregement to female participation)

Early Stage Investigators

WINERCOST website

www.winercost.com

- Scientific books and Proceedings
- 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



Lambis Baniotopoulos

Thank you very much
for your attention!

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April2017
C. Baniotopoulos – Wind energy technology reconsideration to enhance the concept of smartcities

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Wind Imaginaries Workshop The Challenge of Societal Acceptance of Urban Wind Energy

Ruben Paul Borg, Neveen Hamza

TU 1304 – WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

The Challenge of Societal Acceptance of Urban Wind Energy

Ruben Paul Borg[a] and Neveen Hamza[b]

[a] University of Malta
[b] Newcastle University

Case Studies

1. **Valletta Grand Harbour** Malta: Marsa Area.
2. **Jesmond Dene**, Newcastle upon Tyne, England.

References:
Google Earth

Attributes for assessment:

1. Environment
2. Planning
3. Social
4. Economic

---

1. Environment

- Prevailing Wind and wind resource
- Surface roughness
- Exposure
- Vibration
- Noise level
- Flicker
- Ecological assessment – natural habitats, birds etc.

2. Planning

- Land use
- Historical value of site
- Accessibility
- Visual considertaions
- Noise
- Ease of construction, marshland / forest – river etc.
- Access to Grid and impact on electricity grid

3. Social

- Social Engagement
- Visual impact and landscape value
- Historic setting and memory of site

4. Economic

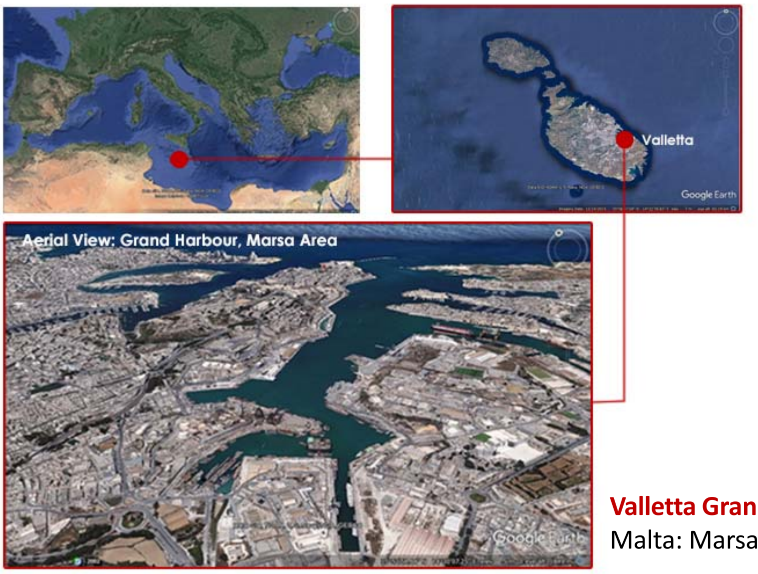
- Life time
- Maintenance
- Asset management
- Efficiency
- End of life considerations.

Barriers and Opportunities

Alternative settings:

- Degraded Area / Industrial Area requiring regeneration
- Existing industrial facilities
- Historic / Cultural setting
- Park setting

Case Study 1



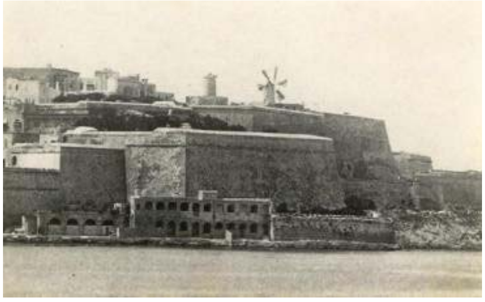
Valletta Grand Harbour
Malta: Marsa Area.

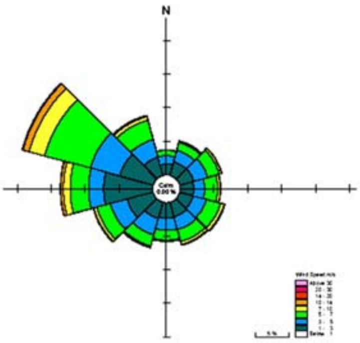

Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat / Copernicus
Google Earth
2012


HAMRUN
FLORIANA

History of Wind Energy in Malta

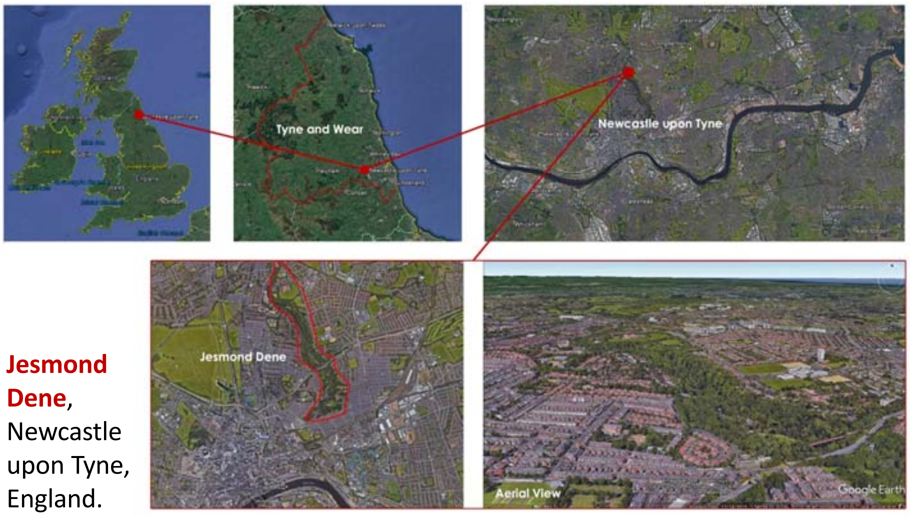
- Windmill on the outskirts of villages with surrounding open space.
- Windmills Perched on the high Bastions of Valletta





Ref. Busuttil A. et al., 2008, Energy scenarios in Malta, International Journal of Hydrogen Energy, 33

Case Study 2



Jesmond Dene, Newcastle upon Tyne, England.


Image Landsat / Copernicus
Google Earth
1945
54°59'35.88" N 1°35'33.84" W elev 52 m eye alt 779 m


Google Earth
1945
54°59'28.55" N 1°35'32.38" W elev 48 m eye alt 477 m

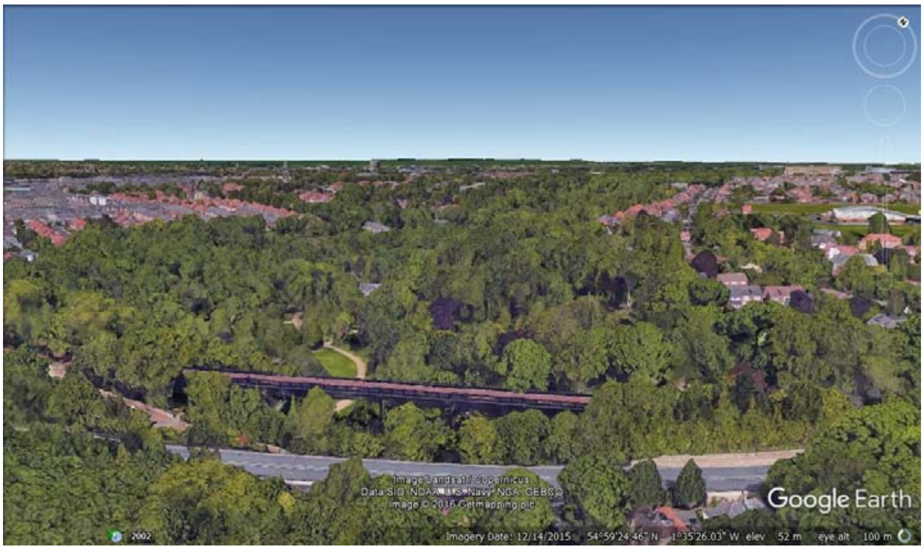
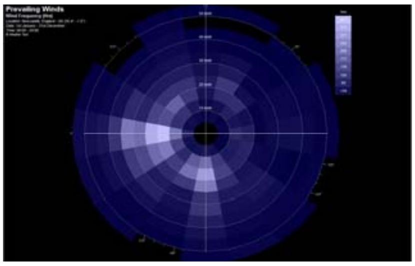
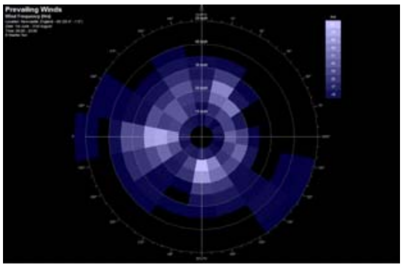
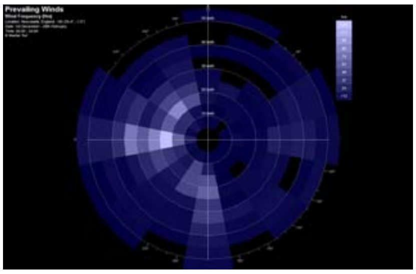


Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2016 Getmapping plc
Google Earth
2002
Imagery Date: 12/14/2015 54°59'24.46" N 1°35'26.03" W elev 52 m eye alt 100 m


Google







Case Studies WINERCOST Training School - Naples

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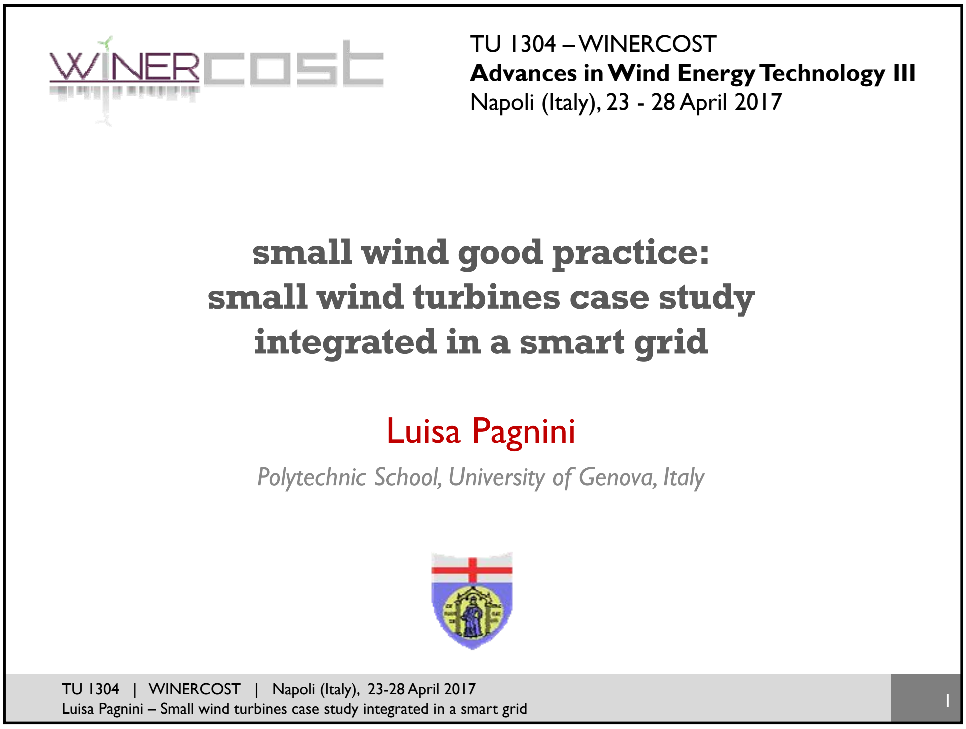
COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Small Wind Good Practice: Small Wind Turbines Case Study Integrated in a Smart Grid

Luisa Pagnini

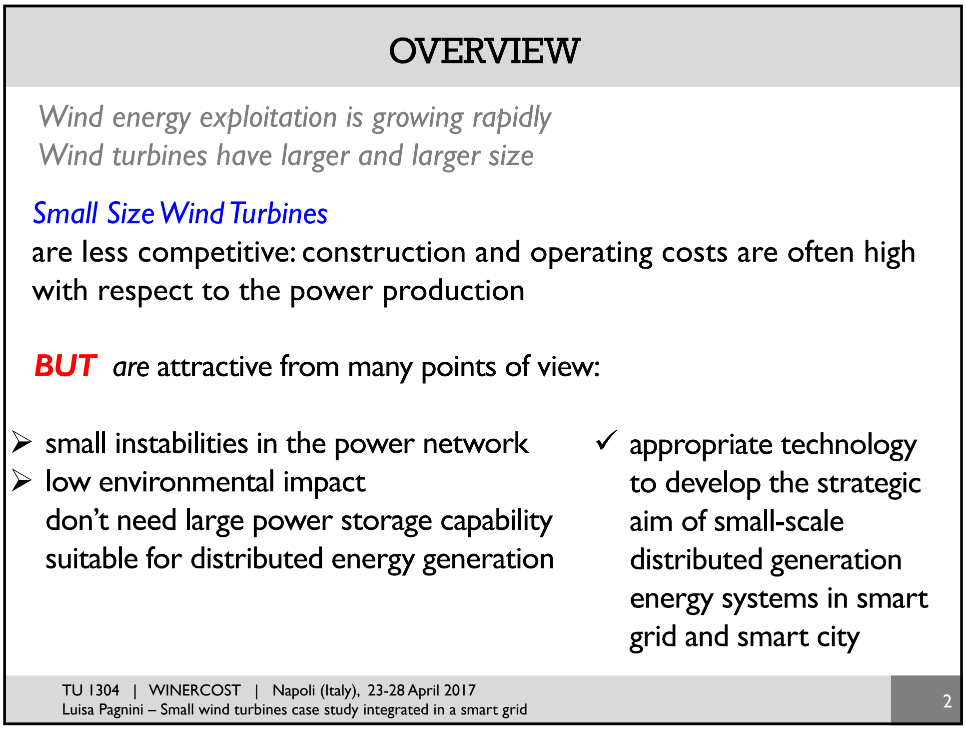


TU 1304 – WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

small wind good practice: small wind turbines case study integrated in a smart grid

Luisa Pagnini

Polytechnic School, University of Genova, Italy



OVERVIEW

Wind energy exploitation is growing rapidly
Wind turbines have larger and larger size

Small Size Wind Turbines
are less competitive: construction and operating costs are often high with respect to the power production

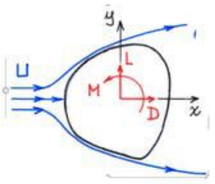
BUT *are* attractive from many points of view:

- small instabilities in the power network
- low environmental impact
  don't need large power storage capability
  suitable for distributed energy generation

✓ appropriate technology to develop the strategic aim of small-scale distributed generation energy systems in smart grid and smart city

OVERVIEW

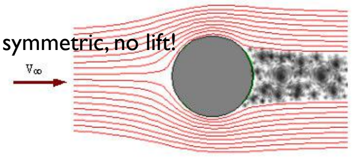
There are two forces in play: Lift and Drag. The **Lift Force** is perpendicular to the wind direction. It is caused by a pressure difference between the air on either side of the blade. The **Drag Force** is in the same direction as the wind. The ratio between lift and drag largely depends on the shape of the blade and the angle of the main line of the blade (chord line) and the main wind direction - the angle of attack.

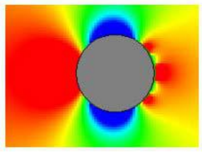


stream flow

pressures

symmetric, no lift!

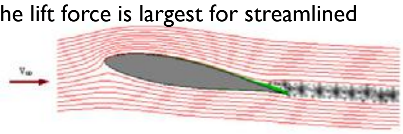


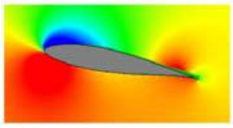


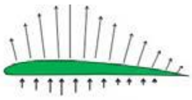
🟦 -

🟥 +

The lift force is largest for streamlined



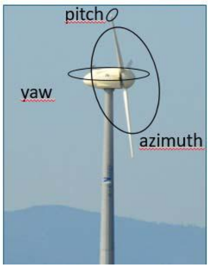




Depending on the design of the turbine, either drag or lift moves the blades.

OVERVIEW

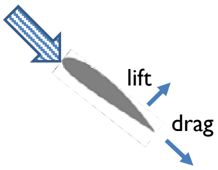
Horizontal Axis Wind Turbines (HAWTs)



Main degrees of freedom

- **Azimuth**
  - rotation of rotor about its shaft due to the torque
- **Yaw**
  - rotation of nacelle about the vertical lengthwise axis of the tower
- **Pitch**
  - rotation of blades about their lengthwise axis due to pitch control

Turbines based on lift force:
the wind is flowing on both sides of the blade, which has different geometrical profiles, thus creating at the upper surface a low pressure area with respect to the pressure on the lower face. This produces a lift force on the blade which rotates around the hub.



OVERVIEW

Horizontal Axis Wind Turbines (HAWTs)

- is the most common technology in use for large wind turbines

- need to be aligned with the direction of the wind, allowing the wind to flow parallel to the axis of rotation

- the rotor should always be perpendicular to the wind: a wind vane is mounted to measure the direction.
This signal is coupled with a yaw motor, which continuously turns the nacelle into the wind

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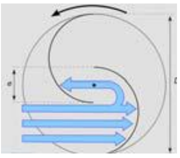
OVERVIEW

Vertical Axis Wind Turbines (VAWTs)

Savonius Rotor

based on drag force



Darreus Rotor

H-type Darreus

based on lift force

OVERVIEW

Vertical Axis Wind Turbines (VAWTs)

- designed to act correspondingly towards air
- do not require any yaw mechanism, pitch regulation: few movable parts and lower maintenance costs.
- quite low rotating speed and thus producing low noise

have received less financial support

BUT

attractive for smaller size applications, especially in complex contexts like urban areas

---

OVERVIEW

VAWTs versus HAWTs

HAWT

Advantages

☐ Lower cut-in wind speed
☐ Higher efficiency
☐ Lower cost /power
☐ Ability to furl rotor out of wind

Disadvantages

- Active yaw drive
- Difficult maintenance
- Many moving parts

VAWT

Advantages

☐ no yaw mechanism
☐ no pitch regulation
☐ few movable parts → lower maintenance costs
☐ low rotating speed → produce low noise

Disadvantages

- Low wind speed
- Low efficiency
- Difficult over speed control
- Difficult starting

WIND TURBINES IN SMART CITIES AND SMART GRIDS

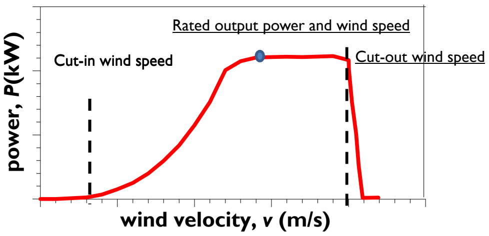
ISSUES

✓ **power curve**
Which is the actual behavior and power production?

✓ **optimal planning of the mix of power production units**
competitive with other renewable sources? (e.g. PV solar)

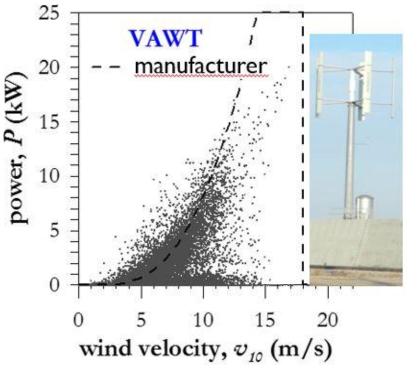
✓ **structural response and safety:**
their behavior is as much complex as the behavior of the large size turbines. Which are major shortcomings that may concern structural safety?

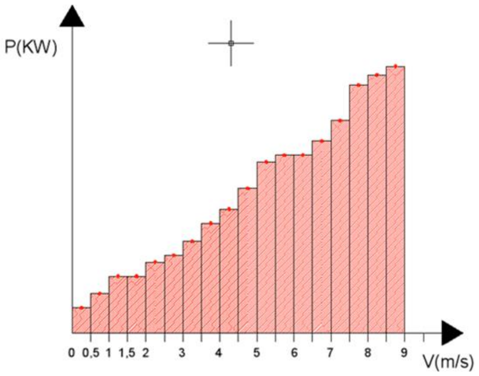
POWER CURVE



Cut-in wind speed - this is the minimum wind speed at which the turbine blades overcome friction and begin to rotate
Cut-out speed - This is the speed at which the turbine blades are brought to rest to avoid damage from high winds. Not all turbines have a well-defined cut-out speed.
Power curve - this is the steady power delivered by the turbine as a function of steady wind speed between the cut-in and cut-out speeds.

POWER CURVE





International Electrotechnical Commission, IEC 61400-12

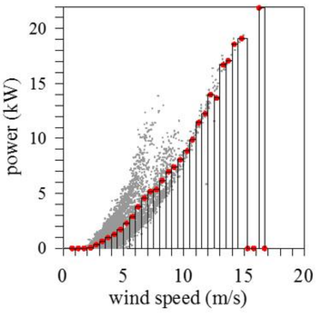
The measured power curve is determined by the **method of bins** calculating the mean values of the wind speed and power output for each wind speed bin

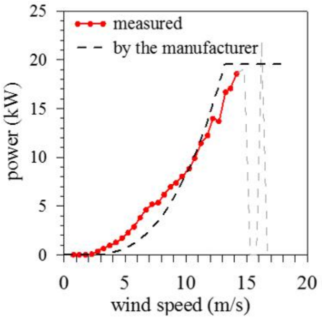
$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{n,1,j}$$

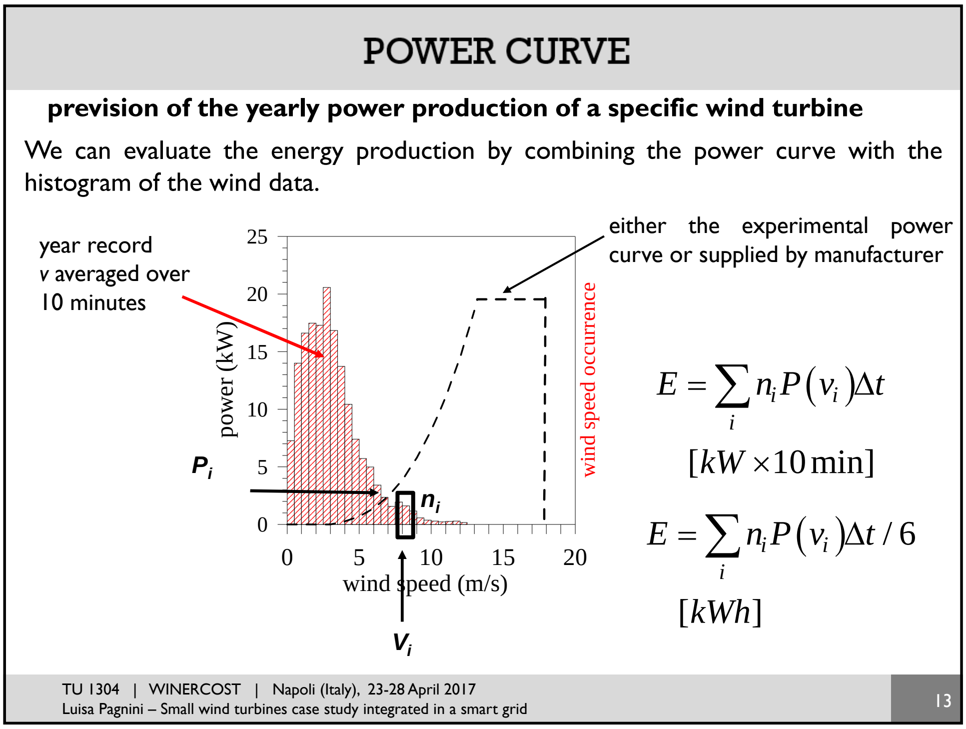
$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{n,1,j}$$

POWER CURVE

Method of bins
(International Electrotechnical Commission, IEC 61400-12)







POWER CURVE

prevision of the yearly power production of a specific wind turbine

We can evaluate the energy production by combining the power curve with the histogram of the wind data.

year record
v averaged over
10 minutes

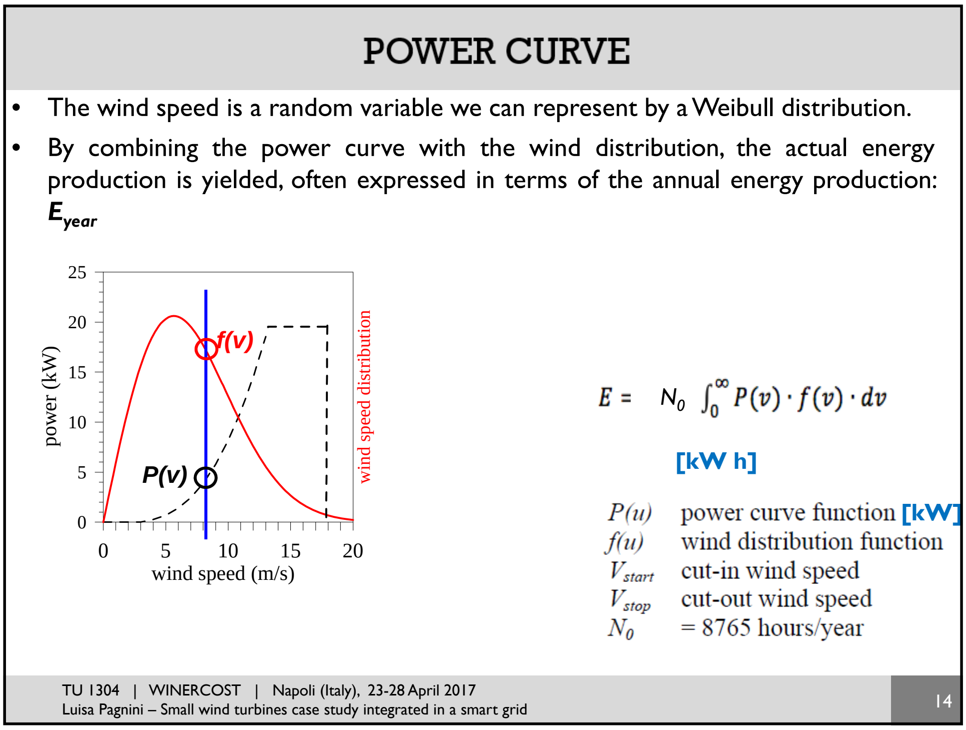
either the experimental power curve or supplied by manufacturer

$$E = \sum_i n_i P(v_i)\Delta t$$

$$[kW \times 10\,\mathrm{min}]$$

$$E = \sum_i n_i P(v_i)\Delta t / 6$$

$$[kWh]$$



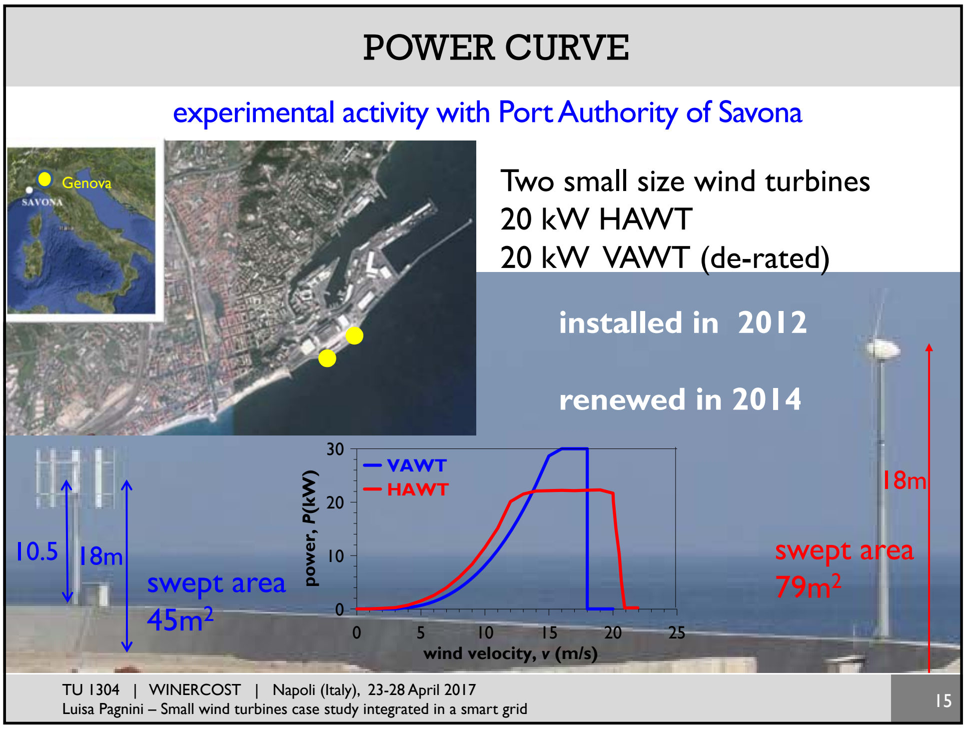
POWER CURVE

- The wind speed is a random variable we can represent by a Weibull distribution.
- By combining the power curve with the wind distribution, the actual energy production is yielded, often expressed in terms of the annual energy production: $\boldsymbol{E_{year}}$

$$E = N_0 \int_0^{\infty} P(v)\cdot f(v)\cdot dv$$

[kW h]

$P(u)$	power curve function **[kW]**
$f(u)$	wind distribution function
V_{start}	cut-in wind speed
V_{stop}	cut-out wind speed
N_0	= 8765 hours/year



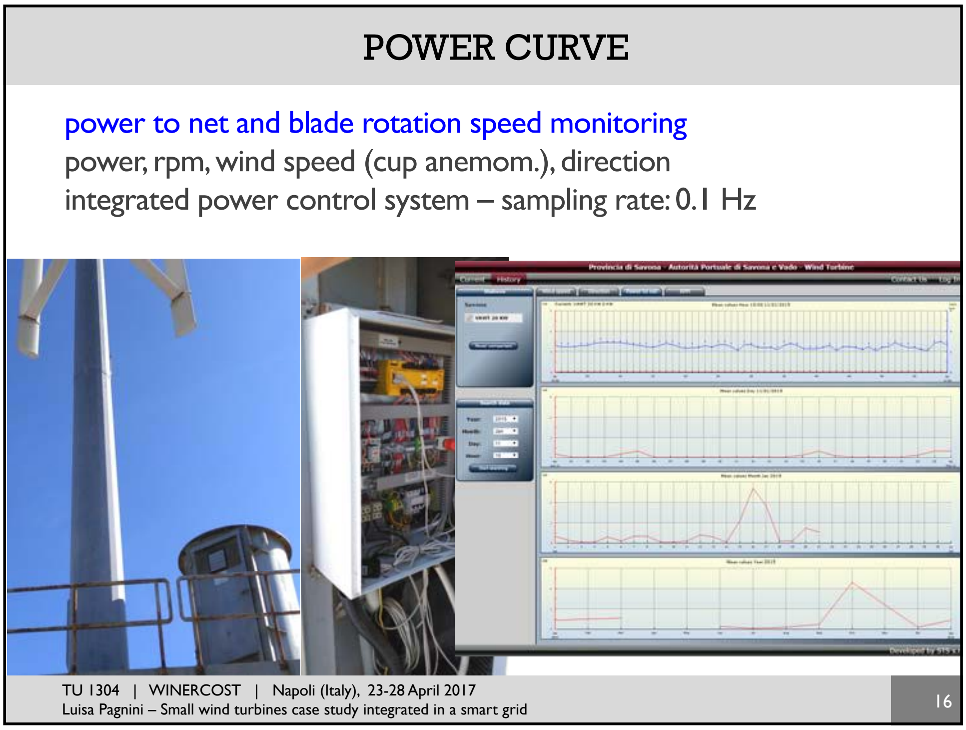
POWER CURVE

experimental activity with Port Authority of Savona

Two small size wind turbines
20 kW HAWT
20 kW VAWT (de-rated)

installed in 2012

renewed in 2014



POWER CURVE

power to net and blade rotation speed monitoring
power, rpm, wind speed (cup anemom.), direction
integrated power control system – sampling rate: 0.1 Hz

POWER CURVE

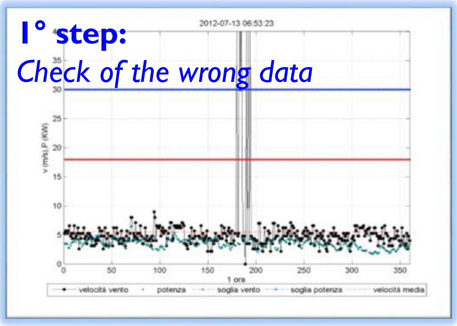
wind monitoring

cup anemometer
sampling rate: 0.1 Hz

sonic anemometer
sampling rate: 10 Hz

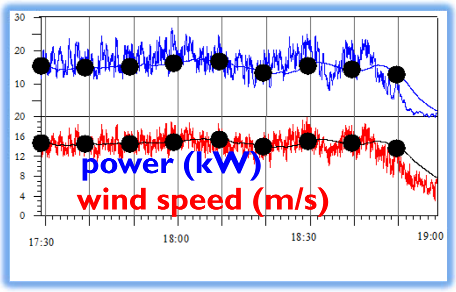
POWER CURVE

data base and transfer to the turbine hub
(sonic anemometer)

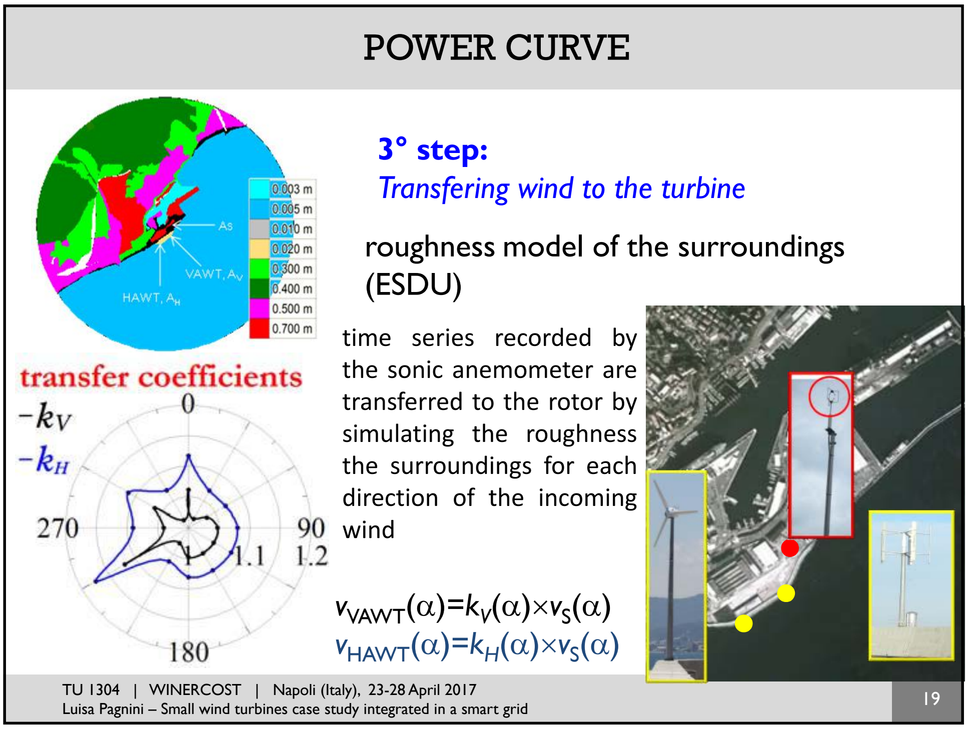


1° step:
Check of the wrong data

2° step:
Average over 10-minutes power, velocity, direction, turbulence intensity



3° step:
Transfering wind to the turbine



POWER CURVE

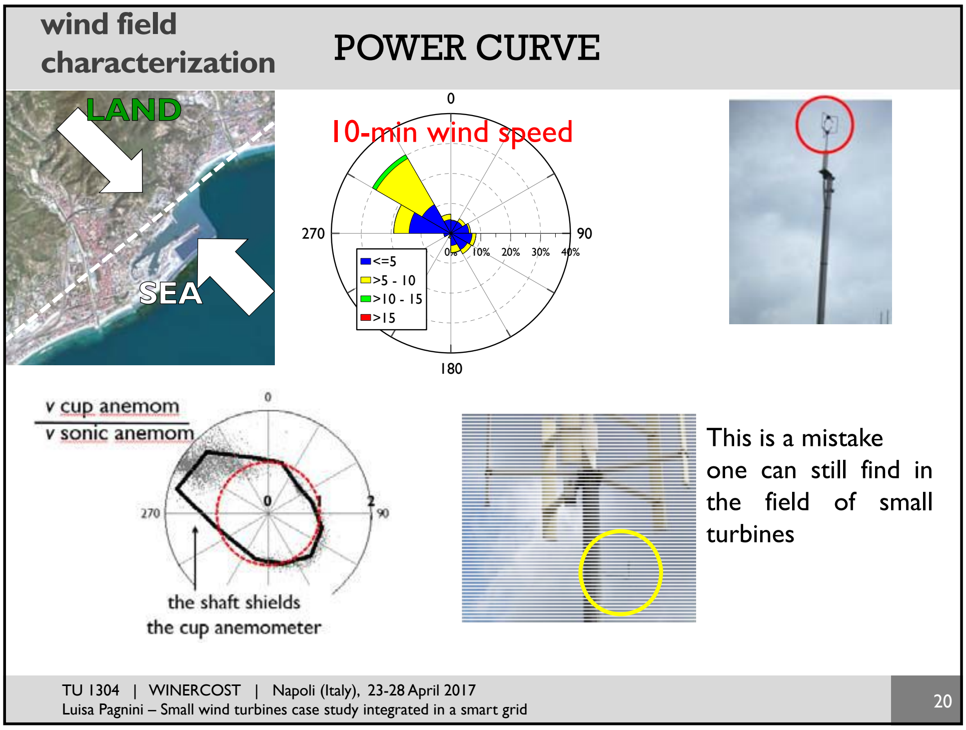
3° step:
Transfering wind to the turbine

roughness model of the surroundings (ESDU)

transfer coefficients

time series recorded by the sonic anemometer are transferred to the rotor by simulating the roughness the surroundings for each direction of the incoming wind

$$v_{VAWT}(\alpha)=k_V(\alpha)\times v_S(\alpha)$$
$$v_{HAWT}(\alpha)=k_H(\alpha)\times v_S(\alpha)$$

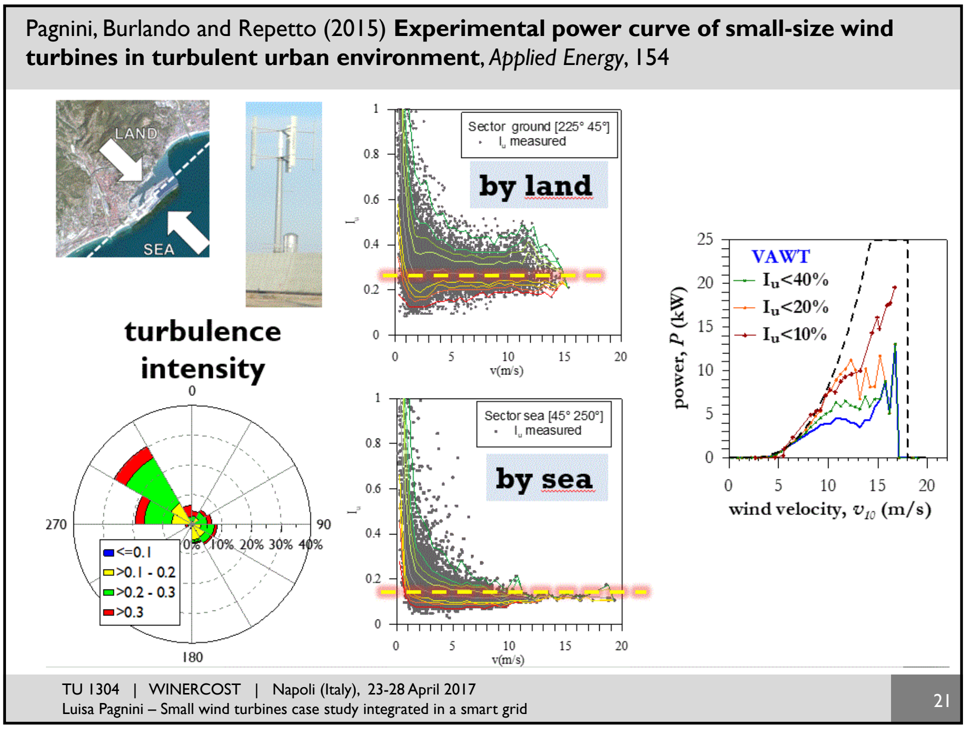


wind field characterization

POWER CURVE

the shaft shields the cup anemometer

This is a mistake one can still find in the field of small turbines

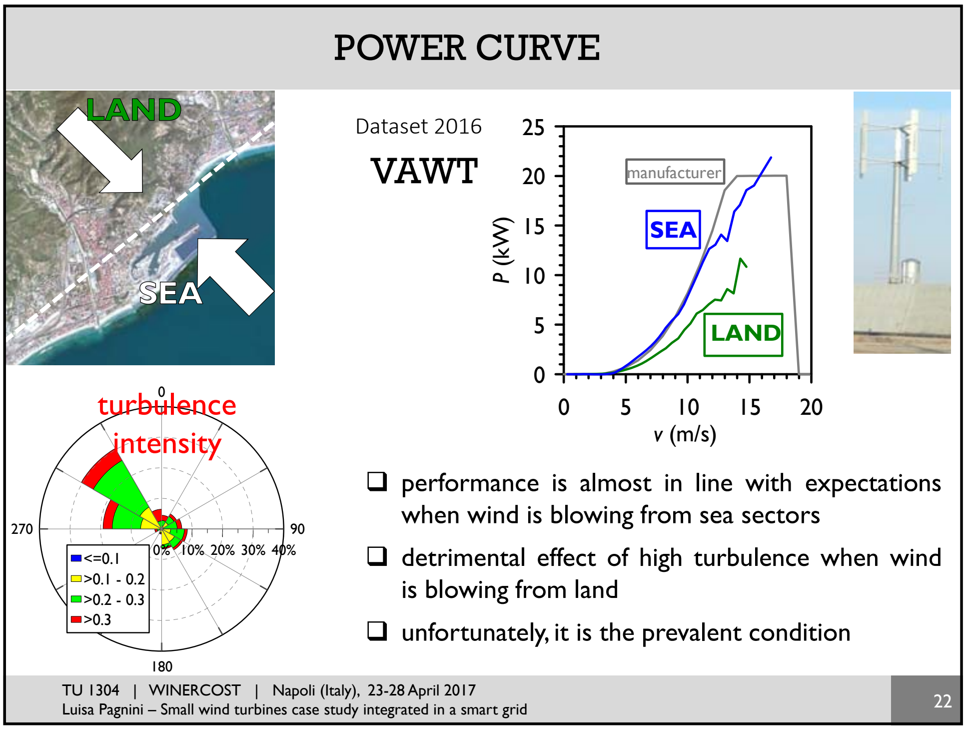


Pagnini, Burlando and Repetto (2015) **Experimental power curve of small-size wind turbines in turbulent urban environment**, *Applied Energy*, 154

turbulence intensity

by land

by sea

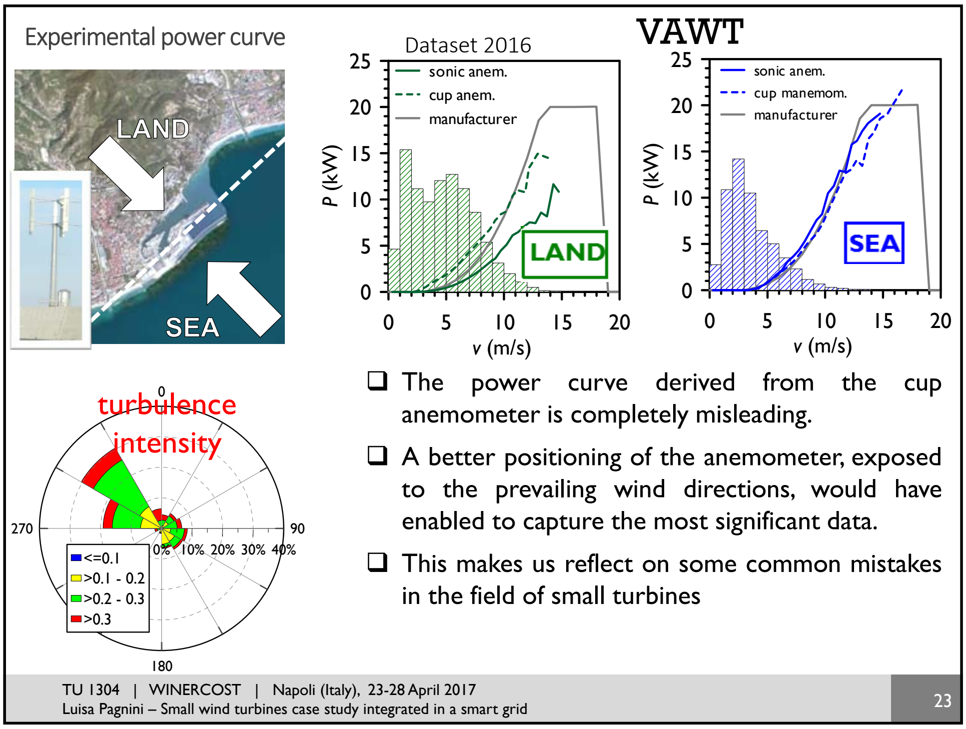


POWER CURVE

Dataset 2016

VAWT

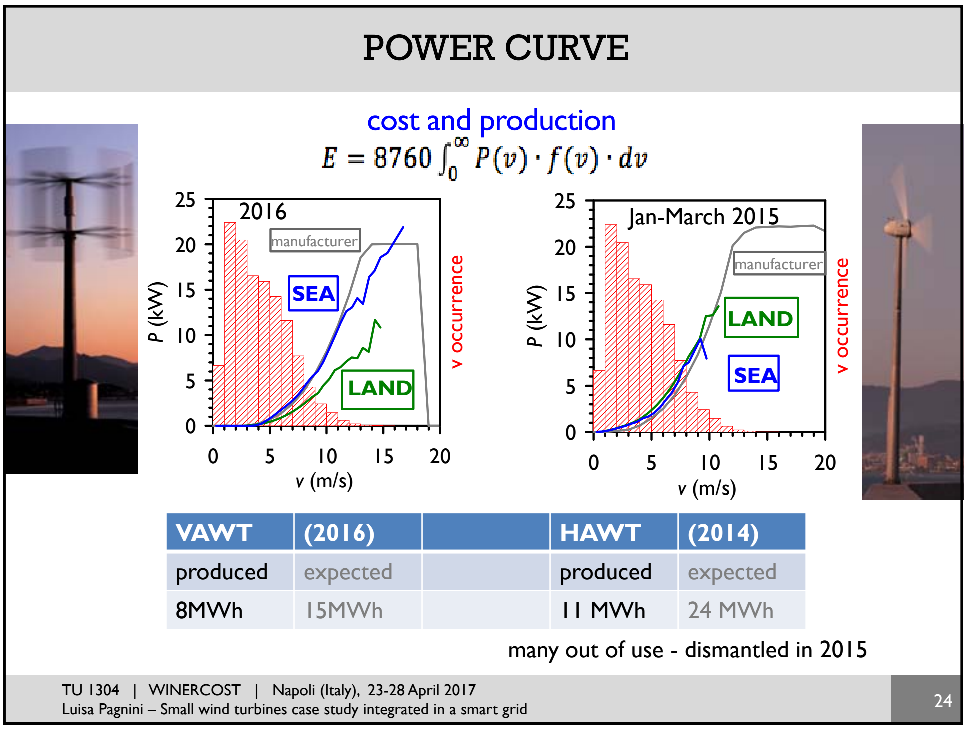
- ☐ performance is almost in line with expectations when wind is blowing from sea sectors
- ☐ detrimental effect of high turbulence when wind is blowing from land
- ☐ unfortunately, it is the prevalent condition



Experimental power curve

VAWT

- ☐ The power curve derived from the cup anemometer is completely misleading.
- ☐ A better positioning of the anemometer, exposed to the prevailing wind directions, would have enabled to capture the most significant data.
- ☐ This makes us reflect on some common mistakes in the field of small turbines



POWER CURVE

cost and production

$$E = 8760 \int_0^\infty P(v) \cdot f(v) \cdot dv$$

VAWT	(2016)		HAWT	(2014)
produced	expected		produced	expected
8MWh	15MWh		11 MWh	24 MWh

many out of use - dismantled in 2015

SMALL SIZE WTS: MIX PLANNING

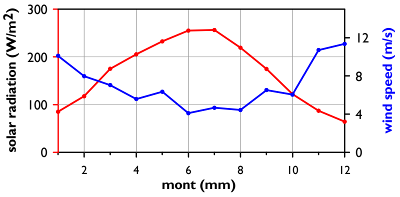
in smart cities it is necessary to optimally manage energy sources and end-user needs
considering: distributed generation / intermittent renewables / storage / grid constraints
and: the daily and seasonal variation of the renewable source and of the electrical demand

The Savona Campus - University of Genova
courses of engineering, medical and social sciences

SMALL SIZE WTS: MIX PLANNING

The Savona Campus - University of Genova
courses of engineering, medical and social sciences

integrated power producton between
PV solar and wind



SMART ENERGY BUILDING

completely powered by renewable sources
Includes a gymnasium where users
produce electrical power feeding the electrical grid

SMALL SIZE WTS: MIX PLANNING

Smart Polygeneration Microgrid (SPM)
of Savona Campus - University of Genova

plug-in electrical vehicles

PV units

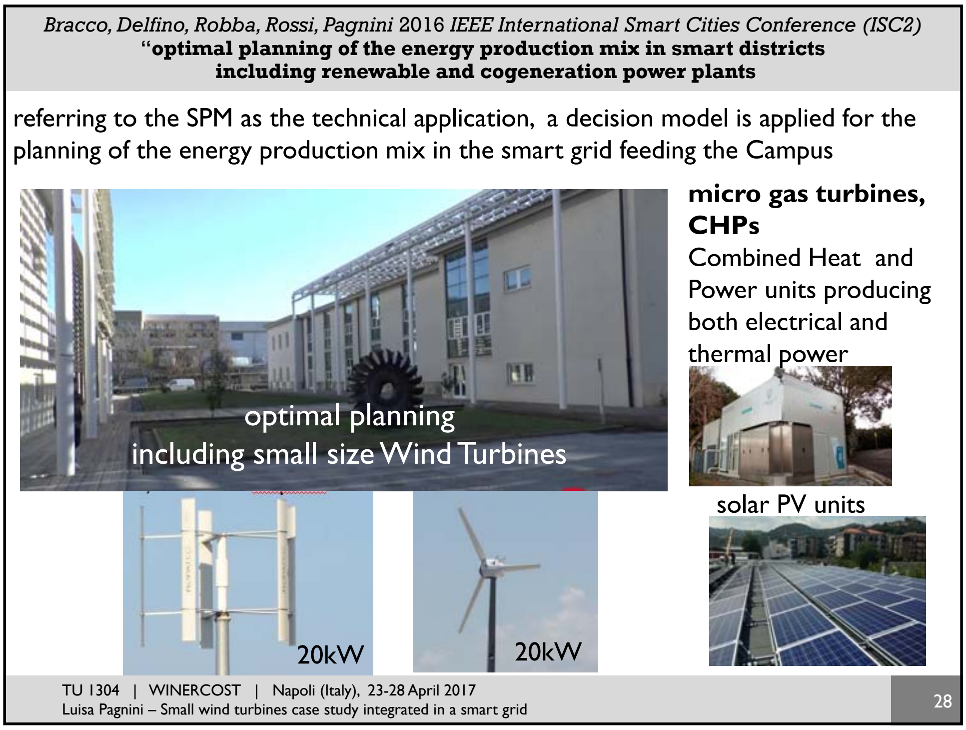
chiller : waste heat into cooling energy

control room

concentrated solar power

gas turbine

storage



Bracco, Delfino, Robba, Rossi, Pagnini 2016 *IEEE International Smart Cities Conference (ISC2)*
"optimal planning of the energy production mix in smart districts including renewable and cogeneration power plants

referring to the SPM as the technical application, a decision model is applied for the planning of the energy production mix in the smart grid feeding the Campus

micro gas turbines, CHPs
Combined Heat and Power units producing both electrical and thermal power

optimal planning
including small size Wind Turbines

20kW

20kW

solar PV units

SMALL SIZE WTS: MIX PLANNING

decision variables - at site ***s*** year ***y***, month ***m***, daily hour ***t***

$\boxed{S^{PV}_{s,\alpha}}$ [m²]: surface covered by PV panels with tilt α;

$\boxed{n^{w}_{s}}$: number of WTs

$\boxed{n^{CHP}_{s,\beta}}$: number of micro-turbines

costs and benefits of the grid

$$C^{Grid}_{s,y,m,t} = \underbrace{c^{el}_{s,y,m,t}}_{\text{cost power purchased from the grid}} E^{IN}_{s,y,m,t} - \underbrace{b^{el}_{s,y,m,t}}_{\text{benefit power sold to the grid}} E^{OUT}_{s,y,m,t}$$

costs and maintainance of the units

$$C^{CHP}_{s,y,m,t} \quad C^{PV}_{s,y,m,t} \quad C^{W}_{s,y,m}$$

Maintenance

SMALL SIZE WTS: MIX PLANNING

optimization of the object function:
installation costs + annual discounted operating costs

Installation costs:

Annual discounted operating costs

$$\min\left\{K + \sum_{y=1}^{Y} \frac{C_y}{(1+i)^y}\right\}$$

PV surface installed in site *s* inclined *α*

Number of microturbines (CHP) of kind *β* in site *s*

Number of wind turbines in site *s*

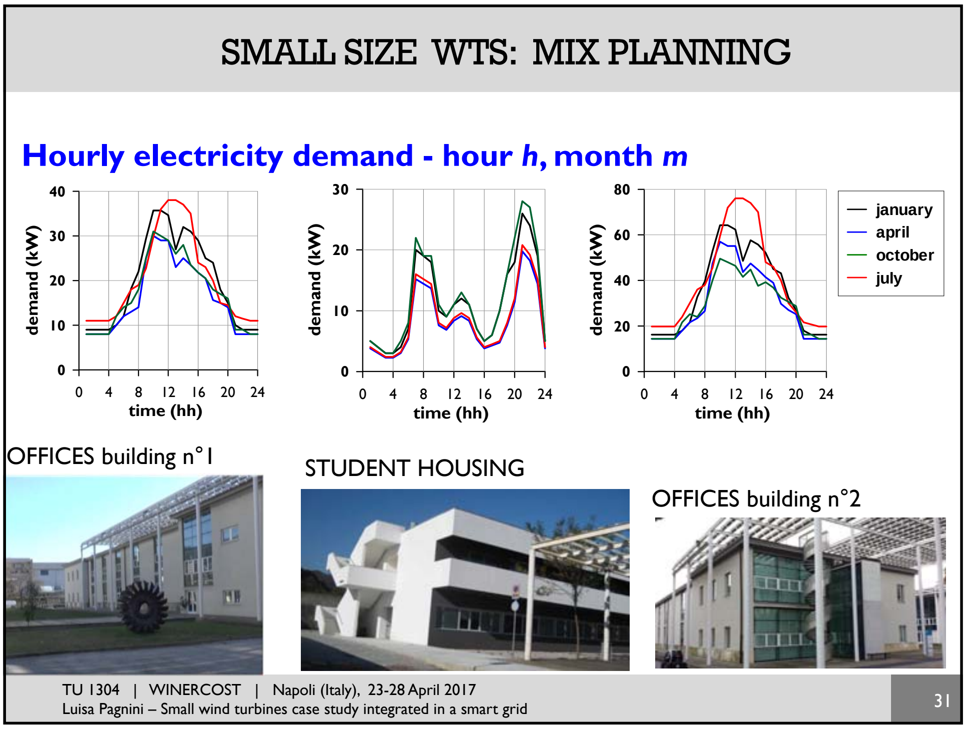
$$K = \sum_{s=1}^{S}\left(\sum_{\alpha=1}^{N_\alpha} k^{PV}_{\alpha} S^{PV}_{s,\alpha} \delta^{PV}_{s,\alpha} + \sum_{\beta=1}^{N_\beta} k^{CHP}_{\beta} n^{CHP}_{s,\beta} + k^{W} n^{W}_{s}\right)$$

Unit costs

$$C_y = \sum_{s=1}^{S}\sum_{m=1}^{M}\left[n_m \sum_{t=0}^{T-1}(C^{GRID}_{s,y,m,t} + C^{CHP}_{s,y,m,t} + C^{PV}_{s,y,m,t} + C^{W}_{s,y,m})\right]$$

Number of days in month *m*

for grid purchase, microturbines, photovoltaics, and wind turbines: maintainance



SMALL SIZE WTS: MIX PLANNING

Hourly electricity demand - hour *h*, month *m*

OFFICES building n°1

STUDENT HOUSING

OFFICES building n°2

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
Luisa Pagnini – Small wind turbines case study integrated in a smart grid

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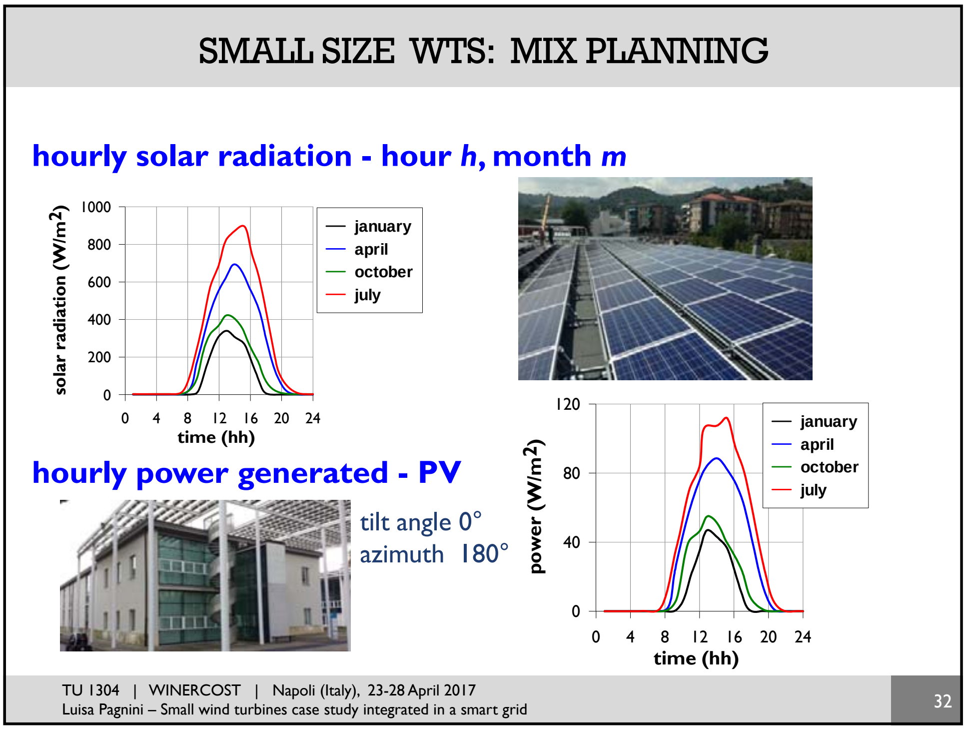


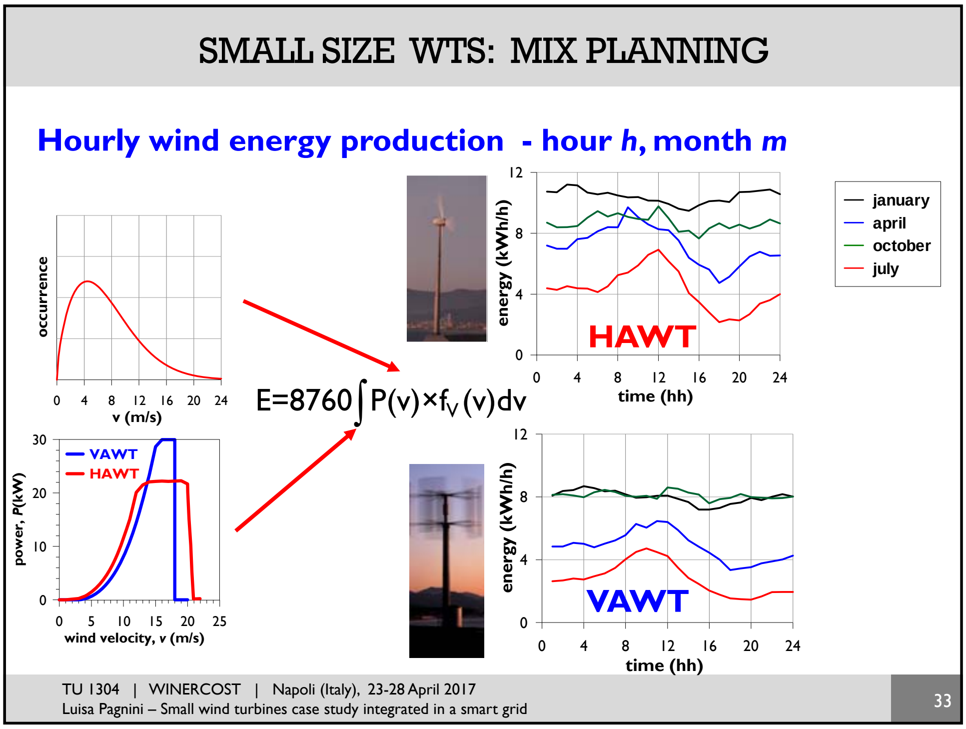
SMALL SIZE WTS: MIX PLANNING

hourly solar radiation - hour *h*, month *m*

hourly power generated - PV

tilt angle 0°
azimuth 180°

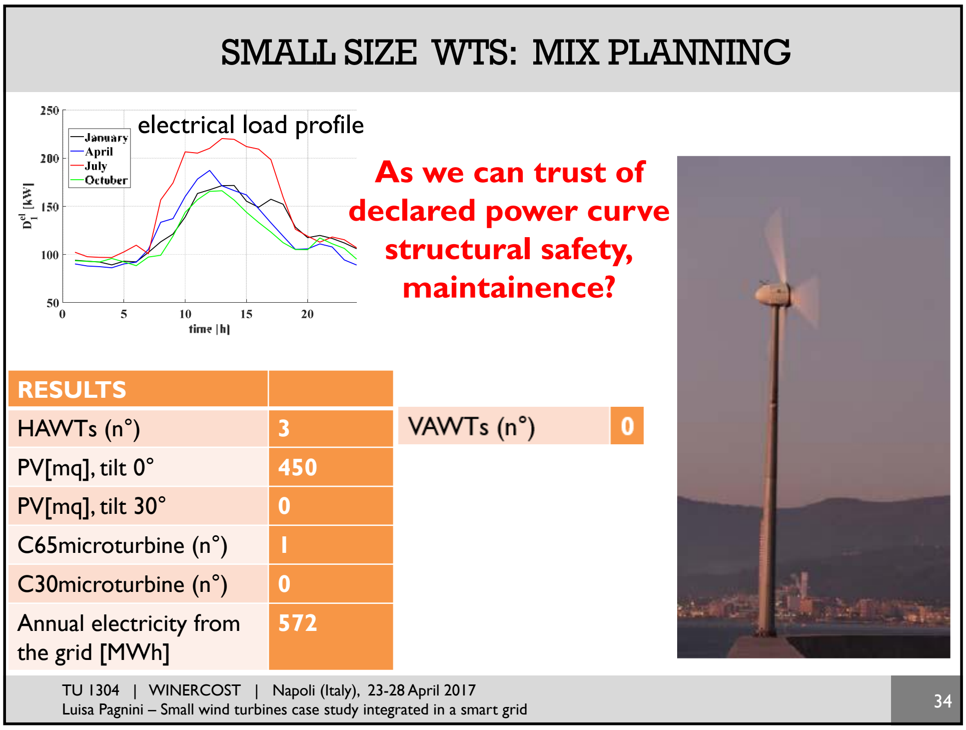
TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
Luisa Pagnini – Small wind turbines case study integrated in a smart grid



SMALL SIZE WTS: MIX PLANNING

Hourly wind energy production - hour *h*, month *m*

$$E=8760\int P(v)\times f_V(v)dv$$



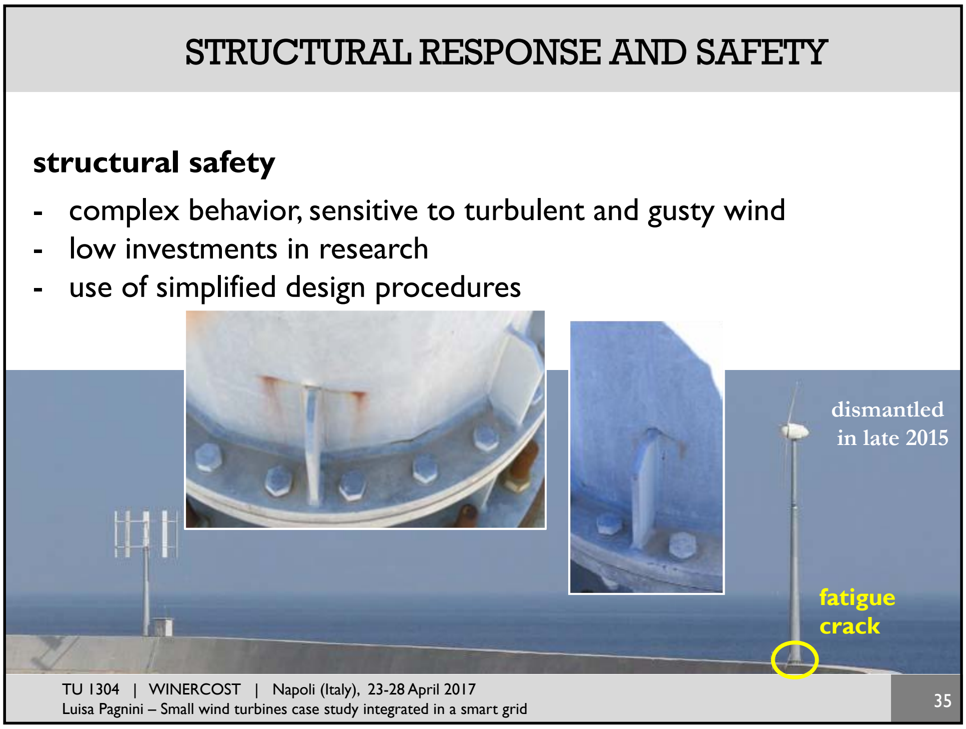
SMALL SIZE WTS: MIX PLANNING

electrical load profile

As we can trust of declared power curve structural safety, maintainence?

RESULTS	
HAWTs (n°)	3
PV[mq], tilt 0°	450
PV[mq], tilt 30°	0
C65microturbine (n°)	1
C30microturbine (n°)	0
Annual electricity from the grid [MWh]	572

VAWTs (n°)	0



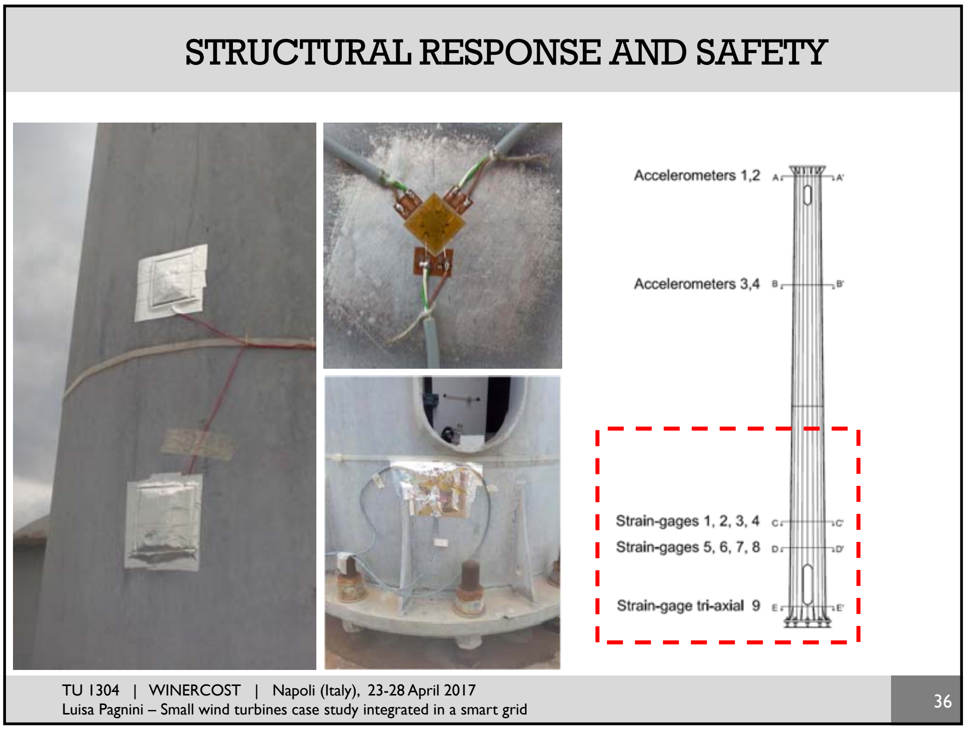
STRUCTURAL RESPONSE AND SAFETY

structural safety

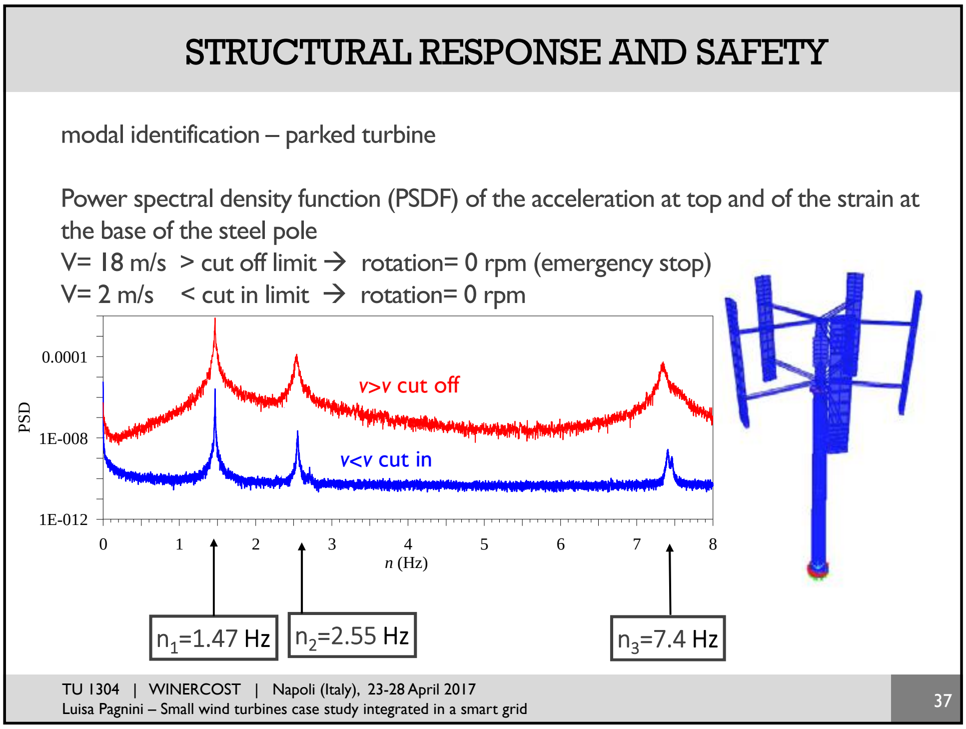
- complex behavior, sensitive to turbulent and gusty wind
- low investments in research
- use of simplified design procedures

dismantled in late 2015

fatigue crack



STRUCTURAL RESPONSE AND SAFETY



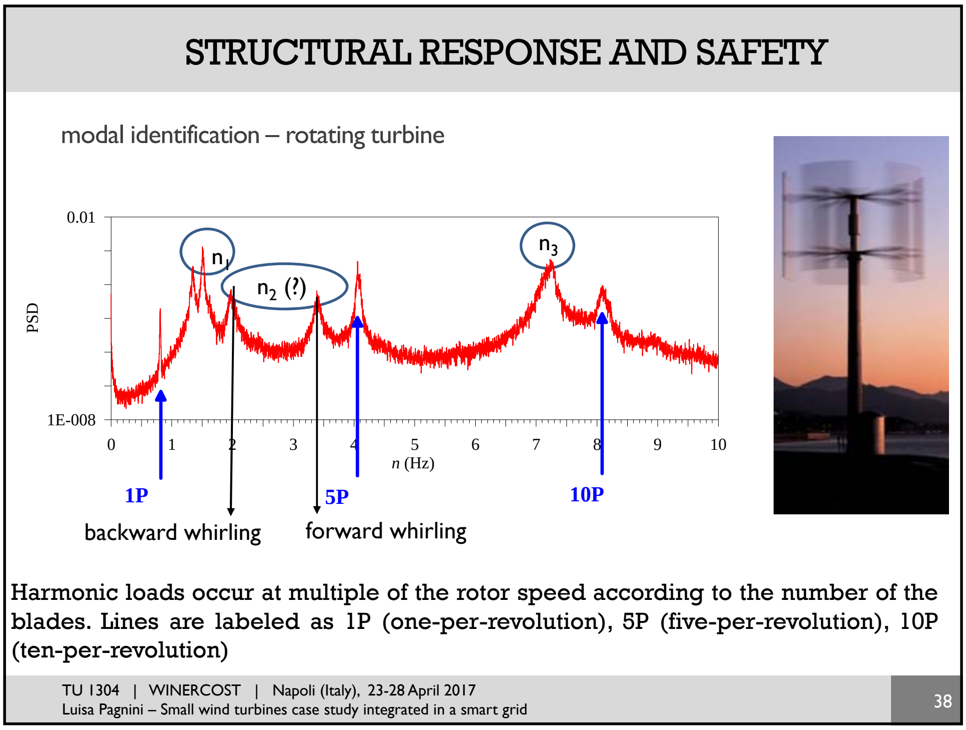
STRUCTURAL RESPONSE AND SAFETY

modal identification – parked turbine

Power spectral density function (PSDF) of the acceleration at top and of the strain at the base of the steel pole

V= 18 m/s > cut off limit → rotation= 0 rpm (emergency stop)

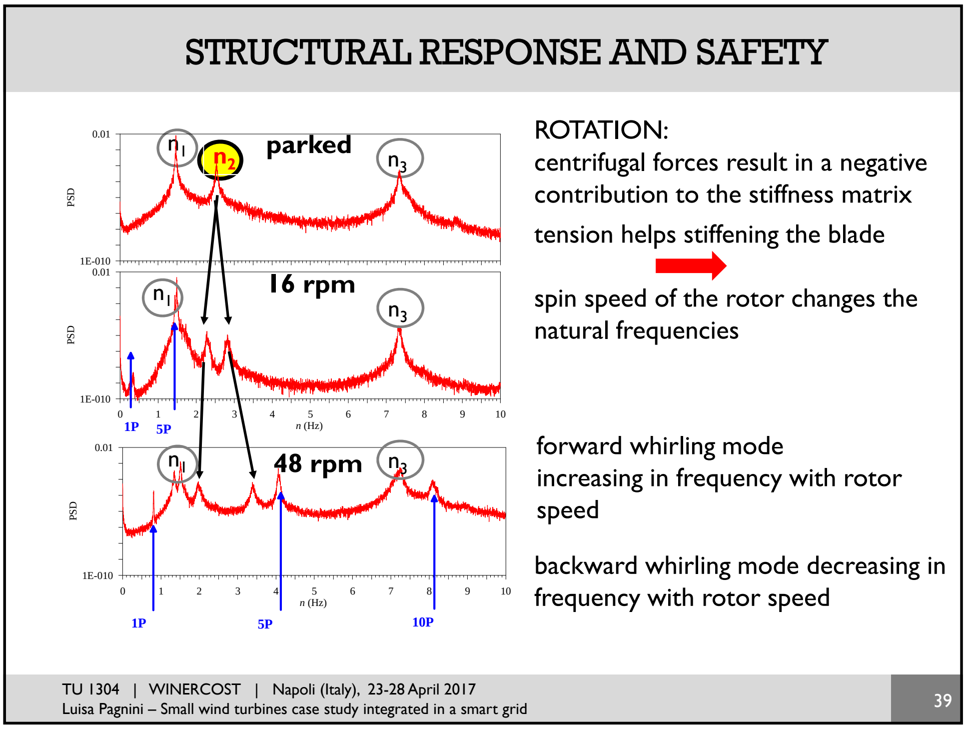
V= 2 m/s < cut in limit → rotation= 0 rpm



STRUCTURAL RESPONSE AND SAFETY

modal identification – rotating turbine

Harmonic loads occur at multiple of the rotor speed according to the number of the blades. Lines are labeled as 1P (one-per-revolution), 5P (five-per-revolution), 10P (ten-per-revolution)



STRUCTURAL RESPONSE AND SAFETY

ROTATION:
centrifugal forces result in a negative contribution to the stiffness matrix

tension helps stiffening the blade

→

spin speed of the rotor changes the natural frequencies

forward whirling mode increasing in frequency with rotor speed

backward whirling mode decreasing in frequency with rotor speed

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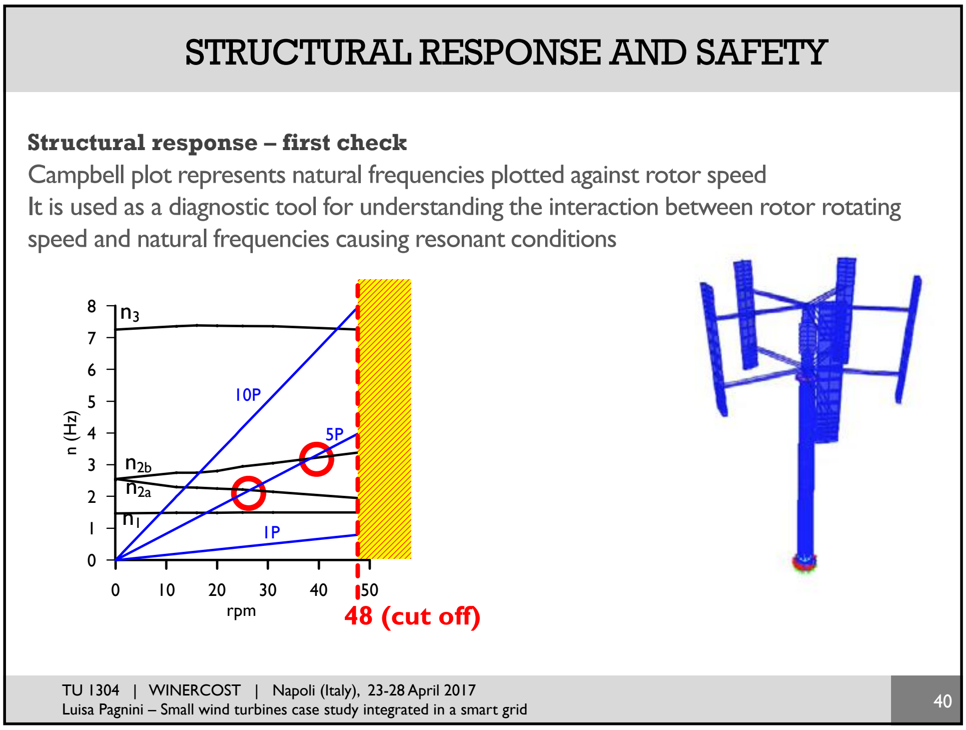


STRUCTURAL RESPONSE AND SAFETY

Structural response – first check

Campbell plot represents natural frequencies plotted against rotor speed
It is used as a diagnostic tool for understanding the interaction between rotor rotating speed and natural frequencies causing resonant conditions

STRUCTURAL RESPONSE AND SAFETY

Structural response

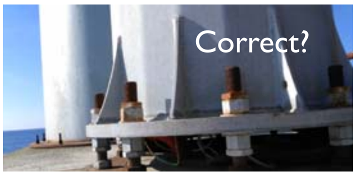
- ❑ these intersections have to be avoided
- ❑ fatigue damages have been experienced by turbines of similar typology in the connecting bolts between the blades and the support arms

STRUCTURAL RESPONSE AND SAFETY

HAWT

- ❑ Many out of service/repairs
- ❑ Fatigue cracks and dismantled in 2015

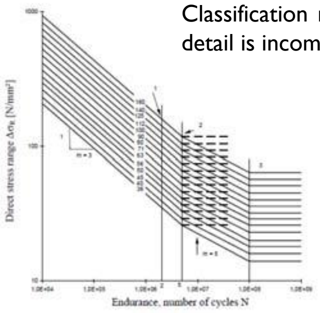
STRUCTURAL RESPONSE AND SAFETY

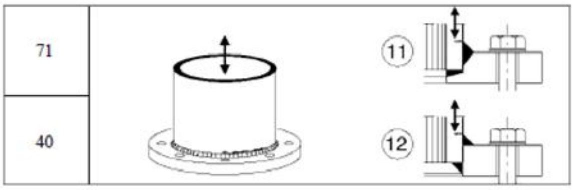


S–N curve approach is the basic method for fatigue strength evaluation of welded joints. The method is based on the design nominal stress, without taking into account explicitly the stress discontinuity due to the presence of the joint.

The geometry of the joint with its inherent stress distribution is taken into account by grouping joints with a similar behavior into a single fatigue class.

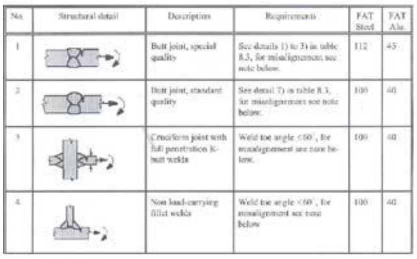
Classification method is simple to use, but difficult to apply if the object detail is incomparable to any classified joints



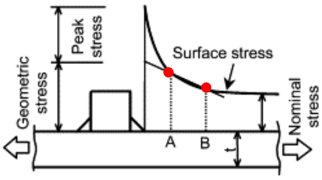


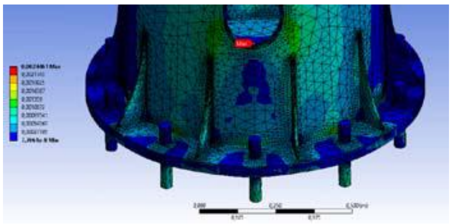
STRUCTURAL RESPONSE AND SAFETY

HOT SPOT approach

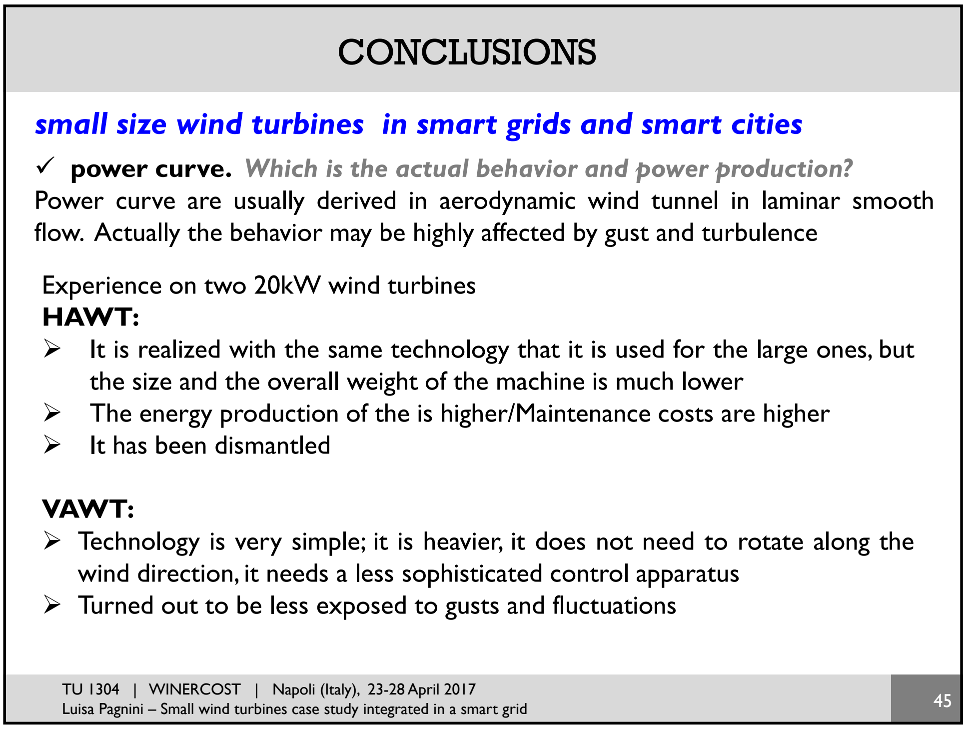


No.	Structural detail	Description	Requirements	FAT Steel	FAT Alu.
1		Butt joint, special quality	See details 1) to 3) in table 8.3, for misalignment see note below.	112	45
2		Butt joint, standard quality	See detail 7) in table 8.3, for misalignment see note below.	100	40
3		Cruciform joint with full penetration K-butt welds	Weld toe angle ≤60°, for misalignment see note below.	100	40
4		Non load-carrying fillet welds	Weld toe angle ≤60°, for misalignment see note below	100	40





once we have created the hot spot model, stress in the detail for the fatigue analysis is obtained by a linear (or quadratic) interpolation using two points at a given distance from the welding



CONCLUSIONS

small size wind turbines in smart grids and smart cities

✓ **power curve.** ***Which is the actual behavior and power production?***

Power curve are usually derived in aerodynamic wind tunnel in laminar smooth flow. Actually the behavior may be highly affected by gust and turbulence

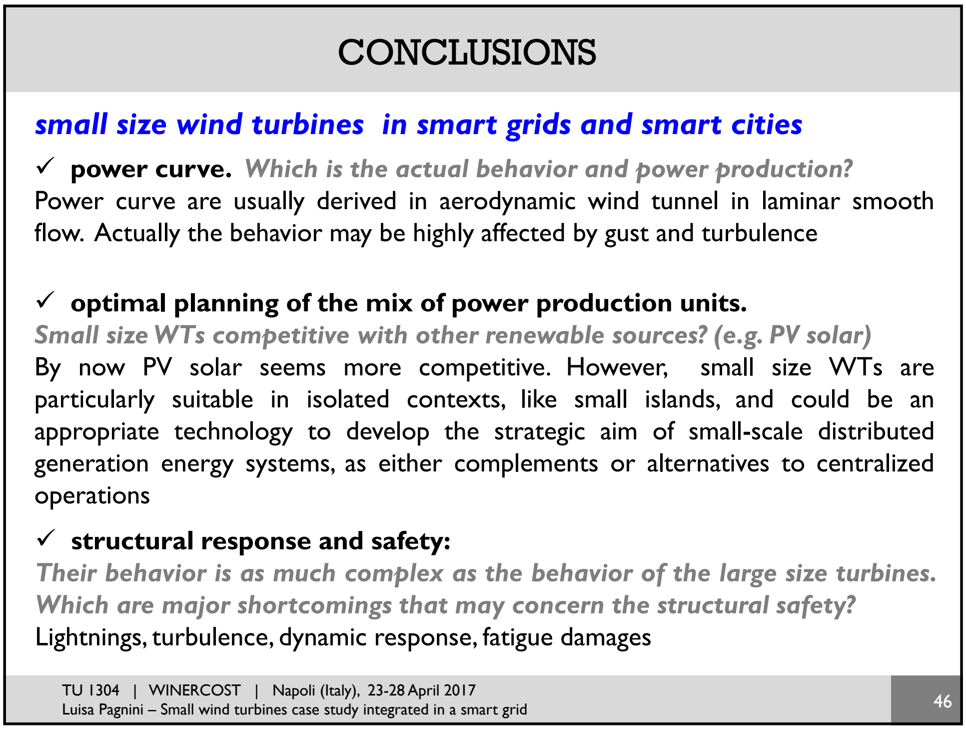
Experience on two 20kW wind turbines

HAWT:

- It is realized with the same technology that it is used for the large ones, but the size and the overall weight of the machine is much lower
- The energy production of the is higher/Maintenance costs are higher
- It has been dismantled

VAWT:

- Technology is very simple; it is heavier, it does not need to rotate along the wind direction, it needs a less sophisticated control apparatus
- Turned out to be less exposed to gusts and fluctuations



CONCLUSIONS

small size wind turbines in smart grids and smart cities

✓ **power curve.** ***Which is the actual behavior and power production?***

Power curve are usually derived in aerodynamic wind tunnel in laminar smooth flow. Actually the behavior may be highly affected by gust and turbulence

✓ **optimal planning of the mix of power production units.**

Small size WTs competitive with other renewable sources? (e.g. PV solar)

By now PV solar seems more competitive. However, small size WTs are particularly suitable in isolated contexts, like small islands, and could be an appropriate technology to develop the strategic aim of small-scale distributed generation energy systems, as either complements or alternatives to centralized operations

✓ **structural response and safety:**

Their behavior is as much complex as the behavior of the large size turbines. Which are major shortcomings that may concern the structural safety?

Lightnings, turbulence, dynamic response, fatigue damages

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Introduction to Turbulence and CFD

Hassan Hemida

TU 1304 – WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

Introduction to Turbulence and CFD

Dr Hassan Hemida (PhD, LicEng, MSc, BSc, CEng)

Department of Civil Engineering, School of Engineering, University of Birmingham, UK

UNIVERSITY OF
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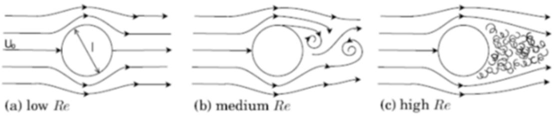
Table of content

- What is turbulent flow
- Initiation of turbulent flow
- Characteristics of turbulent flow
- Governing equations
- Turbulence statistics
- Turbulence scales
- The Reynolds' decomposition and the averaging equations
- Direct numerical simulations (DNS)
- Reynolds Averaged Navier Stocks (RANS)
- Large-eddy simulations (LES)
- Detached-eddy simulations (DES)
- CFD approaches

What is turbulent flow?

- Turbulence is the state of fluid motion that is characterised by apparently random and chaotic three-dimensional vorticity.
- When turbulence is present, it usually dominates all other flow phenomena and results in increased energy dissipation, mixing, heat transfer, and drag.

Initiation of turbulence



(a) low Re (b) medium Re (c) high Re

$Reynolds\ number\ Re = ul/\nu$

- At very low Re, the flow is laminar everywhere and the flow instability, due to the existence of the cylinder, is too small to generate turbulent flow
- Increasing Re, the flow becomes turbulent only in the wake of the cylinder and is laminar upstream and in the boundary layers.
- At high Re, the flow separates from the surface of the cylinder and becomes completely turbulent in the wake and in the boundary layer .

Characteristics of turbulent flow

At Reynolds number above a so-called critical Re the flow is turbulent.

Main characteristics:

- Irregular (Random and chaotic)
- Occurs at high numbers
- Three dimensional
- Wide range of length scale??
- Diffusive
- Dissipative
- Turbulence is a feature of the flow, not of the fluid.

Methods of studying turbulent flow

- Measurements at full scale and full Reynolds number
  - – Normally to measure the velocity and pressure.
  - – Very expensive.
  - – In most of the cases it is not possible.
- Measurements at small scale (wind tunnel).
- Computational fluid dynamics (CFD)—solving a set of equations, governing the fluid motions.
- Analysis of the data.

Governing equations

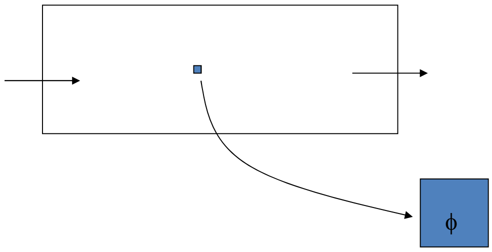
- The governing equations of fluid flow represent mathematical statements of the conservation laws of physics:
- The mass of fluid is conserved → continuity equation.
- The rate of change of momentum equal to the sum of forces on a fluid particle (Newton’s second law) → momentum equation.
- The rate of change of energy is equal to the rate of heat addition to and the rate of work done on a fluid particle → energy equation.

Governing equations

ϕ: mass → Continuity

ϕ: momentum → Momentum

ϕ: energy → Energy equation



$$\overbrace{\text{Rate of increase of }\phi\text{ of fluid element}}^{\text{Rate of change}} + \overbrace{\text{Net rate of flow of }\phi\text{ out of fluid element}}^{\text{convection}} = \overbrace{\text{Rate of increase of }\phi\text{ due to diffusion}}^{\text{diffusion}} + \overbrace{\text{Rate of increase of }\phi\text{ due to source}}^{\text{source}}$$

Governing equations

The Differential Form

- **In vector form**

$$\underbrace{\frac{\partial(\rho\phi)}{\partial t}}_{\text{Rate of change}} + \underbrace{\mathbf{div}(\rho\phi\mathbf{u})}_{\text{convection}} = \underbrace{\mathbf{div}(\Gamma\,\mathbf{grad}\,\phi)}_{\text{diffusion}} + \underbrace{S_\phi}_{\text{source}}$$

- **In tensor form**

Continuity →
$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad i= 1, 2, 3$$

N. S. Equations →
$$\frac{\partial(\rho u_i)}{\partial t} + u_j\frac{\partial(\rho u_i)}{\partial x_j} = \frac{-\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\Gamma\frac{\partial u_i}{\partial x_j}) + S_\phi$$

In general, these equations are parabolic, which require intial and boundary conditions to be solved.

Governing equations

Are there special equations for turbulent flow?

Navier-Stokes equation

$$\frac{\partial(\rho u_i)}{\partial t} + \overset{\text{Non-linear term}}{\boxed{u_j\frac{\partial(\rho u_i)}{\partial x_j}}} = \frac{-\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu\frac{\partial u_i}{\partial x_j}) + S_\phi$$

It is the same form of Navier-Stokes equation valid for Laminar and Turbulent flow. At high *Re*, small disturbances to the flow are no longer damped by the flow, but begin to grow by taking energy from the original laminar flow. The non-linear term in the equation is responsible for these disturbances.

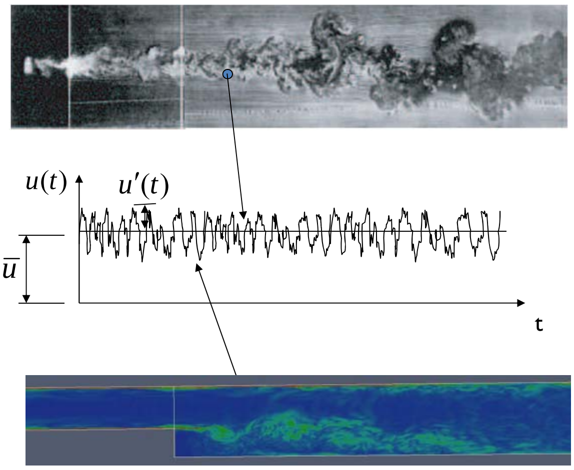
Note

When you set a CFD simulation you should first decide if the flow is laminar or turbulent. Setting a turbulent flow simulation to a laminar flow will result in wrong results and visa versa.

Turbulence statistics

- At Reynolds number above the so-called critical Re the flow is turbulent.
- Reynolds decomposition

$$u(t) = \overline{u} + u'(t)$$



Turbulence statistics

Time-averaged flow

$$u(t) = \overline{u} + u'(t)$$

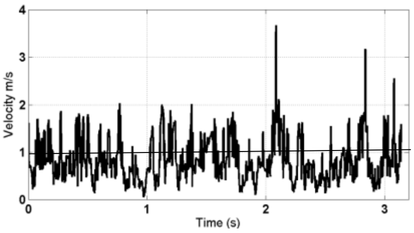
$\overline{u}$ Time average, Mean, Ensemble average

$u'(t)$ Time varying fluctuating component

$$\overline{u} = \frac{1}{\Delta t}\int_0^{\Delta t} u(t)dt$$

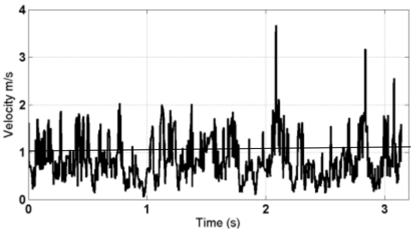
Note that the time average of the fluctuating component is zero

$$\overline{u'(t)} = \frac{1}{\Delta t}\int_0^{\Delta t} (u(t) - \overline{u})dt = 0$$



Turbulence statistics

Variance, root mean square, kinetic energy and turbulent intensity



- **Variance**

$$\overline{u'^2} = \frac{1}{\Delta t}\int_0^{\Delta t} u'^2 dt$$

- **RMS (standard deviation)**

$$u'_{rms} = \sqrt{\overline{(u')^2}} = \left[\frac{1}{\Delta t}\int_0^{\Delta t} u'^2 dt\right]^{1/2}$$

The r.m.s values of the velocity components express the average magnitude of the velocity fluctuations

- ***Turbulent* kinetic energy *k***

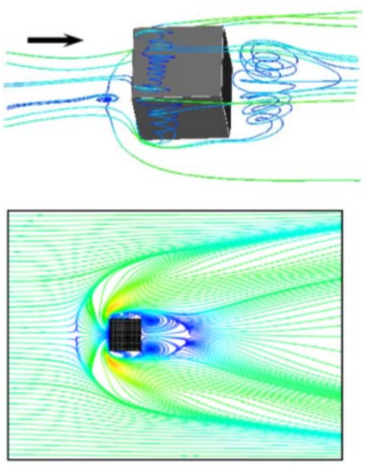
$$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$$

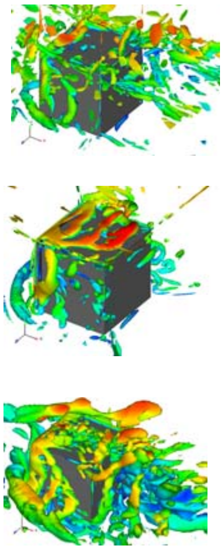
- **Turbulent intensity**

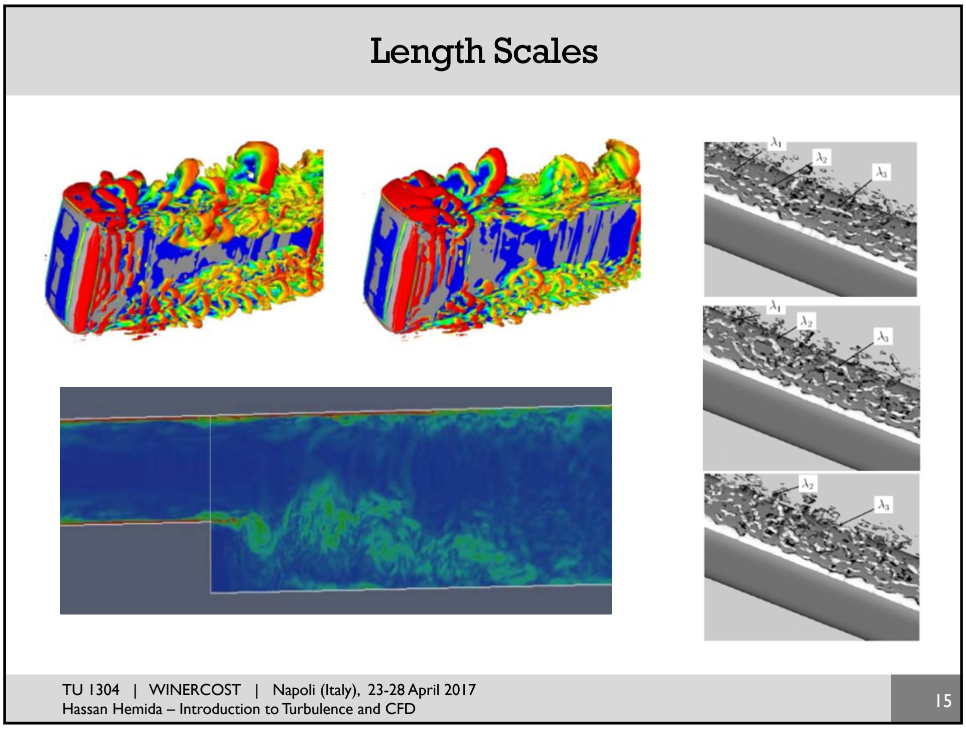
$$T_i = \frac{\left(\frac{2}{3}k\right)^{1/2}}{U_{ref}} = \frac{\sqrt{\frac{1}{3}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)}}{U_{ref}} = \frac{u'_{rms}}{U_{ref}}$$

Turbulent scales

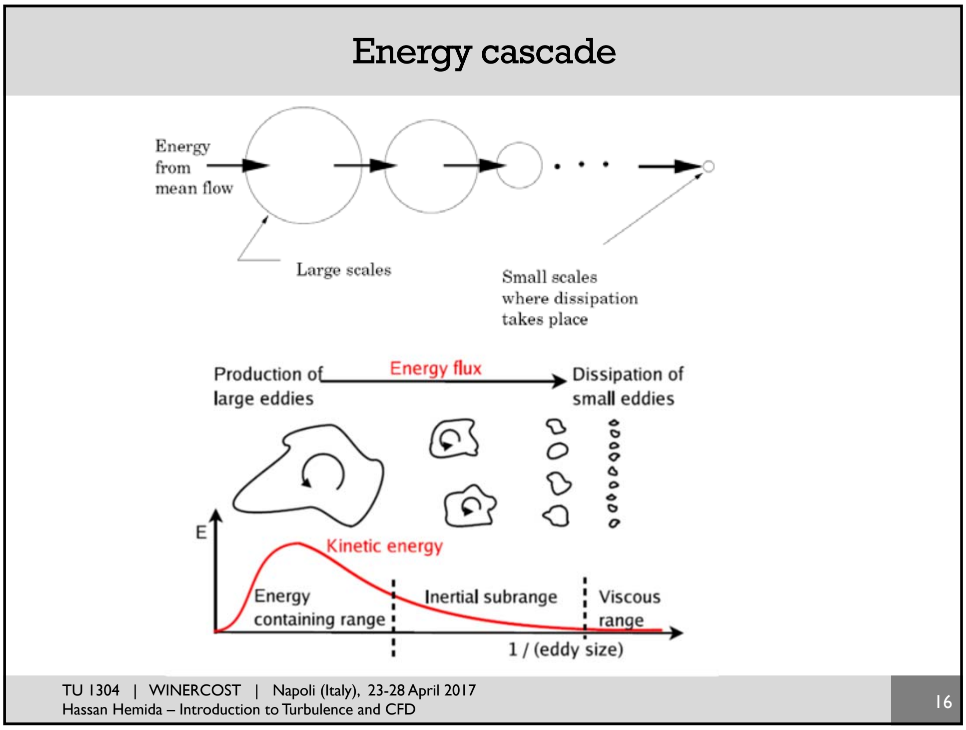
- Length scales
- Velocity scales
- Time scales







Length Scales



Energy cascade

Energy from mean flow

Large scales

Small scales where dissipation takes place

Production of large eddies

Energy flux

Dissipation of small eddies

E

Kinetic energy

Energy containing range

Inertial subrange

Viscous range

1 / (eddy size)

Smallest scales

What is the size of the smallest eddy that dissipates energy?

Smallest scales

This question has been answered by the hypotheses of Kolmogorov, stating that in every turbulent flow *at sufficiently high Reynolds number*, the statistics of the small-scale motions have a universal form that is uniquely determined by fluid viscosity, ν and dissipation, ε.

Smallest scales

Using Kolmogorov hypothesis, the following scales are obtained:

Length scales $\eta = \left(\frac{\nu^3}{\varepsilon} \right)^{1/4}$

Velocity scale $v = \left(\nu\varepsilon \right)^{1/4}$

Time scale $\tau = \left(\frac{\nu}{\varepsilon} \right)^{1/2}$

These are the Kolmogorov scales—smallest scales of the flow.

Estimation of dissipation ε

- The dissipation rate is given approximately as:

$$\varepsilon \sim \frac{\text{Energy extracted from large eddies}}{\text{Turn-over time of large eddies}}$$

$$\sim \frac{u^2}{l/u} \sim \frac{u^3}{l}$$

$$\frac{\eta}{l} = \mathrm{Re}_l^{-3/4}$$

u: mean velocity
l: large length scale

Example

Estimate the Kolmogorov microscale for u = 1.0 m/s and l = 0.1m for air and water.

Example

Solution

$$\frac{\eta}{l} = \mathrm{Re}_l^{-3/4}$$

- For air: Re_l =1 × (0.1)/15 × 10–6 ≈ 7 × 10^3. Therefore $l/\boldsymbol{\eta} \approx 8 \times 10^2$, so: $\boldsymbol{\eta} \approx 1.2 \times 10^{-4}$ m or 0.12 mm.
- For water: Re_l =1 × (0.1)/$10^{-6} \approx 10^5$. Therefore $l/\boldsymbol{\eta} \approx 5 \times 10^3$, so: $\boldsymbol{\eta} \approx 2 \times 10^{-5}$ m or 0.02 mm.

Computational fluid dynamics (CFD)

There are two approaches for numerical solving of the governing equations.

- The fist one is to solve directly the governing equations to resolve all the turbulent scales in the flow. This approach is called Direct Numerical Simulation (DNS).
- The other approach is to first average the governing equations in time or in space and solve the resulting equations.
  - Averaging in time means that we damp out all the turbulent fluctuations in time and we do not resolve any turbulent scale at all. This approach is called Reynolds Average Navier-Stocks (RANS).
  - Averaging in space means that we resolve turbulent scales larger than the averaging space (or filter width) and we model the effect of the turbulent scales smaller than the filter width. The later is called Large-Eddy Simulation (LES) and Detached-Eddy Simulation (DES).

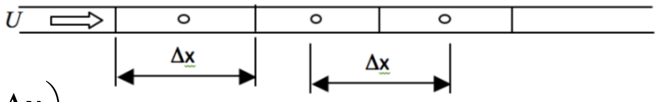
Direct numerical simulation (DNS)

- Direct Numerical Simulations (DNS) means that we solve the governing equations of the flow to generate the exact instantaneous motions. No assumptions or simplifications are needed for DNS, since the number of equations is the same as the number of unknowns (four equations for four unknowns, u_i and p).
- The minimum vortex size that can be obtained from a numerical simulation is the size of the cell of the computational domain, Δ.
- Thus, to resolve all the scales of the flow, the cell size should be of the same size as the smallest scales in the flow--the Kolmogorov dissipation scales.

Direct numerical simulation (DNS)

The time step, *Δt*, required by DNS should be very small to resolve the flow in time. There are two factors that control the choice of the time step. It should be smaller than the Kolmogorov time scale, τ, and, in order to maintain numerical stability and accuracy, the time step should be small enough that the fluid particles do not move more than one grid spacing in each time step.

$$\frac{U\Delta}{\Delta x} \leq 1.0$$



$$\Delta t = \min\left(\tau, \frac{\Delta x}{u}\right)$$

Direct numerical simulation (DNS)

- DNS is therefore restricted to low or moderate Reynolds numbers. For high Reynolds numbers, the flow is dominated by very fine structures associated with very small scales. The total number of cells needed to resolve all the scales is very high and hence the computational cost is also very high. This makes DNS infeasible at the present time for solving high Reynolds number flow.
- However, even if our computers were able to solve a more complicated flow in an adequate time, we would sometimes need to average the huge random data in order to understand turbulence.

The time-averaged equation

Use the Reynolds decomposition

$$u(t) = \overline{u} + u'(t)$$

Substitute in (2) and re-arrange the equation we get:

$$\rho\left[\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j}\right] = \frac{-\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{u}_i}{\partial x_j} - \rho\overline{u'_i u'_j}\right)$$

The extra term $\rho\overline{u'_i u'_j}$ is a result of the averaging process. This term, is not a stress at all, but simply a re-worked version of the fluctuating contribution to the non-linear acceleration terms. The fact that it can be written this way, however, indicates that at least as far as the mean motion is concerned, it acts as though it were a stress — hence its name, the Reynolds stress.

It is the appearance of the Reynolds stress which makes the turbulence problem so difficult — at least from the engineers perspective. Even though we can pretend it is a stress, the physics which give rise to it are very different from the viscous stress.

The time-averaged equations

The Reynolds stress term consists of six unknowns. These need to be modelled. Most of the RANS models are based on the assumption that there exists an analogy between the action of the viscous stress and the Reynolds stress on the mean flow. Boussinesq approximation states that the Reynolds stresses proportional to the rate of deformation of the mean flow:

$$-\overline{u'_i u'_j} = \nu_t\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}$$

ν_t Turbulent eddy viscosity (property of the flow)

$k = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$ Turbulent kinetic energy

$\delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$ Kronecker delta function

There exists many RANS models based on the eddy viscosity assumption

Turbulence modeling

- There are different turbulence modeling to model turbulent viscosity, ν_t, examples are:
  - – Prandtl's length model (zero equation model)
  - – Spalarat-Almaras model (one equation model)
  - – *K*-epsilon *k*-ω, SST, SAS, SSG and many others models (two equations model)
  - – *Reynolds stress turbulence model (six equation turbulence model)*

Turbulence modeling

➢ Mixed length model

$$\nu_t = l_{mix}^2 \left|\Delta \bar{u}\right|$$

- – The mixing-length, l_{mix}, however, has to be specified as a function of position. In unbounded flows, l_{mix} is of the order of 0.1 times the layer width. Close to a wall, l_{mix} is of the order of 0.4 times distance from the wall; BUT, in the immediate vicinity of the wall where viscous effects predominate, it diminishes more rapidly.
- – Not accurate close to walls and needs wall function.

Turbulence modeling

- ***K-epsilon model***

The main idea of the *k*-ε model is to find an expression for the eddy viscosity in terms of *k* and ε. We use dimensional analysis to find that expression as follow.

$$\nu_t \quad \propto \quad k^a \quad \varepsilon^b$$

$$\left[m^2/s\right] \qquad \left[m^2/s^2\right] \qquad \left[m^2/s^3\right]$$

This gives:

$$\nu_t = C_\mu \frac{k^2}{\varepsilon}$$

Turbulence modeling

- ***K-epsilon model***
  - *Cμ = 0.009* $\quad \nu_t = C_\mu \frac{k^2}{\varepsilon}$
  - There are two extra transport equations; one for k and one for ε.
  - There are many constants in all the two equations models. These constants were obtained using different assumptions and specific types of flow. Therefore different models work well in a specific flow but there is no single turbulence model that works for all types of flows.
  - *K-epsilon and k-w* are the most common turbulence models that are used widely in industry.

Large-Eddy Simulation (LES)

- Large eddy simulation (LES) decomposes the structures of the flow into large and small scales. The large motions of the flow are directly simulated while the influence of the small scales on the large scale motions is modelled. Hence LES is a kind of compromise between RANS and DNS.
- LES requires less computational effort than DNS but more effort than RANS. The computational demands also increase significantly in the vicinity of walls, and simulating such flows usually exceeds the limits of modern supercomputers. For this reason, zonal approaches are often adopted, with RANS or other empirically-based models replacing LES in the wall region.

LES--Filtering

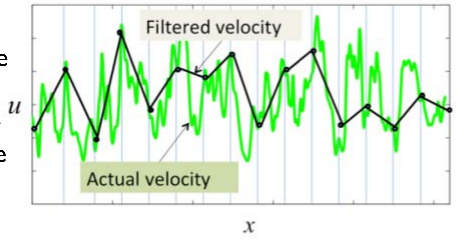
- the actual velocity, $u_i(x,t)$ is decomposed into a filtered part $\bar{U}_i(x,t)$ and a sub-grid component of velocity $\bar{U}_i(x,t)$ as:

$$u_i(x,t)=\bar{U}_i(x,t)+U_i''(x,t)$$

- The filtered velocity $U_i''(x,t)$ is obtained by filtering the actual velocity as follow:

$$\bar{U}_i(x,t)=\int_{\Omega} G(x,r)u_i(x-r,t)\,dr$$

where the integration is over the entire flow domain, Ω, and *Gx,r* is the filter function. The filtered velocity is not the same as the actual velocity field and the difference is the residual, *Ui''x,t* .



LES-equations

- The filtered continuity and momentum equations for incompressible flow are:

$$\frac{\partial \bar{U}_\imath}{\partial x_i} = 0$$

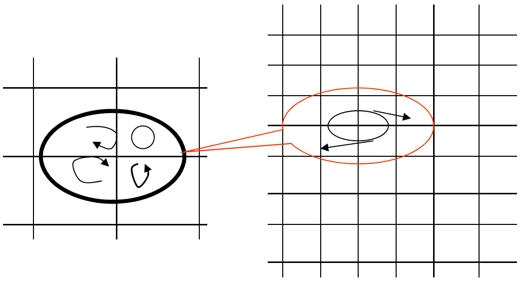
$$\frac{\partial \bar{U}_\imath}{\partial t} + \bar{U}_\jmath \frac{\partial \bar{U}_\imath}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \bar{U}_\imath}{\partial x_j} - Q_{ij}\right)$$

- where Q_{ij} are the residual stresses defined as:

$$Q_{ij} = \overline{U_\imath' U_\jmath'} + \overline{U_\imath' \overline{U_\jmath'}} + \overline{\overline{U_\imath'} U_\imath'} = \overline{u_\imath u_\jmath} - \bar{U}_\imath \bar{U}_\jmath$$

Sub-grid scale stresses

The smallest eddies that can be resolved in any grid is of the size of the grid. However, the flow includes smaller scales than the resolved ones (size of the cell). The residual stresses are a direct consequence of the filtering process and it compensates for the effect of the unresolved or subgrid scale eddies on the resolved eddies.



Sub-grid scale stresses

The turbulence models for the residual stresses are analogous to the models used for the Reynolds stresses by RANS. We know that small scales tend to be more homogeneous and universal and less affected by the boundary conditions. Thus, their models are simpler and require few adjustments when applied for different flows.

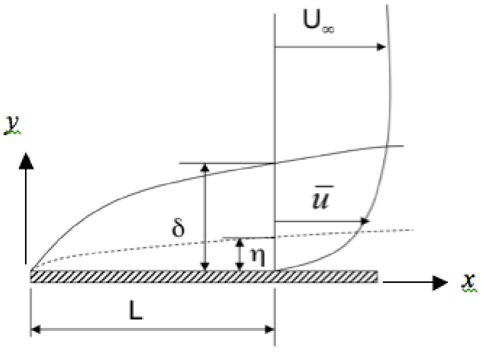
$$Q_{ij} = 2\nu_{SGS}\overline{S_{ij}} \qquad \overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)$$

The simplest one was proposed by Smagorinsky

$$\nu_{SGS} = (C_S\Delta)^2\sqrt{2\overline{S_{ij}}\ \overline{S_{ij}}}$$

The Turbulent Boundary Layer and LES

- The no-slip boundary condition demands that the velocity component tangential to the wall be the same as the tangential velocity of the wall. If the wall is at rest relative, then the no-slip condition demands the tangential flow velocity be identically zero at the surface.
- Experiments and order of magnitude of the governing equations of turbulent flow show that the boundary layer of turbulent flow can be divided into two layers:
  - ☐ inner and
  - ☐ outer layers.



Turbulent boundary layer and LES

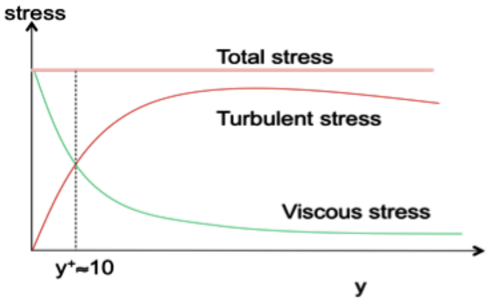
- Inner region
  - – Integrate the NS equations to find:

$$u_* = \sqrt{\frac{\tau_w}{\rho}}, \quad \text{and} \quad y^+ = \frac{y u_*}{\nu}$$

$$u_*^2 = -\overline{u'v'} + \nu \frac{\partial \bar{u}}{\partial y}.$$

For viscous sub-layer, $y^+ < 3$

$$u^+ = \frac{\bar{u}}{u_*} = \frac{u_* y}{\nu} = y^+$$



- Outer layer

$$u^+ = \frac{1}{k}\ln\left(Ey^+\right)$$

Turbulent boundary layer and LES

- The main idea of LES is to resolve the large energetic scales in the flow. In the viscous-sub layer the large energetic scales are of the size of the y^+~1.0. So in order to resolve the flow in the boundary layer then the cell size in the boundary layer should be small enough to satisfy the condition of y^+~1.0 or less. For high Re, this condition is very hard to satisfy as y^+~1 means a cell size of micrometers and the mesh size will be incredibly large to be solved in a normal supercomputer.

Detached-Eddy Simulation (DES)

- In the DES approach, the unsteady RANS models are employed in the near-wall regions, while the filtered versions of the same models are used in the regions away from the wall, i.e. LES.
- The LES region is normally associated with the core turbulent region where large turbulence scales play a dominant role. In this region, the DES models recover the respective sub-grid models. In the near-wall region, the respective RANS models are recovered.

CFD approaches

Direct numerical simulations (DNS)	• **All scales are being resolved.** • **No turbulence model needed.** • **Requires huge amount of cells.** • **Only used for research.**
Large Eddy Simulation (LES)	• **Large eddies are being resolved.** • **Subgrid-scale model used for eddies smaller than the grid size.** • **Accurate results.** • **Requires too many cells for engineering problems.** • **Mostly used for research and recently used by industry**

CFD approaches

Reynolds Averaged Navier-Stokes (RANS)	• By far the most common approach for engineering problems • Moderate number of cells required • Turbulence modelling is needed
Hybrid LES-RANS, DES	• Utilizes the advantages of LES • Less number of cells required than that of LES • More accurate results than RANS • Turbulence modelling is needed

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Advances in Wind Energy Technology III

Wind Tunnel Testing

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Advances in Wind Energy Technology III
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Wind Tunnel Testing

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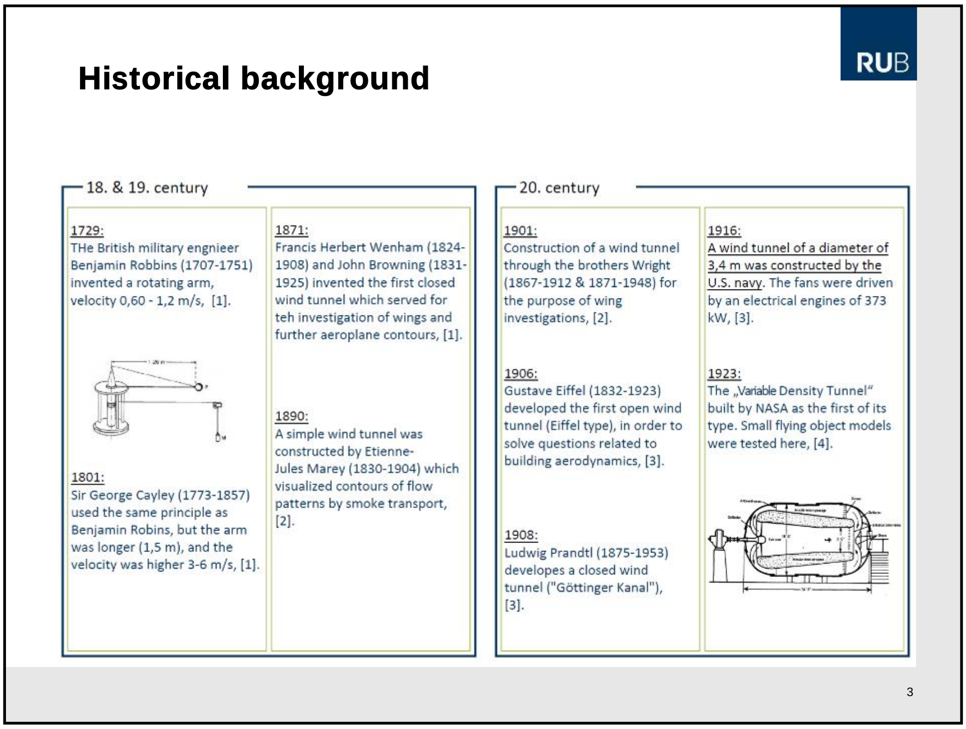
Rüdiger Höffer et al. – Wind Tunnel Testing

RUB

Chapter 1: Developments

- Historical background
- Boundary Layer Wind Tunnels



Historical background

RUB

18. & 19. century

1729:
THe British military engnieer Benjamin Robbins (1707-1751) invented a rotating arm, velocity 0,60 - 1,2 m/s, [1].

1801:
Sir George Cayley (1773-1857) used the same principle as Benjamin Robins, but the arm was longer (1,5 m), and the velocity was higher 3-6 m/s, [1].

1871:
Francis Herbert Wenham (1824-1908) and John Browning (1831-1925) invented the first closed wind tunnel which served for teh investigation of wings and further aeroplane contours, [1].

1890:
A simple wind tunnel was constructed by Etienne-Jules Marey (1830-1904) which visualized contours of flow patterns by smoke transport, [2].

20. century

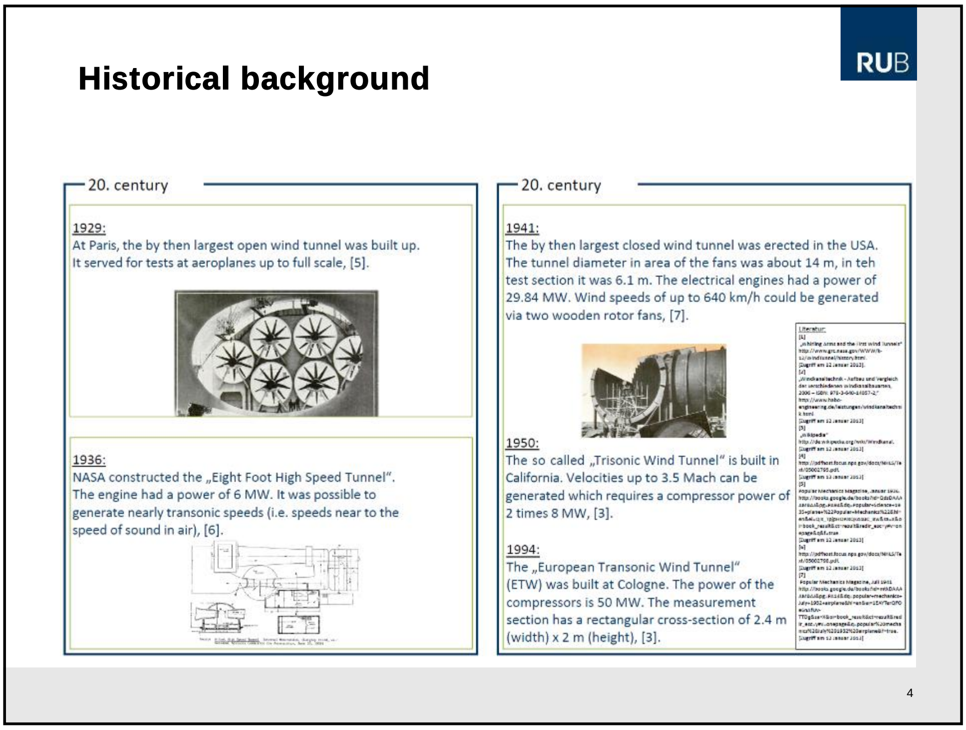
1901:
Construction of a wind tunnel through the brothers Wright (1867-1912 & 1871-1948) for the purpose of wing investigations, [2].

1906:
Gustave Eiffel (1832-1923) developed the first open wind tunnel (Eiffel type), in order to solve questions related to building aerodynamics, [3].

1908:
Ludwig Prandtl (1875-1953) developes a closed wind tunnel ("Göttinger Kanal"), [3].

1916:
A wind tunnel of a diameter of 3,4 m was constructed by the U.S. navy. The fans were driven by an electrical engines of 373 kW, [3].

1923:
The „Variable Density Tunnel" built by NASA as the first of its type. Small flying object models were tested here, [4].



Historical background

RUB

20. century

1929:
At Paris, the by then largest open wind tunnel was built up. It served for tests at aeroplanes up to full scale, [5].

1936:
NASA constructed the „Eight Foot High Speed Tunnel". The engine had a power of 6 MW. It was possible to generate nearly transonic speeds (i.e. speeds near to the speed of sound in air), [6].

20. century

1941:
The by then largest closed wind tunnel was erected in the USA. The tunnel diameter in area of the fans was about 14 m, in teh test section it was 6.1 m. The electrical engines had a power of 29.84 MW. Wind speeds of up to 640 km/h could be generated via two wooden rotor fans, [7].

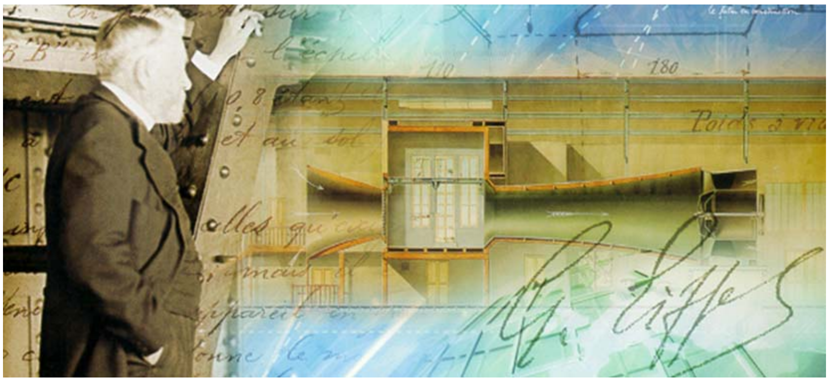
1950:
The so called „Trisonic Wind Tunnel" is built in California. Velocities up to 3.5 Mach can be generated which requires a compressor power of 2 times 8 MW, [3].

1994:
The „European Transonic Wind Tunnel" (ETW) was built at Cologne. The power of the compressors is 50 MW. The measurement section has a rectangular cross-section of 2.4 m (width) x 2 m (height), [3].

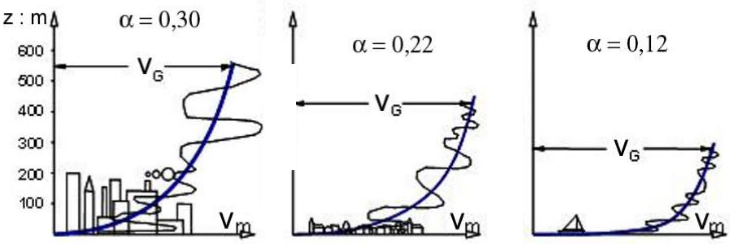
Literatur:
[1]
„Whirling Arms and the First Wind Tunnels" http://www.grc.nasa.gov/WWW/k-12/windtunnel/history.html.
[Zugriff am 12 Januar 2013].
[2]
„Windkanaltechnik - Aufbau und Vergleich der verschiedenen Windkanalbauarten, 2006 – ISBN: 978-3-640-14057-2," http://www.hobo-engineering.de/leistungen/windkanaltechnik.html
[Zugriff am 12 Januar 2013]
[3]
„Wikipedia" http://de.wikipedia.org/wiki/Windkanal.
[Zugriff am 12 Januar 2013]
[4]
http://pdfhost.focus.nps.gov/docs/NHLS/Text/05002795.pdf.
[Zugriff am 12 Januar 2013]
[5]
Popular Mechanics Magazine, Januar 1936. [illegible]
[Zugriff am 12 Januar 2013]
[6]
http://pdfhost.focus.nps.gov/docs/NHLS/Text/05002795.pdf.
[Zugriff am 12 Januar 2013]
[7]
Popular Mechanics Magazine, Juli 1941 [illegible]
[Zugriff am 12 Januar 2013]

Boundary Layer Wind Tunnels

Wind tunnel of Eiffel type
(Alexandre Gustave Eiffel 1832 – 1923)

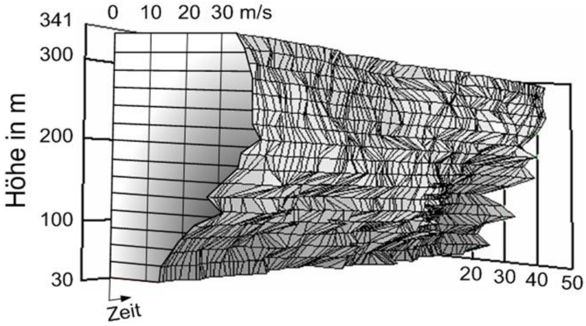


Atmosperic boundary layer



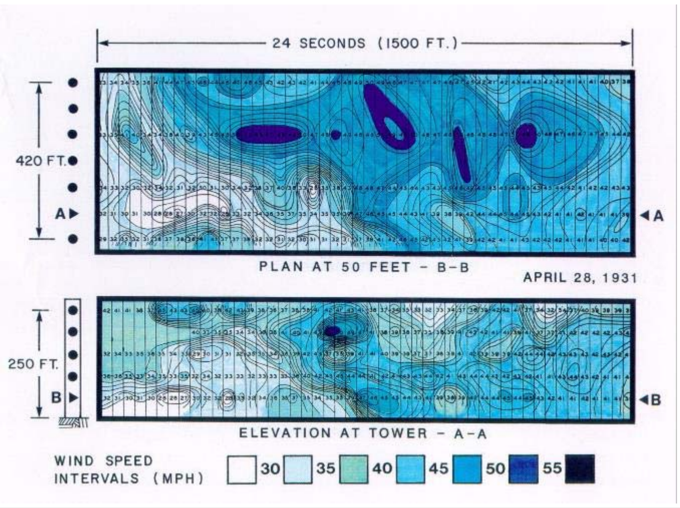
$$v_m(z) = v_{ref} \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Turbulent wind field at Gatow, Germany

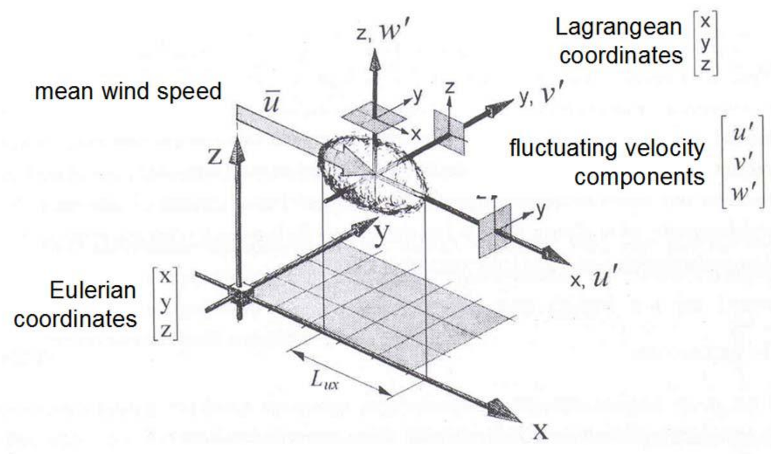


20 sec. cutout from storm Daria (25.01.1990, measurements by Peil et. al)

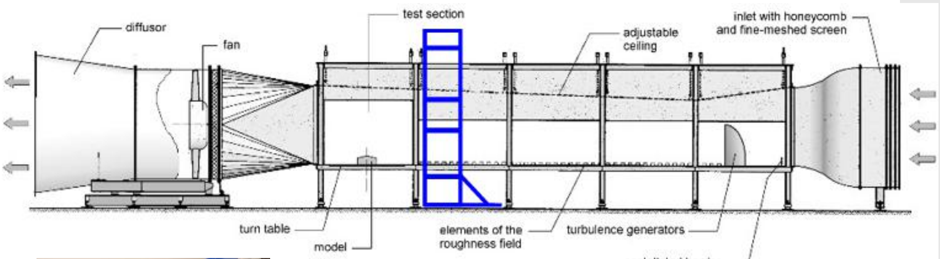
Gust structure of a wind field

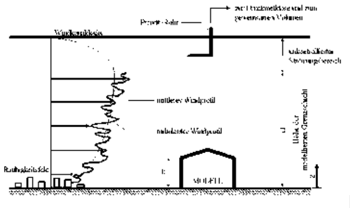


Taylor‘s hypothesis of „frozen“ turbulence

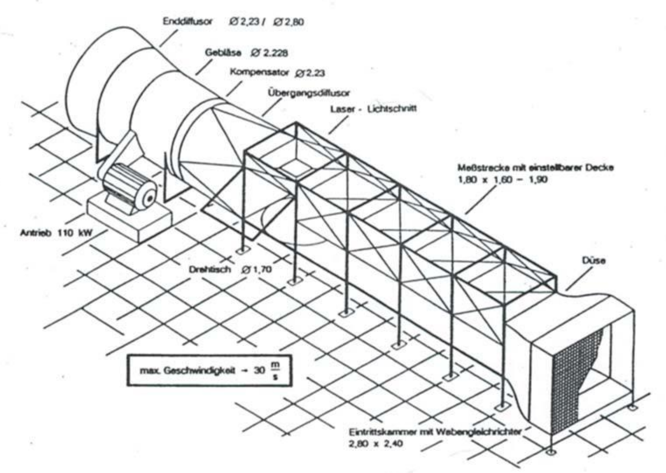


Boundary Layer Wind Tunnel at RU Bochum



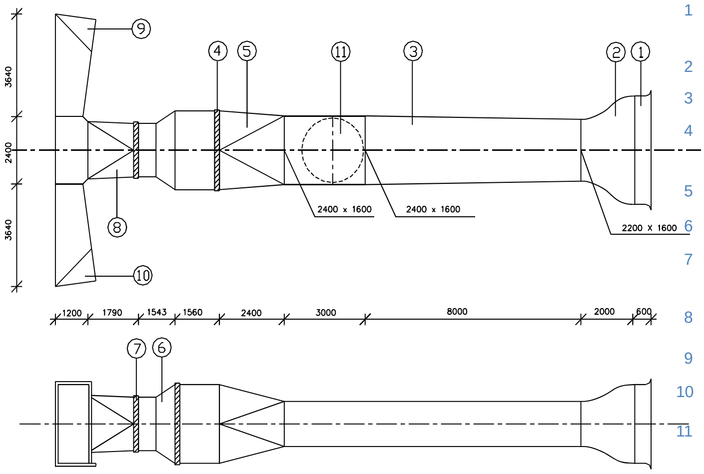


Boundary Layer Wind Tunnel at RU Bochum



Italian boundary layer wind tunnel at CRIACIV, Prato / Florence

Italian boundary layer wind tunnel at CRIACIV, Prato / Florence



1 Inlet and honeycomb web

2 Contractor

3 Roughness field

4 Isolating joint

5 Diffusor

6 Fan

7 Isolating joint

8 Diffusor

9 Diffusor

10 Diffusor

11 Measurement section and turn table

Chapter 2: Similarity Requirements

- **Scaling**
- **Similarity of the incoming flow**
- **Similarity of the flow over a bluff body**
- **Similarity of the wind loads**
- **Similarity of the reactions (dynamic reactions of building structures e.g. in order to investigate oscillations of aeroelastic responses of structures**

Scaling

Scales

- Geometry scale

$$\lambda_{geom} = \frac{L_{model}}{L_{full\,scale}}$$

- Velocity scale

$$\lambda_u = \frac{\bar{u}(h)_{model}}{\bar{u}(h)_{full\,scale}}$$

- Time scale

$$\lambda_T = \frac{T_{model}}{T_{full\,scale}} = \frac{L_{model}}{L_{full\,scale}} \cdot \frac{\bar{u}(h)_{full\,scale}}{\bar{u}(h)_{model}} = \frac{\lambda_{geom}}{\lambda_u}$$

- Frequency scale

$$\lambda_{freq} = \frac{1}{\lambda_T}$$

Similarity of the incoming flow

- Mean wind profile

$$\alpha_{full\,scale} = \alpha_{full\,scale}$$

- Turbulence intensity in the height H of the upper building edge

$$I_u(H)_{full\,scale} = I_u(H)_{model}$$

- Profile of the turbulence intensity (for high buildings)

$$I_u(z/H)_{full\,scale} = I_u(z/H)_{model}$$

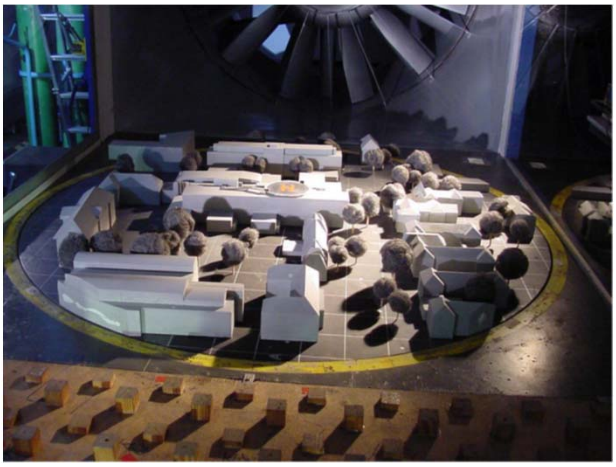
- Height of the simulated boundary layer

$$\delta_{sim} \geq 2H$$

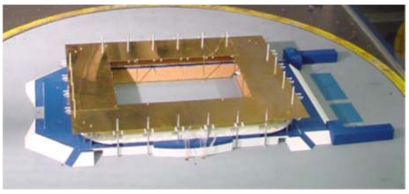
- Distribution of the velocity fluctuations over frequencies

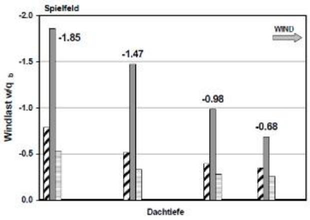
$${\frac{f \cdot S_u(f,z)}{\sigma_u^2(z)}}_{full\,scale} = {\frac{f \cdot S_u(f,z)}{\sigma_u^2(z)}}_{model}$$

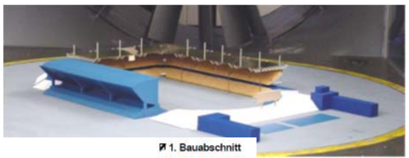
Example: geometric similarity



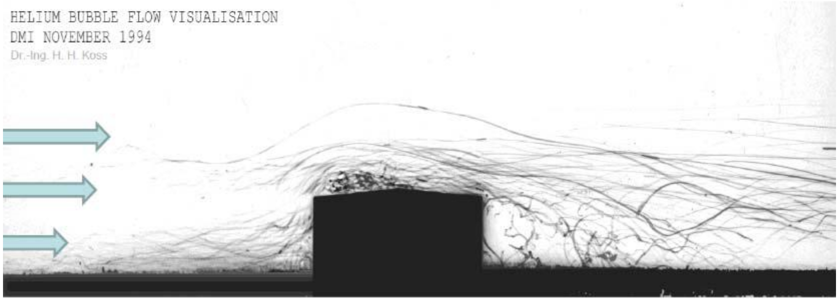
Example: Construction states







Example: Similarity of incoming flow quantities and geometric measures



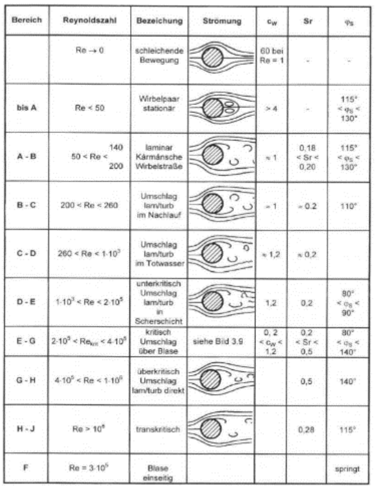
Similarity of the flow over a bluff body

Reynolds number

- Similarity of the flow over a bluff body

$$Re = \frac{w^2 \rho}{\eta \frac{w}{D}} = \frac{w \cdot D \cdot \rho}{\eta} = \frac{mass\,effects}{friction\,effects}$$

- Separation lines are fixed through the sharp edges of the buildings
  Re > 10.000 => similarity
- Especially problematic in case of rounded surfaces (e.g. cooling towers) => installation of wires or rips to increase surface roughness



Bereich	Reynoldszahl	Bezeichung	Strömung	c_W	Sr	φ_S
	$Re \to 0$	schleichende Bewegung		60 bei Re = 1	-	-
bis A	Re < 50	Wirbelpaar stationär		> 4	-	115° < φ_S < 130°
A - B	50 < Re < 140 200	laminar Kármánsche Wirbelstraße		≈ 1	0,18 < Sr < 0,20	115° < φ_S < 130°
B - C	200 < Re < 260	Umschlag lam/turb im Nachlauf		≈ 1	≈ 0.2	110°
C - D	260 < Re < $1 \cdot 10^3$	Umschlag lam/turb im Totwasser		≈ 1,2	≈ 0,2	
D - E	$1 \cdot 10^3$ < Re < $2 \cdot 10^5$	unterkritisch Umschlag lam/turb in Scherschicht		1,2	0,2	80° < φ_S < 90°
E - G	$2 \cdot 10^5$ < Re_{krit} < $4 \cdot 10^5$	kritisch Umschlag über Blase	siehe Bild 3.9	0, 2 < c_W < 1,2	0,2 < Sr < 0,5	80° < φ_S < 140°
G - H	$4 \cdot 10^5$ < Re < $1 \cdot 10^6$	überkritisch Umschlag lam/turb direkt			0,5	140°
H - J	Re > 10^6	transkritisch			0,28	115°
F	Re = $3 \cdot 10^5$	Blase einseitig				springt

M.V. Morkovin (1964)

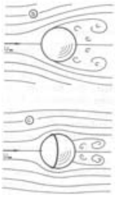
Similarity of the flow over a bluff body

$Re_{Natur} < Re_{Modell}$

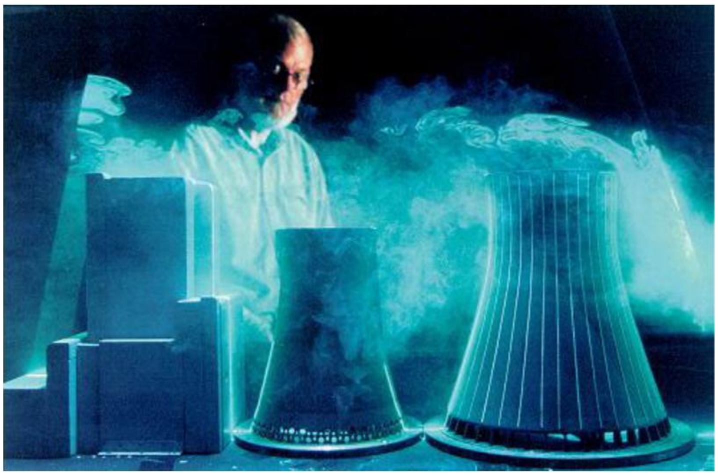
möglich mit

Zusatzmaßnahmen

z.B. „Stolperdraht“



Example: surface roughness



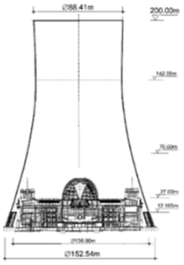
Example: Similar interferences

Öltanks

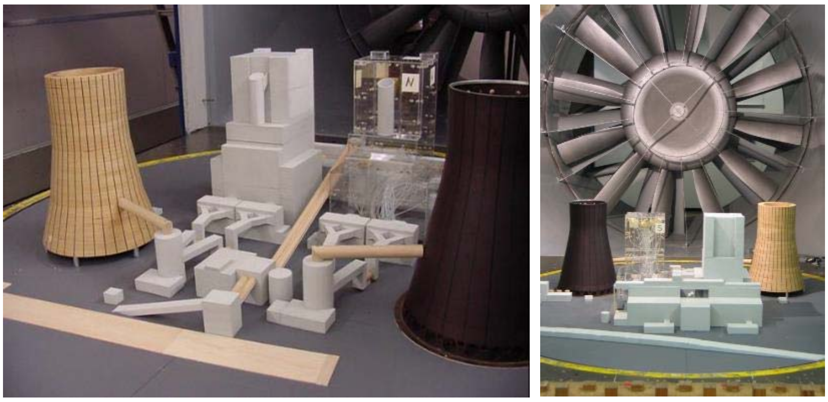
Kühltürme

Example: Similar interferences

Zweitgrößte Kühlturm der Welt
(RWE-Kraftwerk Niederaußem)



Example: Similar interferences

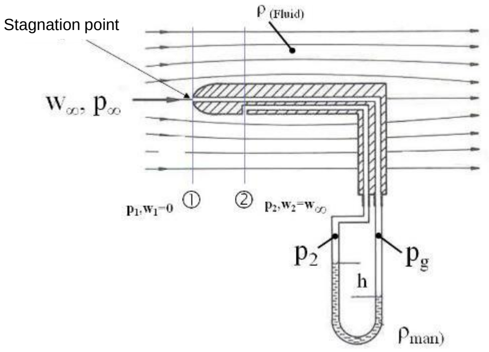


Example: similarity of wind effects

Chapter 3: Measurement of velocities and pressures

- Prandtl-tube (Pitot-tube)
- Hot wire probes
- Others
  - Laser-Doppler Anemometry
  - Particle Image Velocimetry
- Pressures
  - Piezo-resistive differentiell pressure sensors
  - Optimised tubing
  - Calibration

Prandtl-tube



$$w_\infty = \sqrt{\frac{\varrho_{man}}{\varrho} \cdot 2 \cdot g \cdot h}$$

Hot wire probes

Constant Current Anemometry - CCA

- U = R·I: Electric current I [V] remains constant and resistance R [Ω] is measured
- The flow cools down the fine wire, temperature gradient is measured
- Problem: thermal inertia of the wire => turbulences can hardly be measured

Constant Temperature Anemometry - CTA

- The electric resistance and by that also the temperature of the wires are kept constant
- The voltage is measured, which is required to control the electric resistance in order to keep the temperature constant.
- Possible temperature fluctuation are directly compensated by voltage, the thermal inertia of the wire is not dominant. Mean and high frequency signals of voltage are measures of respective mean flow values and turbulent flow fluctuations.

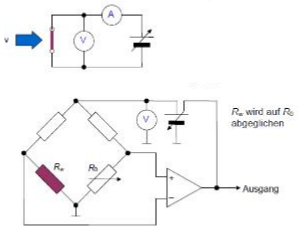
Hot wire probes
Constant Temperature Anemometry (CTA)

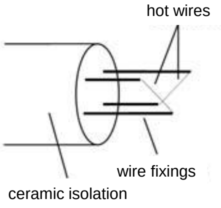
King‘s approximation
of heat loss of fine wires:

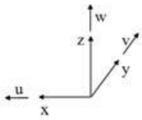
$$I^2 \cdot R_S = (T_S - T_F) \cdot A + B \cdot v^{0,5}$$

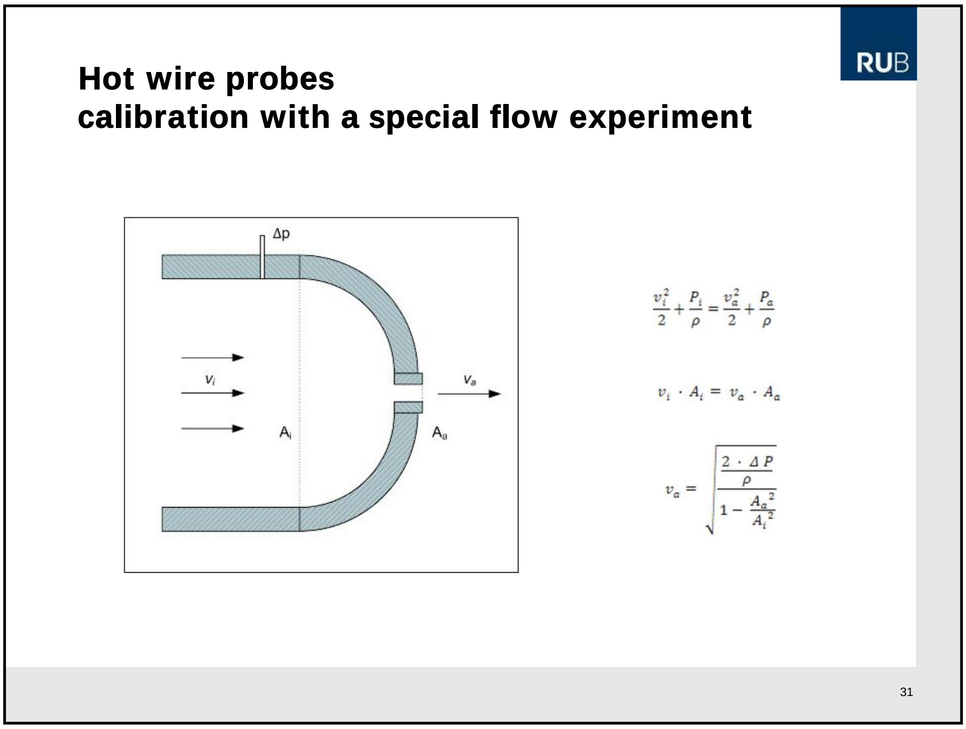
I – electric current, R_S – electric resistance,
T_S – temperature of wire, T_F – temperature of fluid,
v – flow speed

Wheatstone bridge









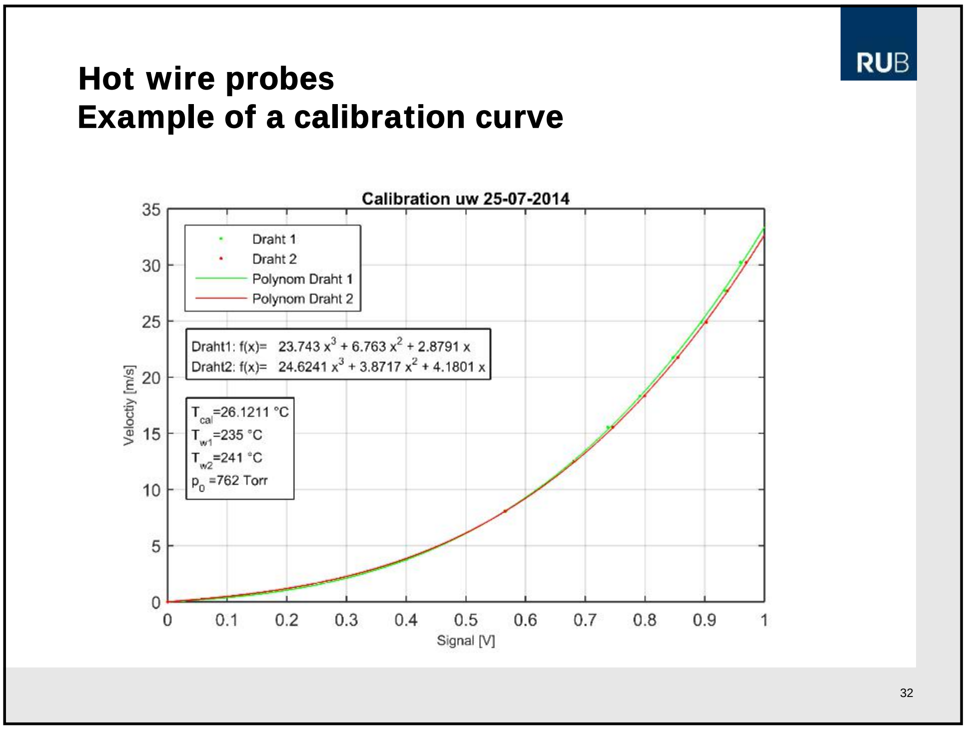
RUB

Hot wire probes
calibration with a special flow experiment

$$\frac{v_i^2}{2}+\frac{P_i}{\rho}=\frac{v_a^2}{2}+\frac{P_a}{\rho}$$

$$v_i \cdot A_i = v_a \cdot A_a$$

$$v_a = \sqrt{\frac{\frac{2 \cdot \Delta P}{\rho}}{1-\frac{{A_a}^2}{{A_i}^2}}}$$

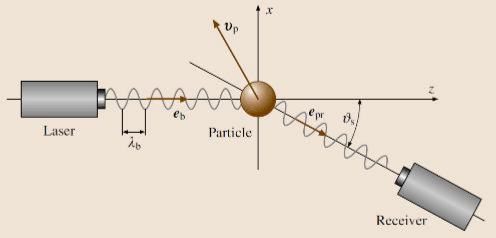


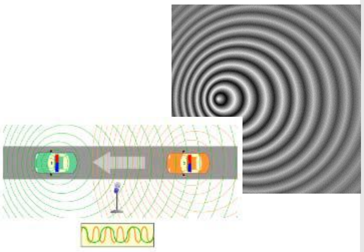
RUB

Hot wire probes
Example of a calibration curve

Further measurement methods
Laser Doppler Anemometry - LDA

- LDA is an optical and non invasive measurement technique.
- Measurement of frequency shifts of the reflection waves of light diffusing particles (water steam, solid particles of few µm of diameter).
- Particles are recipients and emittors of the collected light.
- The measured frequency shift is a measure of the instantaneous particle velocity.

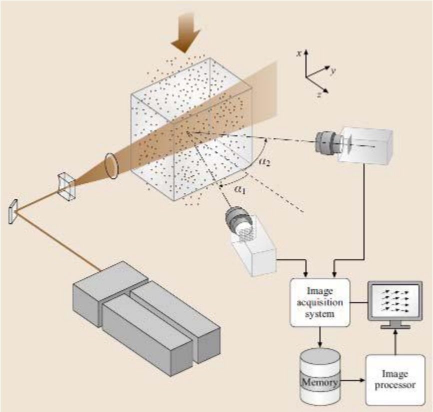


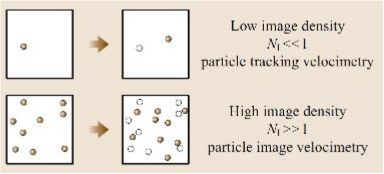


Further measurement methods
Particle Image Velocimetry - PIV

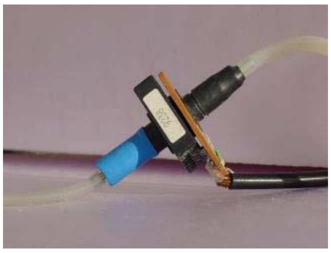
- Optical and non invasive measurement technique
- A velocity distribution of a planar section in a flow field is measured during a minimal interval of time.
- A planar light-section of the flow is measured using a pulsed laser and a cylindrical lense.
- Die reflection of the light from the particles, which are transported with the flow, is photographed by a CCD camera.
- The correlation of subsequent photographs at equal time steps deliver an accurate picture of the incremental positions of particles from which a field of flow velocities can be derived.

Further measurement methods
Particle Image Velocimetry - PIV

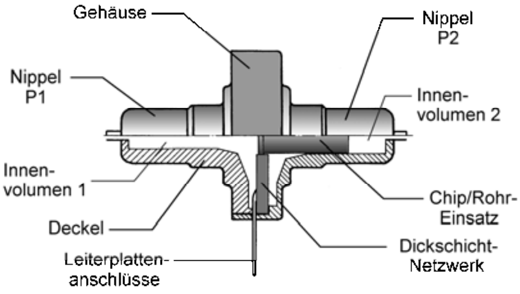




Pressure measurement: pressure sensor and optimized tubing system



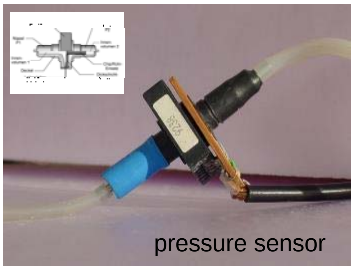
Differential pressure sensor (principles)

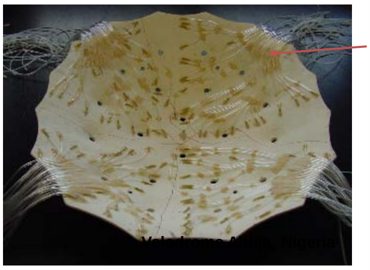


Calibration:
50 mmWs ÷ 4905 mV (490,5 Pa)

Pressure measurement: pressure sensor and optimized tubing system

Pressure measurement: pressure sensor and optimized tubing system





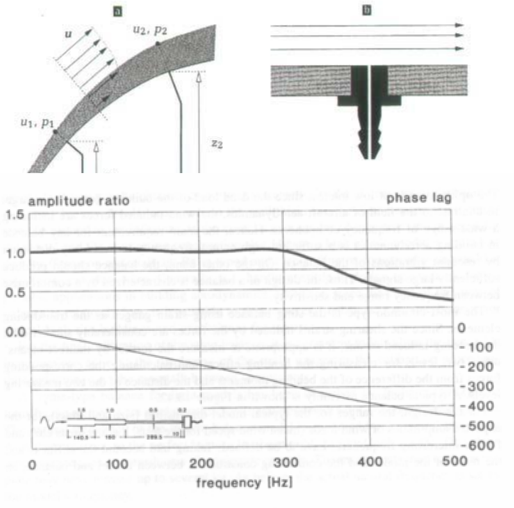


Fig. 10.41. Example of an optimized four-stage tube system.

Chapter 4:
Wind Tunnel Projects

- Pressure analysis
- Analysis of strains
- Analysis of critical velocities

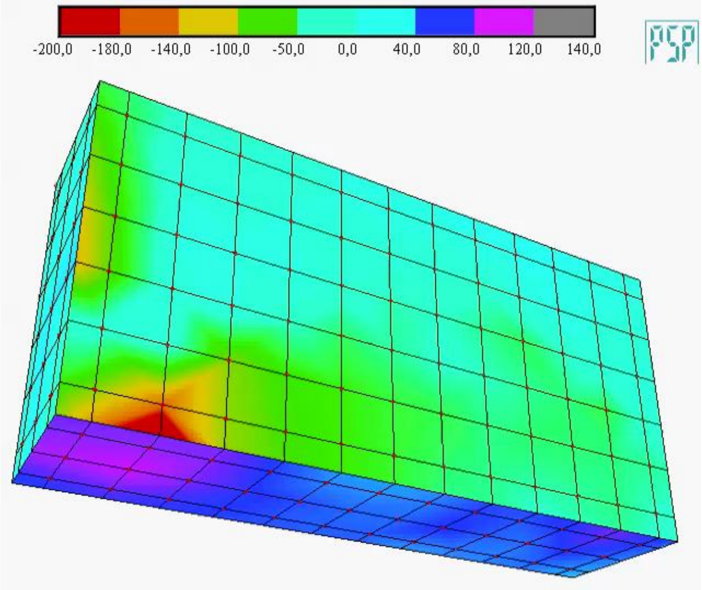
Pressure measurement at the built environment

Experimente
am Modell der
MSV-Arena

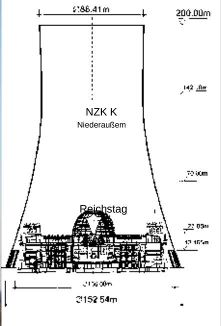
Pressure model Shanghai Ship Terminal, 2009

Pressure model Shanghai Ship Terminal, 2009

Pressure measurement: time resolution

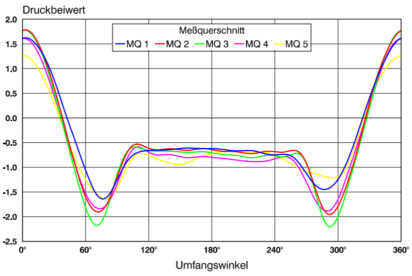


Pressure model of a group of cooling towers

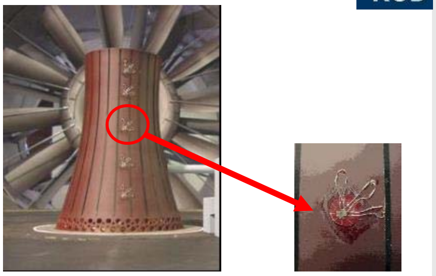


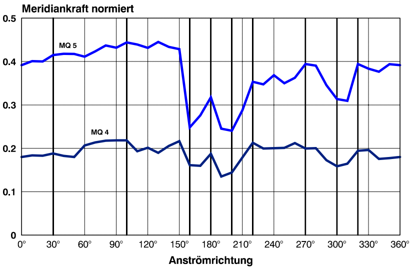
World‘s largest cooling tower
(RWE-Kraftwerk Niederaußem)

Strain measurements in a group arrangements



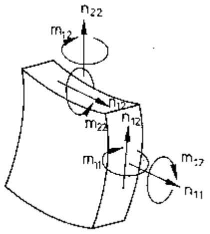
Pressure distribution

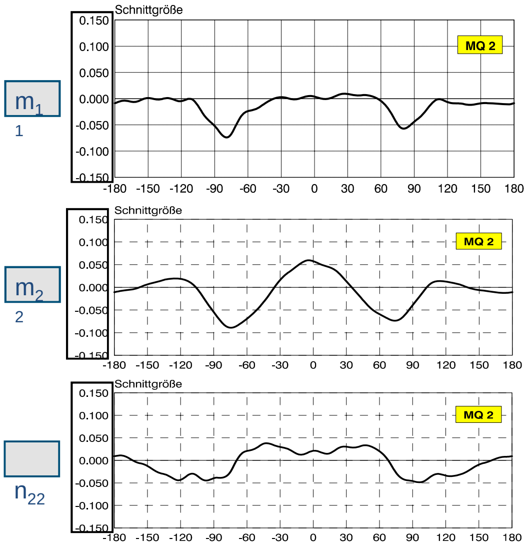




Meridional tension force as a function on the angle of attack of the wind (group arrangement)

Strain measurements in a group arrangements

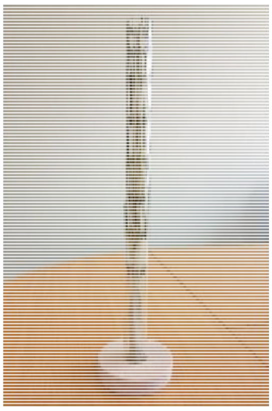


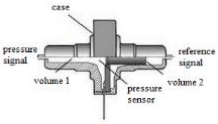


Measured internal forces for the isolated shell

Stationary wind tunnel model for wind pressure measurements

- Pressure measurements in different levels along the height of the model
- Boundary layer wind profile





Pressures correlation model development for circular cylinder

Vertical and horizontal wind forces correlation (quasi-stationary case), influence of turbulence and eddy shedding to the rms-response (Niemann 1990)

Extension of the model for non-stationary case is needed

Non-stationary wind tunnel model for response measurements

Boundary layer wind field

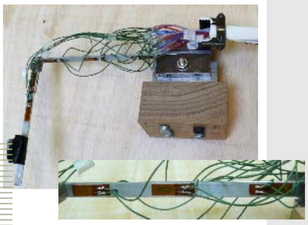
Model: circular cylinder with rotor (rotation is being considered)

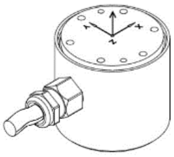
Response of the structure (base bending moments and shear forces) will be measured using high frequency force balance (lower picture)

Force balance measures response that represents superposition of different modes

Rotor thrust force and wind load on the tower must be separated

Bending moment at hub height due to rotor bending will be measured using strain gauges (upper picture) in wind tunnel





COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Wind Generation Mechanics and Wind Speed Statistics

Francesco Ricciardelli

COST is supported by the EU Framework Programme Horizon 2020

TU 1304 – WINERCOST
Advances in Wind Energy Technology

Wind generation mechanisms and wind speed statistics

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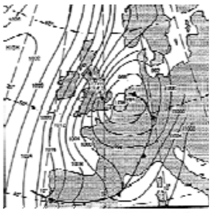
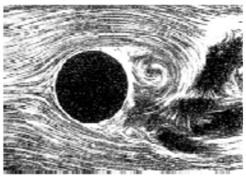
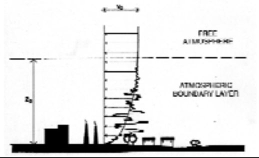
Department of Civil Engineering, Design, Building and Environment
Università della Campania Luigi Vanvitelli, ITALY

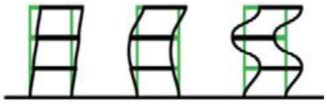
The Wind Loading Chain

Atmospheric circulation – Atmospheric Boundary Layer – Aerodynamics – Structural Dynamics – Design criteria

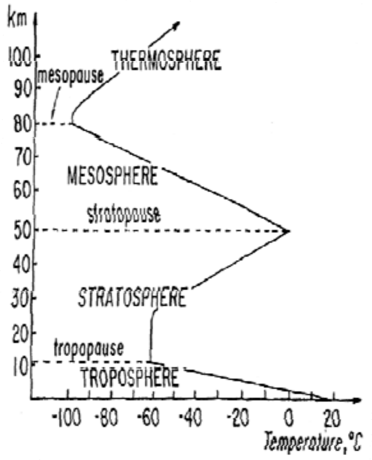








Layers of the atmosphere

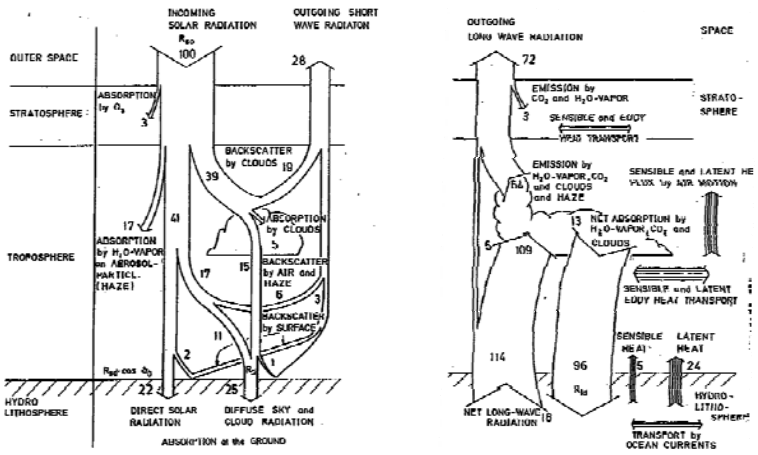


The Troposphere contains about 90% of the mass of the atmosphere, and is the layer in which human activities take place. The thickness of the Troposphere changes with latitude, ranging between 9 Km at the equator and 16 Km at the poles

The Stratosphere contains 97% of the ozone of the atmosphere, which absorbs ultraviolet radiation

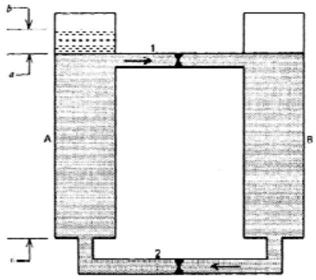
The Stratopause reflects the solar radiation downward

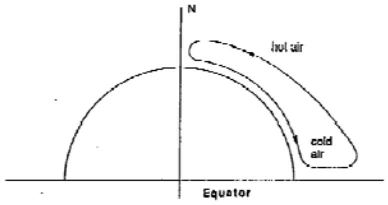
Atmospheric heat exchange



Global heat balance keeps the earth temperature constant

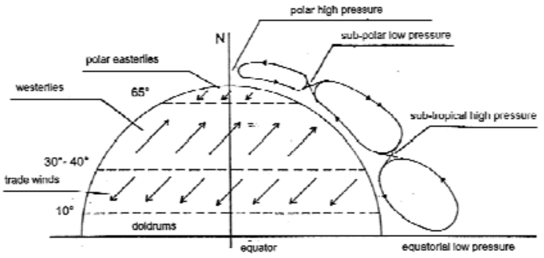
Monocellular circulation model





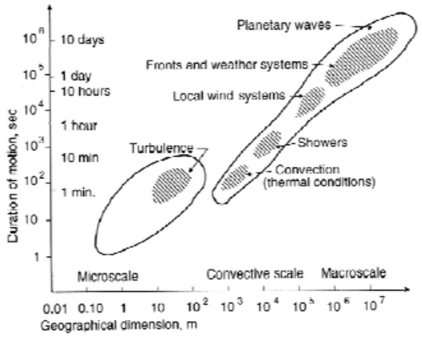
The monocellular model neglects of the vertical temperature and humidity gradient, ad well as the effects of friction and of earth rotation

Tricellular circulation model (Bergeron)



The non uniform distribution of continents and clouds are the causes of a sub polar low pressure zone (polar front) and of a subtropical pressure zone, which in turn cause at tricellular circulation pattern

The deviation with respect to the meridian is the effect of the Coriolis force and of friction



Atmospheric circulation

Primary circulation (planetary scale): polar easterlies, westerlies, trade winds

Secondary circulation (synoptic scale): anticyclones, extra tropical cyclones, tropical cyclones (hurricanes, typhoons, cyclones), monsoons

Local winds: Foehn, Bora, Chinook, thunderstorms, breezes, tornados

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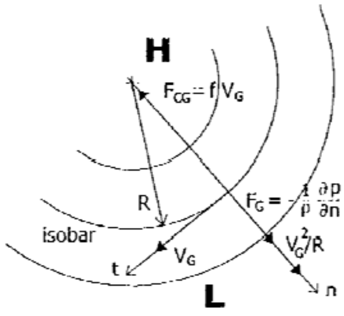
Anticyclones

Synoptic systems consisting in a clockwise (in the northern hemisphere) circulation around a high pressure zone. They move in the southwest-northeast direction and bring good weather and low winds.

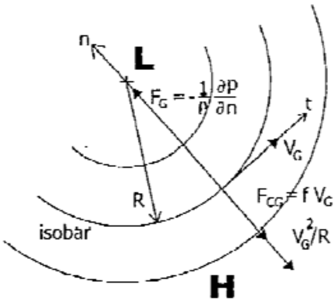
They are the result of
action of pressure grad
Corioli forces, friction f
and centrifugal forces.



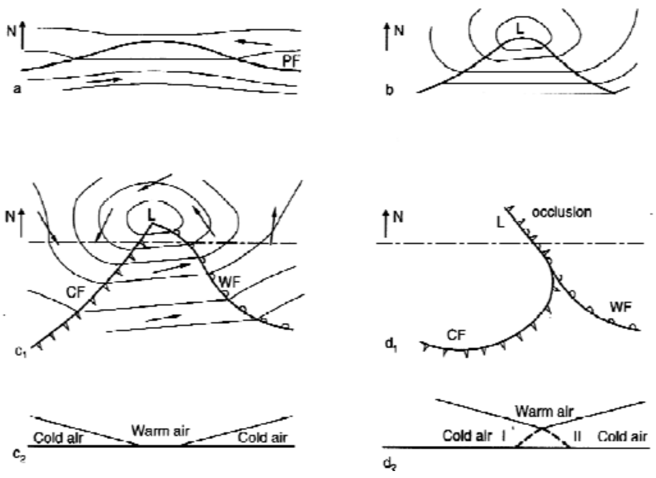
Extra tropical Cyclones

Also are synoptic systems, consisting in a counter-clockwise (in the northern hemisphere) circulation around a low pressure zone. They move in the west-east direction and bring bad weather and high winds.

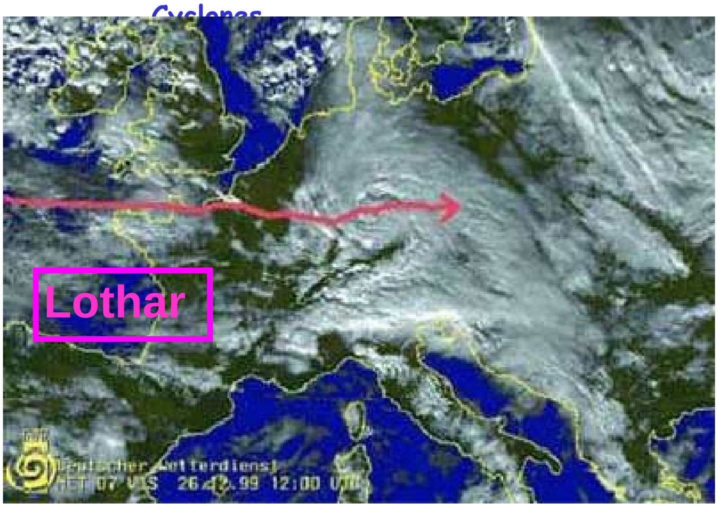
They also are the result of the action of pressure gradients, Corioli forces, friction forces and centrifugal forces.



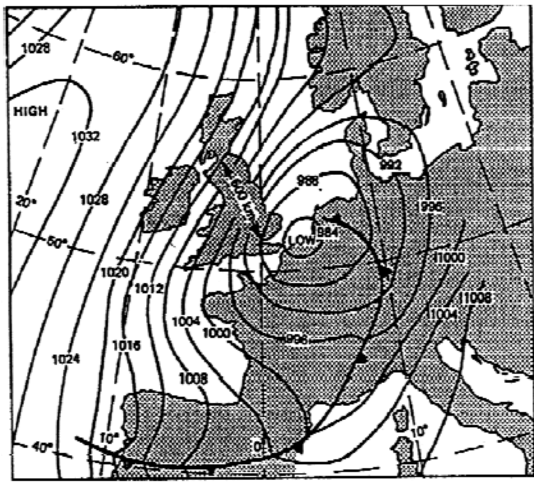
Extra tropical Cyclones



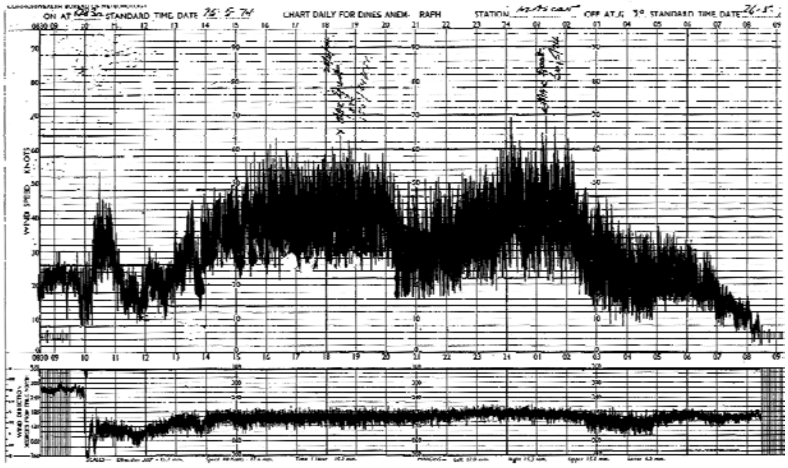
Extra tropical Cyclones



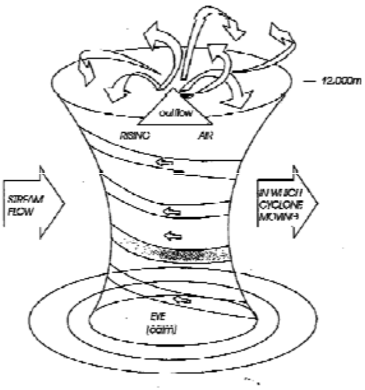
Extra tropical Cyclones



Extra tropical Cyclones



Tropical Cyclones

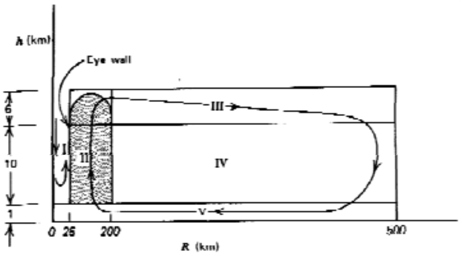


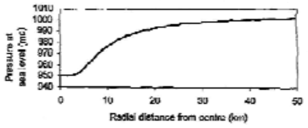
Tropical Cyclones are generated at sea, and their energy comes from the latent heat of evaporating water, with a minimum temperature of 26°

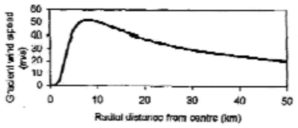
They generate at latitudes in the range of 5° e i 20°, and die as they propagate towards higher latitudes or as they hit the land

The tend to avoid large cities due to the heat island effect

Tropical Cyclones







Tropical Cyclones have a diameter in the order of hundreds of kilometres, an height of about 10 Km, and surface wind speeds which can exceed 120 Km/hr (peak speeds of 250 Km/hr)

Their convective velocity is between 5 and 50 Km/hr

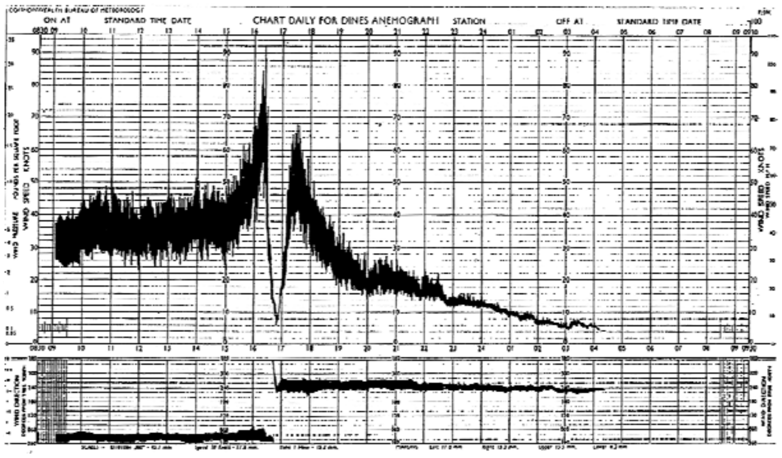
The central part, the eye, has a diameter in the range of 10 to 80 Km, and relatively low winds

Tropical Cyclones

They take place towards the end of the summer and the beginning of the autumn (August-September in the northern hemisphere, February –March in the southern hemisphere)

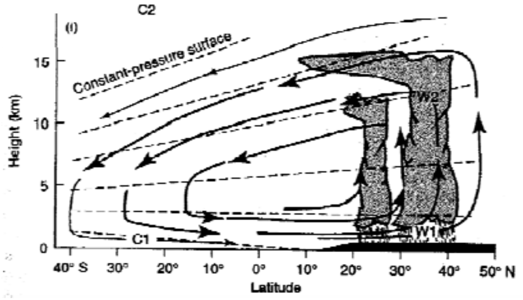
They are called Hurricanes in the Caribbean, Typhoons in the sea of China and Cyclones in south-eastern Asia and in Australia

Tropical Cyclones



Tropical Cyclones

Monsoons

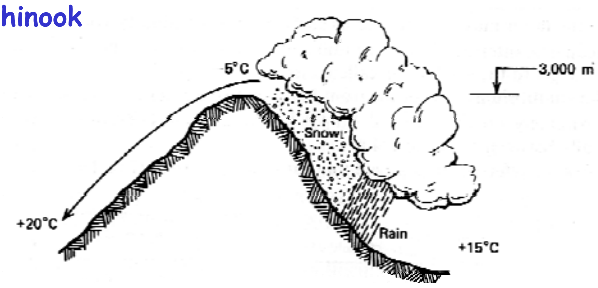


Monsoons characterise the climate of the Indian subcontinent, and are associated with the different thermal inertia of land and sea

In the winter the dry monsoon blows in the northeast-southwest direction, from the colder land to the warmer sea

In the summer the wet monsoon blows in the southwest-northeast direction, from the colder sea to the warmer land

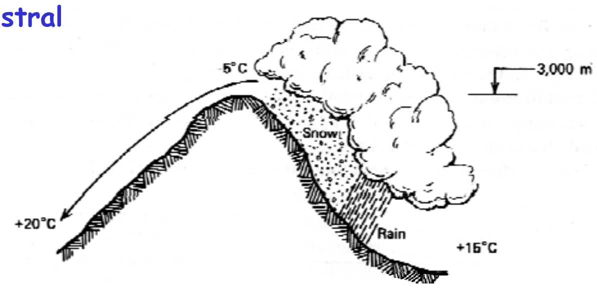
Foehn and Chinook



As warm, humid air is pushed upwards by the mountains it cools downs and releases moisture in the form of rain or snow

The warm and wet wind associated with the phenomenon is called Foehn in the Alps and Chinook in the Rocky Mountains

Bora and Mistral



As the cold and dry air flows downhill the adiabatic exchange may prove insufficient to warm it up. As this occurs part of the potential energy of the air mass is transformed into kinetic energy

The cold and dry wind associated with the phenomenon is called Bora in north-eastern Italy and Mistral in southern France. Wind speeds can exceed 200 Km/hr

If wind flows in a valley a jet effect can further increase the speed

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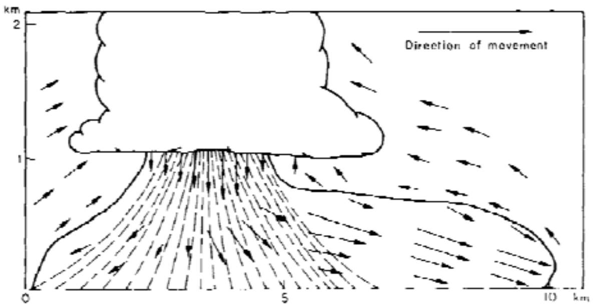
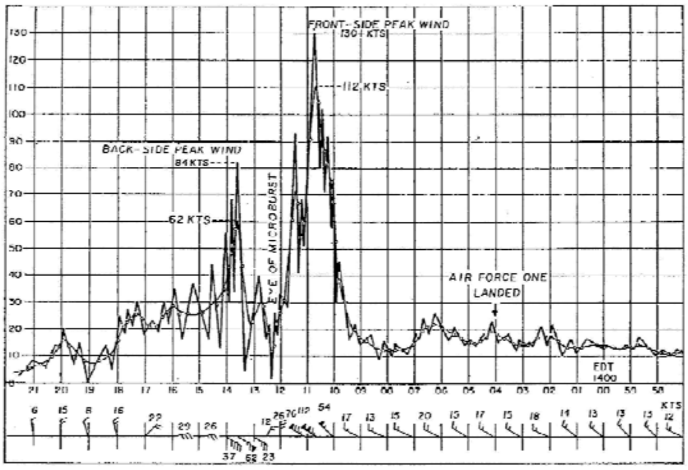
Thunderstorms



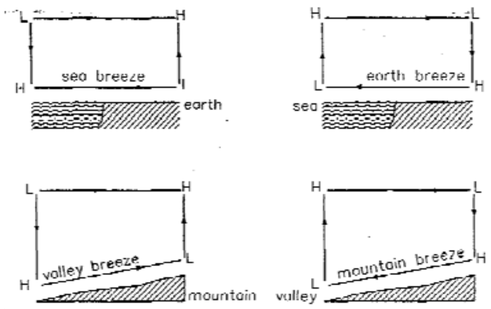
Masses of warm and wet air move upward. As they mix with colder air they cool down and sink. This causes heavy rain, which further drags the air down

Their duration is in the range of 5 to 30 minutes

Thunderstorms



Breezes



They are the result of the pressure gradient associated with the different thermal inertia of land and water, or of thermal variations at different altitudes

Tornados

Tornadoes are small scale circulatory systems, with a diameter in the order of hundreds of metres

The tangential wind speed can be in the order of 300 to 400 Km/hr

Their convective velocity is in the order of 30 to 100 Km/hr, and have a life in the order of the hour

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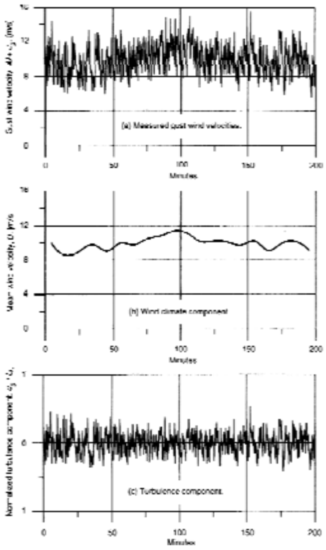
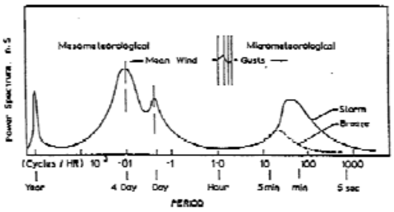


Modelling the aeolian circulation



$$u(t) = U + u'(t)$$
$$v(t) = \cancel{V} + v'(t)$$
$$w(t) = \cancel{W} + w'(t)$$

The Coriolis force

The equations of the air flow are written in a reference set which rotates with the earth, therefore is not inertial

There results that an additional inertia force has to be introduced to compensate for this, which is termed Coriolis Force and which acts on moving masses

The Coriolis force per unit volume acting on an air mass has direction orthogonal to both the air velocity vector $\mathbf{V}$ and the earth rotation vector $\mathbf{\Omega}$, and its magnitude is proportional to them:

$$\boxed{\mathbf{F}_c = 2\rho(\mathbf{V} \wedge \mathbf{\Omega})}$$

The modulus of the Coriolis force is: $F_c = |\mathbf{F}_c| = \rho f V$

where f is the Coriolis parameter $f = 2|\mathbf{\Omega}|\sin\varphi$

φ being the latitude and $|\Omega| = 0.729 \cdot 10^{-4}$ rad/s the modulus of the earth rotation

---

Equation of motion in free atmosphere

The forces acting on the air mass are:

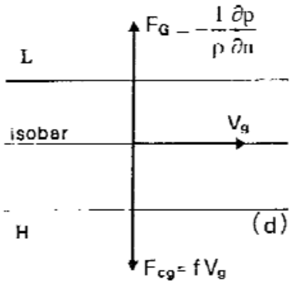
- Pressure gradient
- Coriolis force
- Centrifugal force
- Friction forces

In free atmosphere friction forces vanish; if the isobars are straight lines, then the trajectories are also straight and the centrifugal forces vanish; this occurs for large circulatory systems

Therefore, in free atmosphere, in case the isobars are straight lines the Coriolis force has to balance the pressure gradient

The Coriolis force is orthogonal to the wind velocity, therefore also the pressure gradient has to be orthogonal to the wind velocity, which is parallel to the isobars

Equation of motion in free atmosphere



$$\frac{\partial p}{\partial n} + \rho f V_g = 0$$

$$\boxed{V_g = -\frac{1}{\rho f}\frac{\partial p}{\partial n}}$$

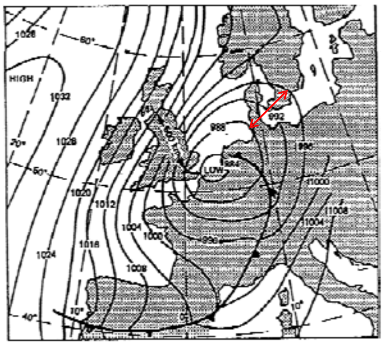
where V_g is the geostrophic wind speed, that is the gradient wind speed for the particular case of straight isobars

Geostrophic wind speed: sample calculation

$$\frac{\partial p}{\partial n} = -\frac{8 \text{ millibar}}{500 \text{ Km}} = -\frac{800 \text{ Pa}}{500000 \text{ m}}$$

$$f = 2|\Omega|\sin\varphi$$
$$= 2\cdot 0.729\cdot 10^{-4} \text{ rad/s}\cdot\sin(55°)$$
$$=1.19\cdot 10^{-4}$$

$$\rho = 1.29 \text{Kg/m}^3$$



$$V_g = -\frac{1}{\rho f}\frac{\partial p}{\partial n} = \frac{1}{1.29\cdot 1.19\cdot 10^{-4}}\frac{1}{625} = 10.3 \text{ m/s}$$

Equation of motion in free atmosphere

In case the isobars are curved the Coriolis force, the pressure gradient and the centrifugal force have to be in equilibrium

$$\frac{\partial p}{\partial n}+\rho f V_G+\frac{\rho V_G^2}{R}=0$$

where V_G is the gradient wind speed and R is the radius of curvature of the isobars; the direction of the trajectories is still that of the isobars

$$\boxed{V_G=-\frac{fR}{2}+\sqrt{\frac{f^2R^2}{4}-\frac{R}{\rho}\frac{\partial p}{\partial n}}}$$

Cyclonic circulation

$$\boxed{V_G=-\frac{fR}{2}-\sqrt{\frac{f^2R^2}{4}-\frac{R}{\rho}\frac{\partial p}{\partial n}}}$$

Anticyclonic circulation

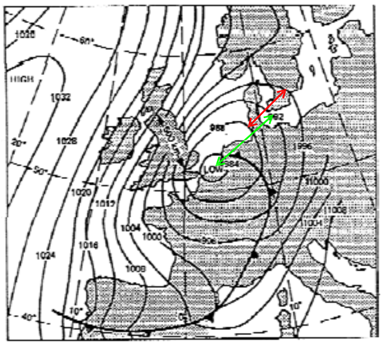
Gradient wind speed: sample calculation

$$\frac{\partial p}{\partial n}=-\frac{8\text{ millibar}}{500\text{ Km}}=-\frac{800\text{ Pa}}{500000\text{ m}}$$

$$f=2|\Omega|\sin\varphi$$
$$=2\cdot 0.729\cdot 10^{-4}\text{ rad/s}\cdot\sin(55°)$$
$$=1.19\cdot 10^{-4}$$

$$\rho=1.29\text{ Kg/m}^3$$

$$R=1000\text{ Km}=10^6\text{ m}$$

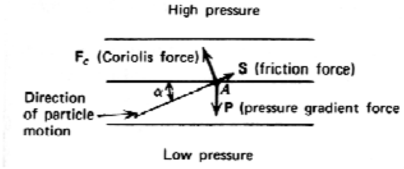


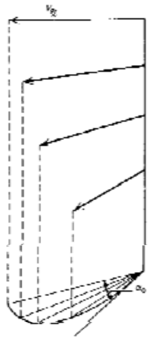
$$V_G=-\frac{fR}{2}+\sqrt{\frac{f^2R^2}{4}-\frac{R}{\rho}\frac{\partial p}{\partial n}}=9.6\text{ m/s}$$

Equation of motion in the low atmosphere

In the atmospheric boundary layer the wind speed varies with height and friction forces arise, parallel to the wind velocity and proportional to the vertical velocity gradient

The friction forces cause the trajectories to deviate from the tangent to the isobars





Friction forces take their maximum value at the ground (z=0) and vanish outside the atmospheric boundary layer (z=z_g)

The trajectories take their characteristic pattern named Ekman spiral

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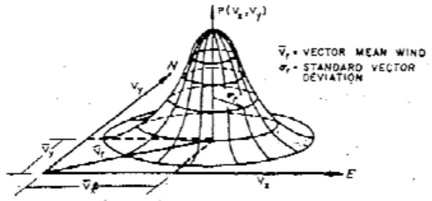
Distribution of the mean wind speed

The (600 s or 3600 s) mean wind speed vector is dealt with as a bivariate random variable, whose components are V_x and V_y

A Gaussian distribution is usually adopted, which describes reasonably well the observed behaviour; for an isotropic circulation and in the case in which the two mean components are uncorrelated the joint probability distribution is:

$$p_{V_x,V_y}(v_x,v_y)=\frac{1}{2\pi\sigma^2}\exp\left\{-\frac{\left[v_x-\bar{V}_x{}^2+v_y-\bar{V}_y{}^2\right]}{2\sigma^2}\right\}$$

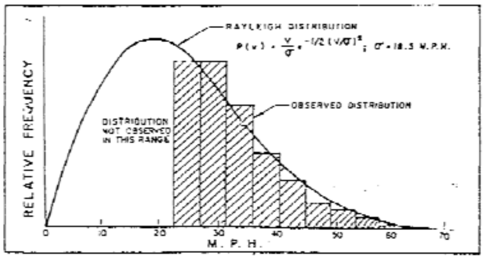


Distribution of the mean wind speed

If the mean wind speed vector is Gaussian, then its modulus is Rayleigh distributed:

$$p_V(u) = \frac{u}{\sigma}\exp\left(-\frac{u^2}{2\sigma^2}\right) \qquad V = \sqrt{V_x^2 + V_y^2}$$

to which corresponds the cumulated probability function:



$$P_V(u) = 1 - \exp\left(-\frac{u^2}{2\sigma^2}\right)$$

Distribution of the mean wind speed

Field measurements proved the mean wind speed vector not to be exactly Gaussian

As a consequence the Rayleigh distribution does not provide an accurate description of the wind speed modulus, especially at low values

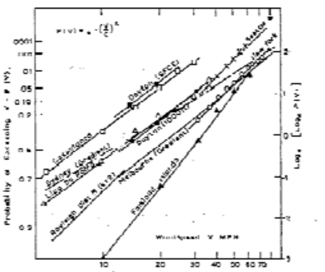
To overcome this problem a more flexible two-parameter Weibull distribution is often used, which better interpolates the experimental data

$$P_V(u) = 1 - \exp\left[-\left(\frac{u}{c}\right)^k\right]$$

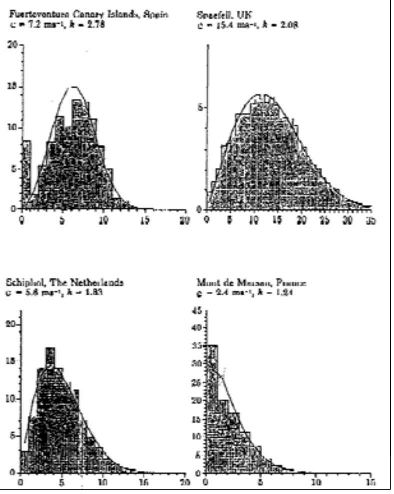
The c and k parameters are the dispersion and the exponent of the distribution

For k = 2 the Weibull distribution coincides with a Rayleigh distribution

Distribution of the mean wind speed



	c(mph)	k
Dayton (Ohio) Surface	8.8	1.7
Dayton (Ohio) 1000 ft.	15.9	1.7
Casablanca	9.3	1.5
Falkland Islands	33.0	2.5
Lido da Roma	15.2	1.5
New York (F.J.K. airport 500M)	25.5	1.87
Seattle airport (500M)	19.0	1.9
Sydney (gradient)	17.4	1.34
Melbourne (gradient)	23.4	1.64

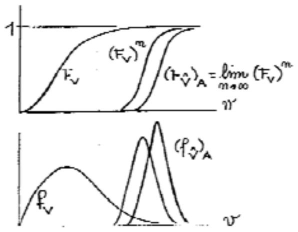


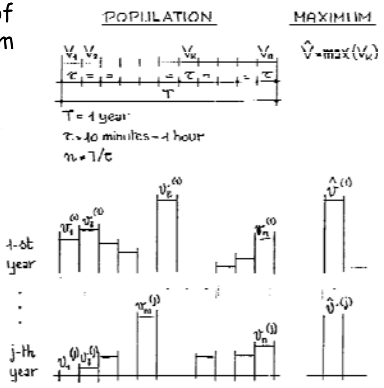
Distribution of the annual maxima

For wind engineering purposes it is of interest the distribution of the annual maxima

If the events V_k are statistically independent then the distribution of the maxima can be obtained from that of the mean wind speed:

$$P_{\hat{V}}(u) = \left[P_V(u)\right]^n$$





Distribution of the annual maxima

In real life the events fail to be statistically independent, as the length of a storm is longer than the averaging period; for this reason the Gumbel distribution (first type maxima distribution) is usually adopted:

$$P_V(u) = \exp\left\{-\exp\left[-a\left(u-U\right)\right]\right\}$$

in which U is the modal value and $1/a$ the dispersion

The relation between the annual maximum and its probability of occurrence is:

$$\hat{V} = U + \frac{1}{a}\left[-\ln\left(-\ln P_{\hat{V}}\right)\right]$$

The probability that a given value of the mean wind speed be exceeded in one year is:

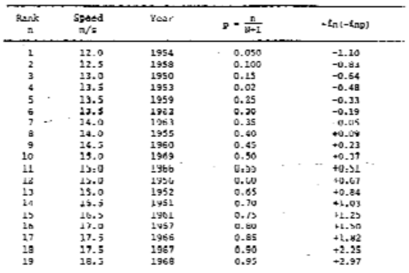
$$P\left[u > \hat{V}\right] = 1 - P_V(u)$$

Distribution of the annual maxima

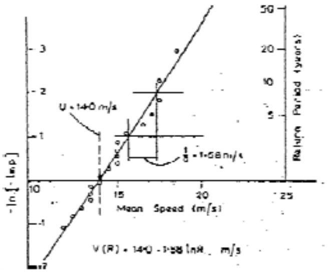
The parameters of the distribution of the maxima are derived from the measured series of the mean wind speed V

Each yearly maximum of the mean wind speed is an element of the sample

For a reasonable estimate of the distribution parameters at least 20 years of measurement are necessary



Rank n	Speed m/s	Year	$p = \frac{n}{N+1}$	$-\ell n(-\ell np)$
1	12.0	1954	0.050	-1.10
2	12.5	1958	0.100	-0.83
3	13.0	1950	0.15	-0.64
4	13.5	1953	0.02	-0.48
5	13.5	1959	0.25	-0.33
6	13.5	1962	0.30	-0.19
7	14.0	1963	0.35	-0.05
8	14.0	1955	0.40	+0.09
9	14.5	1960	0.45	+0.23
10	15.0	1969	0.50	+0.37
11	15.0	1966	0.55	+0.51
12	15.0	1956	0.60	+0.67
13	15.0	1952	0.65	+0.84
14	15.5	1951	0.70	+1.03
15	16.5	1961	0.75	+1.25
16	17.0	1957	0.80	+1.50
17	17.5	1966	0.85	+1.82
18	17.5	1967	0.90	+2.25
19	18.5	1968	0.95	+2.97



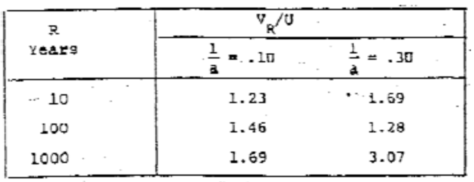
Return Period

A description of the annual maxima can be made based on return periods (in years):

$$R(u) = \frac{1}{1 - P_V(u)}$$

From the definition of the return period it is possible to express the annual maximum as a function of the Gumbel parameters:

$$\hat{V} = U + \frac{1}{a} \ln R$$



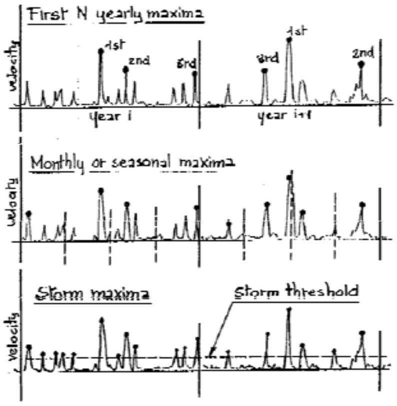
R Years	V_R/U	
	$\frac{1}{a} = .10$	$\frac{1}{a} = .30$
10	1.23	1.69
100	1.46	1.28
1000	1.69	3.07

Homogeneity of high winds

Usually the annual maximum is taken from recorded wind speeds as the largest valued recorded within a given year

At a given site, however, wind storms can have a different natures, i.e. extra tropical cyclones, thunderstorms, breezes, etc.; In this case the use of one single distribution for statistically non-homogeneous events can prove incorrect

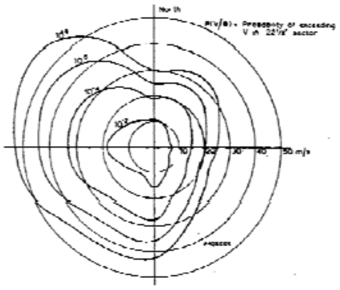
To overcome this problem, events associated with different causes have to be treated separately



Wind directionality effects

The structural response associated with the design speed is evaluated for all possible wind angles, and it depends on the characteristics of the structure

For a more accurate analysis, bringing less conservative results, it would be appropriate to take into account directionality effects, i.e. to use directional distributions of the wind speed; this because in most of the cases the worst wind incidence direction does not coincide with the weakest structural axis



The characteristics of the directional distributions may differ substantially from one another, as they can be associated with different generation mechanisms

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Distribution of the annual maxima

The main advantage of the approach based on a Gumbel distribution is that it is based on the measured annual maxima, therefore the statistics are highly reliable

The drawbacks of the approach based on a Gumbel distribution are:

1. Continuous measurements are required for a rather large number of years
2. In spite of the large amount of data, the statistics are derived from a limited number of events
3. The model is unable to accurately model the left tail of the distribution of maxima, that is it is unreliable for short return periods (in the order on one year)

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

The atmospheric boundary layer and wind turbulence characteristics

Francesco Ricciardelli

TU 1304 –WINERCOST
Advances in Wind Energy Technology

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The atmospheric boundary layer and wind turbulence characteristics

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The atmospheric boundary layer

The Atmospheric Boundary Layer (ABL) is the portion of the atmosphere in which the flow is influenced by the presence of the ground

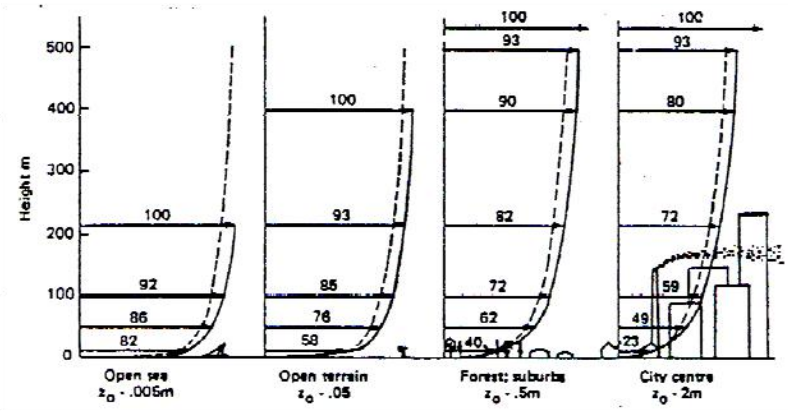
The thickness δ of the ABL can be defined based on a number of variables, therefore its value depends on the particular criterion adopted.

However, it mainly depends on the ground roughness, and is in the range of about one kilometre on open see to a few kilometres in city centres with a high density of tall buildings

For the purpose of the evaluation of wind effects on structures only the lower portion of the ABL is of interest. Therefore reference is made to a conventional height, above which the effects of the ground roughness are considered negligible. This is termed geostrophic height, z_g

The atmospheric boundary layer

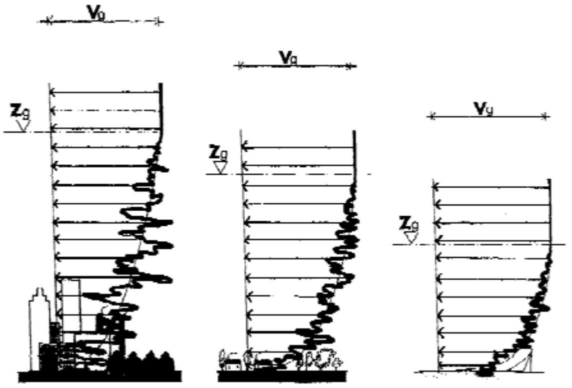
The mean wind speed inside the ABL varies with height, from zero at ground level to a maximum value equal to the geostrophic speed at the upper limit of the ABL



The atmospheric boundary layer

The development of the ABL is caused by friction at the ground. In addition o the shaping of a mean wind velocity profile, friction causes a mixing in the flow, which generates the atmospheric turbulence

The larger the friction stresses the larger the turbulence they generate



The atmospheric boundary layer

A measure of the ground friction is given by the surface shear τ_o:

$$\tau_o = \rho u_*^2$$

in which u_* is the shear velocity, and which represents the law of the wall

The ABL is, in fact, a turbulent boundary layer and energy transfer between faster and slower layers occurs through turbulent mixing. The energy is then dissipated in the lower layers through viscosity

The turbulent energy transfer between the layers is described through the fictitious shear stresses τ_x and τ_y which are called the Reynolds stresses

---

The atmospheric boundary layer

The air motion inside the ABL is described through the velocity components:

$$u(t) = U + u'(t)$$
$$v(t) = V + v'(t)$$
$$w(t) = W + w'(t)$$

The existence of a gap in the long term velocity spectrum allows to assume that the mean and fluctuating components are independent, and can therefore be investigated separately

The spatial distribution of the mean components is described in deterministic way, and is related to the gradient velocity

The gradient speed is considered a random variable

Equations of the mean flow

For an atmospheric flow, assuming that air is an incompressible fluid the equations of momentum balance and of continuity are:

$$U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial x}-fV-\frac{1}{\rho}\frac{\partial \tau_x}{\partial z}=0$$

$$U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial y}+fU-\frac{1}{\rho}\frac{\partial \tau_y}{\partial z}=0$$

$$\frac{1}{\rho}\frac{\partial p}{\partial z}+g=0$$

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0$$

which contain 6 unknowns; additional phenomenological equations (closure equations) have to be introduced to obtain a solution

---

Equations of the mean flow

Closure equations are those relating the Reynolds stresses to the velocity gradient, which are in the form of the law of the wall

$$\tau_x=\rho K(x,y,z)\,\frac{\partial U}{\partial z}$$

$$\tau_y=\rho K(x,y,z)\,\frac{\partial V}{\partial z}$$

$$K(x,y,z)=L^2(x,y,z)\sqrt{\left(\frac{\partial U}{\partial z}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2}$$

$K(x,y,z)$ = turbulent viscosity

$L(x,y,z)$ = mixing length

Either the turbulent viscosity or the mixing length have to be known for the equations to be solved

Equations of the mean flow

Upon differentiation of the third momentum equation with respect to x and y one obtains

$$\frac{\partial}{\partial x}\left(\frac{\partial p}{\partial z}\right) = -\rho\,\frac{\partial}{\partial x}\left(\frac{1}{\rho}\right)\frac{\partial p}{\partial z}$$

$$\frac{\partial}{\partial y}\left(\frac{\partial p}{\partial z}\right) = -\rho\,\frac{\partial}{\partial y}\left(\frac{1}{\rho}\right)\frac{\partial p}{\partial z}$$

Assuming that the air density is constant in horizontal planes (stratification), it is found that the horizontal pressure gradient is constant with height

$$\frac{\partial}{\partial z}\left(\frac{\partial p}{\partial x}\right) = 0$$

$$\frac{\partial}{\partial z}\left(\frac{\partial p}{\partial y}\right) = 0$$

Therefore the pressure gradient is the same at all elevations in the ABL, and coincident to that outside the ABL

$$\frac{\partial p}{\partial n} = \rho\left[fV_G \pm \frac{V_G^2}{R}\right]$$

Equations of the mean flow

Being the storm scale much larger than the local scale, it is possible to assume that the isobars are locally straight, which brings

$$\frac{\partial p}{\partial x} = \rho f V_{gx} \quad ; \quad \frac{\partial p}{\partial y} = \rho f V_{gy}$$

where V_{gx} and V_{gy} are the components of the geostrophic wind velocity in the x and y directions

For large storms it is also reasonable to assume that the flow is locally homogeneous in horizontal planes, that is

$$\frac{\partial U}{\partial x} = 0 \quad ; \quad \frac{\partial V}{\partial y} = 0$$

Equations of the mean flow

Neglecting the vertical component of the mean wind speed, the x and y momentum equations are:

$$f\;V_{gx}-V=\frac{1}{\rho}\frac{\partial\tau_x}{\partial z}$$

$$f\left(V_{gy}+U\right)=\frac{1}{\rho}\frac{\partial\tau_y}{\partial z}$$

Assuming that the x is parallel to the ground shear the following boundary conditions apply:

$$U=V_{gx} \qquad z=z_g$$
$$V=V_{gy} \qquad z=z_g$$
$$U=V=0 \qquad z=0$$

where z_g is the thickness of the ABL

$$\tau_x=\tau_y=0 \qquad z=z_g$$
$$\tau_x=\tau_0 \qquad z=0$$
$$\tau_y=0 \qquad z=0$$

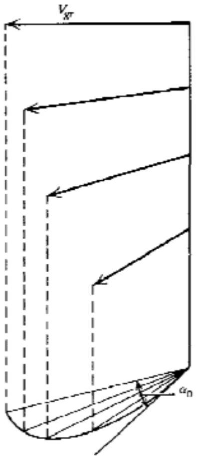
Equations of the mean flow

With the further assumption that the turbulent viscosity is locally constant, the x and y momentum equation have the solution

$$U(z)=\frac{V_g}{\sqrt{2}}\left[1-e^{-az}\left(\cos az-\sin az\right)\right]$$

$$V(z)=\frac{V_g}{\sqrt{2}}\left[1-e^{-az}\left(\cos az+\sin az\right)\right]$$

where $a=\sqrt{f/2K}$



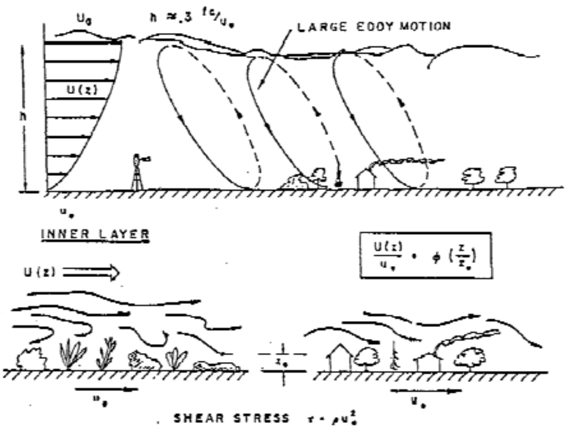
These are the equations of the Ekman spiral, whose accuracy is bound to the hypothesis of constant turbulent viscosity

Equations of the mean flow – similarity approach

Following a phenomenological approach one can assume that the ABL is divided into two regions, a surface layer and a outer layer

In the outer layer the air motion is scaled to the ABL thickness z_g

In the surface layer the air motion is scaled to the roughness length z_o



Equations of the mean flow – similarity approach

In the surface layer it is possible to relate the surface shear to the wind speed U at some height z, to the roughness length and to the air density

$$\tau_o = F(U(z), z_o, \rho)$$

as $\tau_o = \rho u_*^2$ then $\dfrac{U(z)}{u_*} = f_1\left(\dfrac{z}{z_o}\right)$

In the outer layer it is possible to relate the defect velocity to the surface shear, to the ABL thickness and to the air density

$U(z) - V_g = F(\tau_o, z_g, \rho)$ or $\dfrac{U(z)}{u_*} = \dfrac{V_g}{u_*} + f_2\left(\dfrac{z}{z_g}\right)$

Equations of the mean flow – similarity approach

A transition region must exist in which both expressions are reasonably acceptable, and in which they provide the same result

$$f_1\left(\frac{z}{z_0}\right) = f_1\left(\frac{z}{z_g}\frac{z_g}{z_0}\right) = \frac{V_g}{u_*} + f_2\left(\frac{z}{z_g}\right)$$

For a multiplying factor inside the function f_1 to become an additive quantity outside the function f_2 the two functions must be logarithmic, in particular

$$f_1\left(\frac{z}{z_0}\right) = \frac{1}{k}\ln\left(\frac{z}{z_0}\right)$$

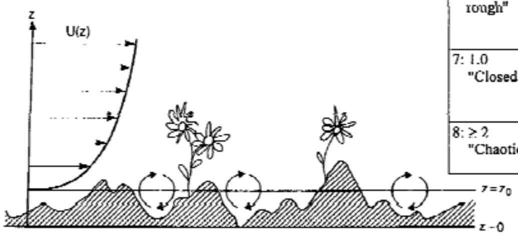
There results the logarithmic wind speed profile

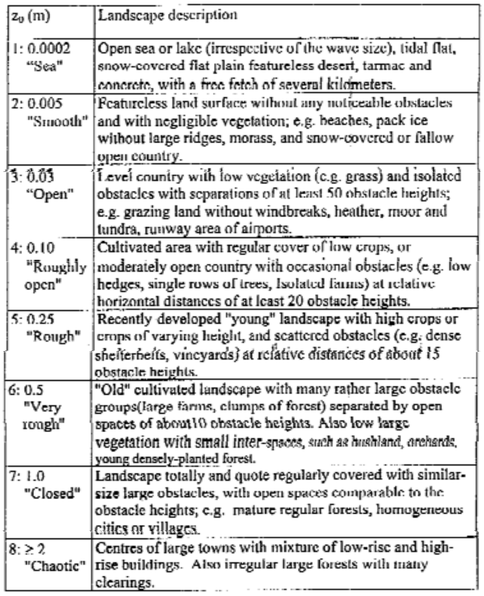
$$\boxed{U(z) = \frac{1}{k}u_*\ln\left(\frac{z}{z_0}\right)}$$

$k = 0.4 =$ von Karman constant

Roughness length

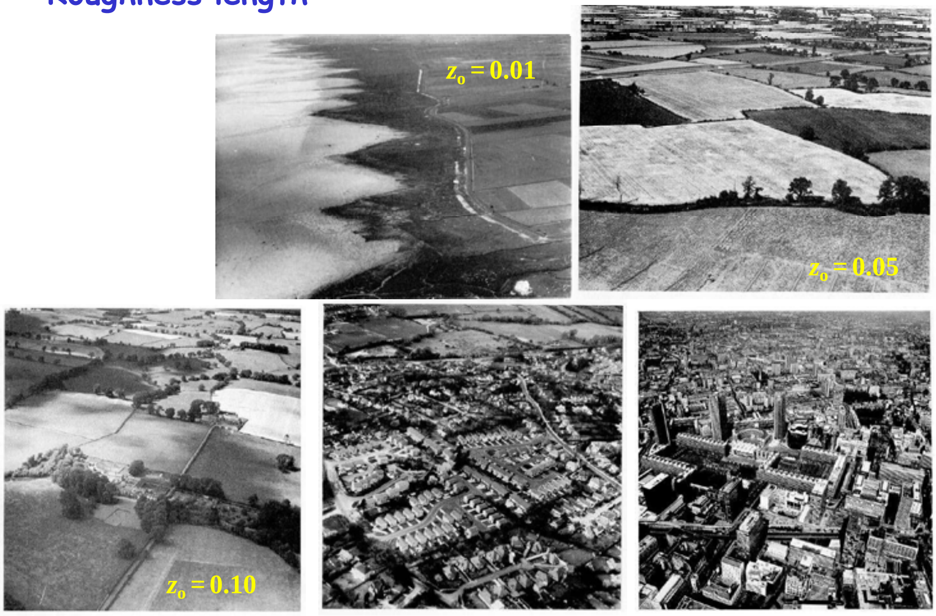
The roughness length characterises the average size of the vortices which form within the roughness elements





z₀ (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 and concrete, with a free fetch of several kilometers.
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: 0.5 "Very rough"	"Old" cultivated landscape with many rather large obstacle groups(large farms, clumps of forest) separated by open spaces of about10 obstacle heights. Also low large vegetation with small inter-spaces, such as bushland, orchards, young densely-planted forest.
7: 1.0 "Closed"	Landscape totally and quote 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: ≥ 2 "Chaotic"	Centres of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

Roughness length



Equations of the mean flow – similarity approach

The logarithmic law has been obtained for the lower portion of the ABL, therefore it tends to loose accuracy in the intermediate and upper portion of the ABL

Full scale measurements have shown that the logarithmic profile is reasonably accurate up to a height of

$$z = c_1 \cdot \frac{u_*}{f} \qquad c_1 = 0.015 \div 0.03$$

For practical applications a conventional limit of 200 m is accepted

In order to appropriately model the flow also in the upper portion of the ABL, a modified logarithmic law can be used

$$U(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) + 5.75\frac{z}{\delta} - 1.88\left(\frac{z}{\delta}\right)^2 - 1.33\left(\frac{z}{\delta}\right)^3 + 0.25\left(\frac{z}{\delta}\right)^4\right]$$

Equations of the mean flow – similarity approach

The depth of the ABL can be approximated as

$$\delta = c \cdot \frac{u_*}{f} \qquad c = 0.15 \div 0.4$$

where the value $c = 0.167$ is usually adopted

When the modified logarithmic profile is used the geostrophic wind velocity turns out to be

$$V_g = \frac{u_*}{k}\left[\ln\left(\frac{u_*}{f z_0}\right) + 1\right]$$

Equations of the mean flow – similarity approach

For structural engineering purposes the modified logarithmic profile can be approximated as

$$U(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) + 5.75\frac{z}{\delta}\right]$$

Which keeps about the same accuracy of the modified logarithmic profile up to a height of 300 m

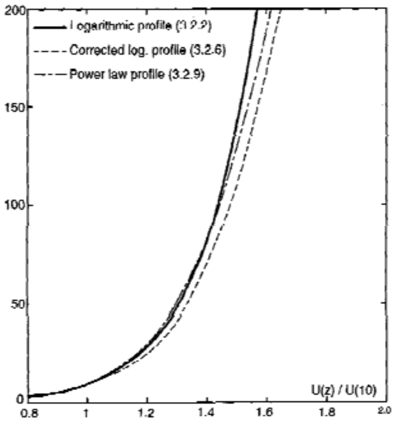
Power law mean wind speed profile

As an alternative to the logarithmic profile a power law profile is sometimes adopted [Hellmann, 1916]

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

The exponent of the power law depends on the terrain roughness

There is no physical justification to the power law profile, but if properly calibrated it provides a good approximation of the actual velocity distribution



Power law mean wind speed profile

As it is monotonically increasing, the power law profile does not meet the requirement that the mean wind velocity must never exceed the geostrophic value

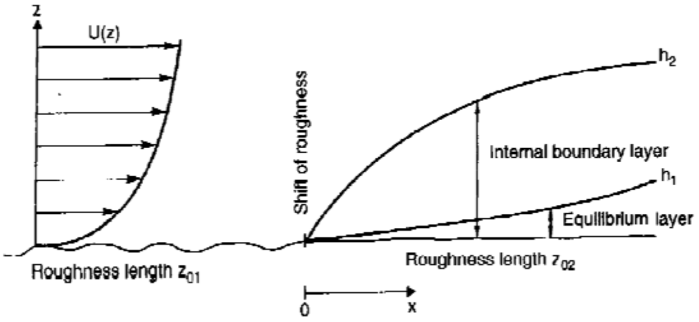
For this reason its validity is usually limited to heights lower than

$$z_g = 765 \cdot \alpha + 195$$

Above z_g the mean wind velocity is assumed to be constant

Terrains with non-homogeneous roughness

A change in roughness causes a modification in the mean wind profile, which propagates downstream the point of roughness change

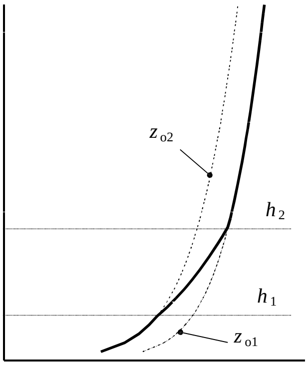


Terrains with non-homogeneous roughness

In theory the profiles applying for $z < h_1$ and $z > h_2$ must be joined for $h_1 < z < h_2$

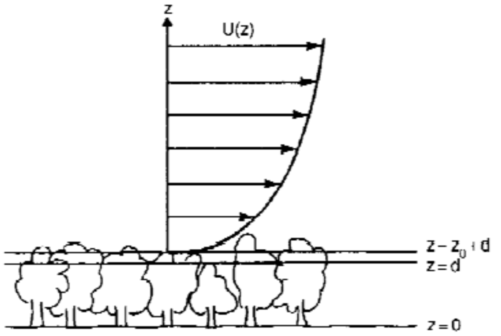
For practical applications the following two cases are considered:

1. If the construction is lower than h_1, then the profile of roughness z_{o2} is used
2. If the construction is higher than h_1, then the profile of roughness z_{o1} is used for $z > h_2$, and a modified z_{o2} profile is used below h_2

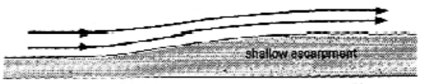


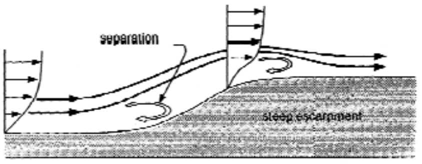
Displacement of the mean wind profile

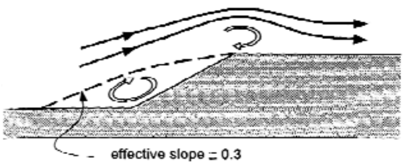
When the roughness is very dense it is necessary to consider a zero plane displacement d equal to the average height of the roughness elements, and consequently reduce the roughness length

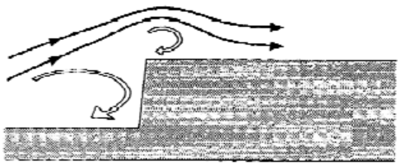


Topography effects







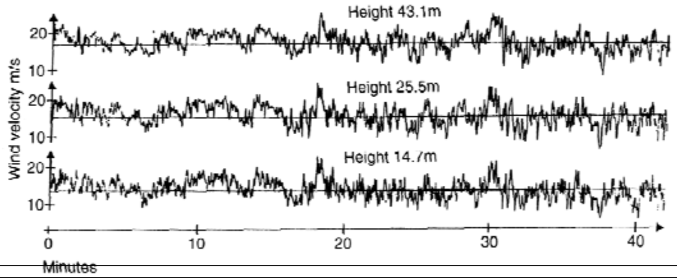


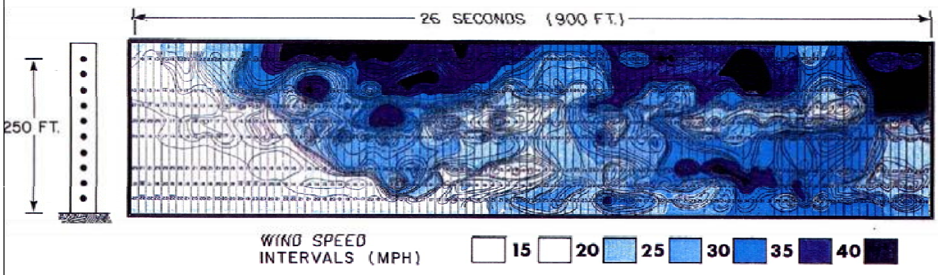
Atmospheric turbulence

The atmospheric turbulence is modelled as a Gaussian, ergodic, nil mean multivariate random field

$$\boxed{\begin{aligned} u(P,t) &= u(x,y,z,t) \\ v(P,t) &= v(x,y,z,t) \\ w(P,t) &= w(x,y,z,t) \end{aligned}}$$

A local description and a spatial organisation of turbulence are required





Local description of the atmospheric turbulence

It is assumed that the three turbulent components are statistically independent (uncorrelated) of each other

Time domain description: $R_u(\tau)$ $R_v(\tau)$ $R_w(\tau)$

Frequency domain description $S_u(f)$ $S_v(f)$ $S_w(f)$

Turbulence intensities

$$I_u = \frac{\tilde{u}}{U} = \frac{1}{U} \cdot \sqrt{R_u(0)} = \frac{1}{U} \cdot \left[\int_0^\infty S_u(f) \cdot df \right]^{1/2}$$

$$I_v = \frac{\tilde{v}}{U} = \frac{1}{U} \cdot \sqrt{R_v(0)} = \frac{1}{U} \cdot \left[\int_0^\infty S_v(f) \cdot df \right]^{1/2}$$

$$I_w = \frac{\tilde{w}}{U} = \frac{1}{U} \cdot \sqrt{R_w(0)} = \frac{1}{U} \cdot \left[\int_0^\infty S_w(f) \cdot df \right]^{1/2}$$

The energy cascade

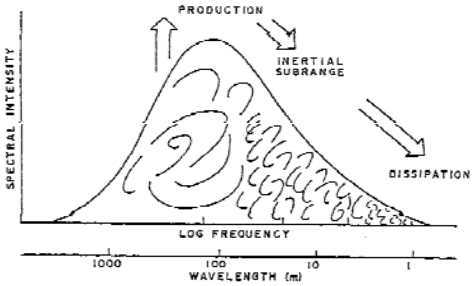
Within turbulence energy is transferred from large size vortices to small size vortices

Small size vortices are responsible for energy dissipation

Kolmogorov hypotheses

The motion of small size vortices is governed by the energy flux and by viscosity, therefore it is independent of boundary conditions; the flow is said to be isotropic

In the inertial subrange energy dissipation depends only on the energy flux, and is independent of viscosity



The energy cascade

For the second Kolmogorov hypothesis it is possible to write

$$F\,[S(K), K, \varepsilon \;\; = 0$$

where K=2π/λ=2πf/U is the wave number and $S(K)$ is the energy associated with the vortices of wave number K (spectrum of turbulence) and ε is the energy flux

The physical dimensions of the quantities in the equation above are

$$S = \left[L^3 T^{-2}\right] \quad ; \quad K = \left[L^{-1}\right] \quad ; \quad \varepsilon = \left[L^2 T^{-3}\right]$$

Dimensional analysis provides the following equation

$$S_u(K) = E(K) = c \cdot \varepsilon^{2/3} \cdot K^{-5/3}$$

with c experimentally found to be 0.5

The energy cascade

In the inertial subrange the energy dissipation is given as

$$\varepsilon = \frac{\tau_o}{\rho}\frac{dU}{dz}$$

Upon substitution of the logarithmic profile one obtains

$$\boxed{\frac{fS_u(z,f)}{u_*^2} = 0.26 \cdot \left(\frac{fz}{U(z)}\right)^{-2/3}}$$

Therefore the Kolmogorov bring that in the inertial subrange the spectrum of the longitudinal component of turbulence is proportional to $f^{-2/3}$

Spectra of the longitudinal component of turbulence

Th. Von Karman (1944)

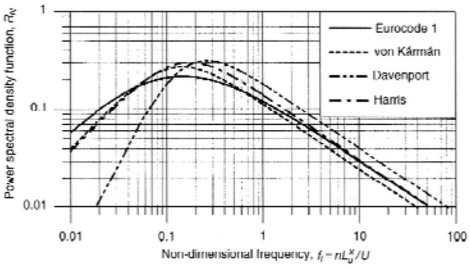
$$\frac{fS_u(z,f)}{u_*^2} = 4\beta\frac{fL_u^x}{U}\cdot\frac{1}{\left[1+70.8\left(\frac{fL_u^x}{U}\right)^2\right]^{5/6}}$$

J.C. Kaimal (1972)

$$\frac{fS_u(z,f)}{u_*^2} = 200\frac{fz}{U(z)}\cdot\frac{1}{\left[1+50\frac{fz}{U(z)}\right]^{5/3}}$$

A.G. Davenport (1961)

$$\frac{fS_u(z,f)}{u_*^2} = 4\left(\frac{1200\,f}{U_{10}}\right)^2\cdot\frac{1}{\left[1+\left(\frac{1200\,f}{U_{10}}\right)^2\right]^{4/3}}$$



Spectra of the lateral and vertical components of turbulence

J.C. Kaimal (1972)

$$\frac{fS_v(z,f)}{u_*^2} = 15\frac{fz}{U(z)}\cdot\frac{1}{\left[1+9.5\frac{fz}{U(z)}\right]^{5/3}}$$

J.L. Lumley, H.A. Panofsky (1964)

$$\frac{fS_w(z,f)}{u_*^2} = 3.36\frac{fz}{U(z)}\cdot\frac{1}{1+10\left(\frac{\square fz}{U(z)}\right)^{5/3}}$$

Spatial organisation of turbulence

Gaining knowledge of the cross spectra of turbulence is non an easy task, for this reason the imaginary part of the cross spectra is neglected, and the real part is given as the product of the local spectrum and a coherence function

For example, for the longitudinal component the cross spectrum for points in a plane orthogonal to the wind direction is

$$S_u(y_1,y_2,z_1,z_2,f) = \sqrt{S_u(y_1,z_1,f)\cdot S_u(y_2,z_2,f)}\cdot\gamma(y_1,y_2,z_1,z_2,f)$$

In case of a homogeneous flow

$$S_u(\Delta y,\Delta z, f) = S_u(f)\cdot\gamma(\Delta y,\Delta z, f)$$

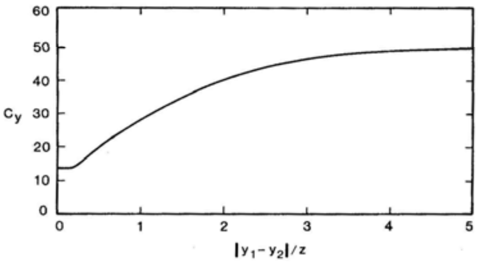
Spatial organisation of turbulence

Coherence decays with distance and frequency; for simplicity it is assumed that the decay rate is the same for distance and frequency and exponential functions are used such as that proposed by Davenport

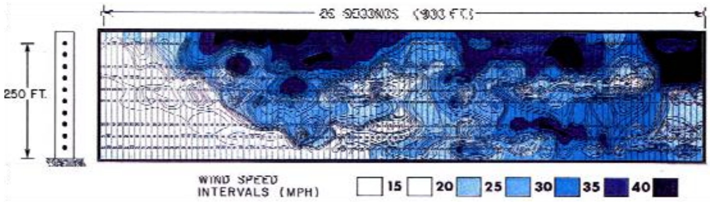
$$\gamma(y_1,y_2,z_1,z_2,f) = \exp\left[-2f\frac{\sqrt{C_z^2(z_1-z_2)^2+C_y^2(y_1-y_2)^2}}{U(z_1)+U(z_2)}\right]$$

in which C_y and C_z are the lateral and vertical decay coefficients

The decay coefficients are functions of the terrain roughness, but for engineering applications it is acceptable to take the constant values C_y=16 and C_z=10



Integral scales of turbulence



Turbulence is seen as a superposition of vortices of different sizes dragged by the mean flow (Taylor hypothesis of "frozen turbulence")

The average sizes of these vortices are characterised through the 9 integral scales of turbulence

$$L_u^x = \frac{1}{\tilde{u}^2}\int_0^\infty R_u(x,0)\cdot dx \qquad L_v^x = \frac{1}{\tilde{v}^2}\int_0^\infty R_v(x,0)\cdot dx \qquad L_w^x = \frac{1}{\tilde{w}^2}\int_0^\infty R_w(x,0)\cdot dx$$

$$L_u^y = \frac{1}{\tilde{u}^2}\int_0^\infty R_u(y,0)\cdot dy \qquad L_v^y = \frac{1}{\tilde{v}^2}\int_0^\infty R_v(y,0)\cdot dy \qquad L_w^y = \frac{1}{\tilde{w}^2}\int_0^\infty R_w(y,0)\cdot dy$$

$$I_u^z = \frac{1}{\tilde{u}^2}\int_0^\infty R_u(z,0)\cdot dz \qquad I_v^z = \frac{1}{\tilde{v}^2}\int_0^\infty R_v(z,0)\cdot dz \qquad I_w^z = \frac{1}{\tilde{w}^2}\int_0^\infty R_w(z,0)\cdot dz$$

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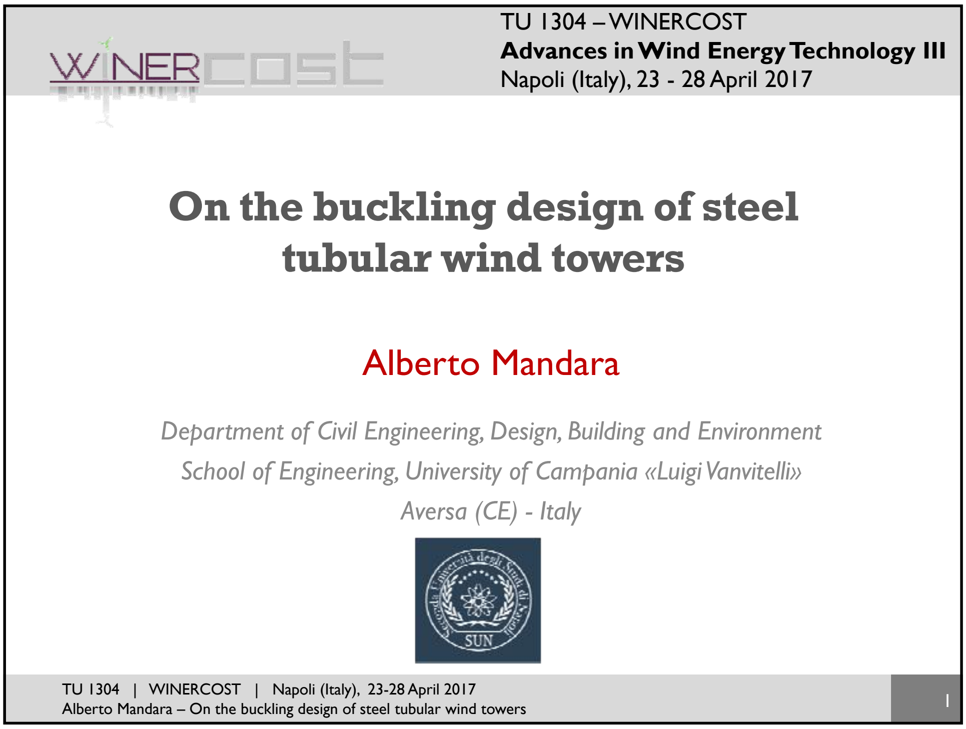
Advances in Wind Energy Technology III

On the buckling design of steel tubular wind towers

Alberto Mandara



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Advances in Wind Energy Technology III
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Alberto Mandara

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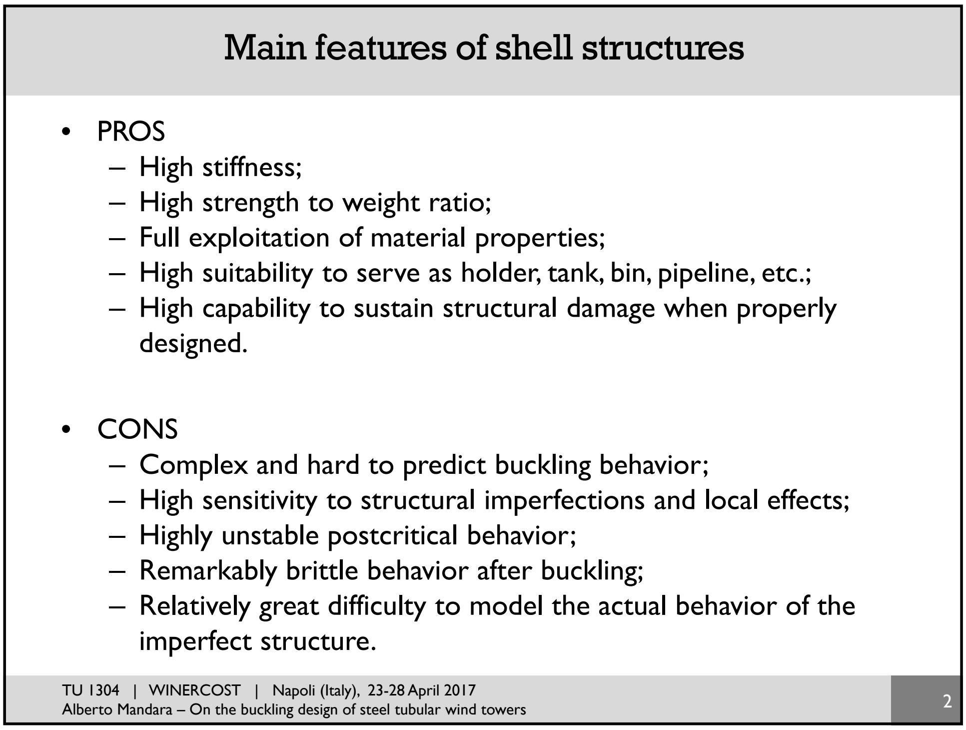
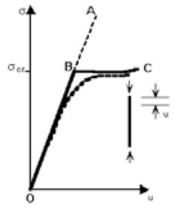


Main features of shell structures

- PROS
  - High stiffness;
  - High strength to weight ratio;
  - Full exploitation of material properties;
  - High suitability to serve as holder, tank, bin, pipeline, etc.;
  - High capability to sustain structural damage when properly designed.

- CONS
  - Complex and hard to predict buckling behavior;
  - High sensitivity to structural imperfections and local effects;
  - Highly unstable postcritical behavior;
  - Remarkably brittle behavior after buckling;
  - Relatively great difficulty to model the actual behavior of the imperfect structure.

Importance of imperfections



Strut buckling

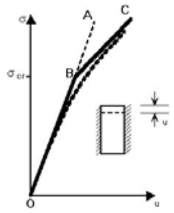
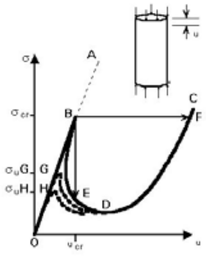
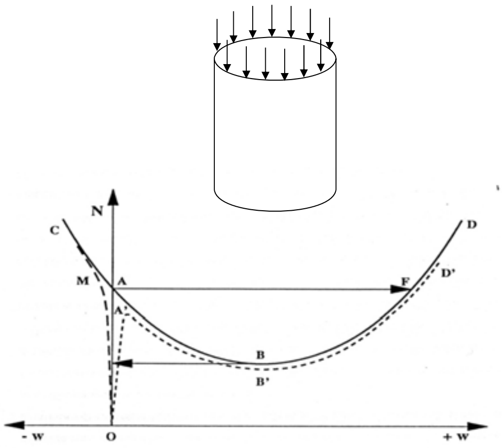


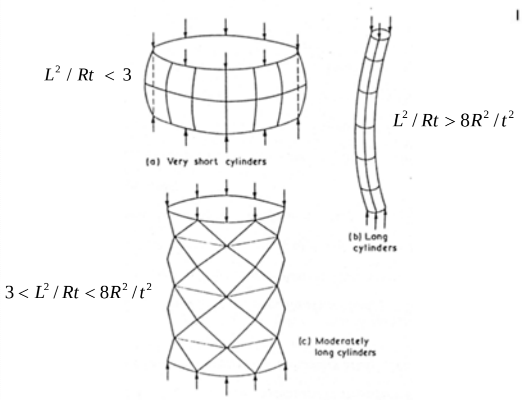
Plate buckling

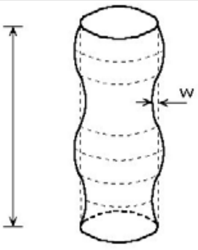


Shell buckling

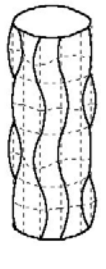


Unstiffened cylinders under axial compression

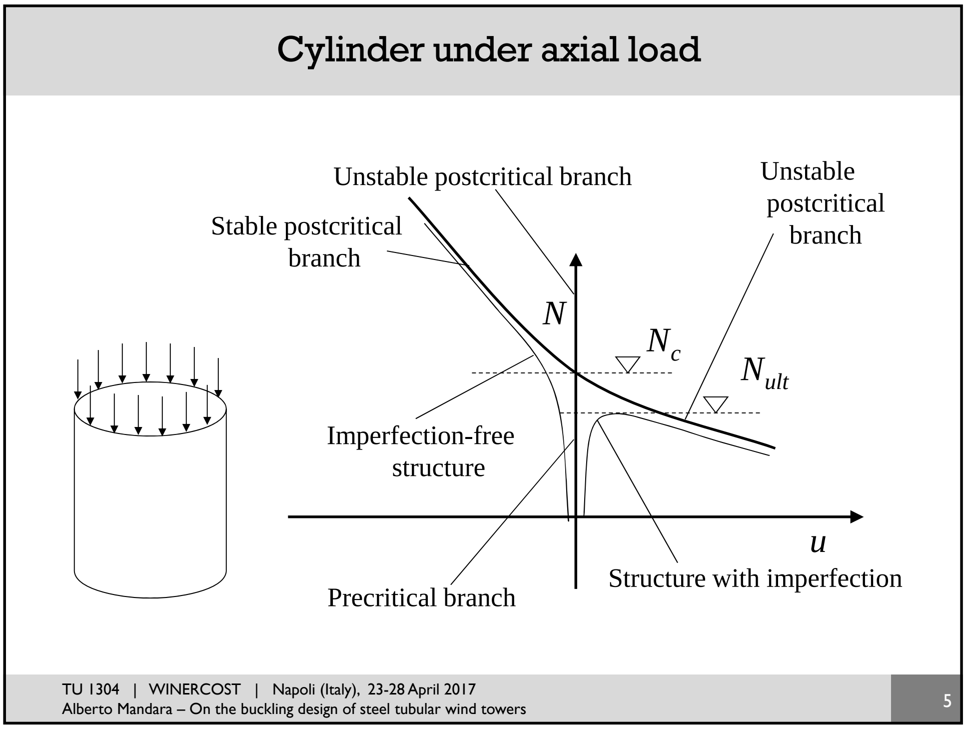




(a) Axisymmetric



(b) Asymmetric



Cylinder under axial load

Unstable postcritical branch

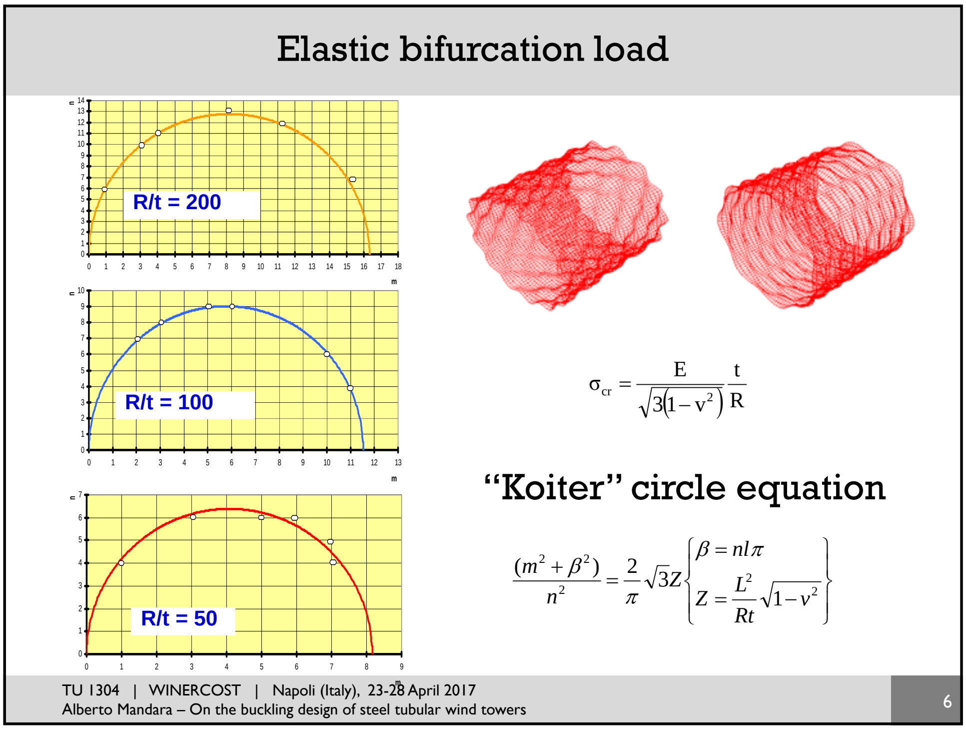
Unstable postcritical branch

Stable postcritical branch

Imperfection-free structure

Structure with imperfection

Precritical branch



Elastic bifurcation load

R/t = 200

R/t = 100

R/t = 50

$$\sigma_{cr} = \frac{E}{\sqrt{3\left(1-v^2\right)}}\frac{t}{R}$$

"Koiter" circle equation

$$\frac{(m^2+\beta^2)}{n^2} = \frac{2}{\pi}\sqrt{3}Z\left\{\begin{array}{l}\beta = nl\pi \\ Z = \frac{L^2}{Rt}\sqrt{1-v^2}\end{array}\right\}$$

Synopsis of buckling loads and critical modes for load cases under consideration in EC3 and EC9

Cylinders under axial load

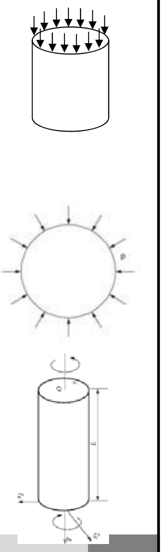
Elastic bifurcation load	Number of circumferential (*n*) and axial (*m*) waves at elastic buckling	Plasticity reduction factor	Number of axial (*m*) waves at plastic buckling
$\sigma_{cr,el} = \frac{E}{\sqrt{3(1-\nu^2)}} \frac{t}{R}$	$\frac{(m^2 + (nL/\pi R)^2)^2}{m^2} = \frac{2}{\pi} \frac{L^2}{Rt} \sqrt{3(1-\nu^2)}$	$\eta = \frac{\sqrt{E_t E_s}}{E}$	$m = \frac{L}{\pi} \sqrt{\frac{12}{Rt\sqrt{6 + 9\frac{E_t}{E_s} + \frac{E_e}{E_t}}}}$

Cylinders under external pressure

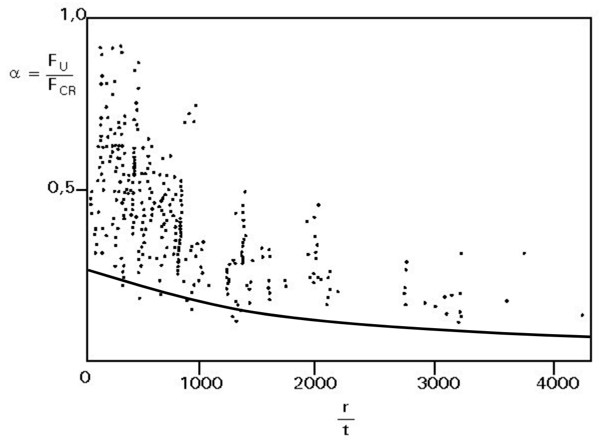
Elastic bifurcation load	Number of circumferential (*n*) and axial (*m*) waves at elastic buckling	Plasticity reduction factor
$p_{cr,el} = \frac{Et/R}{n^2 - 1 + \frac{1}{2}\left(\frac{\pi R}{L}\right)^2} \left[\frac{1}{\left(\left(\frac{nL}{\pi R}\right)^2 + 1\right)^2} + \frac{t^2}{12R^2(1-\nu^2)} \left(n^2 - 1 + \left(\frac{\pi R}{L}\right)^2 \right)^2 \right]$	$n = 2.7 \left(\frac{R}{L}\right)^{0.5} \left(\frac{R}{t}\right)^{0.25}$	$\eta = \frac{1}{4}\frac{E_s}{E} + \frac{3}{4}\frac{E_t}{E}$

Cylinders under torsion

Elastic bifurcation load	Number of circumferential (*n*) and axial (*m*) waves at elastic buckling	Plasticity reduction factor
$\tau_{cr} = 0.75\, E \left(\frac{R}{L}\right)^{1/2} \left(\frac{t}{R}\right)^{5/4}$	$n = 4.2\,(0.75)^{1/8} \sqrt{\frac{R}{L}} \sqrt[4]{\frac{R}{t}}$	$\eta = \frac{E_s}{E}$



Lower Bound Design Philosophy



Imperfection sensitivity analysis

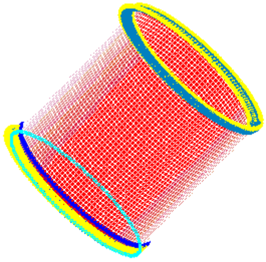
R/t	*R* [mm]	*t* [mm]	*L* [mm]	*L/R*
Cylinders under axial compression				
200	1000	5	2000	2
100	1000	10	2000	2
50	1000	20	2000	2
25	1000	40	2000	2
12.5	1000	80	2000	2
Cylinders under external pressure				
200	1000	5	4000	4
100	1000	10	4000	4
50	1000	20	4000	4
200	1000	5	2000	2
100	1000	10	2000	2
50	1000	20	2000	2
200	1000	5	1000	1
100	1000	10	1000	1
50	1000	20	1000	1
Cylinders under torsion				
200	1000	5	4000	4
100	1000	10	4000	4
50	1000	20	4000	4
200	1000	5	2000	2
100	1000	10	2000	2
50	1000	20	2000	2

Geometric data of analysed cylinders (*R* mean radius, *t* wall thickness, *L* overall length)

Parametric analysis: Shell geometrical data and material features

	$f_{0.2}$ [MPa]	$n_{R.0.}$
Strong hardening alloys	100	10
Weak hardening alloys (Heat-treated alloys)	200	20
	300	30

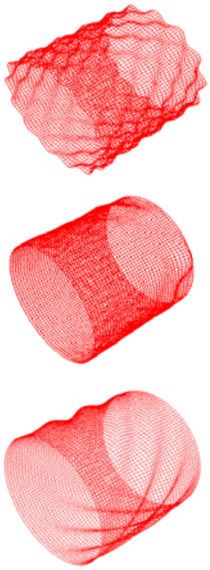
Mechanical features of alloys under consideration.

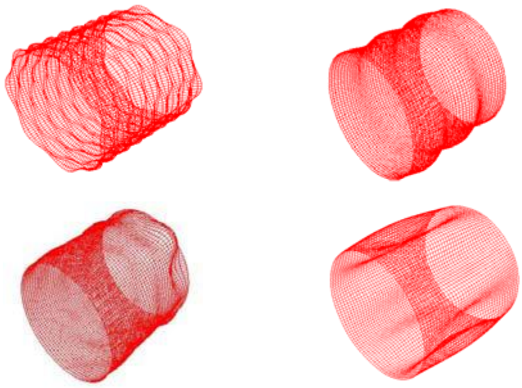


The ABAQUS model

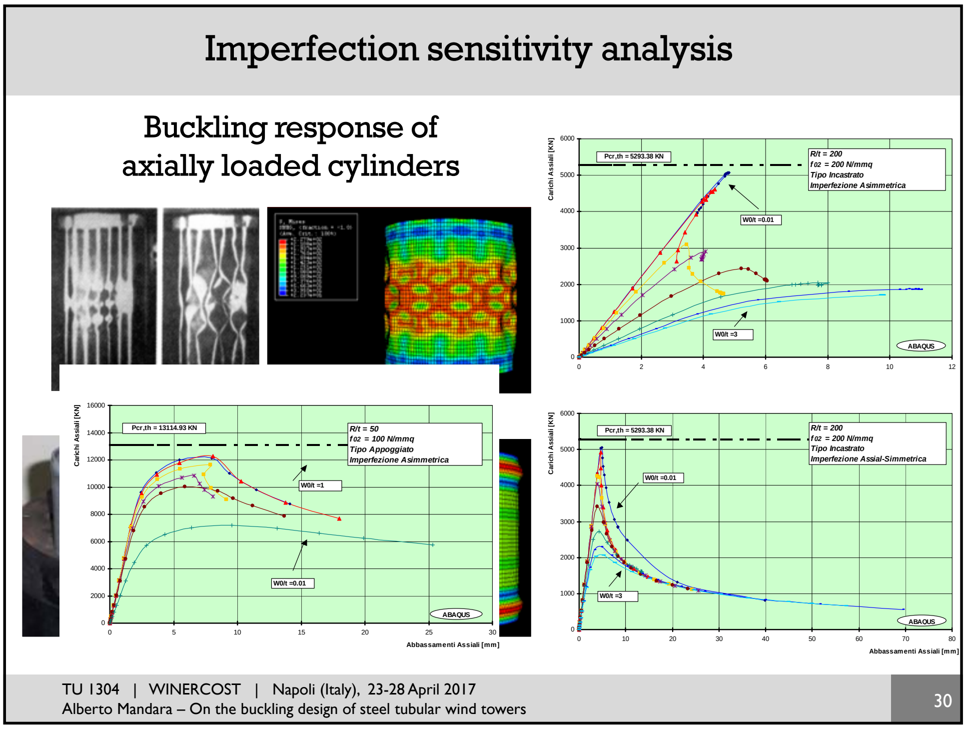
Imperfection sensitivity analysis

The imperfection model





$$w=\sum w_0 e^{-k_{1x}(x-x_o)^2}\cos\left[k_{2x}\pi\frac{(x-x_o)}{L}\right]e^{-k_{1y}(y-y_o)^2}\cos\left[k_{2y}\pi\frac{(y-y_o)}{R}\right]$$



Imperfection sensitivity analysis

Buckling response of axially loaded cylinders

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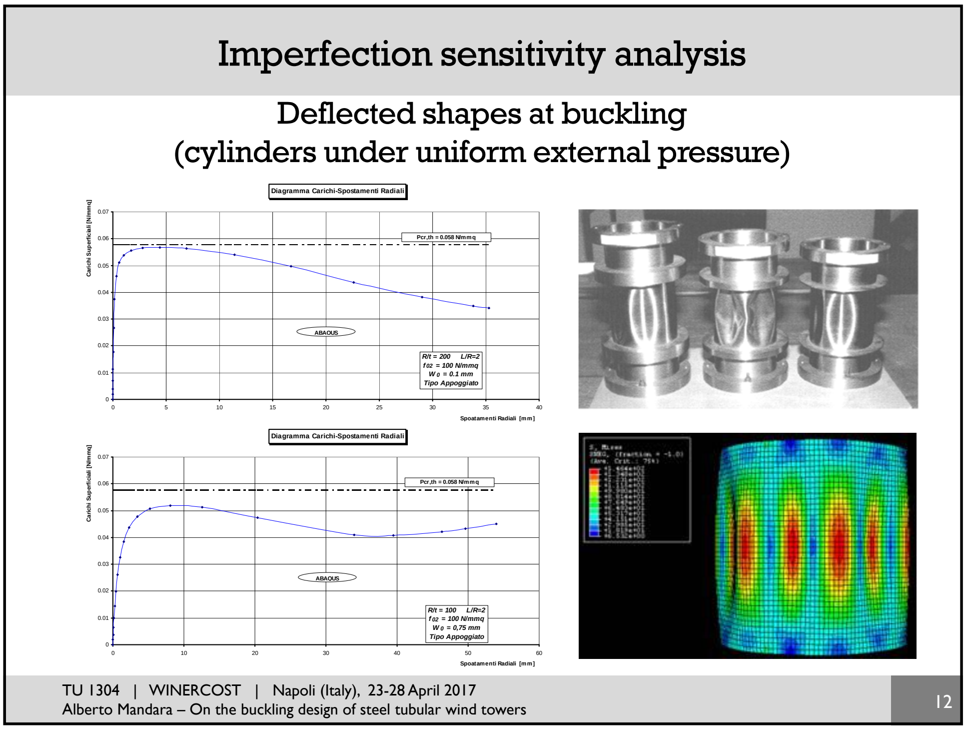

Imperfection sensitivity analysis

Deflected shapes at buckling (cylinders under uniform external pressure)

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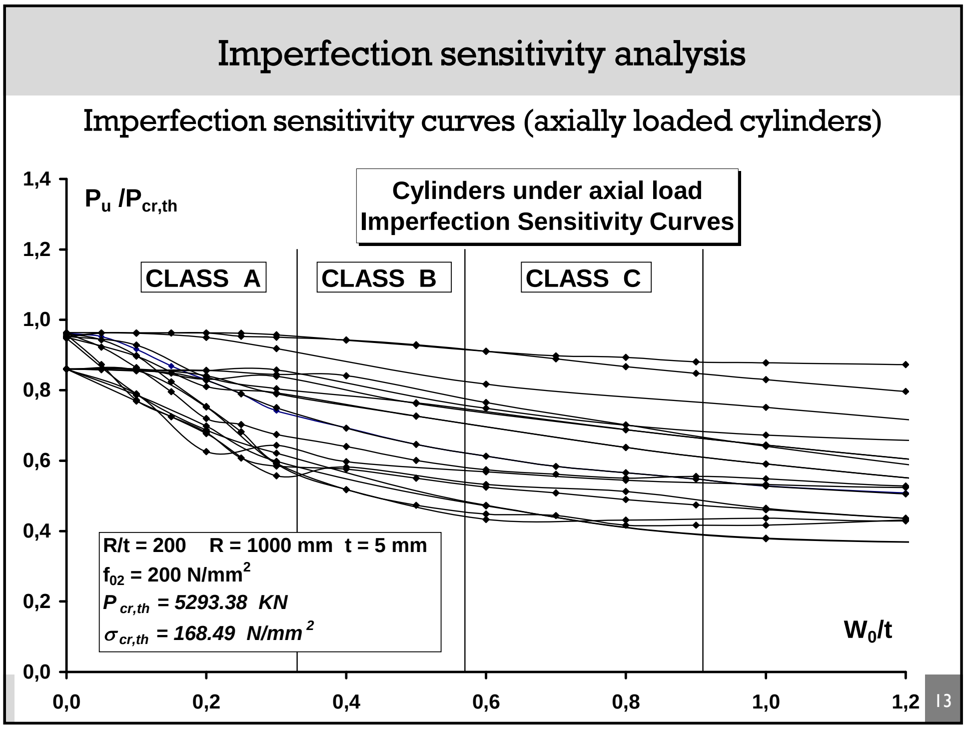
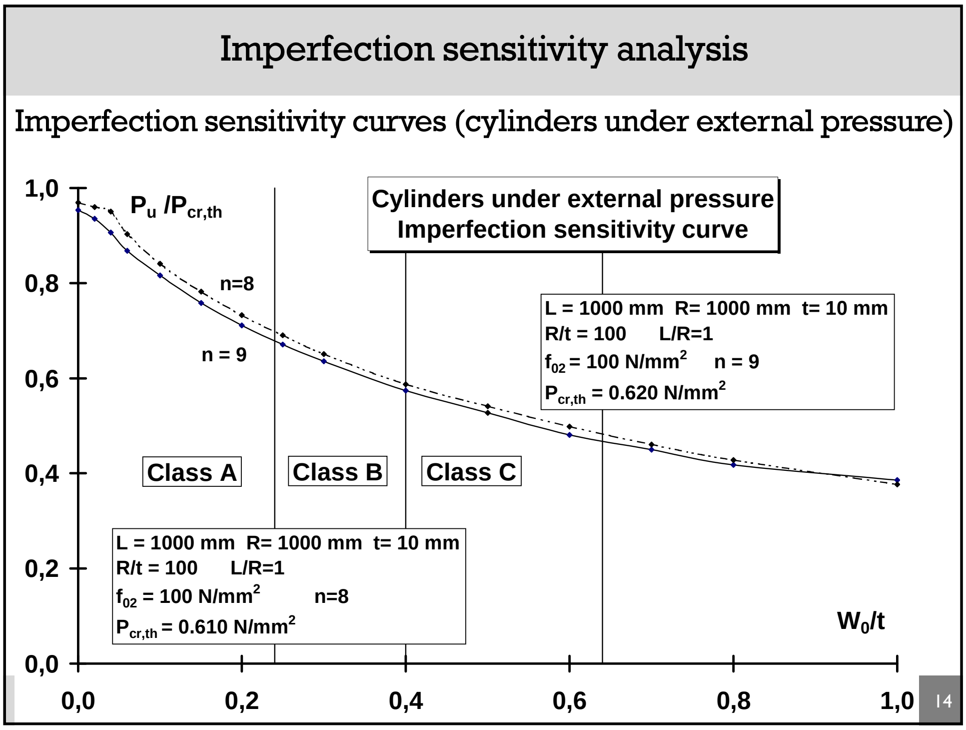


Imperfection sensitivity analysis

Imperfection sensitivity curves (axially loaded cylinders)

Cylinders under axial load
Imperfection Sensitivity Curves

R/t = 200 R = 1000 mm t = 5 mm
f_{02} = 200 N/mm^2
$P_{cr,th}$ = 5293.38 KN
$\sigma_{cr,th}$ = 168.49 N/mm^2



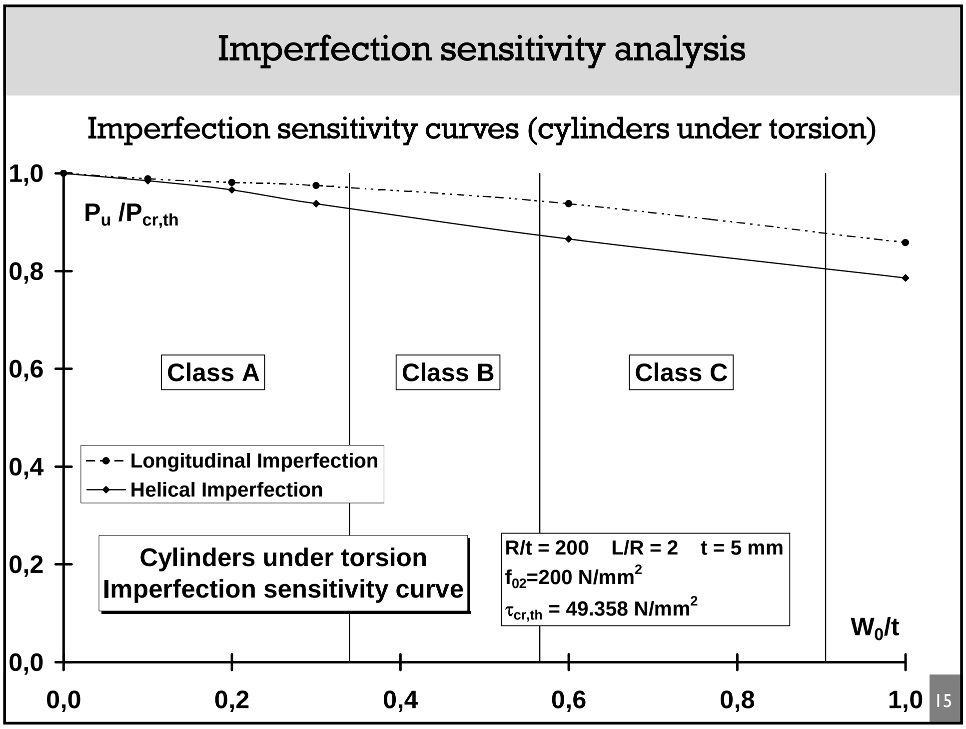
Imperfection sensitivity analysis

Imperfection sensitivity curves (cylinders under external pressure)

Cylinders under external pressure
Imperfection sensitivity curve

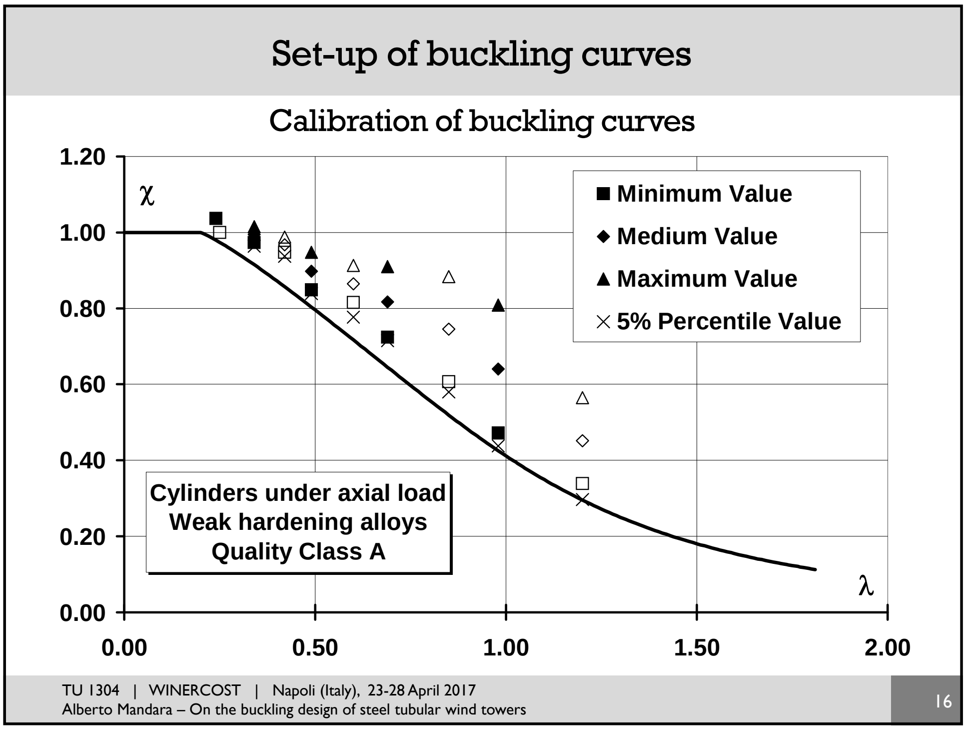
L = 1000 mm R= 1000 mm t= 10 mm
R/t = 100 L/R=1
f_{02} = 100 N/mm^2 n = 9
$P_{cr,th}$ = 0.620 N/mm^2

L = 1000 mm R= 1000 mm t= 10 mm
R/t = 100 L/R=1
f_{02} = 100 N/mm^2 n=8
$P_{cr,th}$ = 0.610 N/mm^2



Imperfection sensitivity analysis

Imperfection sensitivity curves (cylinders under torsion)

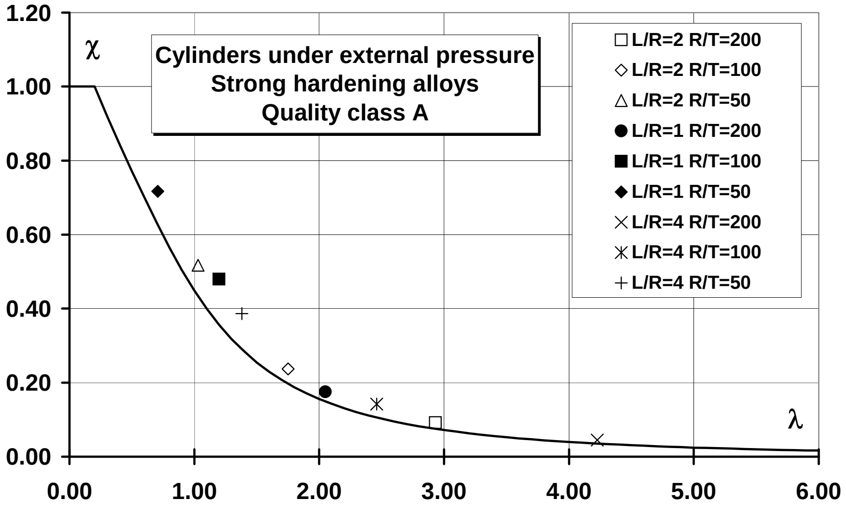


Set-up of buckling curves

Calibration of buckling curves

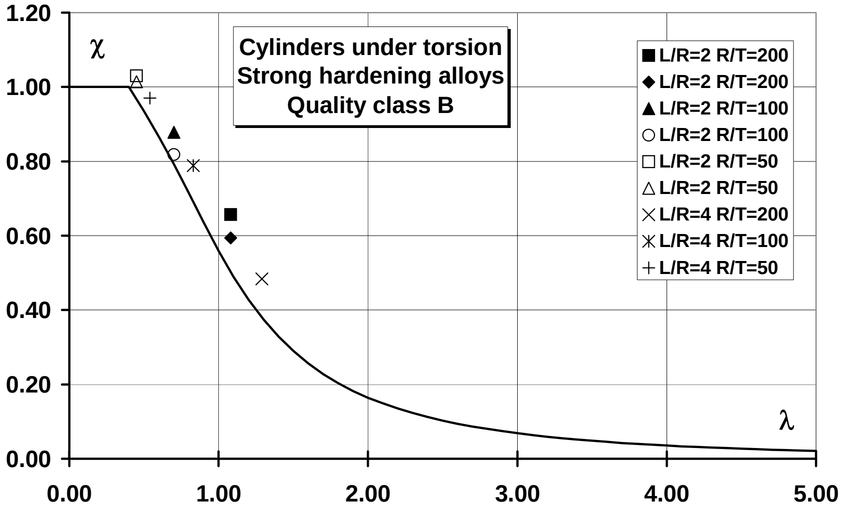
Set-up of buckling curves

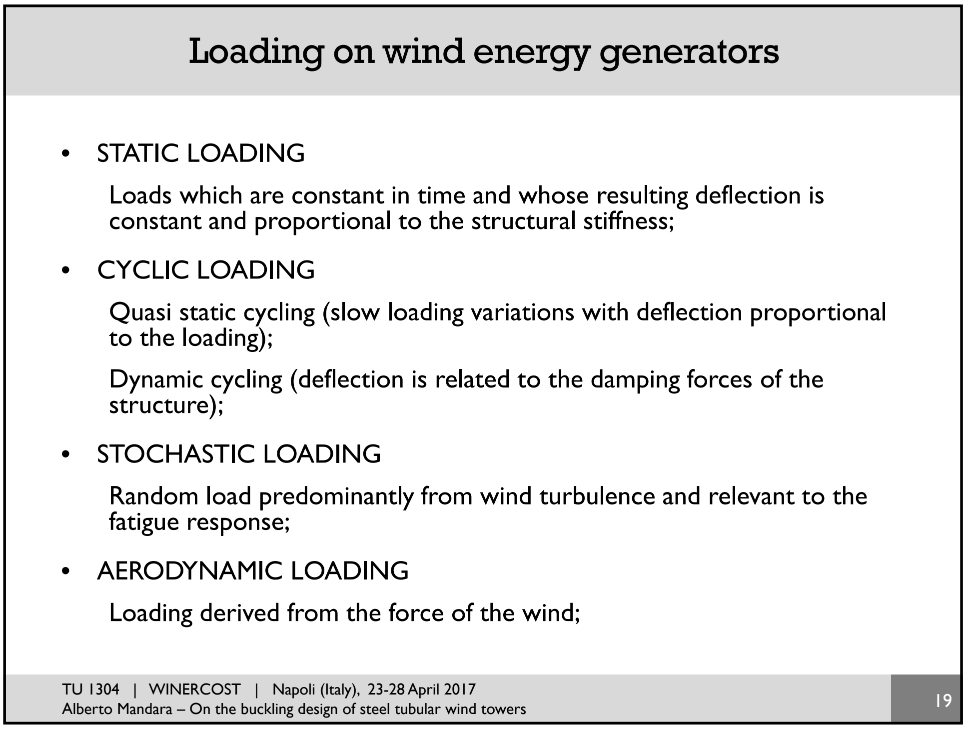
Calibration of buckling curves



Set-up of buckling curves

Calibration of buckling curves





Loading on wind energy generators

- STATIC LOADING

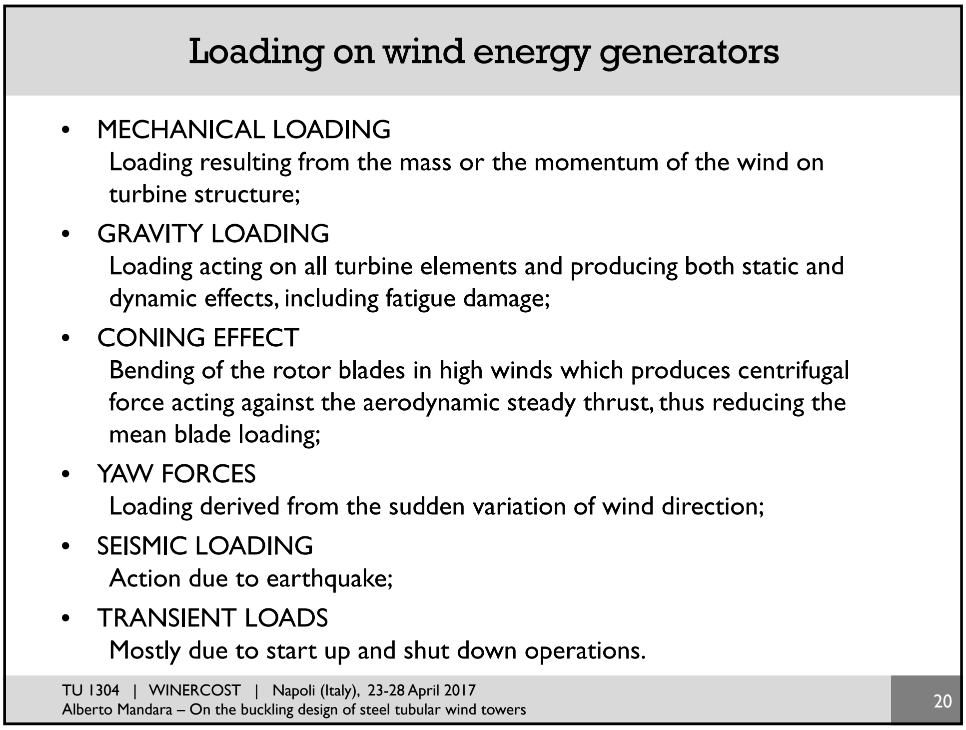
  Loads which are constant in time and whose resulting deflection is constant and proportional to the structural stiffness;
- CYCLIC LOADING

  Quasi static cycling (slow loading variations with deflection proportional to the loading);

  Dynamic cycling (deflection is related to the damping forces of the structure);
- STOCHASTIC LOADING

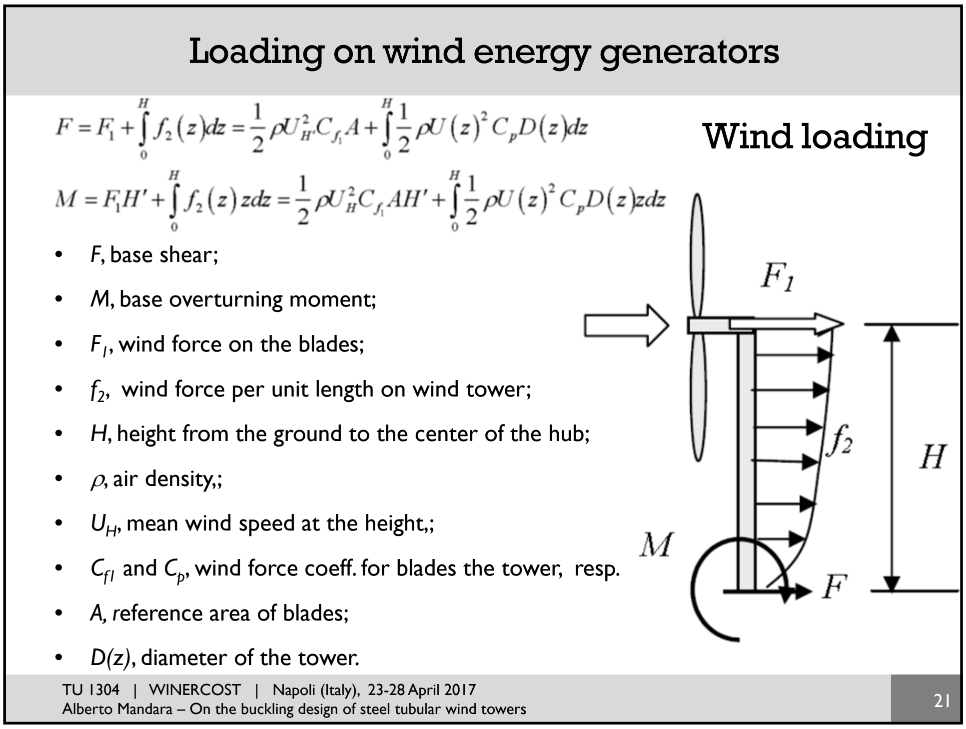
  Random load predominantly from wind turbulence and relevant to the fatigue response;
- AERODYNAMIC LOADING

  Loading derived from the force of the wind;



Loading on wind energy generators

- MECHANICAL LOADING
  Loading resulting from the mass or the momentum of the wind on turbine structure;
- GRAVITY LOADING
  Loading acting on all turbine elements and producing both static and dynamic effects, including fatigue damage;
- CONING EFFECT
  Bending of the rotor blades in high winds which produces centrifugal force acting against the aerodynamic steady thrust, thus reducing the mean blade loading;
- YAW FORCES
  Loading derived from the sudden variation of wind direction;
- SEISMIC LOADING
  Action due to earthquake;
- TRANSIENT LOADS
  Mostly due to start up and shut down operations.



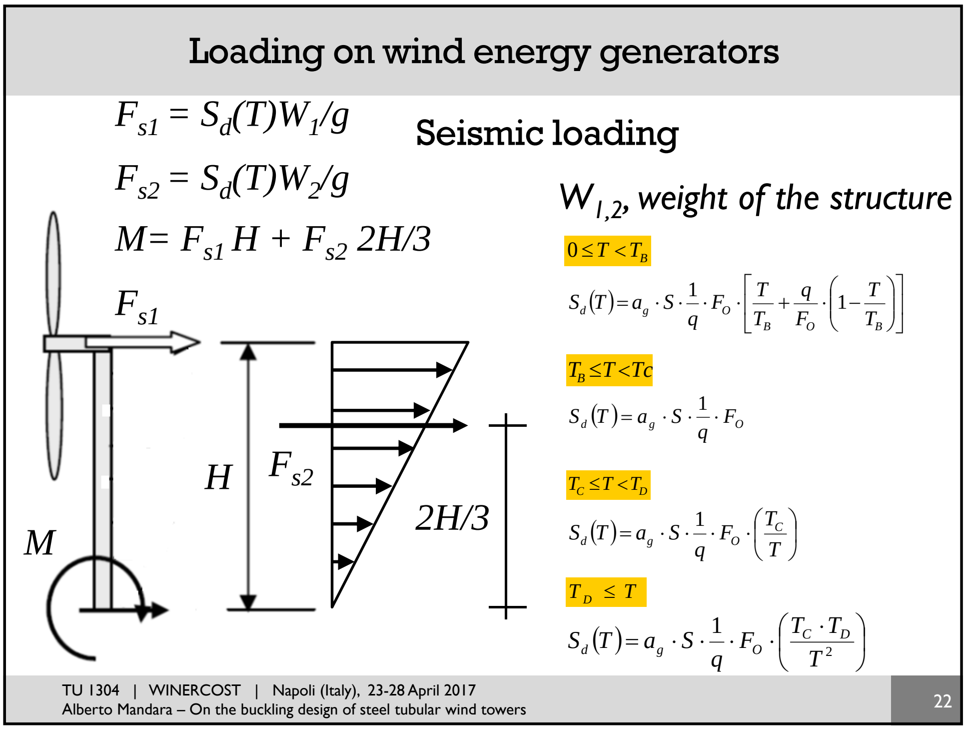
Loading on wind energy generators

$$F = F_1 + \int_0^H f_2(z)dz = \frac{1}{2}\rho U_{H'}^2 C_{f_1} A + \int_0^H \frac{1}{2}\rho U(z)^2 C_p D(z)dz$$

$$M = F_1 H' + \int_0^H f_2(z)zdz = \frac{1}{2}\rho U_H^2 C_{f_1} AH' + \int_0^H \frac{1}{2}\rho U(z)^2 C_p D(z)zdz$$

Wind loading

- *F*, base shear;
- *M*, base overturning moment;
- F_l, wind force on the blades;
- f_2, wind force per unit length on wind tower;
- *H*, height from the ground to the center of the hub;
- ρ, air density,;
- U_H, mean wind speed at the height,;
- C_{fl} and C_p, wind force coeff. for blades the tower, resp.
- *A*, reference area of blades;
- *D(z)*, diameter of the tower.



Loading on wind energy generators

$F_{s1} = S_d(T)W_1/g$

$F_{s2} = S_d(T)W_2/g$

$M = F_{s1} H + F_{s2} 2H/3$

Seismic loading

$W_{1,2}$, weight of the structure

$0 \le T < T_B$

$$S_d(T) = a_g \cdot S \cdot \frac{1}{q} \cdot F_O \cdot \left[\frac{T}{T_B} + \frac{q}{F_O} \cdot \left(1 - \frac{T}{T_B}\right)\right]$$

$T_B \le T < Tc$

$$S_d(T) = a_g \cdot S \cdot \frac{1}{q} \cdot F_O$$

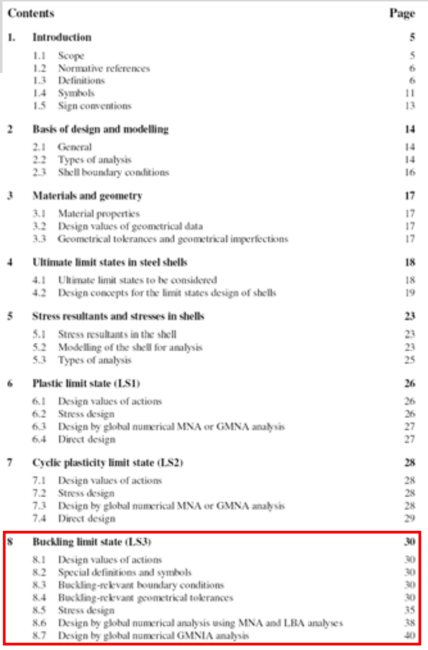
$T_C \le T < T_D$

$$S_d(T) = a_g \cdot S \cdot \frac{1}{q} \cdot F_O \cdot \left(\frac{T_C}{T}\right)$$

$T_D \le T$

$$S_d(T) = a_g \cdot S \cdot \frac{1}{q} \cdot F_O \cdot \left(\frac{T_C \cdot T_D}{T^2}\right)$$

The european codification on shells



Contents **Page**

1. Introduction **5**
1.1 Scope 5
1.2 Normative references 6
1.3 Definitions 6
1.4 Symbols 11
1.5 Sign conventions 13

2 Basis of design and modelling **14**
2.1 General 14
2.2 Types of analysis 14
2.3 Shell boundary conditions 16

3 Materials and geometry **17**
3.1 Material properties 17
3.2 Design values of geometrical data 17
3.3 Geometrical tolerances and geometrical imperfections 17

4 Ultimate limit states in steel shells **18**
4.1 Ultimate limit states to be considered 18
4.2 Design concepts for the limit states design of shells 19

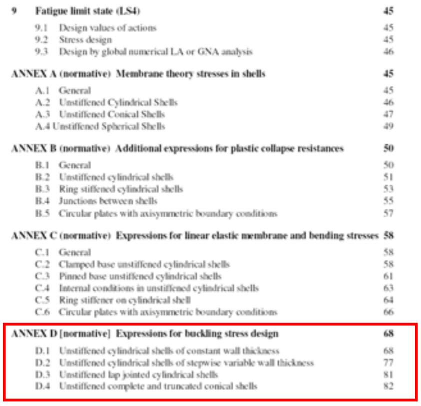
5 Stress resultants and stresses in shells **23**
5.1 Stress resultants in the shell 23
5.2 Modelling of the shell for analysis 23
5.3 Types of analysis 25

6 Plastic limit state (LS1) **26**
6.1 Design values of actions 26
6.2 Stress design 26
6.3 Design by global numerical MNA or GMNA analysis 27
6.4 Direct design 27

7 Cyclic plasticity limit state (LS2) **28**
7.1 Design values of actions 28
7.2 Stress design 28
7.3 Design by global numerical MNA or GMNA analysis 28
7.4 Direct design 29

8 Buckling limit state (LS3) **30**
8.1 Design values of actions 30
8.2 Special definitions and symbols 30
8.3 Buckling-relevant boundary conditions 30
8.4 Buckling-relevant geometrical tolerances 30
8.5 Stress design 35
8.6 Design by global numerical analysis using MNA and LBA analyses 38
8.7 Design by global numerical GMNIA analysis 40

The EN1993-1-6 – Steel Shells



9 Fatigue limit state (LS4) **45**
9.1 Design values of actions 45
9.2 Stress design 45
9.3 Design by global numerical LA or GNA analysis 46

ANNEX A (normative) Membrane theory stresses in shells **45**
A.1 General 45
A.2 Unstiffened Cylindrical Shells 46
A.3 Unstiffened Conical Shells 47
A.4 Unstiffened Spherical Shells 49

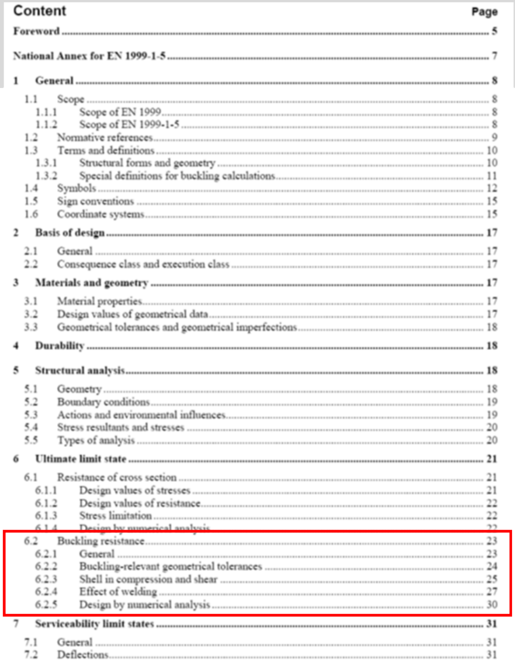
ANNEX B (normative) Additional expressions for plastic collapse resistances **50**
B.1 General 50
B.2 Unstiffened cylindrical shells 51
B.3 Ring stiffened cylindrical shells 53
B.4 Junctions between shells 55
B.5 Circular plates with axisymmetric boundary conditions 57

ANNEX C (normative) Expressions for linear elastic membrane and bending stresses **58**
C.1 General 58
C.2 Clamped base unstiffened cylindrical shells 58
C.3 Pinned base unstiffened cylindrical shells 61
C.4 Internal conditions in unstiffened cylindrical shells 63
C.5 Ring stiffener on cylindrical shell 64
C.6 Circular plates with axisymmetric boundary conditions 66

ANNEX D [normative] Expressions for buckling stress design **68**
D.1 Unstiffened cylindrical shells of constant wall thickness 68
D.2 Unstiffened cylindrical shells of stepwise variable wall thickness 77
D.3 Unstiffened lap jointed cylindrical shells 81
D.4 Unstiffened complete and truncated conical shells 82

The european codification on shells

The EN1999-1-5 Aluminium shells – General part



Content **Page**

Foreword **5**

National Annex for EN 1999-1-5 .... **7**

1 General **8**
1.1 Scope 8
1.1.1 Scope of EN 1999 8
1.1.2 Scope of EN 1999-1-5 8
1.2 Normative references 9
1.3 Terms and definitions 10
1.3.1 Structural forms and geometry 10
1.3.2 Special definitions for buckling calculations 11
1.4 Symbols 12
1.5 Sign conventions 15
1.6 Coordinate systems 15

2 Basis of design **17**
2.1 General 17
2.2 Consequence class and execution class 17

3 Materials and geometry **17**
3.1 Material properties 17
3.2 Design values of geometrical data 17
3.3 Geometrical tolerances and geometrical imperfections 18

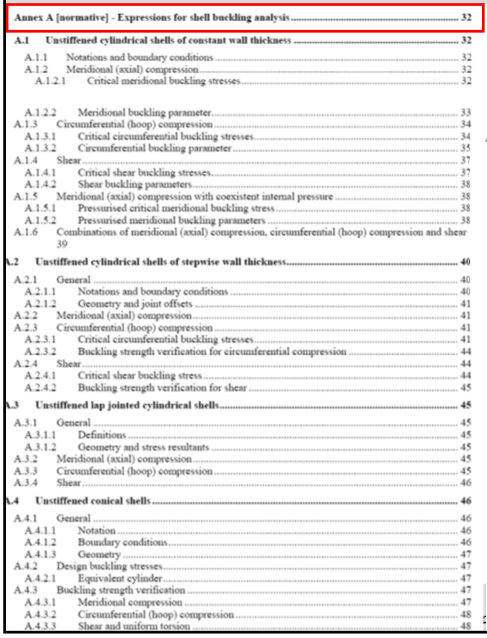
4 Durability **18**

5 Structural analysis **18**
5.1 Geometry 18
5.2 Boundary conditions 19
5.3 Actions and environmental influences 19
5.4 Stress resultants and stresses 20
5.5 Types of analysis 20

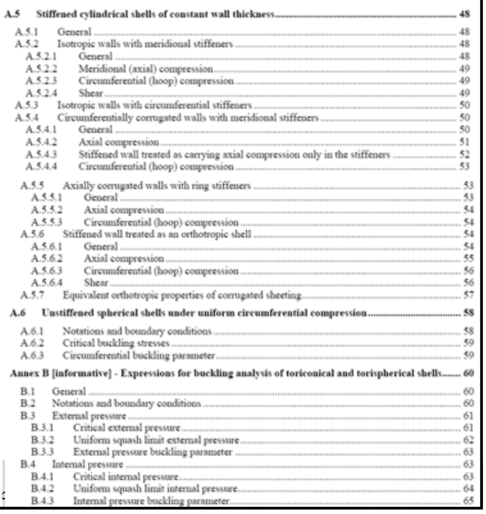
6 Ultimate limit state **21**
6.1 Resistance of cross section 21
6.1.1 Design values of stresses 21
6.1.2 Design values of resistance 22
6.1.3 Stress limitation 22
6.1.4 Design by numerical analysis 22
6.2 Buckling resistance 23
6.2.1 General 23
6.2.2 Buckling-relevant geometrical tolerances 24
6.2.3 Shell in compression and shear 25
6.2.4 Effect of welding 27
6.2.5 Design by numerical analysis 30

7 Serviceability limit states **31**
7.1 General 31
7.2 Deflections 31

The european codification on shells

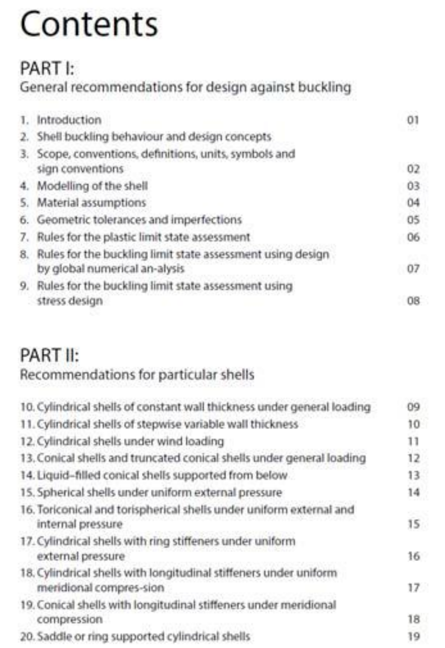


The EN1999-1-5 Aluminium Shells Annexes



The ECCS Recommendations

Buckling of Steel Shells
European Design
Recommendations
5th Edition

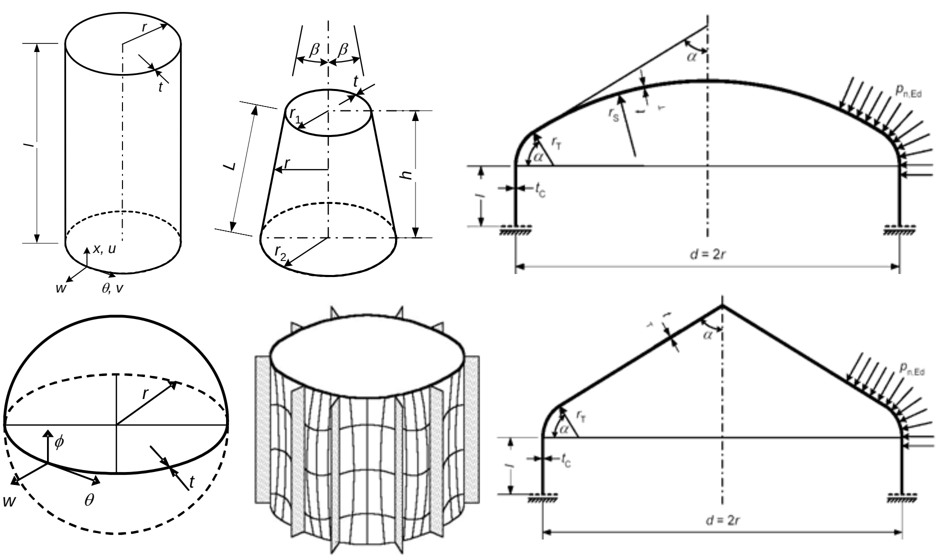


Contents

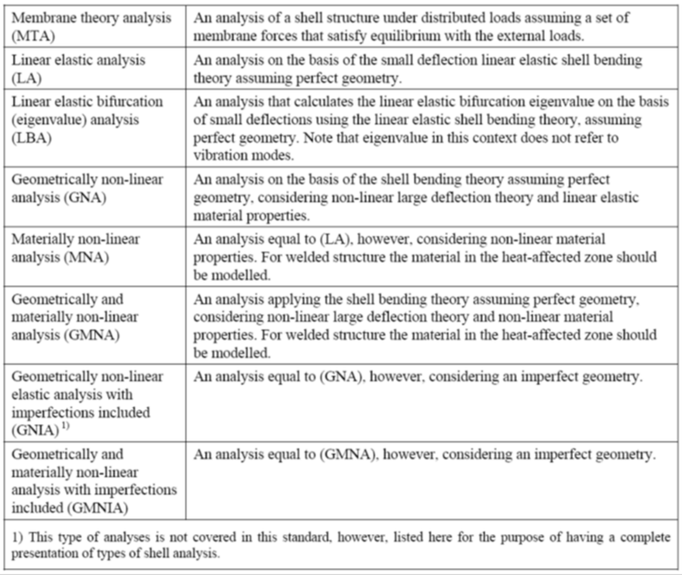
PART I:
General recommendations for design against buckling

PART II:
Recommendations for particular shells

Shell configurations in EN1993-1-6 and EN1999-1-5



Types of shell analysis enabled in EN1993-1-6 and EN1999-1-5



Membrane theory analysis (MTA)	An analysis of a shell structure under distributed loads assuming a set of membrane forces that satisfy equilibrium with the external loads.
Linear elastic analysis (LA)	An analysis on the basis of the small deflection linear elastic shell bending theory assuming perfect geometry.
Linear elastic bifurcation (eigenvalue) analysis (LBA)	An analysis that calculates the linear elastic bifurcation eigenvalue on the basis of small deflections using the linear elastic shell bending theory, assuming perfect geometry. Note that eigenvalue in this context does not refer to vibration modes.
Geometrically non-linear analysis (GNA)	An analysis on the basis of the shell bending theory assuming perfect geometry, considering non-linear large deflection theory and linear elastic material properties.
Materially non-linear analysis (MNA)	An analysis equal to (LA), however, considering non-linear material properties. For welded structure the material in the heat-affected zone should be modelled.
Geometrically and materially non-linear analysis (GMNA)	An analysis applying the shell bending theory assuming perfect geometry, considering non-linear large deflection theory and non-linear material properties. For welded structure the material in the heat-affected zone should be modelled.
Geometrically non-linear elastic analysis with imperfections included (GNIA) [1]	An analysis equal to (GNA), however, considering an imperfect geometry.
Geometrically and materially non-linear analysis with imperfections included (GMNIA)	An analysis equal to (GMNA), however, considering an imperfect geometry.

1) This type of analyses is not covered in this standard, however, listed here for the purpose of having a complete presentation of types of shell analysis.

Shell buckling – EC3 formulation

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

$$\chi = 1 \Leftrightarrow \lambda \le \lambda_0$$

$$\chi = 1 - \beta \left(\frac{\lambda - \lambda_0}{\lambda_p - \lambda_0} \right)^\eta \Leftrightarrow \lambda_0 < \lambda \le \lambda_p$$

$$\chi = \frac{\alpha}{\lambda^2} \Leftrightarrow \lambda_p \le \lambda$$

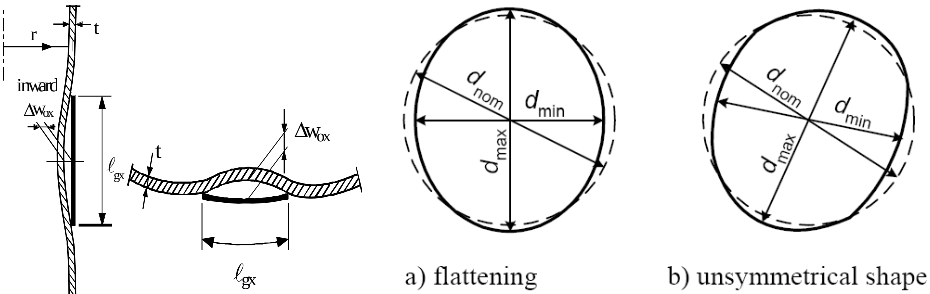
$$\lambda = \sqrt{\frac{f_{yk}}{\sigma_{xRc}}}$$

$$\lambda_p = \sqrt{\frac{\alpha}{1-\beta}}$$

- $\sigma_{x,Rk}$, $\sigma_{\theta,Rk}$, $\tau_{x\theta,Rk}$, characteristic buckling stress;
- χ, buckling factor;
- λ, relative shell slenderness;
- λ_0, squash limit relative shell slenderness;
- λ_p, plastic limit relative shell slenderness;
- β, η, parameters of buckling curve;
- α, elastic imperfection reduction factor;
- f_{yk}, characteristic steel yield stress.

Set-up of buckling curves

Shell buckling – fabrication tolerance classes in EC3



a) flattening

b) unsymmetrical shape

$$U_r = \frac{d_{max} - d_{min}}{d_{nom}} \qquad \frac{w_0}{\ell_{gx}} \le U_{0\,max} \Leftrightarrow \frac{w_o}{t} \le \frac{U_{0\,max}\,\ell_{gx}}{t}$$

$U_{o\,max}$ Dimple tolerance parameter

$\ell_{gx} = 4\sqrt{R\,t}$ Gauge length

Fabrication tolerance quality class	Description
Class A	Excellent
Class B	High
Class C	Normal

Set-up of buckling curves

Expressions of buckling factors according to EC3

	Axial (meridional) load	External pressure and torsion (shear)
λ_0	0.20	0.40
β	0.60	0.60
η	1.00	1.00

Fabrication tolerance quality class	Description	Axial (meridional) load		External pressure (α_θ) and torsion (shear) (α_τ)
		Q	α_x	α_θ or α_τ
Class A	Excellent	40	$\alpha_x = \frac{0.62}{1+1.91\left(1/Q\sqrt{r/t}\right)^{1.44}}$	0,75
Class B	High	25		0,65
Class C	Normal	16		0,50

Set-up of buckling curves

Shell buckling – EC9 formulation

Load cases

- axial compression
- external pressure
- torsion

Unstiffened shells

$$\sigma_{x,\mathrm{Rd}} = \alpha_x \rho_{x,\mathrm{w}} \chi_{x,\mathrm{perf}} \frac{f_\mathrm{o}}{\gamma_\mathrm{M1}}$$

$$\sigma_{\theta,\mathrm{Rd}} = \alpha_\theta \rho_{\theta,\mathrm{w}} \chi_{\theta,\mathrm{perf}} \frac{f_\mathrm{o}}{\gamma_\mathrm{M1}}$$

$$\tau_\mathrm{Rd} = \alpha_\tau \rho_{\tau,\mathrm{w}} \chi_{\tau,\mathrm{perf}} \frac{f_\mathrm{o}}{\sqrt{3}\,\gamma_\mathrm{M1}}$$

Stiffened shells

$$n_{x,\mathrm{Rd}} = \alpha_{n,x} \chi_{x,\mathrm{perf}} \frac{n_{\mathrm{x,Rk}}}{\gamma_\mathrm{M1}}$$

$$p_{n,\mathrm{Rd}} = \alpha_{p,\theta} \chi_{\theta,\mathrm{perf}} \frac{p_{n,\mathrm{Rk}}}{\gamma_\mathrm{M1}}$$

Set-up of buckling curves

Shell buckling – EC9 formulation

$$\chi_{i,\mathrm{perf}} = \frac{1}{\phi_i + \sqrt{\phi_i^2 - \overline{\lambda}_i^2}} \quad \text{but} \quad \chi_{i,\mathrm{perf}} \leq 1{,}00$$

$$\overline{\lambda}_x = \sqrt{\frac{f_o}{\sigma_{x,\mathrm{cr}}}}$$

$$\overline{\lambda}_\theta = \sqrt{\frac{f_o}{\sigma_{\theta,\mathrm{cr}}}}$$

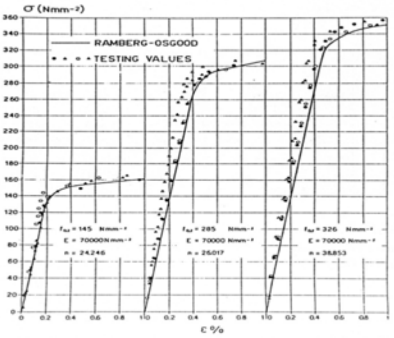
with:

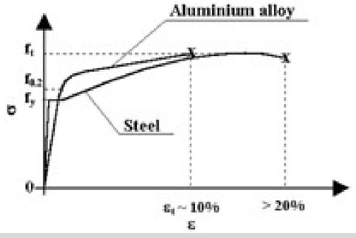
$$\phi_i = 0{,}5\left(1 + \mu_i(\overline{\lambda}_i - \overline{\lambda}_{i,0}) + \overline{\lambda}_i^2\right)$$

$$\overline{\lambda}_\tau = \sqrt{\frac{f_o}{\sqrt{3}\tau_{\mathrm{cr}}}}$$

Material buckling class	Axial (meridional) load		External pressure		Shear (torsion)	
	$\lambda_{x,0}$	μ_x	$\lambda_{\theta,0}$	μ_θ	$\lambda_{\tau,0}$	μ_τ
A (Weak hardening alloys)	0.2	0.35	0.3	0.55	0.5	0.3
B (Strong hardening alloys)	0.1	0.2	0.2	0.7	0.4	0.4

Elasto-plastic bifurcation load





$$\sigma_{cr,pl} = \eta \sigma_{cr,el}$$

$$\eta = \frac{\sqrt{E_t E_s}}{E}$$

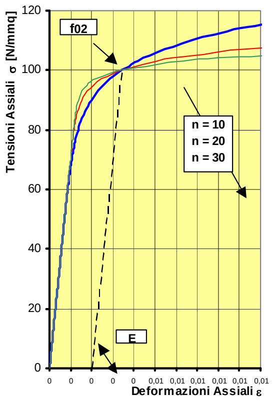
"Ramberg-Osgood" law:

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{f_{02}}\right)^n$$

$$E_t = \frac{d\sigma}{d\varepsilon} = \frac{E}{1 + \frac{0.002nE}{f_{02}}\left(\frac{\sigma}{f_{02}}\right)^{n-1}}$$

$$E_s = \frac{\sigma}{\varepsilon} = \frac{E}{1 + \frac{0.002E}{f_{02}}\left(\frac{\sigma}{f_{02}}\right)^{n-1}}$$

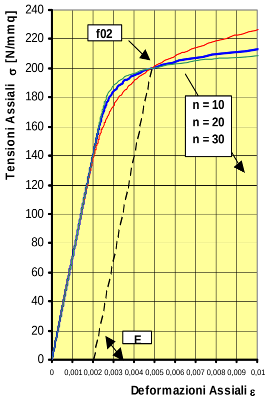
“Ramberg-Osgood” law



High hardening alloy

$f_{0.2}$ =100 N/mm^2

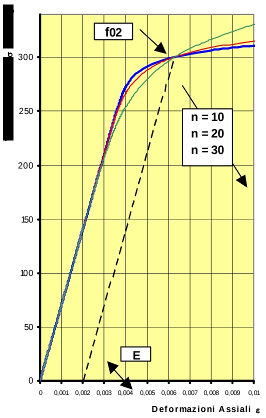
n = 10



Heat treatment alloy

$f_{0.2}$ =200 N/mm^2

n = 20



High strength alloy

$f_{0.2}$ =300 N/mm^2

n = 30

Set-up of buckling curves

Shell buckling – fabrication tolerance classes according to EC9

Fabrication tolerance quality class	Diameter range		
	$d \leq 0{,}5$ m	$0{,}5$ m $< d < 1{,}25$ m	$1{,}25$ m $\geq d$
Class 4	0,010	$0{,}005 + 0{,}0067(1{,}25 - d)$	0,005
Class 3	0,014	$0{,}007 + 0{,}0090(1{,}25 - d)$	0,007
Class 2	0,020	$0{,}010 + 0{,}0133(1{,}25 - d)$	0,010
Class 1	0,030	$0{,}015 + 0{,}0200(1{,}25 - d)$	0,015

Fabrication tolerance quality class	Axial (meridional) load		External pressure (α_θ) and torsion (α_τ)	
	Q	α_x	α_{ref}	α_θ or α_τ
Class 1	**16**	$\alpha_x = \frac{0.62}{1+1.91\left(1/Q\sqrt{r/t}\right)^{1.44}}$	**0,50**	$\alpha_{\theta,\tau} = \frac{1}{1+0{,}2\left(1-\alpha_{ref}\right)\left(\bar{\lambda}-\bar{\lambda}_0\right)/\alpha_{ref}^2}$
Class 2	**25**		**0,65**	
Class 3	**40**		**0,75**	
Class 4	**50-60**		**-**	

Buckling curves - Comparison EC3 vs EC9

EN1993-1-6

$$\chi = 1 \Leftrightarrow \lambda \le \lambda_0$$

$$\chi = 1 - \beta\left(\frac{\lambda - \lambda_0}{\lambda_p - \lambda_0}\right)^{\eta} \Leftrightarrow \lambda_0 < \lambda \le \lambda_p$$

$$\chi = \frac{\alpha}{\lambda^2} \Leftrightarrow \lambda_p \le \lambda$$

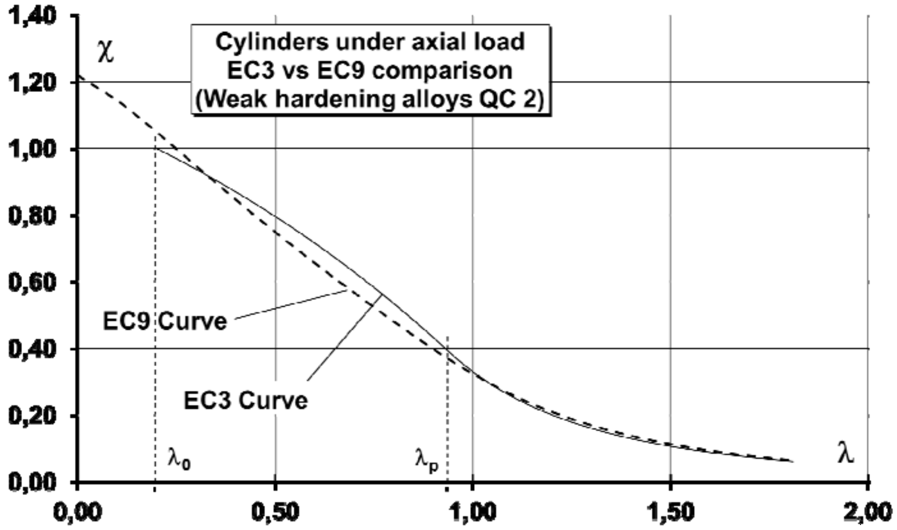
EN1999-1-5

$$\chi = \alpha\chi_{\mathrm{perf}}$$

$$\chi_{\mathrm{perf}} = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}}$$

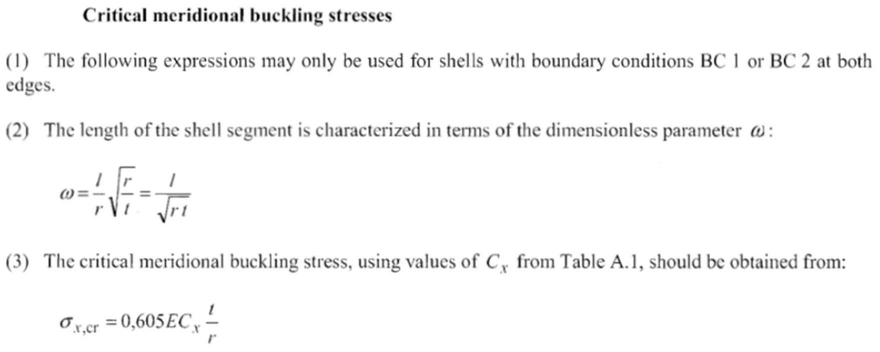
$$\phi = 0.5 \cdot \left[1 + \alpha_0(\lambda - \lambda_0) + \lambda^2\right]$$

Buckling curves - Comparison EC3 vs EC9



Calculation of critical stress according to Eurocodes

Cylinders under axial load



Critical meridional buckling stresses

(1) The following expressions may only be used for shells with boundary conditions BC 1 or BC 2 at both edges.

(2) The length of the shell segment is characterized in terms of the dimensionless parameter ω:

$$\omega = \frac{l}{r}\sqrt{\frac{r}{t}} = \frac{l}{\sqrt{r\,t}}$$

(3) The critical meridional buckling stress, using values of C_x from Table A.1, should be obtained from:

$$\sigma_{x,\mathrm{cr}} = 0{,}605 E C_x \frac{t}{r}$$

Calculation of critical stress according to Eurocodes

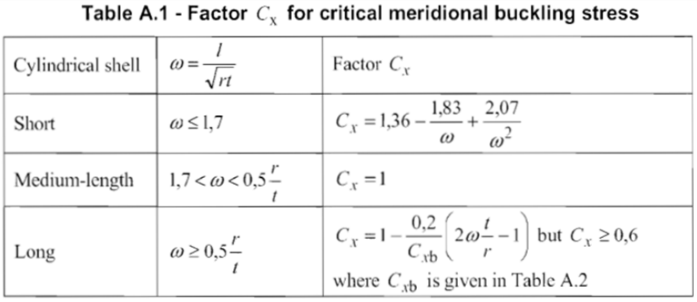


Table A.1 - Factor C_x for critical meridional buckling stress

Cylindrical shell	$\omega = \frac{l}{\sqrt{rt}}$	Factor C_x
Short	$\omega \le 1{,}7$	$C_x = 1{,}36 - \frac{1{,}83}{\omega} + \frac{2{,}07}{\omega^2}$
Medium-length	$1{,}7 < \omega < 0{,}5\frac{r}{t}$	$C_x = 1$
Long	$\omega \ge 0{,}5\frac{r}{t}$	$C_x = 1 - \frac{0{,}2}{C_{x\mathrm{b}}}\left(2\omega\frac{t}{r} - 1\right)$ but $C_x \ge 0{,}6$ where $C_{x\mathrm{b}}$ is given in Table A.2

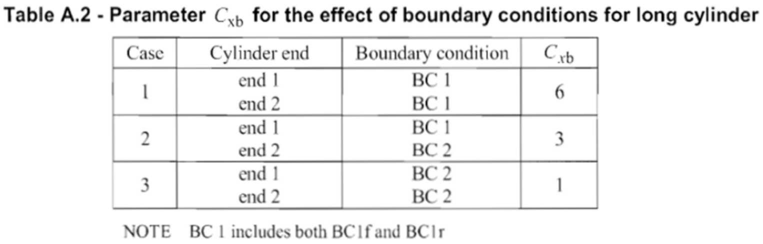


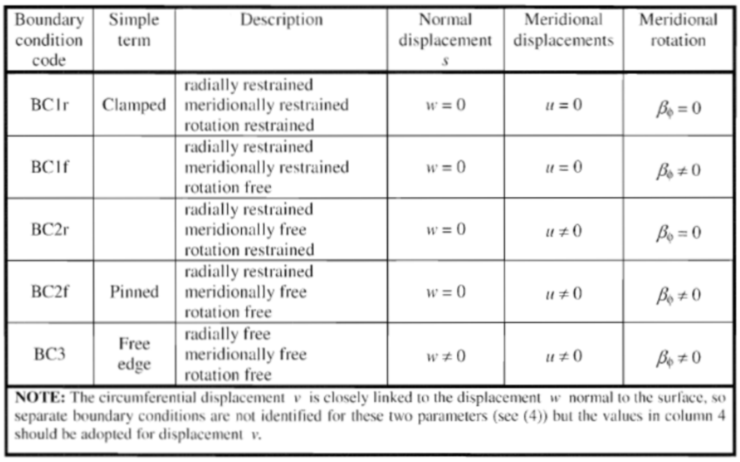
Table A.2 - Parameter $C_{x\mathrm{b}}$ for the effect of boundary conditions for long cylinder

Case	Cylinder end	Boundary condition	$C_{x\mathrm{b}}$
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

NOTE BC 1 includes both BC1f and BC1r

Boundary conditions for shells in EC3 and EC9

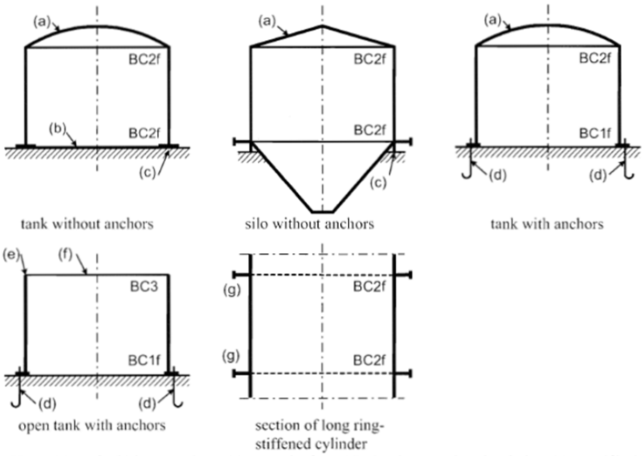
Table 5.1: Boundary conditions for shells



Boundary condition code	Simple term	Description	Normal displacement s	Meridional displacements	Meridional rotation
BC1r	Clamped	radially restrained meridionally restrained rotation restrained	$w = 0$	$u = 0$	$\beta_\phi = 0$
BC1f		radially restrained meridionally restrained rotation free	$w = 0$	$u = 0$	$\beta_\phi \neq 0$
BC2r		radially restrained meridionally free rotation restrained	$w = 0$	$u \neq 0$	$\beta_\phi = 0$
BC2f	Pinned	radially restrained meridionally free rotation free	$w = 0$	$u \neq 0$	$\beta_\phi \neq 0$
BC3	Free edge	radially free meridionally free rotation free	$w \neq 0$	$u \neq 0$	$\beta_\phi \neq 0$

NOTE: The circumferential displacement v is closely linked to the displacement w normal to the surface, so separate boundary conditions are not identified for these two parameters (see (4)) but the values in column 4 should be adopted for displacement v.

Boundary conditions for shells in EC3 and EC9

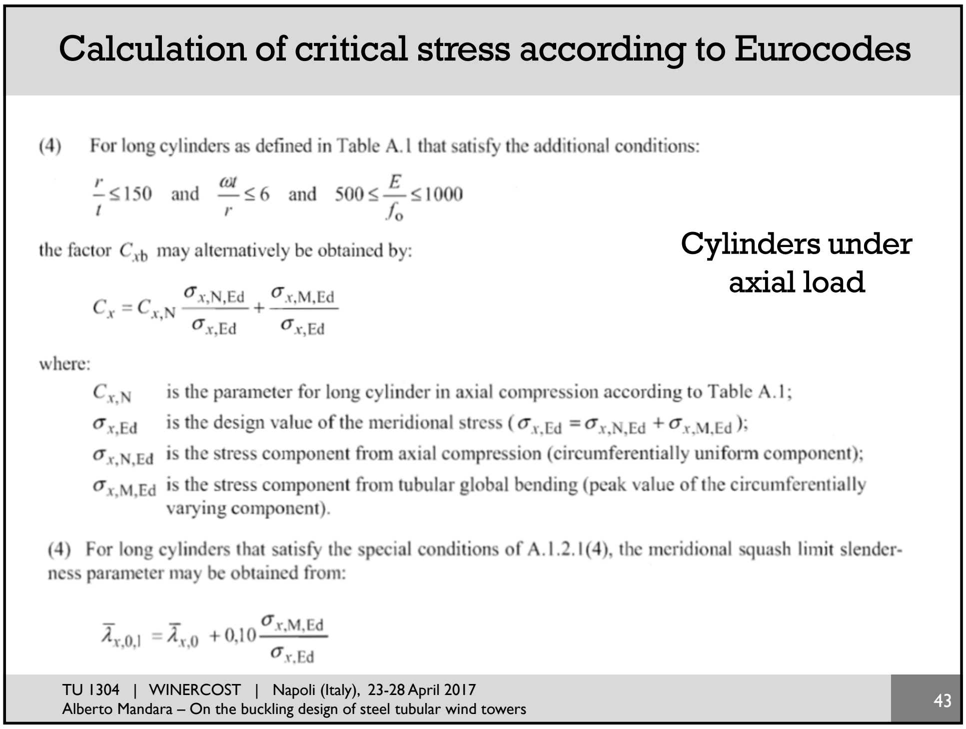


tank without anchors | silo without anchors | tank with anchors

open tank with anchors | section of long ring-stiffened cylinder

Keys: (a) roof, (b) bottom plate, (c) no anchoring, (d) closely spaced anchor bolts, (e) no stiffening ring, (f) free edge, (g) ring stiffener.

Figure 6.1 - Schematic examples of boundary conditions for buckling limit state



Calculation of critical stress according to Eurocodes

Cylinders under axial load

(4) For long cylinders as defined in Table A.1 that satisfy the additional conditions:

$$\frac{r}{t} \leq 150 \quad \text{and} \quad \frac{\omega t}{r} \leq 6 \quad \text{and} \quad 500 \leq \frac{E}{f_o} \leq 1000$$

the factor C_{xb} may alternatively be obtained by:

$$C_x = C_{x,\mathrm{N}} \frac{\sigma_{x,\mathrm{N,Ed}}}{\sigma_{x,\mathrm{Ed}}} + \frac{\sigma_{x,\mathrm{M,Ed}}}{\sigma_{x,\mathrm{Ed}}}$$

where:

$C_{x,\mathrm{N}}$ is the parameter for long cylinder in axial compression according to Table A.1;

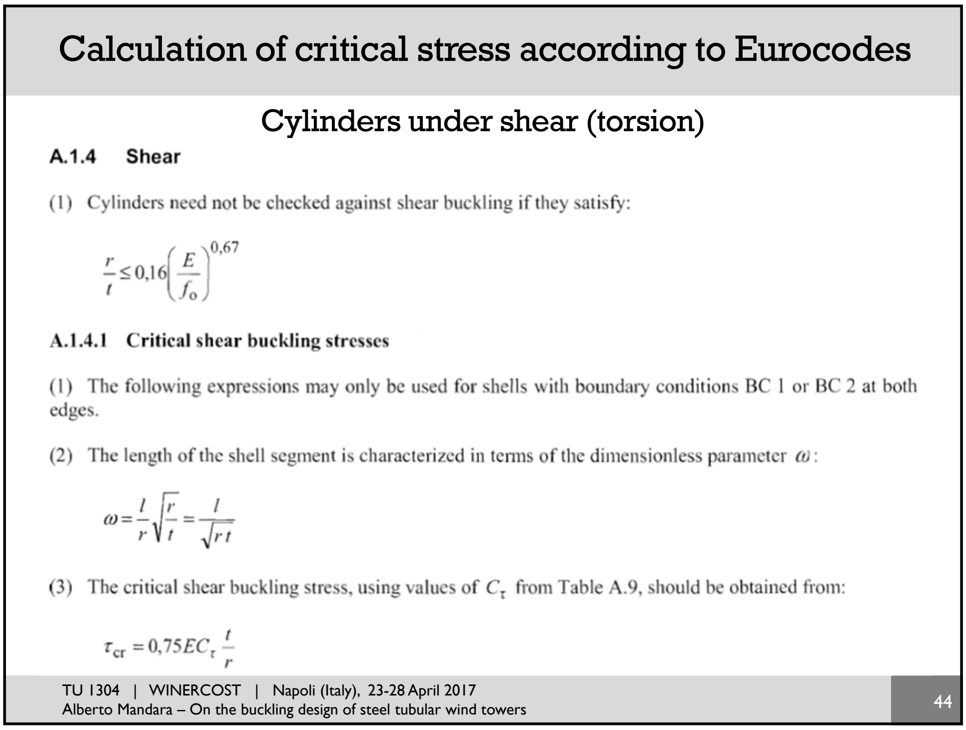
$\sigma_{x,\mathrm{Ed}}$ is the design value of the meridional stress ($\sigma_{x,\mathrm{Ed}} = \sigma_{x,\mathrm{N,Ed}} + \sigma_{x,\mathrm{M,Ed}}$);

$\sigma_{x,\mathrm{N,Ed}}$ is the stress component from axial compression (circumferentially uniform component);

$\sigma_{x,\mathrm{M,Ed}}$ is the stress component from tubular global bending (peak value of the circumferentially varying component).

(4) For long cylinders that satisfy the special conditions of A.1.2.1(4), the meridional squash limit slenderness parameter may be obtained from:

$$\bar{\lambda}_{x,0,1} = \bar{\lambda}_{x,0} + 0{,}10 \frac{\sigma_{x,\mathrm{M,Ed}}}{\sigma_{x,\mathrm{Ed}}}$$



Calculation of critical stress according to Eurocodes

Cylinders under shear (torsion)

A.1.4 Shear

(1) Cylinders need not be checked against shear buckling if they satisfy:

$$\frac{r}{t} \leq 0{,}16 \left(\frac{E}{f_o} \right)^{0{,}67}$$

A.1.4.1 Critical shear buckling stresses

(1) The following expressions may only be used for shells with boundary conditions BC 1 or BC 2 at both edges.

(2) The length of the shell segment is characterized in terms of the dimensionless parameter ω:

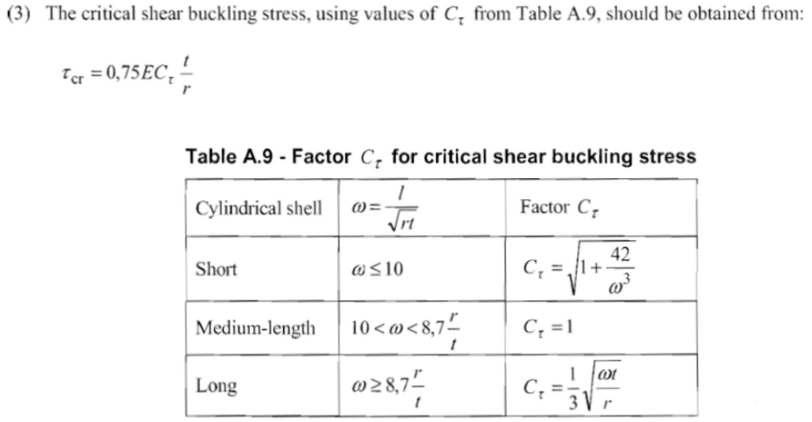
$$\omega = \frac{l}{r} \sqrt{\frac{r}{t}} = \frac{l}{\sqrt{r\,t}}$$

(3) The critical shear buckling stress, using values of C_τ from Table A.9, should be obtained from:

$$\tau_{\mathrm{cr}} = 0{,}75 E C_\tau \frac{t}{r}$$

Calculation of critical stress according to Eurocodes

Cylinders under shear (torsion)



(3) The critical shear buckling stress, using values of C_τ from Table A.9, should be obtained from:

$$\tau_{cr} = 0{,}75 E C_\tau \frac{t}{r}$$

Table A.9 - Factor C_τ for critical shear buckling stress

Cylindrical shell	$\omega = \frac{l}{\sqrt{rt}}$	Factor C_τ
Short	$\omega \leq 10$	$C_\tau = \sqrt{1 + \frac{42}{\omega^3}}$
Medium-length	$10 < \omega < 8{,}7 \frac{r}{t}$	$C_\tau = 1$
Long	$\omega \geq 8{,}7 \frac{r}{t}$	$C_\tau = \frac{1}{3}\sqrt{\frac{\omega t}{r}}$

Buckling checks

1. Calculation of design actions (wind, earthquake, etc.);
2. Calculation of design values of *M* and *N* at the base of the tower as well as in other sections;
3. Calculation of design buckling relevant stresses (σ, τ, etc.);
4. Calculation of buckling strength according to EC3 or EC9
5. Buckling checks using the procedure given in EC3 or EC9.

Buckling checks

- Calculation of design buckling relevant stresses

$$\sigma_{max} = \sigma_N + \sigma_M = \frac{N}{2\pi R t} + \frac{M}{\pi R^2 t}; \qquad \tau = \frac{M_t}{2\pi R^2 t}$$

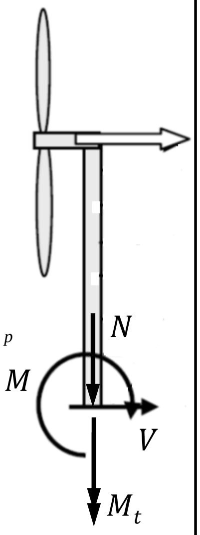
$$\sigma_{x,Rd} = \chi_x f_{yk}/\gamma_m; \quad \tau_{x\vartheta,Rd} = \chi_\tau f_{yk}/(\sqrt{3}\gamma_m)$$

$$\lambda = \sqrt{\frac{f_{yk}}{\sigma_{xRc}}} \qquad \chi = 1 \Leftrightarrow \lambda \le \lambda_0$$

$$\chi = 1 - \beta\left(\frac{\lambda - \lambda_0}{\lambda_p - \lambda_0}\right)^{\eta} \Leftrightarrow \lambda_0 < \lambda \le \lambda_p$$

$$\lambda_p = \sqrt{\frac{\alpha}{1-\beta}} \qquad \chi = \frac{\alpha}{\lambda^2} \Leftrightarrow \lambda_p \le \lambda$$

$$\boxed{\sigma_{max} \le \sigma_{x,Rd}; \quad \tau \le \tau_{x\vartheta,Rd}}$$



Hints for future research

- Buckling of shell structures under dynamic loading;
- Exploitation of existing research on buckling of composite shells;
- Use of additional damping systems;
- Optimization of shell structural design against buckling with special emphasis to WT structures;
- Suggestions for codification advances.

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International Training School, Naples

Advances in Wind Energy Technology III

Structural Response of Wind Turbine Towers to Wind and Earthquakes

Alberto Maria Avossa

TU 1304 – WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

Structural Response of Wind Turbine Towers to Wind and Earthquakes

Alberto Maria Avossa

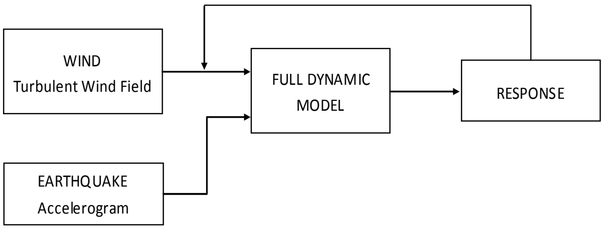
Department of Civil Engineering, Design, Building and Environment
University of Campania "Luigi Vanvitelli"

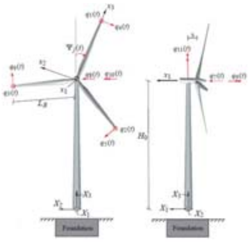
Contents

Motivation

- The spread of the wind energy industry has caused the construction of wind farms in areas prone to high seismic activity.
- The power produced from wind is proportional to the third power of wind speed and to the second power of the rotor radius. Accordingly, to produce more energy one has to increase the rotor diameter and hub height.
- As turbines become larger in size, the structural demand due to the combined effect of wind thrust and seismic loads increase.
- Consequently the analysis of wind turbine operation loading associated to earthquake is of crucial importance for an accurate assessment of their structural safety.
- While there is extensive analytical and empirical information on the seismic vulnerability of buildings and other common structures, similar data are quite poor for wind turbines.
- Within this topic, an approach for multi-risk assessment of land-based HAWT subjected to wind and seismic actions, to be also used within a probabilistic framework, will be presented.

Aeroelastic Model





General equation of motion can be expressed as

$$\boldsymbol{M}_{HAWT}\,\ddot{\boldsymbol{x}} + \boldsymbol{C}_{HAWT}\,\dot{\boldsymbol{x}} + \boldsymbol{K}_{HAWT}\,\boldsymbol{x} = \boldsymbol{F}_{aerodyn}\left(\boldsymbol{U}, \ddot{\boldsymbol{x}}, \dot{\boldsymbol{x}}, \boldsymbol{x}\right) - \boldsymbol{M}_{HAWT}\,\boldsymbol{I}\,\ddot{x}_g(t)$$

$\boldsymbol{M}_{HAWT}$ *Mass matrix*

$\boldsymbol{C}_{HAWT}$ *Damping matrix*

$\boldsymbol{K}_{HAWT}$ *Stiffness matrix*

$\boldsymbol{F}_{aerodyn}\,(\boldsymbol{U}, \ddot{\boldsymbol{x}}, \dot{\boldsymbol{x}}, \boldsymbol{x})$ *Load vector due to the aerodynamic force on the rotor blades*

$\boldsymbol{M}_{HAWT}\,\boldsymbol{I}\,\ddot{x}_g(t)$ *Seismic force vector*

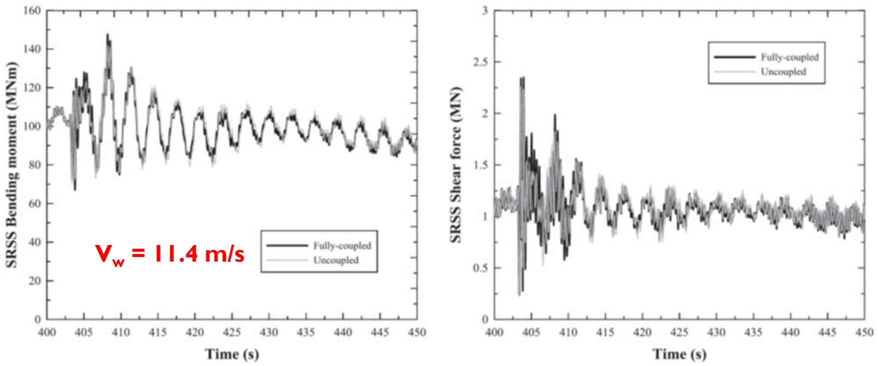
$\ddot{x}_g(t)$ *Base acceleration of earthquake ground motion*

Aeroelastic Model

- *Fully-coupled*, nonlinear time-domain simulations are most indicated to build a numerical solution for the seismic assessment of HAWT. However, the main disadvantage of this approach consist in the high computational costs.
- Considerable attention has been devoted to the use of *decoupling* approach, that permits to evaluate the structural response by the combination of two uncoupled analyses, (i.e. one under wind and another under earthquake only), instead of carry out a fully coupled analysis.
- The response to a given wind state, once computed, could be combined with the response to different potential earthquake events, with a significant reduction of computational costs with respect to fully-coupled time-domain simulations.
- Comparison analyses, available in literature, show a good agreement between the results obtained through coupled and uncoupled approaches encouraging in the use of the uncoupling approach.

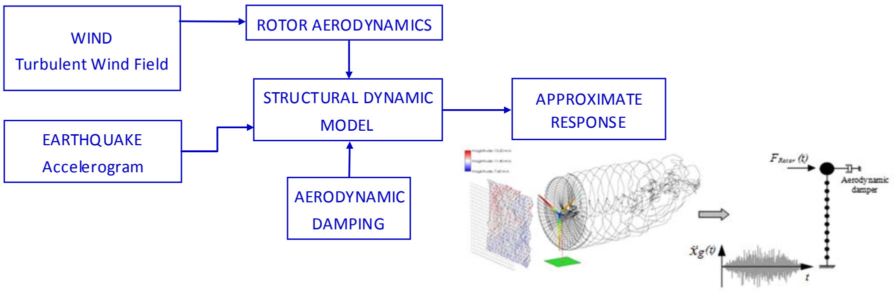
Aeroelastic Model

- Comparison between fully coupled simulation and uncoupled analyses results, for a 5MW land-based HAWT, with fixed and flexible foundation have been developed by Santangelo et al. 2016.



Aerodynamic and Structural Model

The *aerodynamic* and *seismic effects* on the structural model of the HAWT can be evaluated *decoupling* the aerodynamic behaviour of the rotor from the dynamic response of the support structure.



WIND
Turbulent Wind Field

ROTOR AERODYNAMICS

STRUCTURAL DYNAMIC MODEL

APPROXIMATE RESPONSE

EARTHQUAKE
Accelerogram

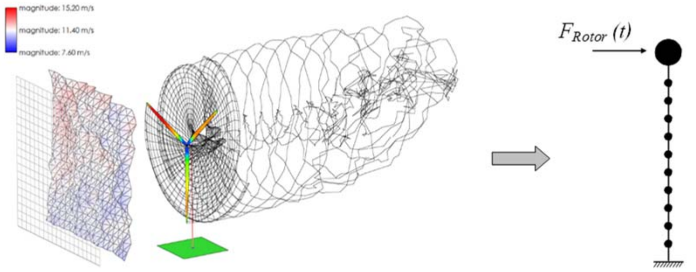
AERODYNAMIC DAMPING

- First, the *aerodynamic response* of the rotor (i.e. with rigid or flexible blades) neglecting the dynamic behavior of the tower structure can be evaluated;
- Then the structural *approximate response* can be calculated applying the *wind thrust of the rotor* and the *seismic excitation* to a structural dynamic model of the tower considering the *aerodynamic damping* and neglecting the feedback.

Aerodynamic Model

The aerodynamic analysis of the rotor, subjected to wind loads, can be carried out in the time-domain through the application of different approaches:

- Blade Element Momentum Theory - implemented in FAST (Jonkman, 2005).
- Lifting Line Theory – Free Vortex Wake algorithm (Vortex Methods) - implemented in QBlade (Marten et al., 2013).
- Computational Fluid Dynamics of the rotor (Fluent, ANSYS).

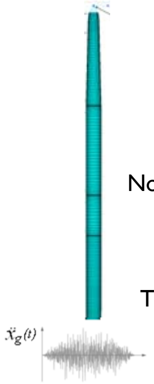


Structural Model

The support structure can be modelled within a FEM software:

- General purpose FEM – ABAQUS, ANSYS etc.
- Structural dedicated FEM – CSi SAP2000, OpenSees, etc.

Ansys - Abaqus



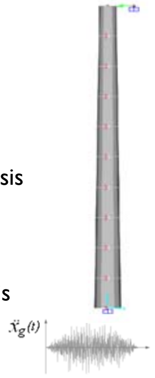
Thin Shell element

Nonlinear and
Buckling behaviour

Nonlinear Static Analysis
(Pushover)

Nonlinear
Time-History Analysis

Csi SAP 2000



Beam element

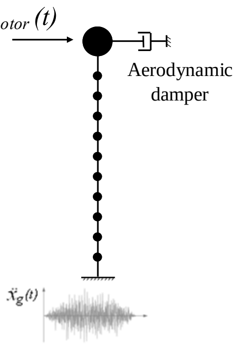
Linear elastic
behaviour

Linear
Static Analysis

Linear
Time-History
Analysis

OpenSees

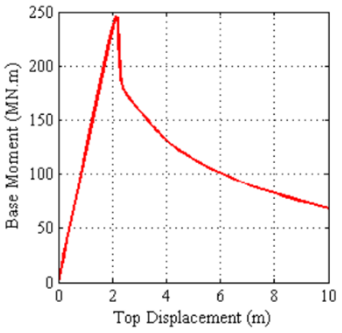
Mazzoni et al. 2006



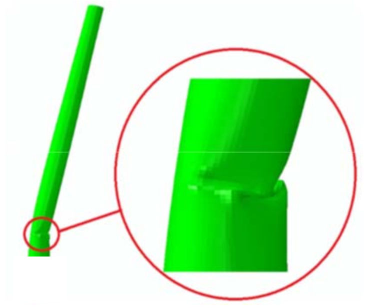
Structural Model

Why global linear analysis?

**Base Moment –
Top Displacement Curve**



**Buckling Ultimate
Failure Condition**

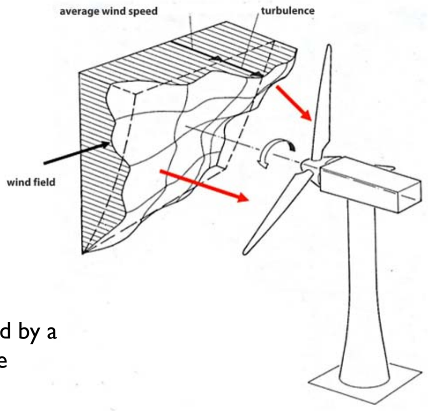


Asareh, et al., 2016

Wind Action

- Generally, the wind field velocity can be decomposed into a mean and fluctuating (i.e. turbulence) parts.

$$u(t) = U + u'(t)$$
$$v(t) = V + v'(t)$$
$$w(t) = W + w'(t)$$



- The mean velocity can be obtained by probabilistic wind climate studies.
- The fluctuating wind part can be defined by a power spectral density and a coherence function.

Wind Action

Wind Mean Profile

The mean vertical wind profile, *U(z)*, can be assumed as power law profile or a logarithmic profile in atmospheric neutral condition.

Power Law

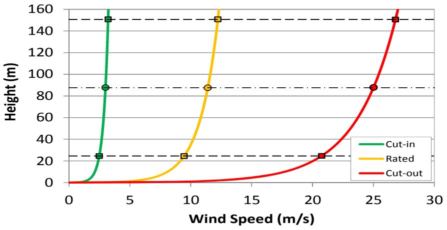
$$U(z) = U_{hub}\,(z/z_{hub})^{\alpha}$$

IEC 61400-1 (2005)
ASCE-AWEA RP (2011)

Logarithmic Law

$$U(z) = U_{hub}\,\frac{\ln(z/z_0)}{\ln(z_{hub}/z_0)}$$

(EC1 ; Italian Code D.M.2008)



U_{hub} mean velocity at hub height

z_{hub} hub height

α power law exponent
(i.e. assumed equal to 0.2 by IEC 61400-1)

z_0 roughness length

Wind Action

Wind Field

For given values of the mean wind speed and turbulence intensity, a wind field can be generated by *Turbsim* (Jonkman, 2009).

Kaimal Spectrum

(proposed by Kaimal et al.1972) to simulate the wind turbulence

$$\frac{f_v\, S_i\left(f_v\right)}{\sigma_i^2} = \frac{4\, f_v\, L_k / U_{hub}}{\left(1+6\, f_v\, L_k\, U_{hub}\right)^{5/3}}$$

f_v frequency in Hertz

S_i single-sided velocity component spectrum (1 longitudinal, 2 lateral, 3 upward)

σ_i STD of the i-th velocity component

L_k velocity component integral scale parameter

Coherence model

proposed by IEC 61400-1

$$\mathrm{Coh}\left(r, f_v\right) = \exp\left\{-12\left[\left(f_v\, r/U_{hub}\right)^2 + \left(0.12\, r/L_c\right)^2\right]^{0.5}\right\}$$

r magnitude of the projection of the separation vector between the two points onto a plane normal to the average wind direction

L_c coherence scale parameter

Wind Action

Wind Field

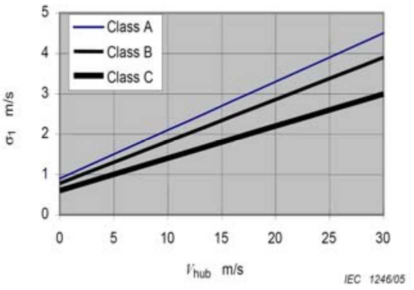
IEC 61400-1 – Normal turbulence model NTM

$$\sigma_1 = I_{ref}\left(0.75\ V_{hub} + b\right)$$
$$b = 5.6\ m/s$$

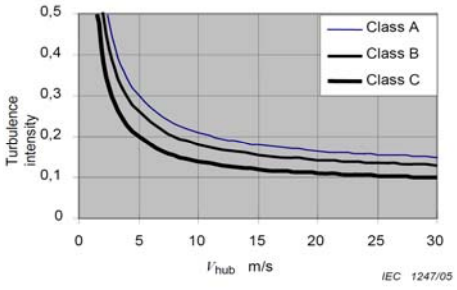
Table 1 – Basic parameters for wind turbine classes[1]

Category

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			



IEC 1246/05



IEC 1247/05

Wind Action

Wind Field

IEC 61400-1 – Normal turbulence model NTM

Table B.1 – Turbulence spectral parameters for the Kaimal model

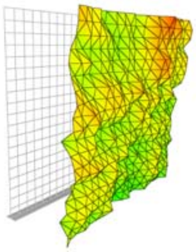
	Velocity component index (*k*)		
	1	2	3
Standard deviation σ_k	σ_1	0,8 σ_1	0,5 σ_1
Integral scale, L_k	8,1 Λ_1	2,7 Λ_1	0,66 Λ_1

Longitudinal turbulence scale parameter

$$\Lambda_1 = \begin{cases} 0.7\,z & z \le 60\,m \\ 42\,m & z > 60\,m \end{cases}$$

Coherence scale parameter

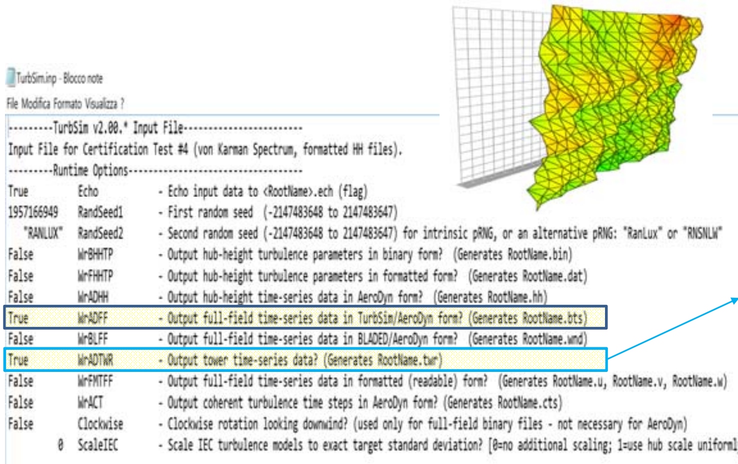
$$L_c = 8.1\,\Lambda_1$$



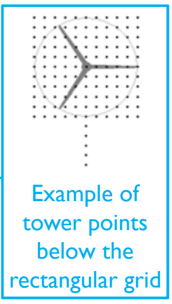
Wind Action

Turbsim (Jonkman, 2005)

Input file setting to generate a Turbulent wind field according to IEC 61400-1.



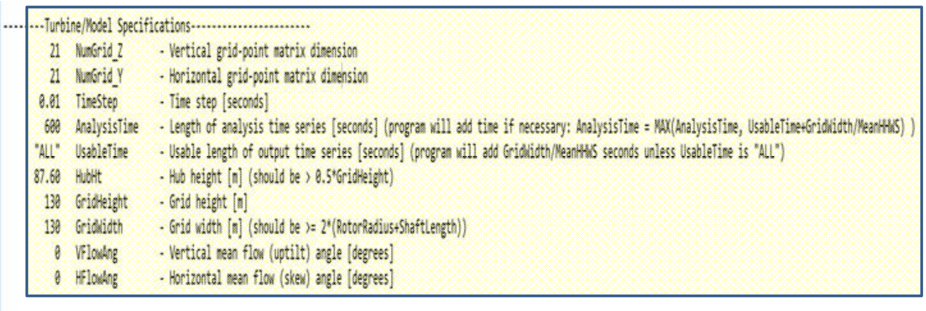
```
---------TurbSim v2.00.* Input File------------------------
Input File for Certification Test #4 (von Karman Spectrum, formatted HH files).
---------Runtime Options-----------------------------------
True          Echo          - Echo input data to <RootName>.ech (flag)
1957166949    RandSeed1     - First random seed  (-2147483648 to 2147483647)
   "RANLUX"   RandSeed2     - Second random seed (-2147483648 to 2147483647) for intrinsic pRNG, or an alternative pRNG: "RanLux" or "RNSNLW"
False         WrBHHTP       - Output hub-height turbulence parameters in binary form?  (Generates RootName.bin)
False         WrFHHTP       - Output hub-height turbulence parameters in formatted form?  (Generates RootName.dat)
False         WrADHH        - Output hub-height time-series data in AeroDyn form?  (Generates RootName.hh)
True          WrADFF        - Output full-field time-series data in TurbSim/AeroDyn form? (Generates RootName.bts)
False         WrBLFF        - Output full-field time-series data in BLADED/AeroDyn form?  (Generates RootName.wnd)
True          WrADTWR       - Output tower time-series data? (Generates RootName.twr)
False         WrFMTFF       - Output full-field time-series data in formatted (readable) form?  (Generates RootName.u, RootName.v, RootName.w)
False         WrACT         - Output coherent turbulence time steps in AeroDyn form? (Generates RootName.cts)
False         Clockwise     - Clockwise rotation looking downwind? (used only for full-field binary files - not necessary for AeroDyn)
          0   ScaleIEC      - Scale IEC turbulence models to exact target standard deviation? [0=no additional scaling; 1=use hub scale uniformly; 2=use individual scales]
```



Example of tower points below the rectangular grid

Wind Action

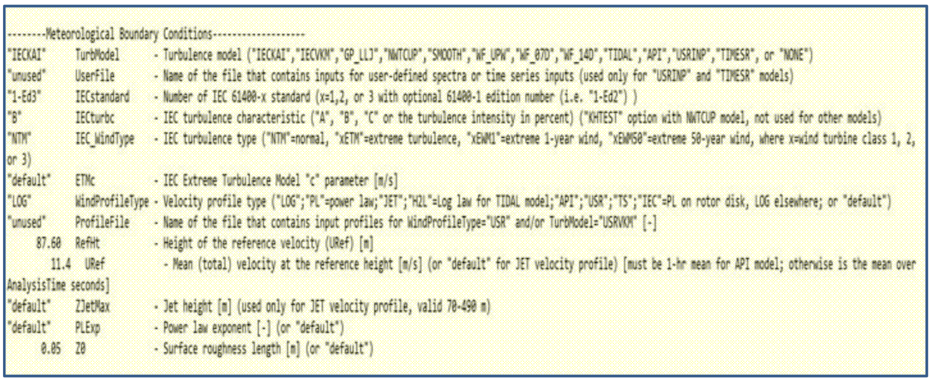
Turbsim (Jonkman, 2005)
Input file setting to generate a Turbulent wind field according to IEC 61400-1.



```
------Turbine/Model Specifications-----------------------
   21   NumGrid_Z       - Vertical grid-point matrix dimension
   21   NumGrid_Y       - Horizontal grid-point matrix dimension
 0.01   TimeStep        - Time step [seconds]
  600   AnalysisTime    - Length of analysis time series [seconds] (program will add time if necessary: AnalysisTime = MAX(AnalysisTime, UsableTime+GridWidth/MeanHHWS) )
"ALL"   UsableTime      - Usable length of output time series [seconds] (program will add GridWidth/MeanHHWS seconds unless UsableTime is "ALL")
87.60   HubHt           - Hub height [m] (should be > 0.5*GridHeight)
  130   GridHeight      - Grid height [m]
  130   GridWidth       - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))
    0   VFlowAng        - Vertical mean flow (uptilt) angle [degrees]
    0   HFlowAng        - Horizontal mean flow (skew) angle [degrees]
```

Wind Action

Turbsim (Jonkman, 2005)
Input file setting to generate a Turbulent wind field according to IEC 61400-1.



```
--------Meteorological Boundary Conditions-------------------
"IECKAI"      TurbModel       - Turbulence model ("IECKAI","IECVKM","GP_LLJ","NWTCUP","SMOOTH","WF_UPW","WF_07D","WF_14D","TIDAL","API","USRINP","TIMESR", or "NONE")
"unused"      UserFile        - Name of the file that contains inputs for user-defined spectra or time series inputs (used only for "USRINP" and "TIMESR" models)
"1-Ed3"       IECstandard     - Number of IEC 61400-x standard (x=1,2, or 3 with optional 61400-1 edition number (i.e. "1-Ed2") )
"B"           IECturbc        - IEC turbulence characteristic ("A", "B", "C" or the turbulence intensity in percent) ("KHTEST" option with NWTCUP model, not used for other models)
"NTM"         IEC_WindType    - IEC turbulence type ("NTM"=normal, "xETM"=extreme turbulence, "xEWM1"=extreme 1-year wind, "xEWM50"=extreme 50-year wind, where x=wind turbine class 1, 2,
or 3)
"default"     ETMc            - IEC Extreme Turbulence Model "c" parameter [m/s]
"LOG"         WindProfileType - Velocity profile type ("LOG";"PL"=power law;"JET";"H2L"=Log law for TIDAL model;"API";"USR";"TS";"IEC"=PL on rotor disk, LOG elsewhere; or "default")
"unused"      ProfileFile     - Name of the file that contains input profiles for WindProfileType="USR" and/or TurbModel="USRVKM" [-]
     87.60    RefHt           - Height of the reference velocity (URef) [m]
        11.4   URef             - Mean (total) velocity at the reference height [m/s] (or "default" for JET velocity profile) [must be 1-hr mean for API model; otherwise is the mean over
AnalysisTime seconds]
"default"     ZJetMax         - Jet height [m] (used only for JET velocity profile, valid 70-490 m)
"default"     PLExp           - Power law exponent [-] (or "default")
      0.05    Z0              - Surface roughness length [m] (or "default")
```

Seismic Action

Seismic Design in *Guidelines on Wind Energy Industry*

Risø-DNV – Guidelines for Design of Wind Turbines (2001)

The wind turbine is represented by a concentrated mass on top of a vertical tower and the seismic actions will be determined by using frequency-domain analysis with a specific response spectrum.

Germanischer Lloyd (GL-2003) → American Petroleum Institute (API-2000)

The investigations of the earthquake generated loads is based on the combination of the wind load and earthquake acceleration with a recurrence period of 475 years. Earthquake load is to combined with standard wind load conditions in a load combination with load factor equal to 1.

International Electrotechnical Commission - IEC-61400-1 (2005)

The design level earthquake is prescribed as a 475 year return period event and the resulting loads must be superimposed with the maximum of operating/emergency shutdown loads with a unit safety factor.

ASCE-AWEA RP-2011

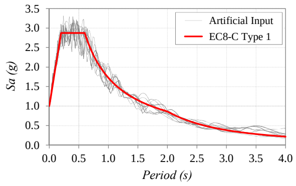
It is suggested that operational and earthquake loads be combined as an absolute sum with a load factor of 0.75. Seismic ground motion values are determined from ASCE 7-10 and spectral response acceleration parameters should be based on 1% of damping values while parked and 5% of the damping value while the turbine is under operational conditions.

Seismic Action

Seismic response history analysis, considering time varying earthquake ground acceleration and operational or emergency stop loads, can be used to more accurately predict response and reduce potential design conservatism.

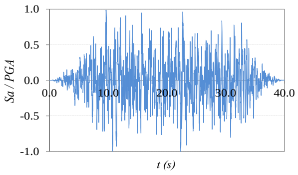
Recorded and simulated accelerograms

- Scaled to the peak ground acceleration ($a_g \cdot S$)
- Match the elastic response spectrum for 5% damping



Artificial accelerograms

- Match the elastic response spectrum for 5% damping
- Duration compatible with Magnitude (Ts > 10s)
- No value of the mean 5% damping elastic spectrum, should be less than 90% of the corresponding value of the EC8 5% elastic response spectrum.

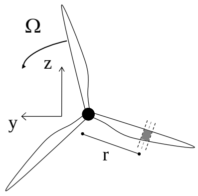


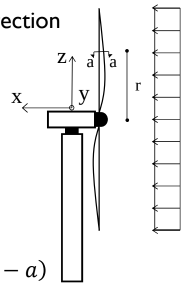
Minimum number of accelerograms: 3

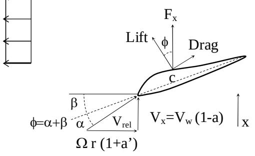
Aerodynamic Damping

Valamanesh and Myers (2014)

- Forces based on Blade Element Momentum theory (BEM)
- Flexibility of rotor is omitted
- Steady uniform wind oriented along fore-aft direction
- First mode of vibration is considered







Fore-aft direction

$$m\,\ddot{x} + c_{st}\,\dot{x} \;+ k\,x = dF_x$$

$$F_x = \frac{1}{2}\rho N_b \int \left[V_{rel}^2 (C_L cos\phi + C_D sin\phi) c(r)\right] dr$$

$$m\,\ddot{x} + [c_{ST} + N_b(A+B)]\,\dot{x} + k\,\mathrm{x} = N_b(A+B)V_w(1-a)$$

$$\boxed{\xi_{AD,x} = \frac{N_b(A+B)}{2\sqrt{k\cdot m}}}$$

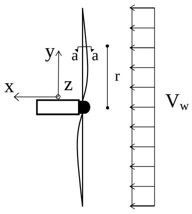
$$A = \rho \int V_w\,(1-a)[C_L\cos(\phi) + C_D\sin(\phi)]\;c(r)\;dr$$

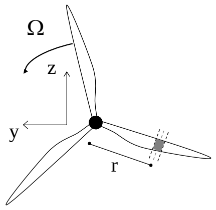
$$B = \frac{1}{2}\rho \int \Omega r\,(1+a')\left[\left(\frac{\partial C_L}{\partial \alpha} + C_D\right)\cos(\phi) + \left(\frac{\partial C_D}{\partial \alpha} - C_L\right)\sin(\phi)\right]\;c(r)\;dr$$

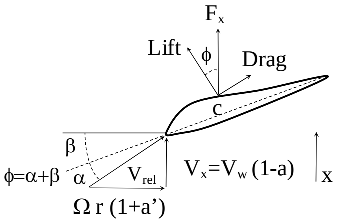
Aerodynamic Damping

Valamanesh and Myers (2014)

Side-to-side







$$F_y = \frac{1}{2}\rho N_b \int \left[V_{rel}^2 (C_L cos\phi + C_D sin\phi) c(r)\right] dr$$

$$m\,\ddot{y} + \left[c_{ST} + N_b\frac{B'-A'}{2}\right]\,\dot{y} + k\,\mathrm{y} = 0$$

$$\boxed{\xi_{AD,y} = \frac{N_b(B'-A')}{4\sqrt{k\cdot m}}}$$

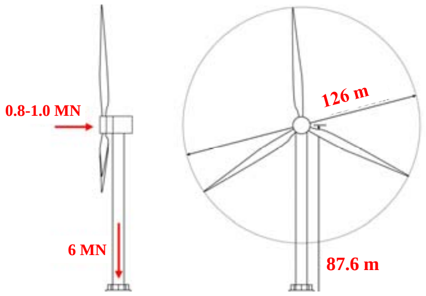
$$A' = \frac{1}{2}\rho \int V_w\,(1-a)\left[\left(\frac{\partial C_L}{\partial \alpha} + C_D\right)\sin(\phi) + \left(C_L - \frac{\partial C_D}{\partial \alpha}\right)\cos(\phi)\right]\;c(r)\;dr$$

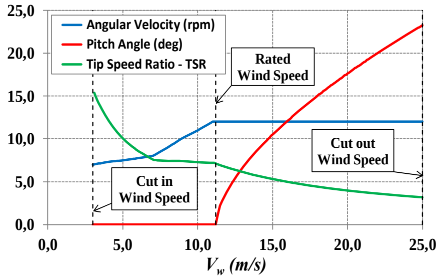
$$B' = \rho \int \Omega r\,(1+a')[C_L\sin(\phi) - C_D\cos(\phi)]\;c(r)\;dr$$

Aerodynamic and Seismic Response

Case Study - 5 MW Land-Based HAWT

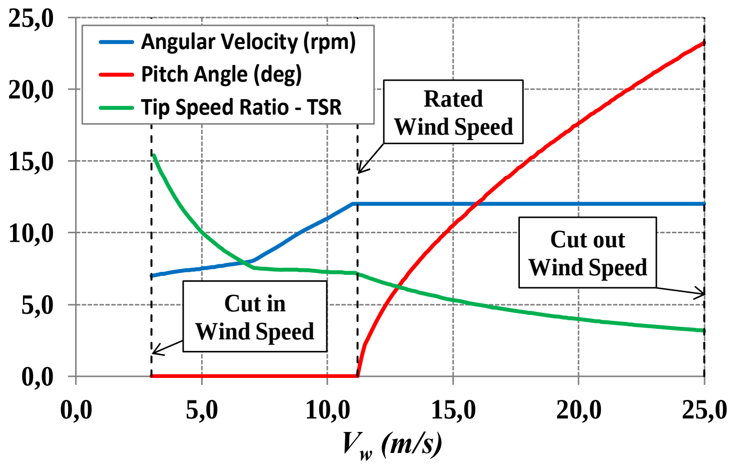
Characteristic	*Value*
Power Output	**5 MW**
Number of blades	**3**
Rotor diameter	**126 m**
Hub height	**87.6 m**
Cut in wind speed	**3 m/s**
Rated wind speed	**11.4 m/s**
Cut out wind speed	**25 m/s**
Rated Tip Speed	**80 m/s**
Cut in rotor speed	**6.9 rpm**
Nacelle Mass	**240000 kg**
Hub Mass	**56780 kg**
Rotor Mass	**53220 kg**
Tower Mass	**347460 kg**
Tower top diameter wall thickness	**3.87m 0.019m**
Tower base diameter wall thickness	**6.00m 0.027m**



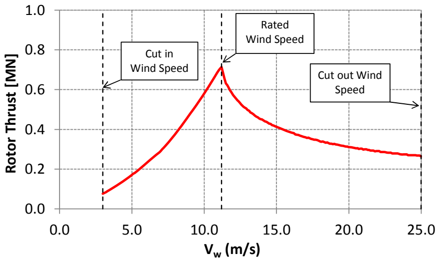


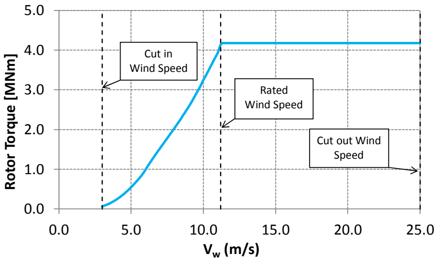
Aerodynamic and Seismic Response

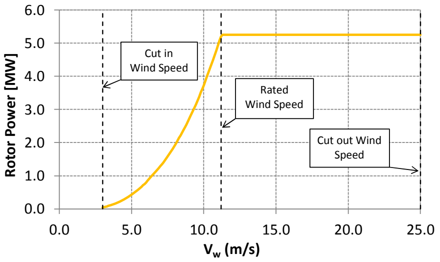
Case Study - 5 MW Land-Based HAWT



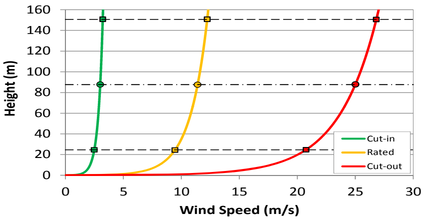
Aerodynamic and Seismic Response







Aerodynamic and Seismic Response

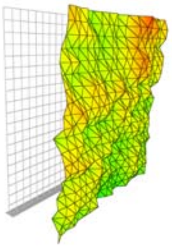


$$U(z) = U(z_r)\,\frac{\ln(z/z_0)}{\ln(z_r/z_0)} \qquad z_0 = 0.05\text{m}$$

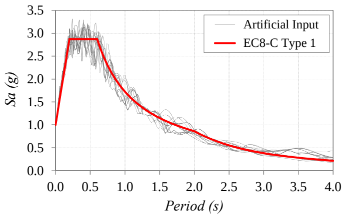
Fifty Turbulent Wind Field

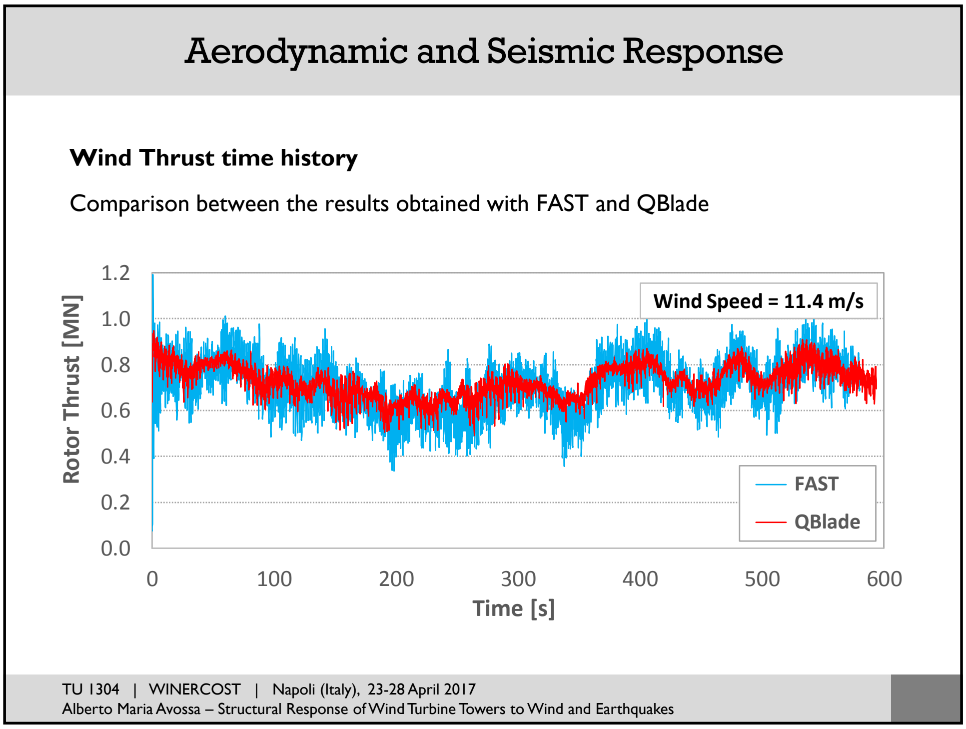
Turbsim
Jonkman, 2009

IEC 61400-1 –
NTM - Medium
Turbulence class B
(grid 21x21 with a step of 6.5 m)



Fifty seismic input
Seismosignal (Seismosoft, 2011)





Aerodynamic and Seismic Response

Wind Thrust time history

Comparison between the results obtained with FAST and QBlade

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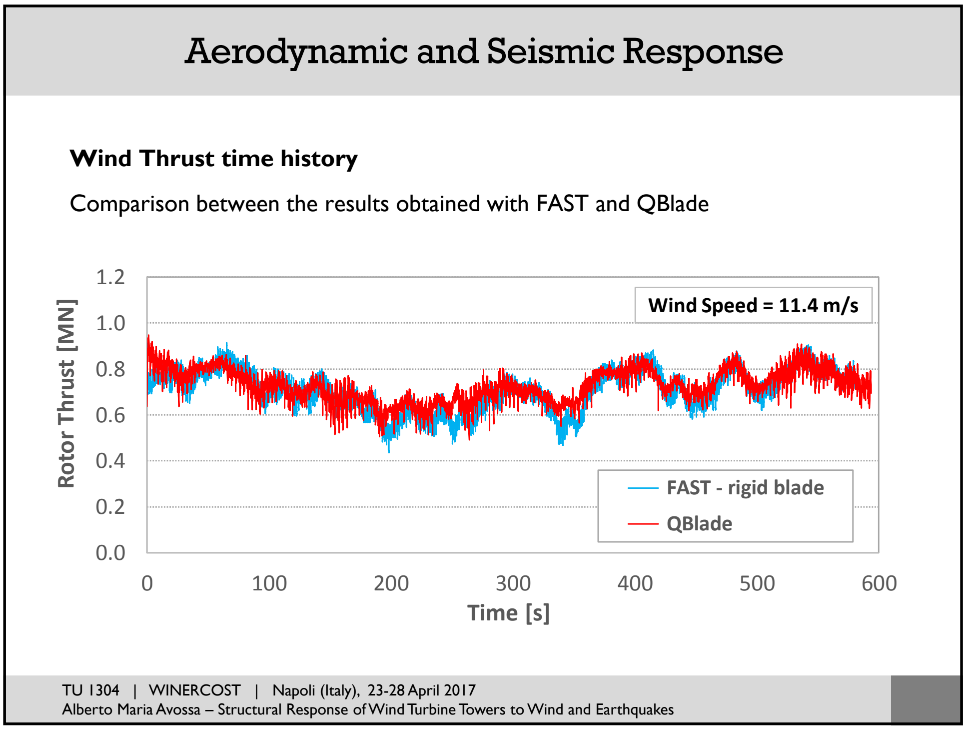
Alberto Maria Avossa – Structural Response of Wind Turbine Towers to Wind and Earthquakes



Aerodynamic and Seismic Response

Wind Thrust time history

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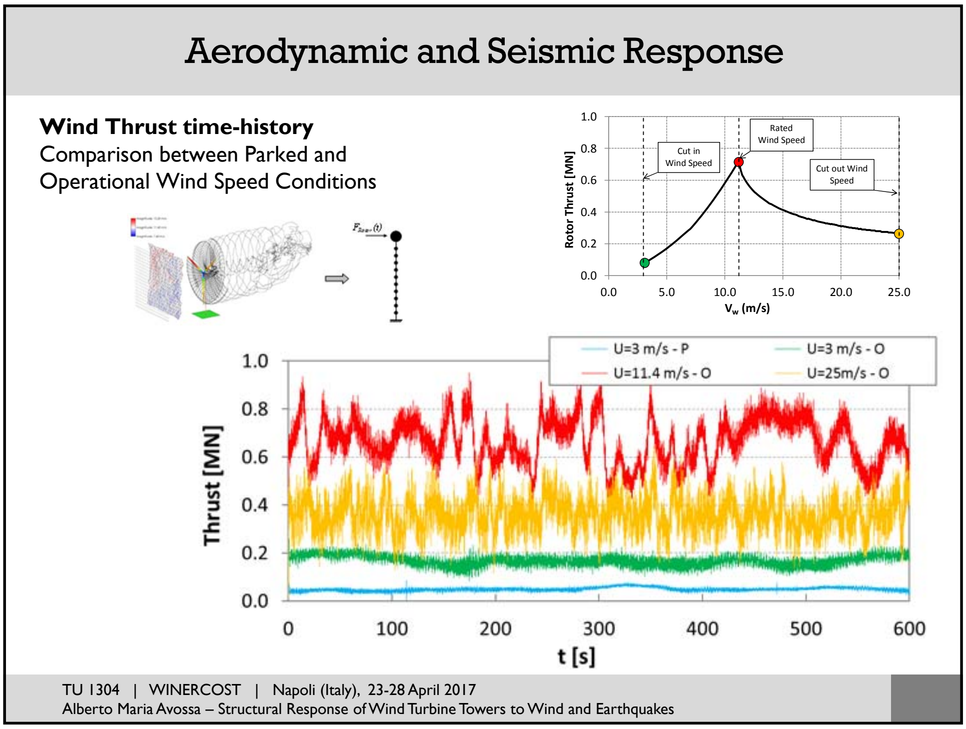

Aerodynamic and Seismic Response

Wind Thrust time-history

Comparison between Parked and Operational Wind Speed Conditions

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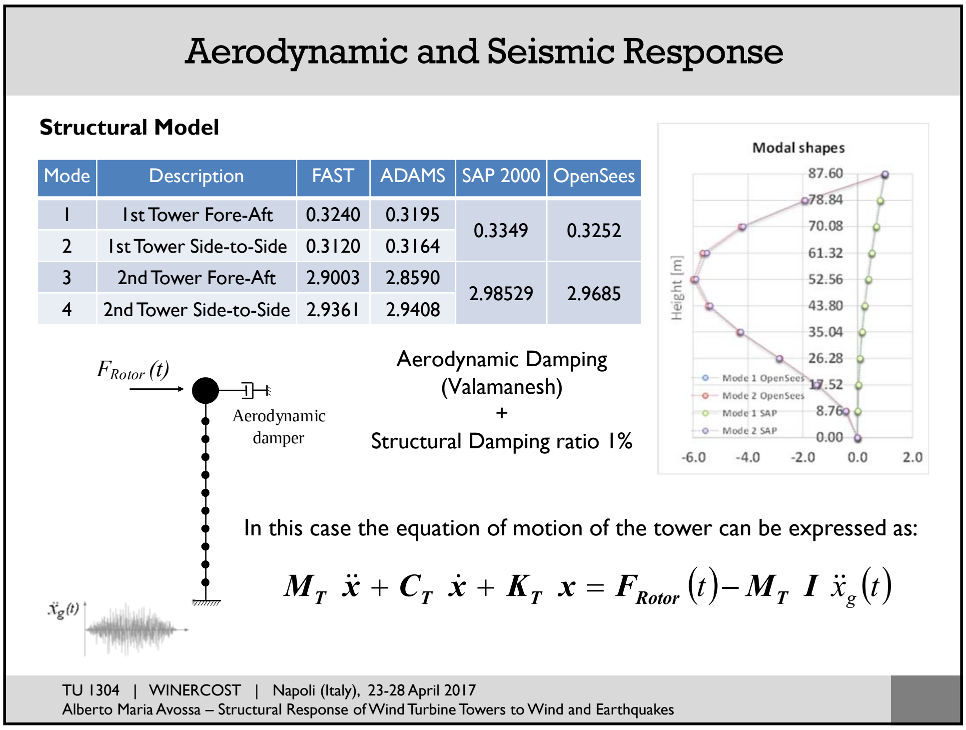


Aerodynamic and Seismic Response

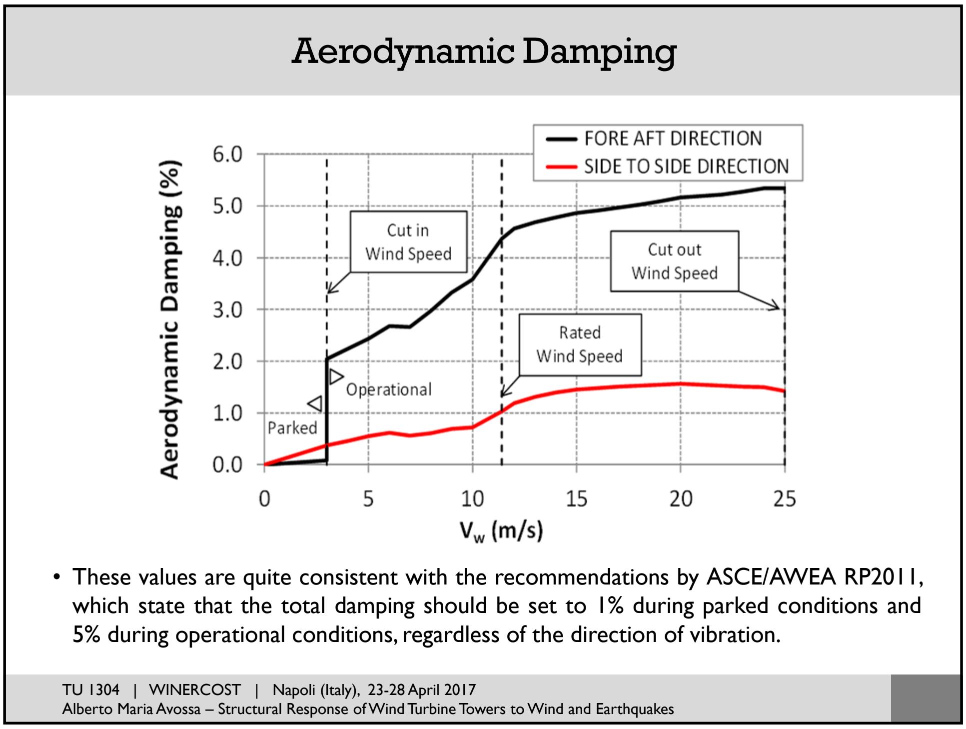
Structural Model

Mode	Description	FAST	ADAMS	SAP 2000	OpenSees
1	1st Tower Fore-Aft	0.3240	0.3195	0.3349	0.3252
2	1st Tower Side-to-Side	0.3120	0.3164		
3	2nd Tower Fore-Aft	2.9003	2.8590	2.98529	2.9685
4	2nd Tower Side-to-Side	2.9361	2.9408		

Aerodynamic Damping
(Valamanesh)
+
Structural Damping ratio 1%

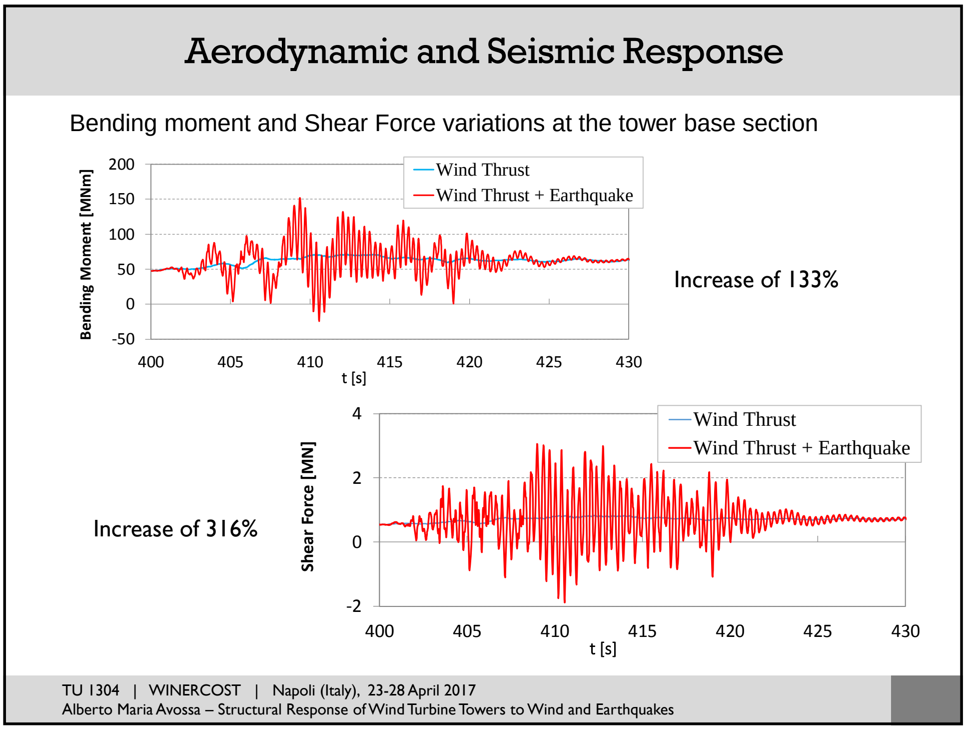
In this case the equation of motion of the tower can be expressed as:

$$M_T\ \ddot{x} + C_T\ \dot{x} + K_T\ x = F_{Rotor}(t) - M_T\ I\ \ddot{x}_g(t)$$



Aerodynamic Damping

- These values are quite consistent with the recommendations by ASCE/AWEA RP2011, which state that the total damping should be set to 1% during parked conditions and 5% during operational conditions, regardless of the direction of vibration.



Aerodynamic and Seismic Response

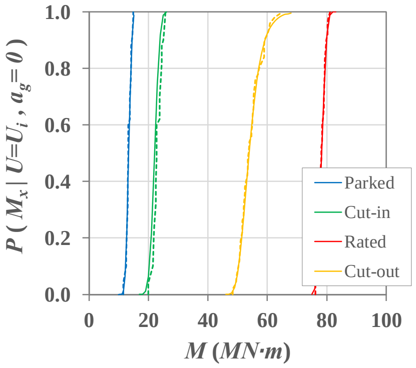
Bending moment and Shear Force variations at the tower base section

Increase of 133%

Increase of 316%

Probabilistic Assessment of Peak Response

For every working condition (parked/operational) the maximum value of the bending moment at the tower base cross-section was evaluated for each combination (2x2500) of wind load (in fore-aft direction) and seismic load (in fore-aft direction or in side-to-side direction).

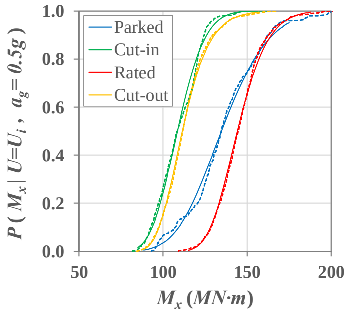


The empirical cumulative distribution function (CDF) of the tower base maximum absolute bending moment M, is fitted to the Generalized Extreme Value (GEV) distribution.

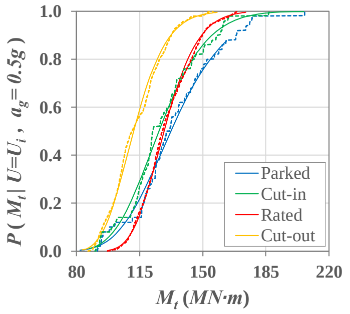
Probabilistic Assessment of Peak Response

- The empirical and fitted CDF of the tower base absolute maximum bending moment are shown for the combination of the wind and seismic action.

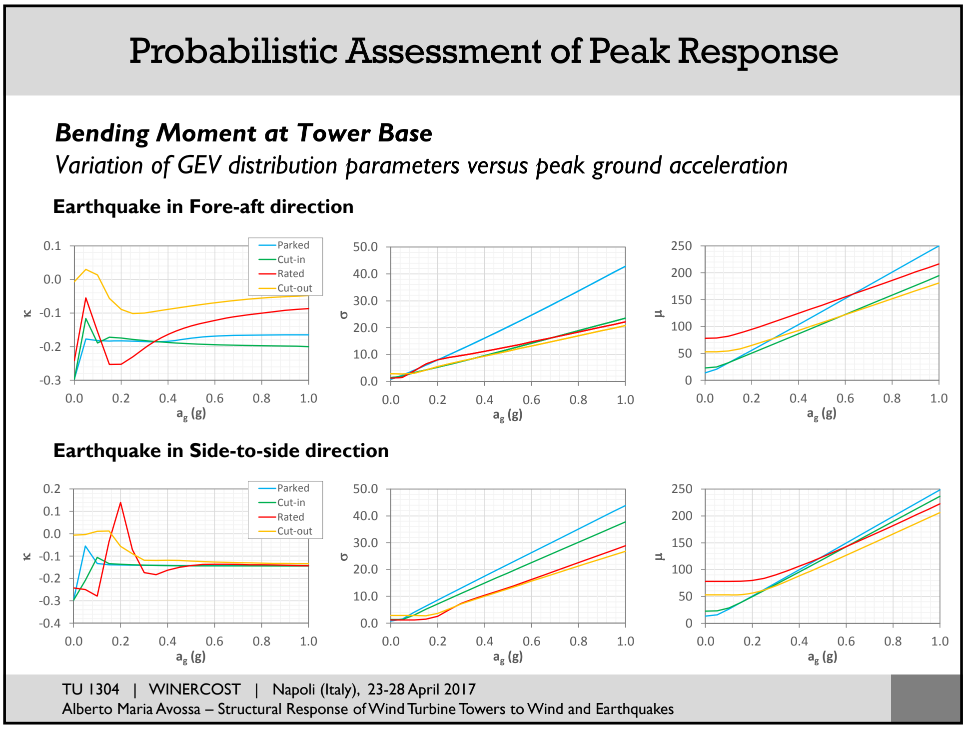
Earthquake in Fore-aft direction



Earthquake in Side-to-side direction



- When the seismic action is in the fore-aft direction, the operational rated scenario brings the largest values of the tower-base bending moment (mean value of μ parameter of 144.2 MN·m).
- For a wind speed of 3 m/s the combined effect of wind and seismic loads are larger for the parked condition if compared to the operational one, because there is no aerodynamic damping.



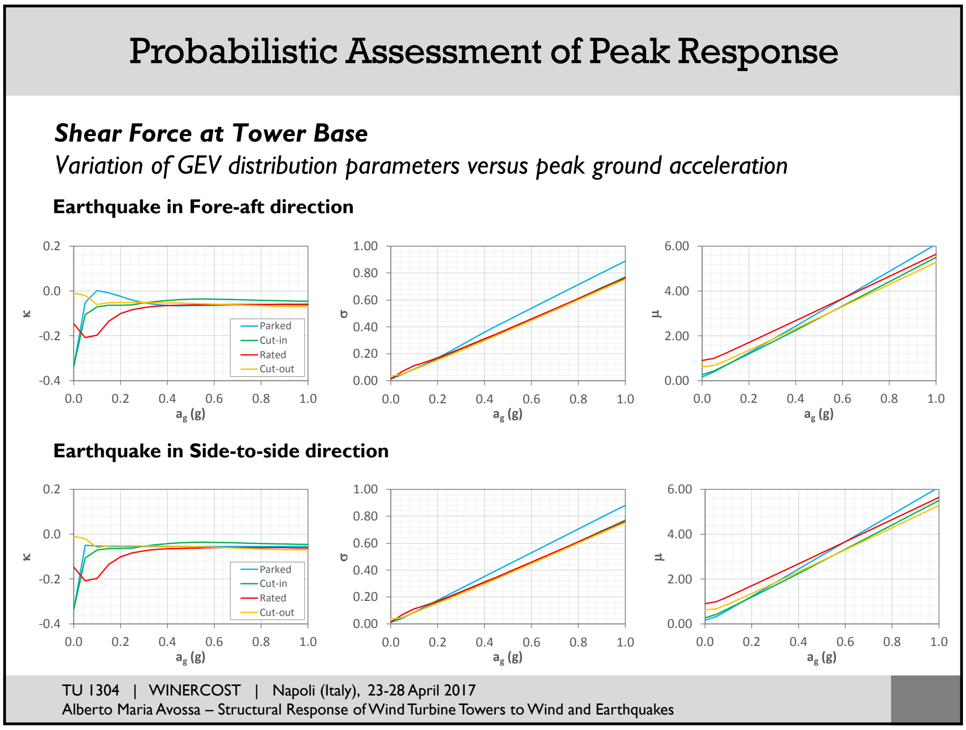
Probabilistic Assessment of Peak Response

Bending Moment at Tower Base

Variation of GEV distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction



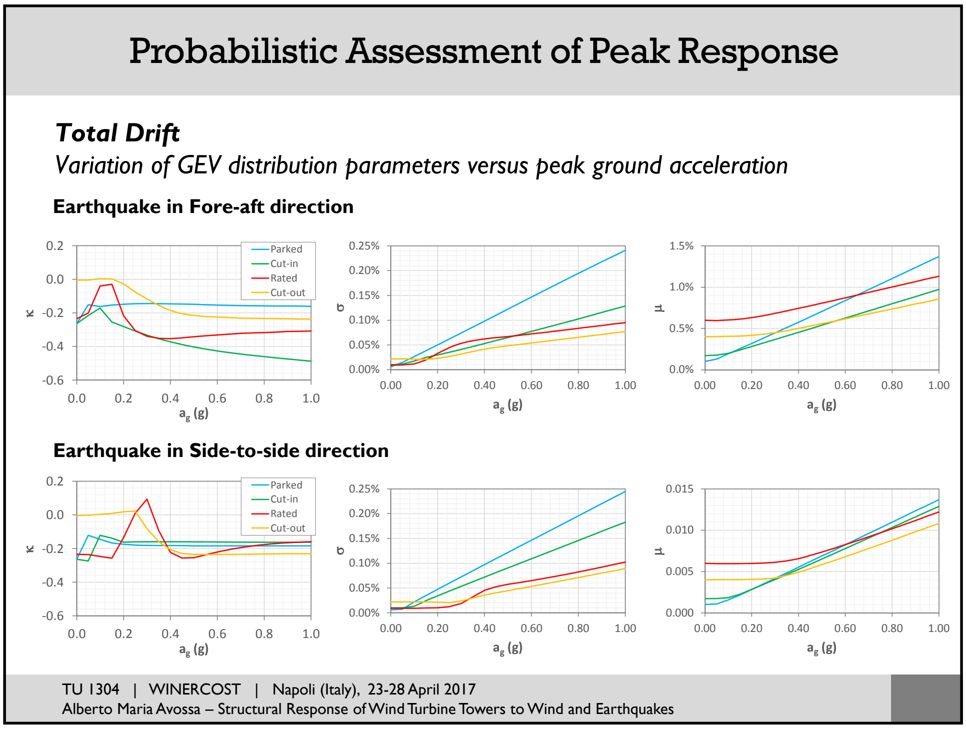
Probabilistic Assessment of Peak Response

Shear Force at Tower Base

Variation of GEV distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction



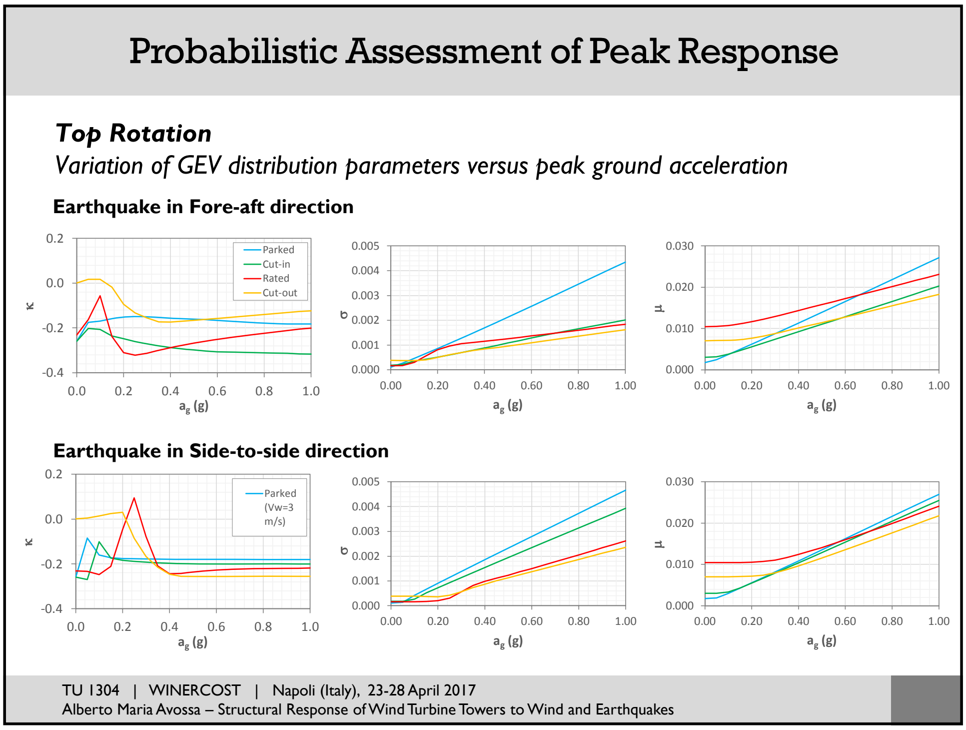
Probabilistic Assessment of Peak Response

Total Drift

Variation of GEV distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction



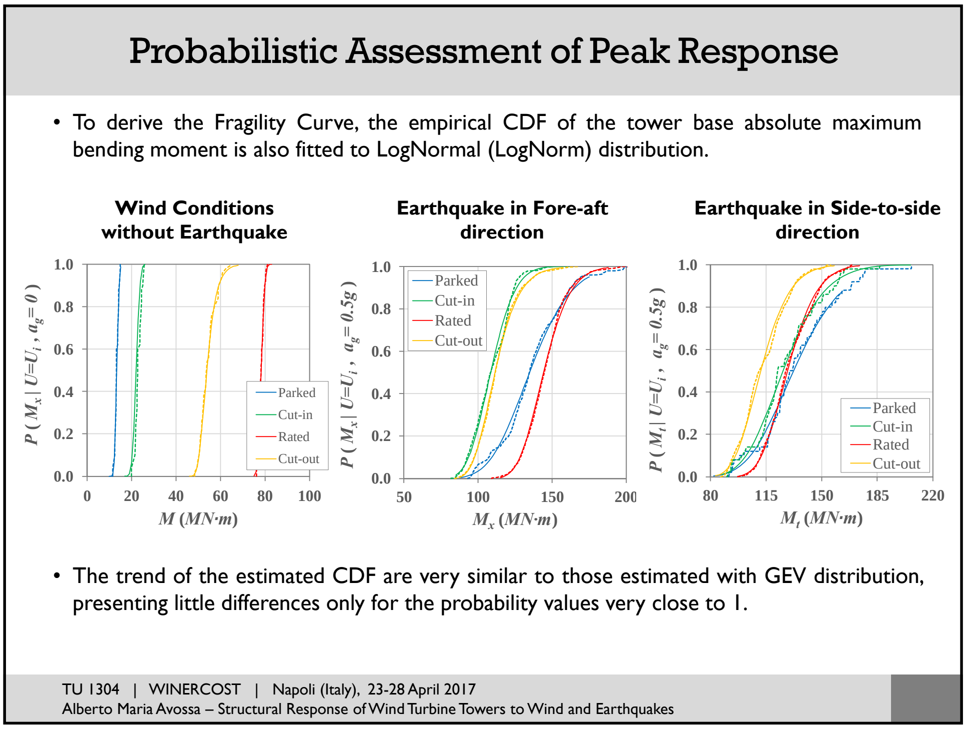
Probabilistic Assessment of Peak Response

Top Rotation

Variation of GEV distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction



Probabilistic Assessment of Peak Response

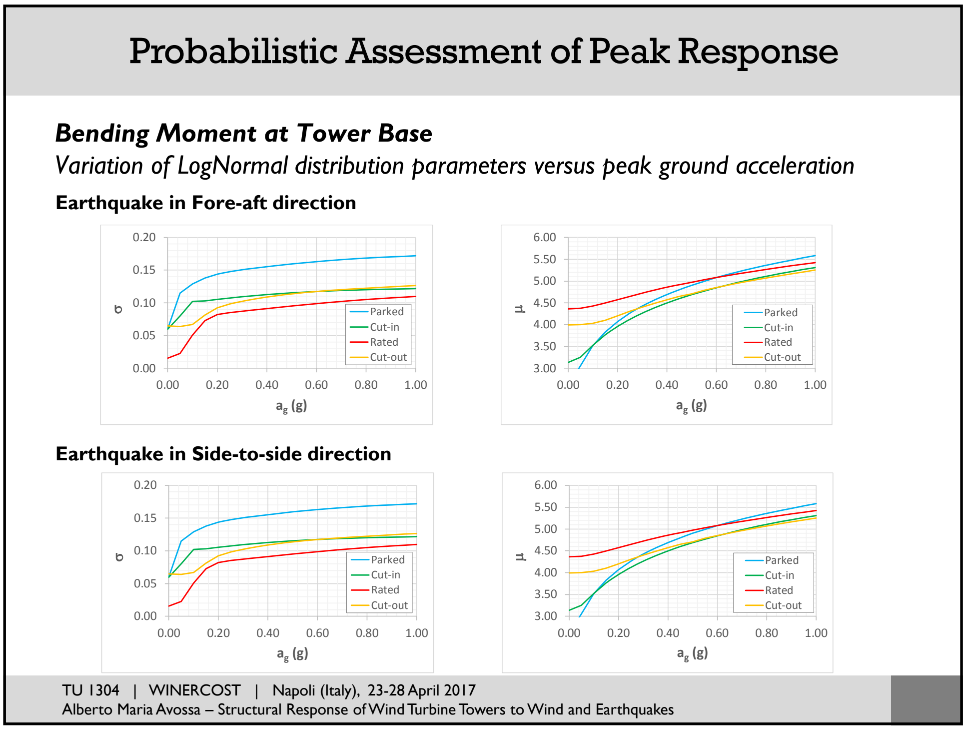
- To derive the Fragility Curve, the empirical CDF of the tower base absolute maximum bending moment is also fitted to LogNormal (LogNorm) distribution.

Wind Conditions without Earthquake

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction

- The trend of the estimated CDF are very similar to those estimated with GEV distribution, presenting little differences only for the probability values very close to 1.



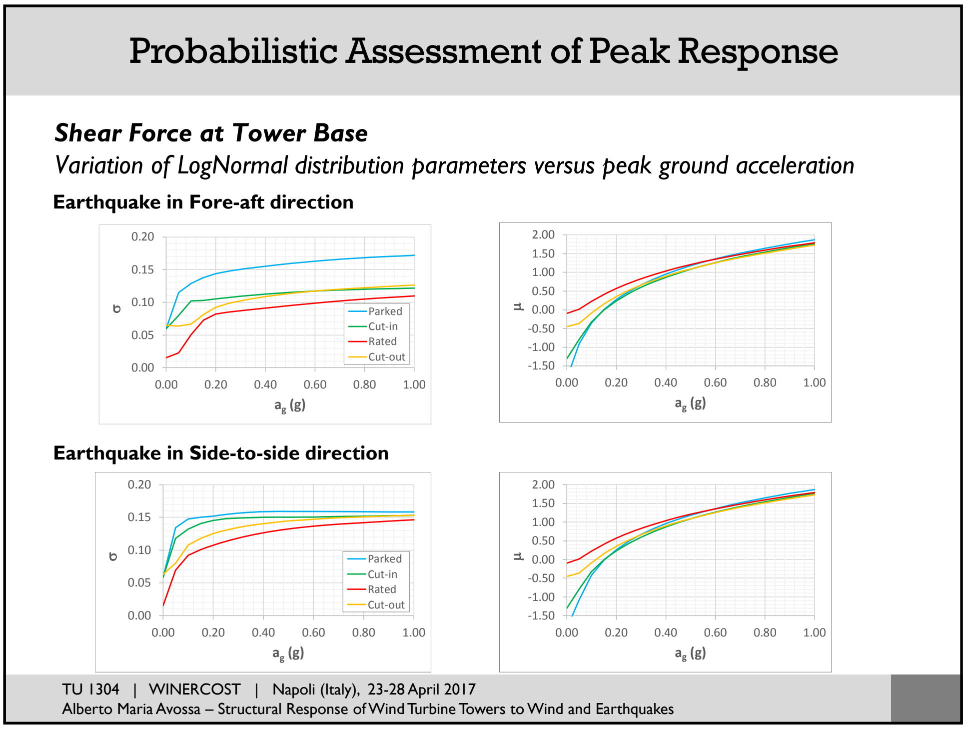
Probabilistic Assessment of Peak Response

Bending Moment at Tower Base

Variation of LogNormal distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction



Probabilistic Assessment of Peak Response

Shear Force at Tower Base

Variation of LogNormal distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction

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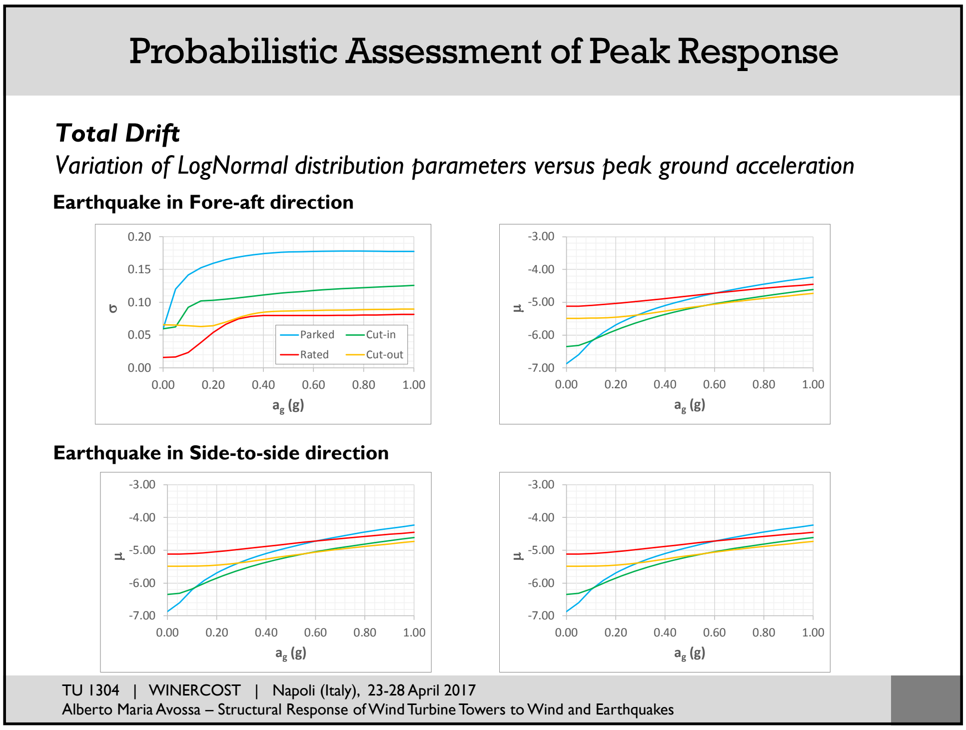
Alberto Maria Avossa – Structural Response of Wind Turbine Towers to Wind and Earthquakes



Probabilistic Assessment of Peak Response

Total Drift

Variation of LogNormal distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction

Earthquake in Side-to-side direction

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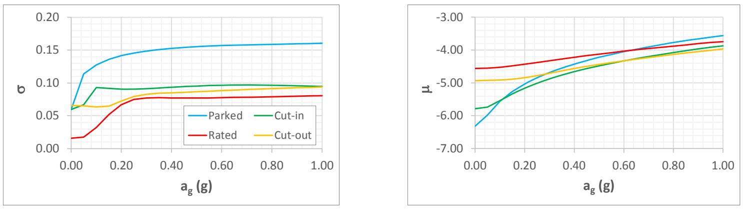
Alberto Maria Avossa – Structural Response of Wind Turbine Towers to Wind and Earthquakes

Probabilistic Assessment of Peak Response

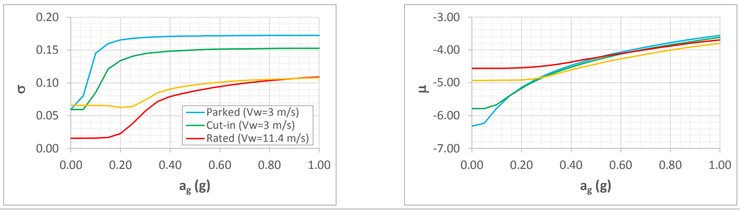
Top Rotation

Variation of LogNormal distribution parameters versus peak ground acceleration

Earthquake in Fore-aft direction



Earthquake in Side-to-side direction



Prediction of Tower Failure Condition

The buckling limit state condition assessment was carried out deterministically by means of the *Stress Design procedure* proposed in the Section 8.5 of EN 1993-1-6.

Design resistance (buckling strength)

$$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_M = \chi_x\, f_{yk}\, A/\gamma_M$$

Buckling reduction factor

$$\chi_x = \chi_x(\lambda_x)$$

Shell slenderness parameter

$$\lambda_x = \sqrt{f_{yk}/\sigma_{x,Rcr}}$$

Elastic critical meridional buckling stress

$$\sigma_{x,Rcr} = 0.605\, E C_x \frac{t}{r}$$

Donnell-Mushtari-Vlasov

For long cylinder that satisfy the conditions

$$\frac{r}{t} \leq 150 \;;\quad \omega \leq 6\frac{r}{t} \;;\quad 500 \leq \frac{E}{f_{yk}} \leq 1000$$

$$C_x = 0.6 + 0.4\left(\sigma_{xE,M}/\sigma_{xE}\right)$$

S355 steel of fabrication tolerance quality class C

Fixing an axial force value of 6.88MN acting on the tower base section, due to the gravity loads, and assuming as negligible the effect of the tangential stress, an ultimate bending moment of 205.8 MNm was assessed.

Fragility Curves Derivation

Fragility is defined as the conditional probability $P_{f,i}$ of a damage measure *(DM)* attaining or exceeding a damage limit state for a given intensity measure *(IM)* of the combined environmental conditions.

$$P_{f,i} = P\left[DMi \middle| EDP = edp\right] \, P\left[EDP = edp \middle| IM = im\right]$$

In this case, the achievement of the tower base ultimate bending moment M_u, corresponding to buckling failure condition is considered. Thus, the fragility curves are defined as

$$P_{f,i} = P\left[\, M \geq M_u \middle| \, U = U_i ; a_g \right]$$

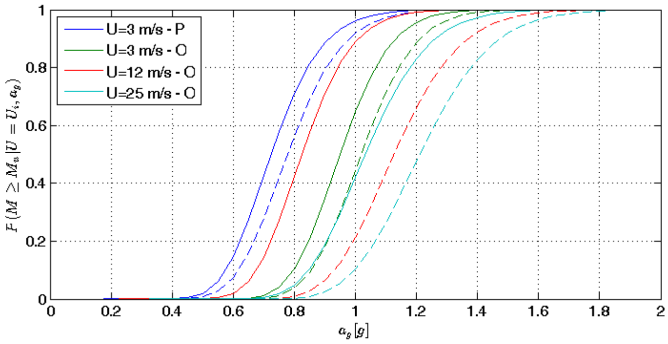
where M_u is the structural capacity, M is the demand corresponding to the *IM* of the combined wind scenario (parked and operational, defined as $U=U_i$) and earthquake intensity a_g of seismic load acting in fore-aft or side-to-side direction and can be also expressed as

$$P_{f,i}\left(a_g\right) = 1 - \Phi\left(\frac{\ln\left(a_g\right) - \mu}{\sigma}\right)$$

where Φ is the standardized normal distribution function.

Fragility Curves Derivation

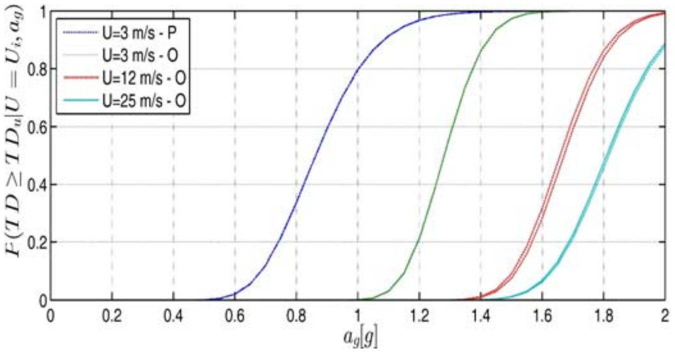
Bending Moment at Tower Base



- Results obtained for the seismic loads acting in the fore-aft (continuous lines) and side-to-side direction show that fragility is higher for the parked condition.
- This is mainly due to the absence of aerodynamic damping value associated to the parked condition respect to the other operational wind conditions.

Fragility Curves Derivation

Top Displacement (Limit State assumed equal to 1.25% of the H_{hub})



- Results obtained for the seismic loads acting in the fore-aft (continuous line) and in side-to-side directions show that fragility is higher for the parked scenario.
- The fragility increases with increasing the operational wind speed for the other operational conditions.

Conclusions

The results of a probabilistic framework for the design of land-based HAWTs subjected to the combined wind and seismic actions are presented. In particular

- The *aerodynamic* and *seismic effects* on the structural model of the HAWT were assessed *decoupling* the aerodynamic behaviour of the rotor from the dynamic response of the support structure.
- The aeroelastic interaction was taken into account through the addition to the structural model of the *aerodynamic damping* evaluated using the closed form solution proposed by Valamanesh and Myers (2014).
- The probabilistic assessment of the peak response of the tower structure was carried out evaluating the empirical and the estimated CDFs of some structural response parameters (tower base maximum bending moment and shear, total drift and top rotation) for the combination of the wind and seismic action.
- The fragility curves for the tower buckling limit state were finally obtained from Monte Carlo simulations of the tower subjected to different wind and seismic loads scenario, using tower base bending moment and total drift as deterministic limit state parameters representative of the structural capacity at ULS and SLS.

The approach here presented could be also used as a part of a complete multi-risk analysis of the land-based structures if the hazard is added to the model.

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COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Wind-wave-structure interaction in Offshore Wind Turbines

Enzo Marino

TU 1304 – WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

Wind-wave-structure interaction in Offshore Wind Turbines

Part 1: *An elementary introduction*

Enzo Marino

Dept. Of Civil and Environmental Engineering

University of Florence

UNIVERSITÀ
DEGLI STUDI
FIRENZE
DICEA
DIPARTIMENTO
DI INGEGNERIA CIVILE
E AMBIENTALE

Outline

- Global figures on Wind Energy capacity
- What is energy?
- WT working principle
- Why Offshore Wind Energy?
- Offshore Wind Turbines: loads and coupled simulations

Outline

- **Global figures on Wind Energy capacity**
- What is energy?
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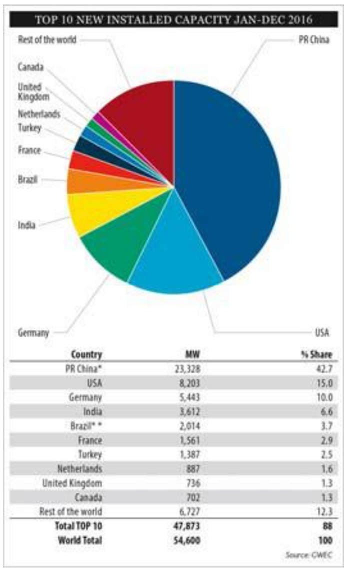
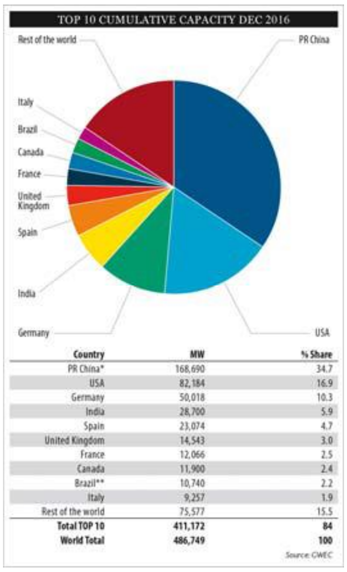
- Offshore Wind Turbines: loads and coupled simulations

Wind energy capacity


TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2016

Country	MW	% Share
PR China*	23,328	42.7
USA	8,203	15.0
Germany	5,443	10.0
India	3,612	6.6
Brazil* *	2,014	3.7
France	1,561	2.9
Turkey	1,387	2.5
Netherlands	887	1.6
United Kingdom	736	1.3
Canada	702	1.3
Rest of the world	6,727	12.3
Total TOP 10	**47,873**	**88**
World Total	**54,600**	**100**

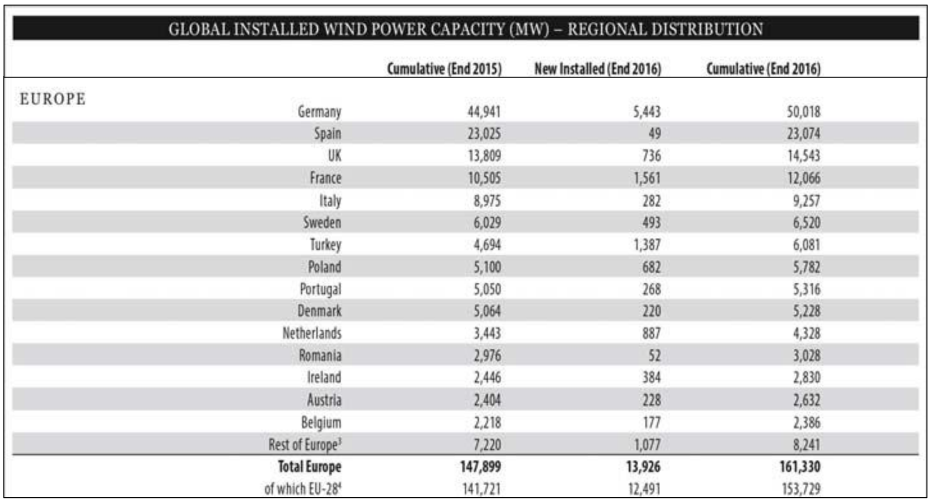
Source: GWEC


TOP 10 CUMULATIVE CAPACITY DEC 2016

Country	MW	% Share
PR China*	168,690	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil**	10,740	2.2
Italy	9,257	1.9
Rest of the world	75,577	15.5
Total TOP 10	**411,172**	**84**
World Total	**486,749**	**100**

Source: GWEC

Wind energy capacity - Europe

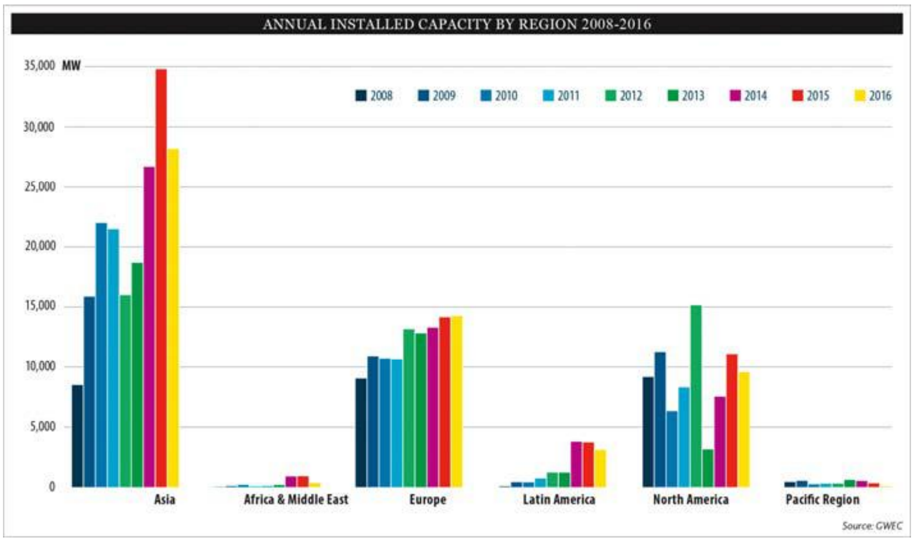


GLOBAL INSTALLED WIND POWER CAPACITY (MW) – REGIONAL DISTRIBUTION

EUROPE	Cumulative (End 2015)	New Installed (End 2016)	Cumulative (End 2016)
Germany	44,941	5,443	50,018
Spain	23,025	49	23,074
UK	13,809	736	14,543
France	10,505	1,561	12,066
Italy	8,975	282	9,257
Sweden	6,029	493	6,520
Turkey	4,694	1,387	6,081
Poland	5,100	682	5,782
Portugal	5,050	268	5,316
Denmark	5,064	220	5,228
Netherlands	3,443	887	4,328
Romania	2,976	52	3,028
Ireland	2,446	384	2,830
Austria	2,404	228	2,632
Belgium	2,218	177	2,386
Rest of Europe[3]	7,220	1,077	8,241
Total Europe	**147,899**	**13,926**	**161,330**
of which EU-28[4]	141,721	12,491	153,729

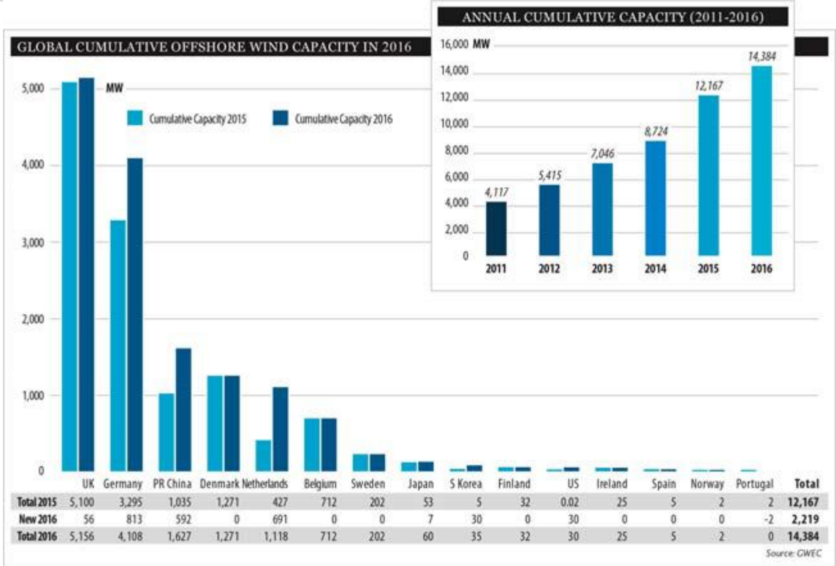
Source: GWEC http://www.gwec.net/global-figures

Wind energy capacity



Source: GWEC

Offshore wind energy capacity



	UK	Germany	PR China	Denmark	Netherlands	Belgium	Sweden	Japan	S Korea	Finland	US	Ireland	Spain	Norway	Portugal	**Total**
Total 2015	5,100	3,295	1,035	1,271	427	712	202	53	5	32	0.02	25	5	2	2	**12,167**
New 2016	56	813	592	0	691	0	0	7	30	0	30	0	0	0	-2	**2,219**
Total 2016	5,156	4,108	1,627	1,271	1,118	712	202	60	35	32	30	25	5	2	0	**14,384**

Source: GWEC

Outline

- Global figures on Wind Energy capacity
- What is energy?
- WT working principle
- Why Offshore Wind Energy (OWE)?
- Offshore Wind Turbines: loads and coupled simulations

The atmospheric boundary layer (ABL)

The ***atmospheric boundary layer*** (ABL) is the lowest part of the atmosphere. It is influenced by its contact with a planetary surface. The thickness of the ABL depends on the roughness of the Earth's surface and ranges from a minimum of about 200 m in the open sea up to a maximum of about 1 km at locations with a high density of tall buildings

The average wind speed within the ABL is variable with altitude, with a maximum equal to the geostrophic velocity at the upper limit, to zero at the ground.

The ***mean wind speed*** increases with the altitude

The ***friction*** between the moving air and the Earth's surface, as well as the friction between layers of air, cause the atmospheric ***turbulence***

What is energy ?

- **Mechanical energy**: is the energy associated with the motion and position of an object – it's given by the sum of *kinetic energy* and *potential energy* present in the components of a mechanical system
- **Mechanical work:** is a quantity that can be described as the product of a force times the distance through which it acts
- **Power:** is the rate at which energy is transferred, used, or transformed (can be seen also as the rate at which **work** is performed)

What is energy ?

Wind possesses kinetic energy!

HOW to EXTRAC this energy?

HOW to transform it into electricity?

⇩

WIND TURBINES

Outline

- Global figures on Wind Energy capacity
- What is energy?
- WT working principle
- Why Offshore Wind Energy (OWE)?
- Offshore Wind Turbines: loads and coupled simulations

Working principle

The primary component of a wind turbine is the energy converter, which transforms the kinetic energy contained in the moving air into mechanical energy.

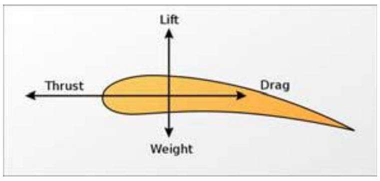
- The air past the rotor makes it rotate (due to the blades shape)
- This means that the interaction of wind with the rotor cerates a torque
- This torque generates mechanical work (torque x rotation)
- The rate of this mechanical work is the power generated by the turbine.
- Unit is watt (W) [10^6 W = 1 MW; 10^9 W = 1 GW]

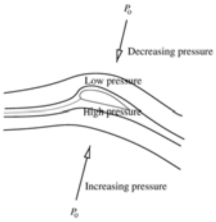
Working principle

How can wind cause blades rotation?

Thanks to the same principle that makes airplanes fly!

*A fluid flowing past the surface of a body exerts surface force on it. The **Lift** is the component of this force perpendicular to the oncoming flow direction*





Lift force results from a pressure difference!

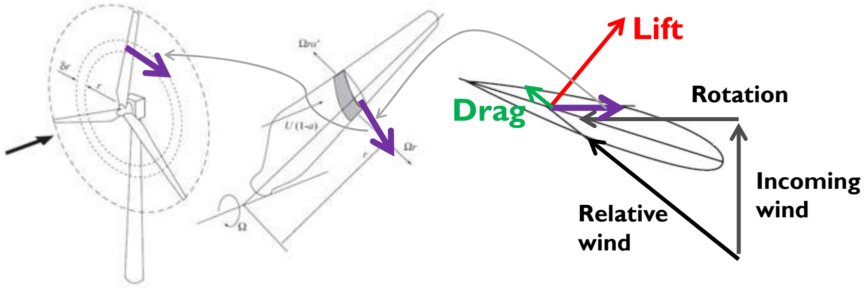
Lift > Weight = Fly!!

Working principle

How can wind cause blades rotation?

Thanks to the same principle that makes airplanes fly!

A fluid flowing past the surface of a body exerts surface force on it. The ***Lift*** *is the component of this force perpendicular to the oncoming flow direction*



Outline

- Global figures on Wind Energy capacity
- WT working principle
- Why Offshore Wind Energy?
- Offshore Wind Turbines: loads and coupled simulations

Why offshore wind energy?

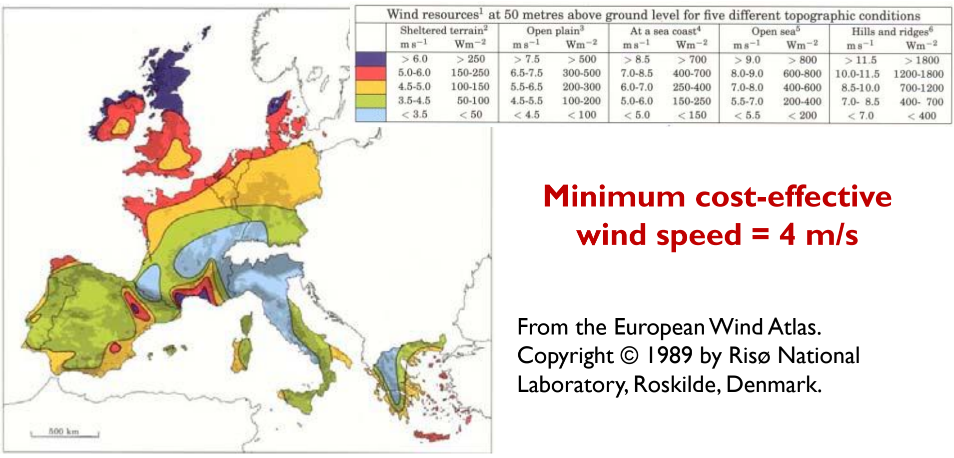
- Lack of space in land in some countries for the development of onshore wind farms
- Wider spaces with resource availability
- Better quality of wind resource: higher wind speed, less turbulence
- Expected general minor impact in the environment with offshore wind farms in comparison with onshore ones
- When far offshore: reduced/eliminated visual and noise impacts

---

Why offshore wind energy? - drawbacks

- Higher costs of the engineering process, construction and operation phases. In onshore wind farms, the cost of wind generator turbines is around 75% total cost of the Project, being this percentage in offshore installations approximately 33%
- Grid connections: need to build longer electrical networks or to strengthen the existing electrical infrastructures
- Lack of highly accurate numerical models to predict the system behaviour

The European onshore wind potential

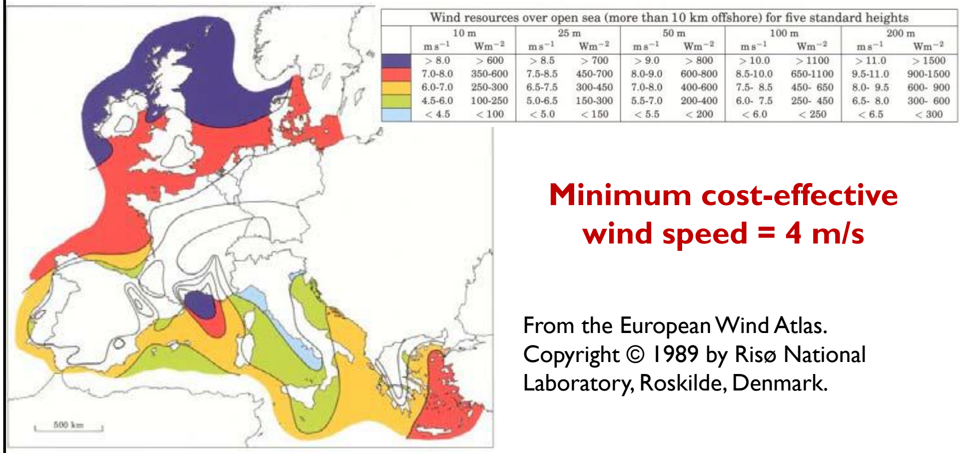


Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
🟪	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
🟥	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
🟨	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
🟩	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
🟦	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Minimum cost-effective wind speed = 4 m/s

From the European Wind Atlas.
Copyright © 1989 by Risø National Laboratory, Roskilde, Denmark.

The European offshore wind 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	
	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$	$\mathrm{m\,s^{-1}}$	$\mathrm{Wm^{-2}}$
🟪	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
🟥	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
🟨	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
🟩	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
🟦	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Minimum cost-effective wind speed = 4 m/s

From the European Wind Atlas.
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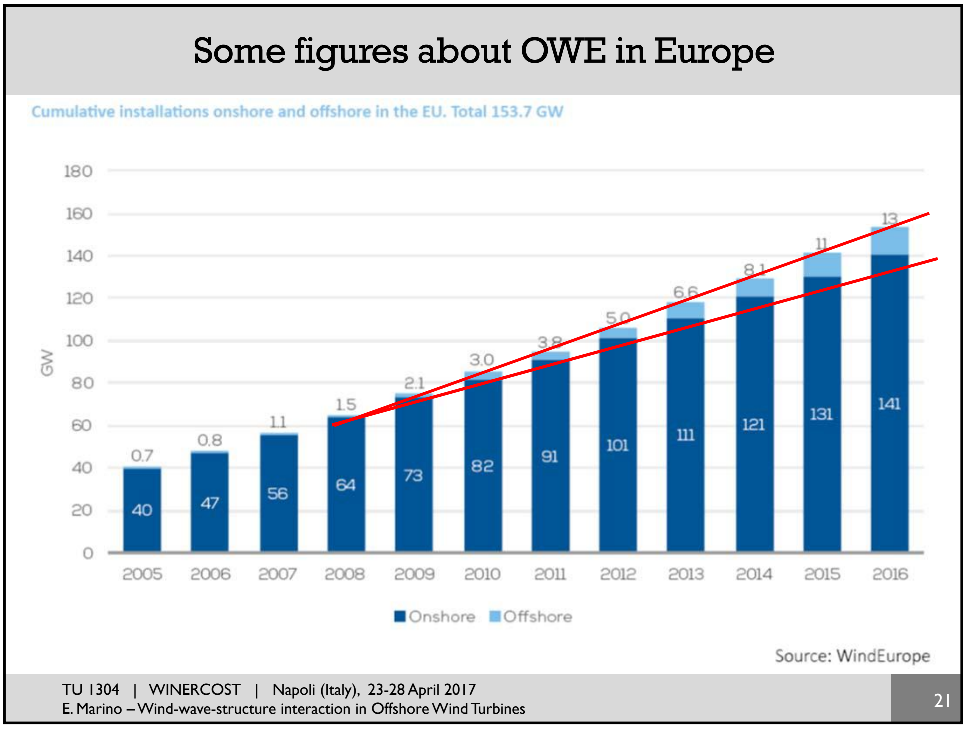
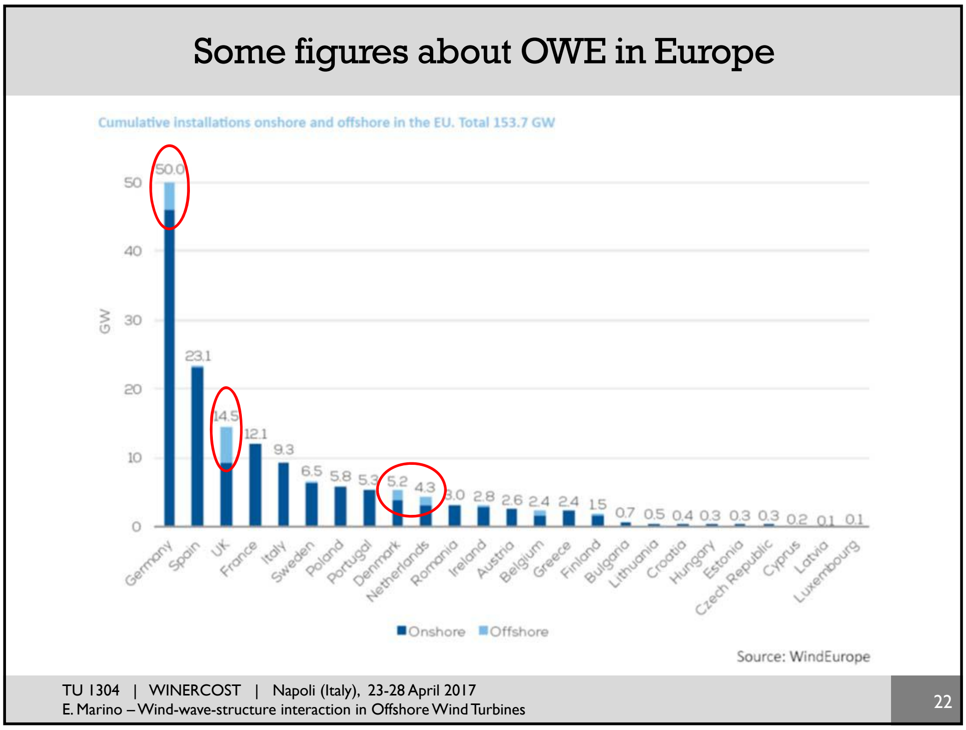


Some figures about OWE in Europe

Cumulative installations onshore and offshore in the EU. Total 153.7 GW

Source: WindEurope



Some figures about OWE in Europe

Cumulative installations onshore and offshore in the EU. Total 153.7 GW

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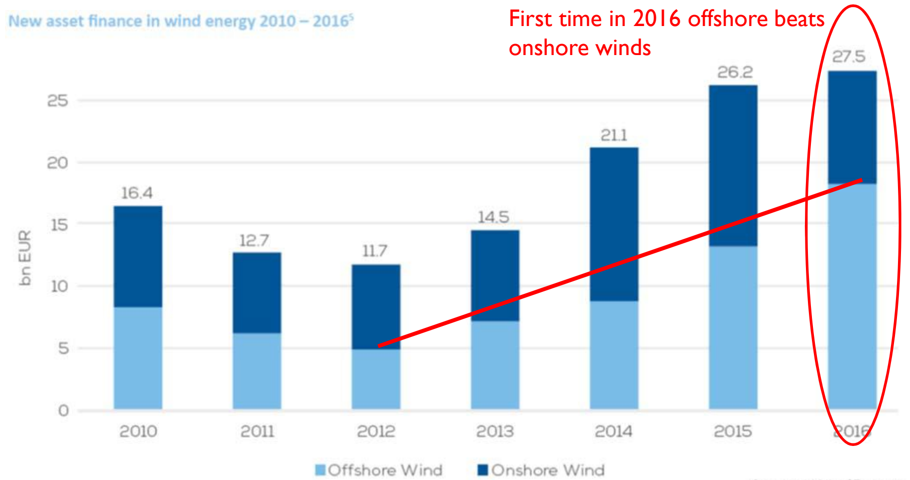
Some figures about OWE in Europe



First time in 2016 offshore beats onshore winds

Source: WindEurope

Outline

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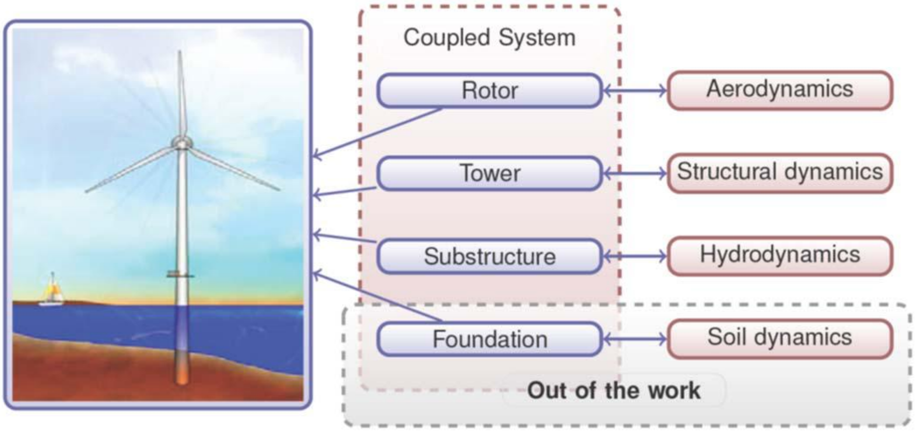
- Offshore Wind Turbines: loads and coupled simulations

Modelling offshore wind turbines



Coupled System

Rotor ↔ Aerodynamics

Tower ↔ Structural dynamics

Substructure ↔ Hydrodynamics

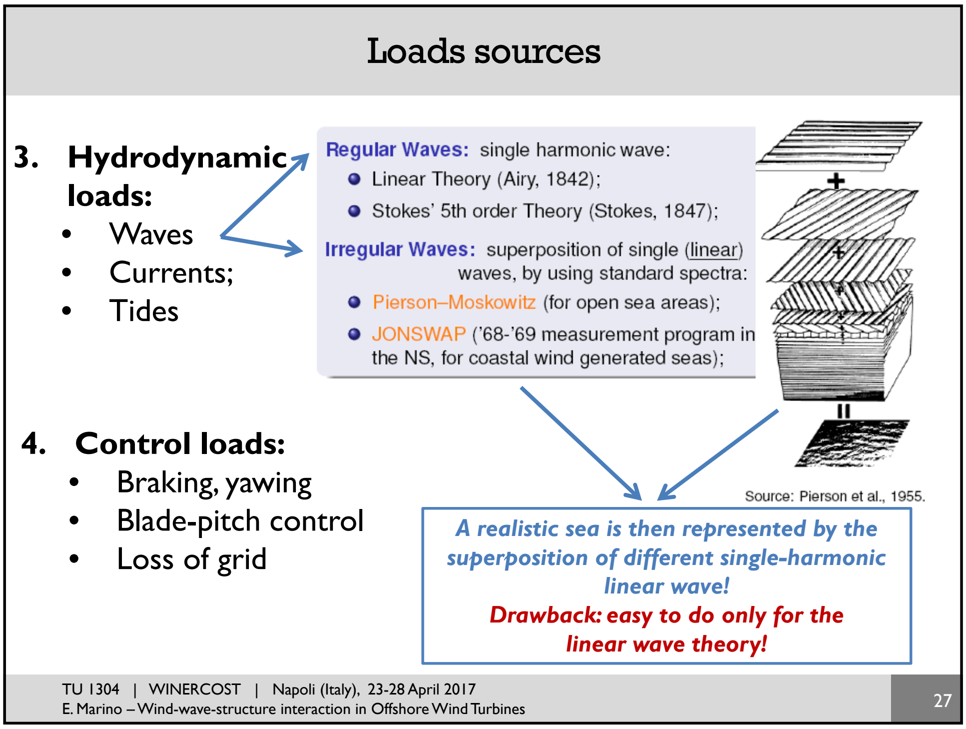
Foundation ↔ Soil dynamics

Out of the work

Loads sources

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;



Loads sources

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

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

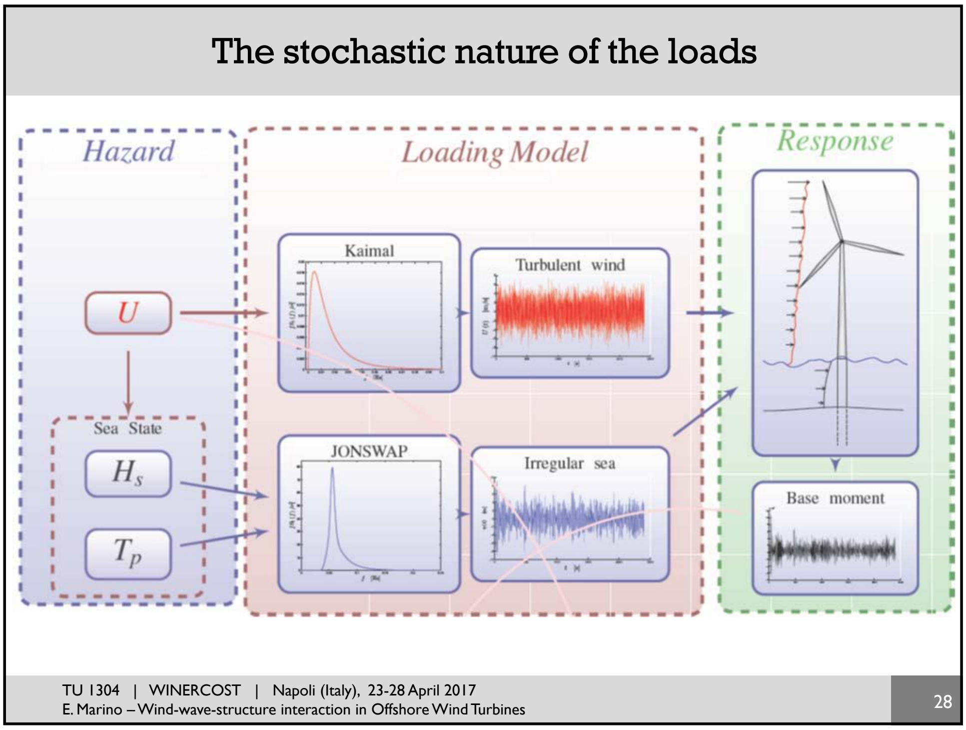
Irregular Waves: superposition of single (linear) waves, by using standard spectra:
- Pierson–Moskowitz (for open sea areas);
- JONSWAP ('68-'69 measurement program in the NS, for coastal wind generated seas);

Source: Pierson et al., 1955.

4. **Control loads:**
   - Braking, yawing
   - Blade-pitch control
   - Loss of grid

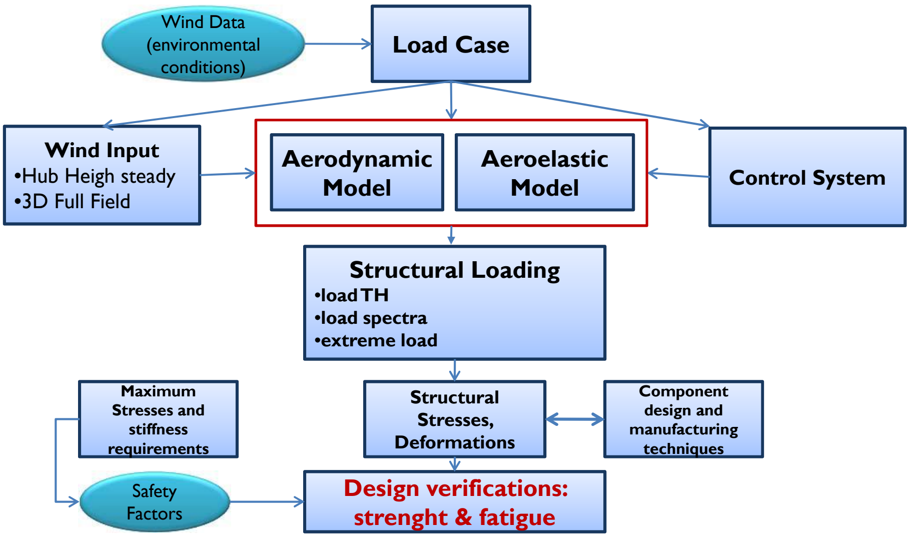
A realistic sea is then represented by the superposition of different single-harmonic linear wave!

Drawback: easy to do only for the linear wave theory!



The stochastic nature of the loads

Simulation layout



Wind Data (environmental conditions)

Load Case

Wind Input
- Hub Heigh steady
- 3D Full Field

Aerodynamic Model

Aeroelastic Model

Control System

Structural Loading
- load TH
- load spectra
- extreme load

Maximum Stresses and stiffness requirements

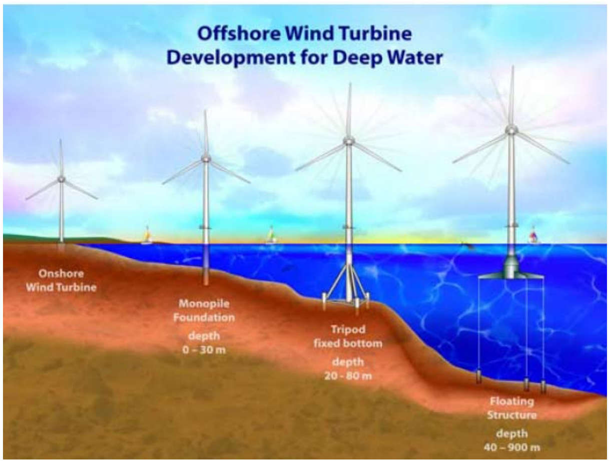
Structural Stresses, Deformations

Component design and manufacturing techniques

Safety Factors

Design verifications: strenght & fatigue

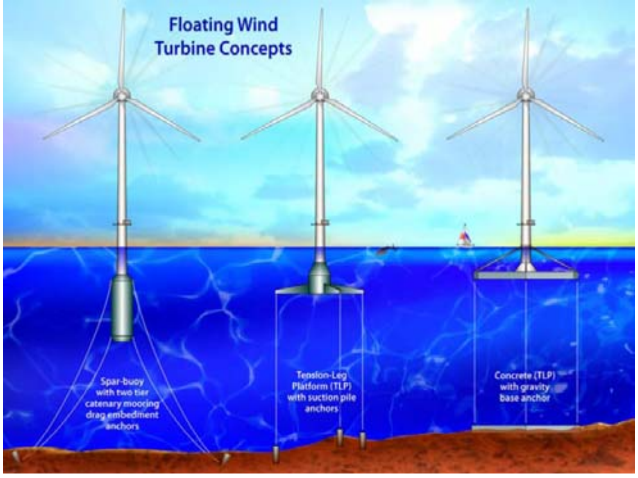
From onshore to the deep waters



- 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.

M. Robinson, W. Musial. Offshore Wind Technology Overview. NWT NREL/PR-500-40462. October 2006.
https://www.nrel.gov/docs/gen/fy07/40462.pdf

Three main types of floating systems



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

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

Source: J. M. Jonkman and M. L. Buhl Jr., “Development and verification of a fully coupled simulator for offshore wind turbines,” in 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2007, pp. 28–53.

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Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28 April 2017

Wind-wave-structure interaction in Offshore Wind Turbines

Part 2: basic aerodynamics, nonlinear wave loads, dynamics

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UNIVERSITÀ
DEGLI STUDI
FIRENZE
DICEA
DIPARTIMENTO
DI INGEGNERIA CIVILE
E AMBIENTALE

Outline

- Aerodynamics: the actuator disc concept
- Linear, weakly and fully nonlinear wave models
- Hydrodynamic loading models
- Coupled simulations and effects of nonlinear waves
- References

Outline

- Aerodynamics: the actuator disc concept
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- References

Aerodynamics: Blade Element Momentum theory I

The primary goal of a wind turbine is to subtract kinetic energy from the wind to transform it first into mechanical energy and then into electrical energy.
Axial momentum :mass flow conservation imposes that

$$Q_\infty = Q_d = Q_w \tag{1}$$

where the subscripts ∞, d and w denote the upstream, disc and wake wind velocities.

Aerodynamics: Blade Element Momentum theory II

Equation (1) can also be written as follows

$$A_\infty U_\infty = A_d U_d = A_w U_w \tag{2}$$

Newton's second law can be naturally applied at the disc by introducing the momentum $K = mU$. At the disc the momentum rate writes as $\dot{K}_d = \rho A_d U_d U$. Thus throughout the disc the momentum rate experiences an overall change given by

$$\Delta \dot{K}_d = \rho A_d U_d \Delta U = \rho A_d U_d \left(U_\infty - U_w\right) \tag{3}$$

and consequently the total forces acting at the disc, basically given by the pressure, must equal

$$A_d \left(p_d^+ - p_d^-\right) = \rho A_d U_d \left(U_\infty - U_w\right) \tag{4}$$

Aerodynamics: Blade Element Momentum theory III

Now, by introducing the *axial flow induction factor* a, which permits to express the velocity at the disc through the far upstream undisturbed velocity U_∞ as $U_d = U_\infty\,(1-a)$, equation (4) turns into

$$\Delta p_d = \rho U_\infty\,(1-a)\,(U_\infty - U_w) \tag{5}$$

The pressure gradient Δp_d can be computed by using twice Bernoulli's equation (once between the upstream undisturbed section and the disc section and once between the disc and the wake sections). This leads to

$$\boxed{p + \rho g h + \frac{\rho U^2}{2} = const.}$$

$$\Delta p_d = \frac{1}{2}\rho\left(U_\infty^2 - U_w^2\right) \tag{6}$$

which replaced into equation (4) finally gives

$$U_w = (1-2a)\,U_\infty \tag{7}$$

Aerodynamics: Blade Element Momentum theory IV

Next, by making use of equation (7) into (4), the total force acting at the rotor disc (the thrust) is given by

$$F_d = 2\rho A_d U_\infty^2 a\,(1-a) \tag{8}$$

The cube of free stream velocity U appears!!
Rem. the wind Atlas… How important is the site-specific wind velocity!

The power developed is

$$P_{yield} = F_d U_d = 2\rho A_d U_\infty^3 a\,(1-a)^2 \tag{9}$$

Machines can only extract a share given by the so called *power coefficient* C_p defined as follows

$$C_p = \frac{P_{yield}}{\frac{1}{2}\rho U_\infty^3 A_d} = 4a\,(1-a)^2 \tag{10}$$

The above coefficient is maximum (Bet's limit.) when $a = 1/3$, therefore we have

$$C_{p_{\max}} = 0.593 \tag{11}$$

Outline

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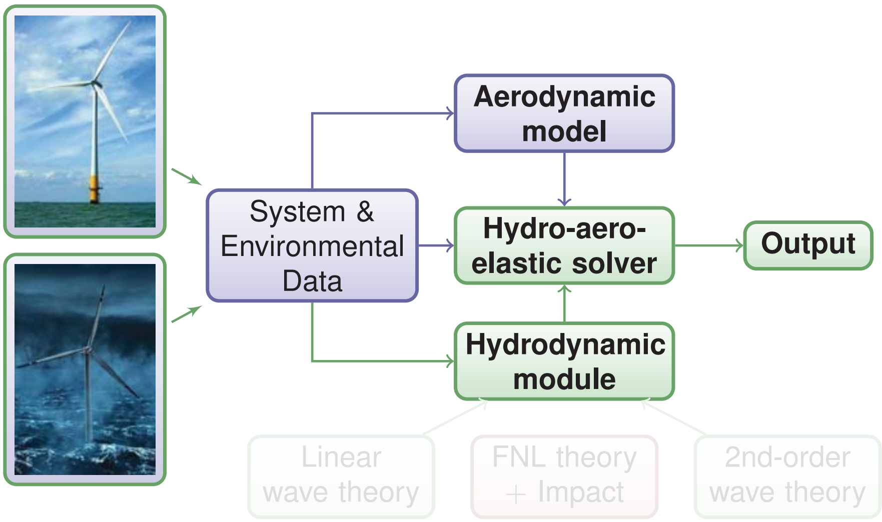
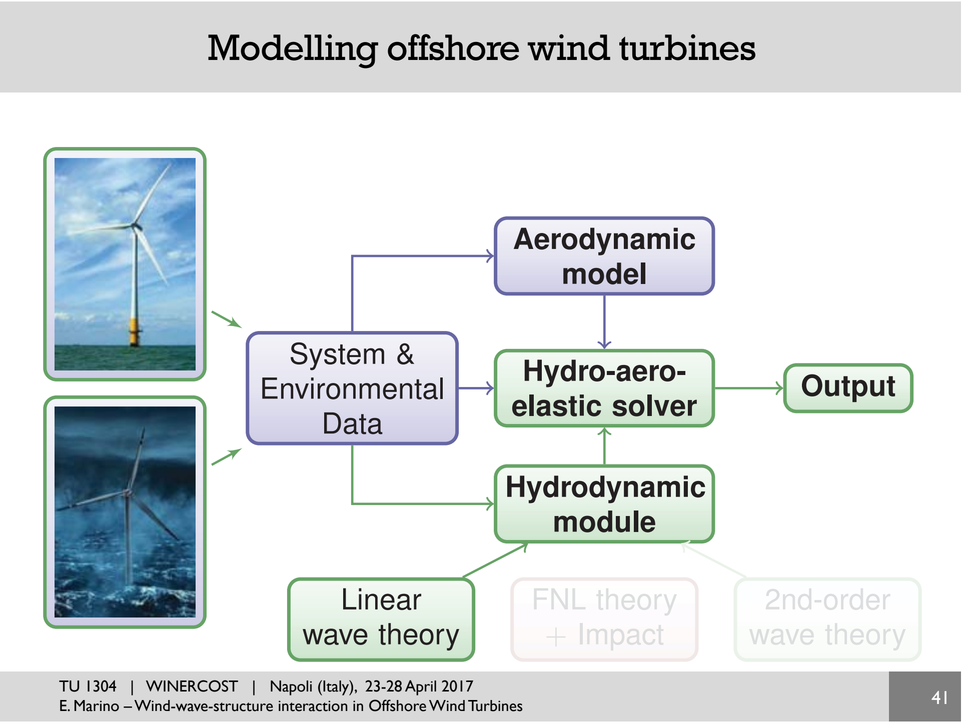
Modelling offshore wind turbines





Modelling offshore wind turbines

System & Environmental Data

Aerodynamic model

Hydro-aero-elastic solver

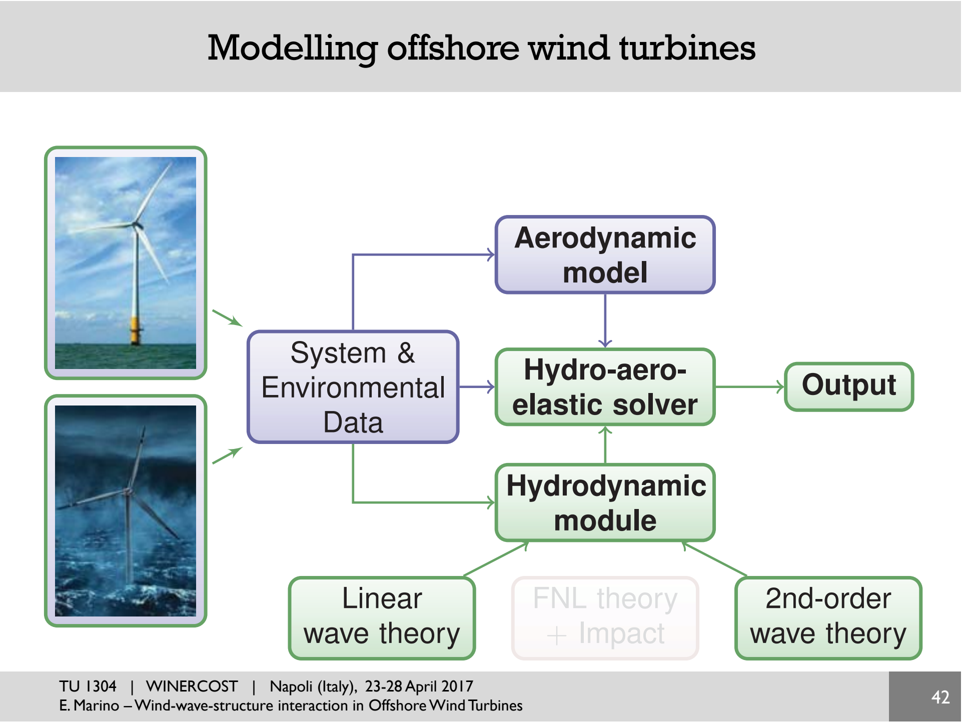
Output

Hydrodynamic module

Linear wave theory

FNL theory + Impact

2nd-order wave theory



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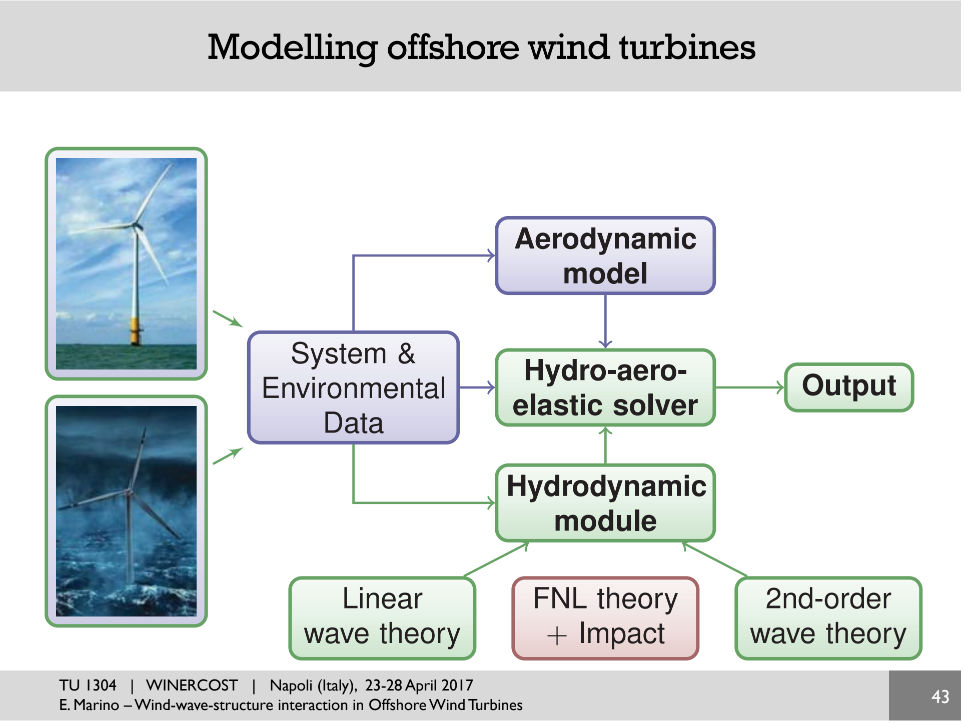

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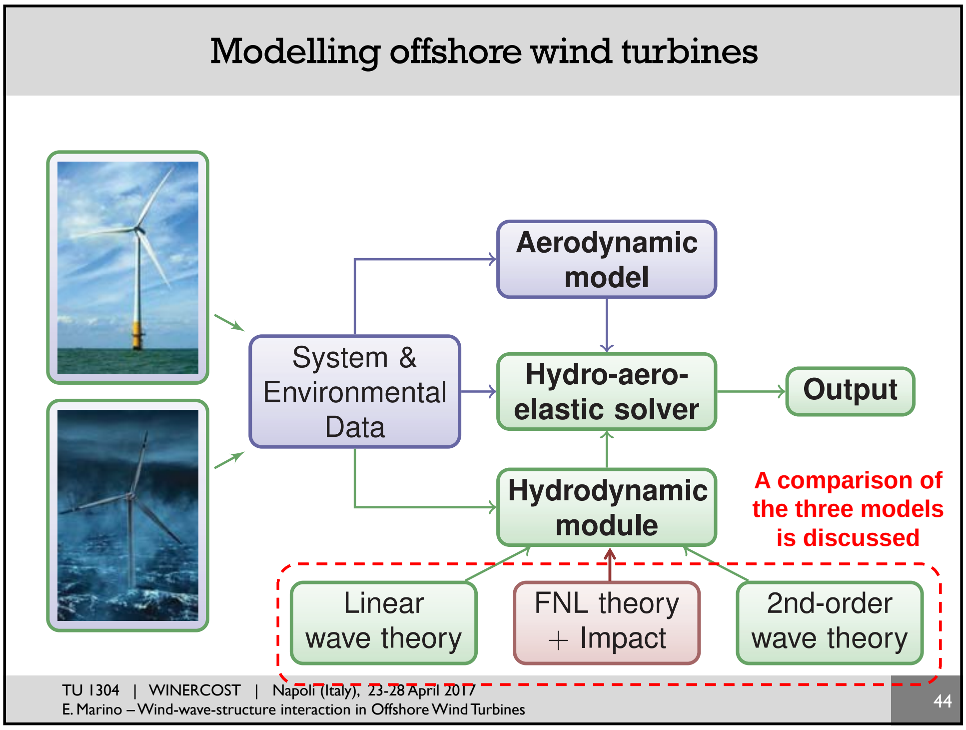


Modelling offshore wind turbines

Aerodynamic model

System & Environmental Data

Hydro-aero-elastic solver

Output

Hydrodynamic module

A comparison of the three models is discussed

Linear wave theory

FNL theory + Impact

2nd-order wave theory

Water waves: governing equations

- Continuity equation (Mass conservation)

$$\frac{D\rho}{Dt} + \rho \mathrm{div}\bar{v} = 0 \qquad (17)$$

- Balance equation

$$\mathrm{div}(\sigma(p,\bar{n})) + \rho\bar{f} - \rho\frac{D\bar{v}}{Dt} = 0 \qquad (18)$$

$$\sigma(p,\bar{n}) = \sigma(p,\bar{n})^T \qquad (19)$$

- Constitutive equation (for Newtonian fluids)

$$\sigma(p,\bar{n}) = (-p - \frac{2}{3}\mu\bar{\nabla}\cdot\bar{v})\bar{\bar{I}} + 2\mu\bar{\bar{D}} \qquad (20)$$

where p is the hydrostatic pressure, $\bar{f}$ is the body (mass) force, $D_{ij} = 1/2(v_{i,j} + v_{j,i})$ is the strain rate tensor, μ is the dynamic viscosity;

Water waves: governing equations

Hypotheses:

1. Homogeneity: $\rho = \mathrm{const}$;
2. Incompressibility: $\mathrm{tr}(\bar{\bar{D}}) = \nabla \cdot \bar{v} = 0$ (consequence of homogeneity (from mass conservation)!);
3. Inviscid fluid: $\mu = 0$;

Therefore, we obtain the Euler equations:

$$\rho \mathrm{div}\bar{v} = 0$$

$$\mathrm{div}(\sigma(p,\bar{n})) + \rho\bar{f} - \rho\frac{D\bar{v}}{Dt} = 0$$

$$\sigma(p,\bar{n}) = -p\bar{\bar{I}}$$

Water waves: governing equations

Under the additional hypothesis that the flow is IRROTATIONAL:

$$\text{curl}\bar{v} = \bar{\nabla} \times \bar{v} = 0$$

the velocity field becomes

$$\bar{v} = \nabla\phi$$

where ϕ is called *velocity potential*.
In the balance equation the total derivative is $\frac{D\bar{v}}{Dt} = \frac{\partial\bar{v}}{\partial t} + (\nabla\bar{v})\,\bar{v}$, where the second term $(\nabla\bar{v})\,\bar{v} = \text{curl}\,(\bar{v}) \times \bar{v} + \frac{1}{2}\nabla\bar{v}^2$ simplifies due to vanishing of the curl. The continuity equations becomes:

$$\nabla^2\phi = 0$$

The balance equation becomes (conservative body force $\bar{f} = -\text{grad}(gy)$) :

$$-\frac{p}{\rho} - gy - \frac{\partial\phi}{\partial t} - \frac{1}{2}\nabla\phi \cdot \nabla\phi = 0$$

Water waves: governing equations

Laplace's equation

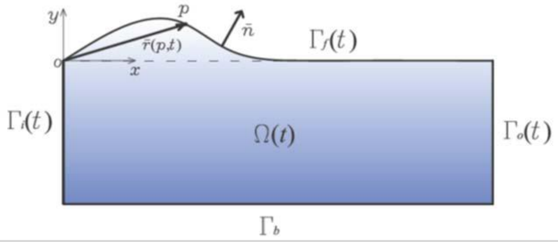
$$\nabla^2\phi\,(p,t) = 0 \quad \forall p, t \in \Omega\,(t)$$

Free Surface Dynamic Boundary Condition (FSDBC)

$$\frac{D\phi\,(p,t)}{Dt} = -\frac{p_a}{\rho} - gy_f + \frac{1}{2}\nabla\phi\,(p,t) \cdot \nabla\phi\,(p,t) \quad \forall p, t \in \Gamma_f\,(t)$$

Free Surface Kinematic Boundary Condition (FSKBC)

$$\frac{D\bar{r}\,(p,t)}{Dt} = \bar{v}\,(p,t) = \nabla\phi\,(p,t) \quad \forall p, t \in \Gamma_f(t)$$



Space discretization: Boundary Element Method I

Laplace's equation together with the boundary and initial conditions represents a Boundary Value Problem (BVP) whose approximate solution is obtained by means of weighted residual methods.

Assume $\phi(p)$ is an approximate solution of Laplace's problem defined on a domain Ω. We have $\nabla\phi(p) \neq 0$.

The error induced by the approximate solution can be minimized as follows

$$\int_{\Omega} \nabla^2 \phi(p) \phi^* = 0 \qquad (21)$$

where ϕ^* is the weighting function.

By choosing as weighting function the Green function

$$\phi^*(p, p_c) = \frac{1}{2\pi} \ln \frac{1}{R} \qquad (22)$$

where $R = \sqrt{(x_p - x_{p_c})^2 + (y_p - y_{p_c})^2}$ is the distance between the point p and the collocation point p_c, we obtain the so called Boundary Integral Equation

Space discretization: Boundary Element Method II

The Boundary Integral Equation

$$c(p_c)\,\phi(p_c) + \int_{\Gamma} \phi(p)\, q^*(p, p_c)\, \mathrm{d}\Gamma - \int_{\Gamma} \phi^*(p, p_c)\, q(p)\, \mathrm{d}\Gamma = 0 \qquad (23)$$

where

$$q(p) = \nabla\phi(p) \cdot \bar{n} \qquad (24)$$

$$q^*(p, p_c) = \nabla\phi^*(p, p_c) \cdot \bar{n} \qquad (25)$$

are respectively the flux (normal velocity component) and the normal derivative of the Green function.

The coefficient $c(p_c)$ depends on the location of the collocation point p_c.

Space discretization: Boundary Element Method V

The boundary integral equation (23) is discretized into *NE* isoparametric quadratic elements in such a way nodal values belonging to *j*–th element are approximated as follows

$$\phi^{(j)} = \sum_{k=1}^{3} \varphi_k(s)\, \phi_k^{(j)} \quad \text{end} \quad q^{(j)} = \sum_{k=1}^{3} \varphi_k(s)\, q_k^{(j)}$$

so that BIE becomes

$$c(p_c)\,\phi(p_c) + \sum_{j=1}^{NE} \int_{\Gamma_j} \sum_{k=1}^{3} \varphi_k(s)\, \phi_k^{(j)} q_{p_c}^{*(j)} \mathrm{d}\Gamma + - \sum_{j=1}^{NE} \int_{\Gamma_j} \sum_{k=1}^{3} \varphi_k(s)\, q_k^{(j)} \phi_{p_c}^{*(j)} \mathrm{d}\Gamma$$

where

$$q_{p_c}^{*(j)} = - \frac{\left(x^{(j)} - x_{p_c}\right) n_x^{(j)} + \left(y^{(j)} - y_{p_c}\right) n_y^{(j)}}{2\pi \left[\left(x^{(j)} - x_{p_c}\right)^2 + \left(y^{(j)} - y_{p_c}\right)^2\right]} \tag{26}$$

$$\phi_{p_c}^{*(j)} = - \frac{1}{4\pi} \ln \left[\left(x^{(j)} - x_{p_c}\right)^2 + \left(y^{(j)} - y_{p_c}\right)^2\right] \tag{27}$$

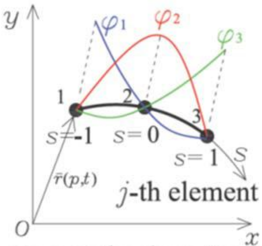
Space discretization: Boundary Element Method IV

The quadratic shape functions are

$$\varphi_1(s) = \frac{1}{2} s (s - 1)$$

$$\varphi_2(s) = (1 - s)(1 + s)$$

$$\varphi_3(s) = \frac{1}{2} s (1 + s)$$



The BIE can be transformed into integrals over the shape functions domain $[-1, 1]$ as follows

$$c(p_c)\,\phi(p_c) + \sum_{j=1}^{NE} \int_{-1}^{1} \sum_{k=1}^{3} \varphi_k(s)\, \phi_k^{(j)} q_{p_c}^{*(j)}(s)\, \mathcal{J}^{(j)}(s) \mathrm{d}s +$$

$$- \sum_{j=1}^{NE} \int_{-1}^{1} \sum_{k=1}^{3} \varphi_k(s)\, q_k^{(j)} \phi_{p_c}^{*(j)}(s)\, \mathcal{J}^{(j)}(s) \mathrm{d}s = 0 \tag{28}$$

Space discretization: Boundary Element Method VI

If the collocation point p_c assumes in turn all NN boundary nodes, the above equation becomes

$$c_i\phi_i + \sum_{j=1}^{NE}\sum_{k=1}^{3} h_{ik}^{(j)}\phi_k^{(j)} - \sum_{j=1}^{NE}\sum_{k=1}^{3} g_{ik}^{(j)} q_k^{(j)} = 0 \qquad i = 1 : NN \qquad (29)$$

that is

$$\begin{aligned} c_i\phi_i &+ h_{i1}^{(1)}\phi_1^{(1)} + h_{i2}^{(1)}\phi_2^{(1)} + h_{i3}^{(1)}\phi_3^{(1)} + \ldots + h_{i1}^{(NE)}\phi_1^{(NE)} + h_{i2}^{(NE)}\phi_2^{(NE)} + h_{i3}^{(NE)}\phi_3^{(NE)} + \\ &- g_{i1}^{(1)}\phi_1^{(1)} - g_{i2}^{(1)}\phi_2^{(1)} - g_{i3}^{(1)}\phi_3^{(1)} - \ldots - g_{i1}^{(NE)}\phi_1^{(NE)} - g_{i2}^{(NE)}\phi_2^{(NE)} - g_{i3}^{(NE)}\phi_3^{(NE)} = 0 \end{aligned}$$

where it has been set

$$h_{ik}^{(j)} = \int_{-1}^{1} q_i^{*(j)}(s)\,\varphi_k(s)\,\mathcal{J}^{(j)}(s)\mathrm{d}s$$

$$g_{ik}^{(j)} = \int_{-1}^{1} \phi_i^{*(j)}(s)\,\varphi_k(s)\,\mathcal{J}^{(j)}(s)\mathrm{d}s$$

The number NN of boundary nodes is given by $NN = 2NE+$number of corners of the domain Ω.

Space discretization: Boundary Element Method VII

Finally, equation (29) can be rewritten in matrix form as follows

$$c_i\phi_i + \hat{H}_{iq}\phi_q = G_{iq}q_q \qquad (30)$$

for which

$$H_{iq}\phi_q = G_{iq}q_q \qquad (31)$$

where $H_{iq} = c_i\delta_{iq} + \hat{H}_{iq}$ and e $i = 1 : NN$ and $q = 1 : 3NE$.
After the "assembling", the system needs to be rearranged according to the boundary condition type in order to get an algebraic system in the standard form

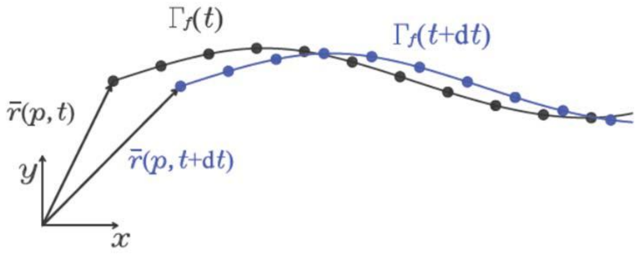
$$A_{ij}X_j = b_i$$

where all the unknown are collected in $\bar{X}$ and all the known terms, among velocity potential and flux, are collected in $\bar{b}$.

Time discretization

To integrate the FSKBC and FSDBC:

$$\bar{r}(p,t+\mathrm{d}t)=\bar{r}(p,t)+\frac{D\bar{r}(p,t)}{Dt}\mathrm{d}t+\frac{1}{2}\frac{D^2\bar{r}(p,t)}{Dt^2}\mathrm{d}t^2+o\left(\mathrm{d}t^2\right)$$
$$\phi(p,t+\mathrm{d}t)=\phi(p,t)+\frac{D\phi(p,t)}{Dt}\mathrm{d}t+\frac{1}{2}\frac{D^2\phi(p,t)}{Dt^2}\mathrm{d}t^2+o\left(\mathrm{d}t^2\right)$$

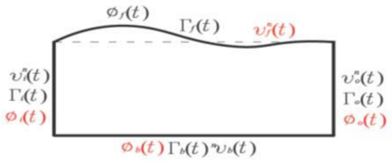


Method of solution: 2–step MEL scheme

It consists in a repeated two–steps procedure: at a fixed time t:

1. $\Gamma_f(t), \Gamma_i(t), \Gamma_b(t), \Gamma_o(t)$
   $\phi_f(t), v_i^n(t), v_b^n(t), v_o^n(t)$
   (known quantities)

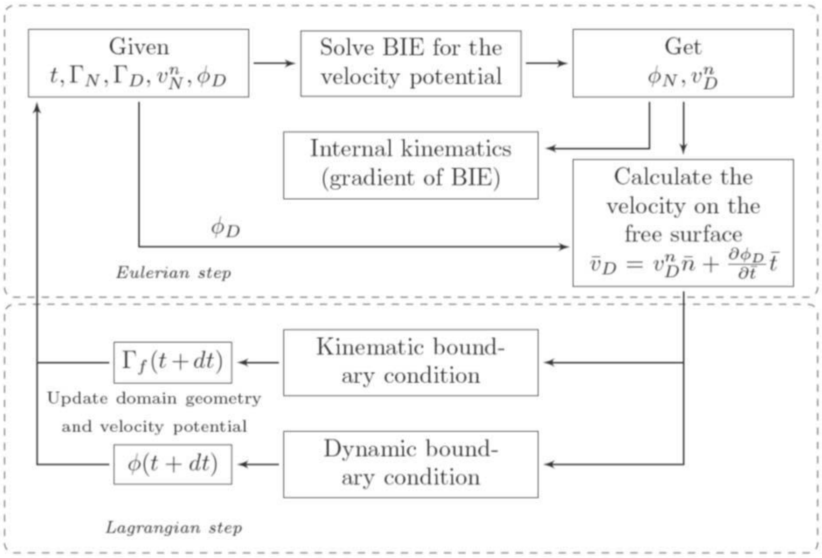
   Solve two BVPs for:
   $\phi_i(t), \phi_b(t), \phi_o(t), v_f^n(t)$
   $\dot{\phi}_i(t), \dot{\phi}_b(t), \dot{\phi}_o(t), \dot{v}_f^n(t)$.
2. Update $\phi_f(t+\mathrm{d}t)$ and $\bar{r}_f(t+\mathrm{d}t)$;



More details on the nonlinear High-Order BEM formulation for nonlinear waves are available in: Marino, E. (2011). *An integrated nonlinear wind-waves model for offshore wind turbines*. Firenze University Press.

(Open access at http://www.fupress.com/catalogo/an-integrated-nonlinear-wind-waves-model-for-offshore-wind-turbines/2237).

2–step MEL scheme – solver flowchart



Linear (Airy) wave theory

Linearization of te dynamic BC leads to: $\dfrac{\partial \phi}{\partial t} + g\eta = 0\ for\ z = \eta(x,t)$

Linearization of te kinematic BC leads to: $\dfrac{\partial \eta}{\partial t} = \dfrac{\partial \phi}{\partial z}\ for\ z = \eta(x,t)$

The surface elevation satisfying the above bs takes the following form:

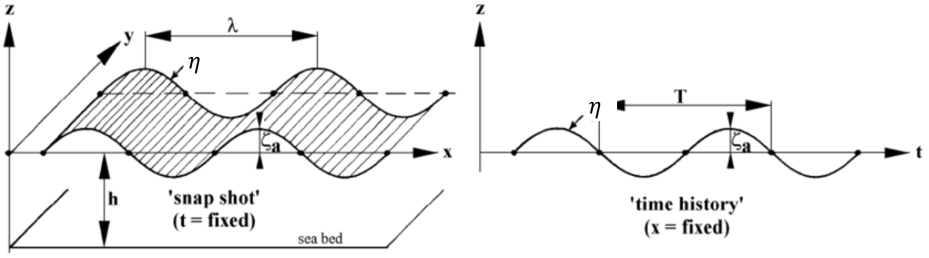
$$\eta(x,t) = A\cos(kx - \omega t)$$

The potential satisfying the above bcs takes the following form:

$$\phi(x,z,t) = \frac{Ag}{\omega}(\cosh k(d+z)/\cosh kd)\sin(kx - \omega t)$$

Where A is the wave amplitude, d is the water depth, ω is the circular frequency and k the wave number.

Linear (Airy) wave theory



Where λ is the wave length and T is the wave period

$$k\lambda = 2\pi \qquad \text{or:} \qquad k = \frac{2\pi}{\lambda}$$

$$\omega T = 2\pi \qquad \text{or:} \qquad \omega = \frac{2\pi}{T}$$

Wave frequency and wavelength are related by means of the dispersion relation:

$$\omega^2 = gd\tanh(kd)$$

$$\omega^2 = gd$$ (for deep waters where $\tanh(kd) \simeq 1$)

Linear and 2nd-order irregul waves

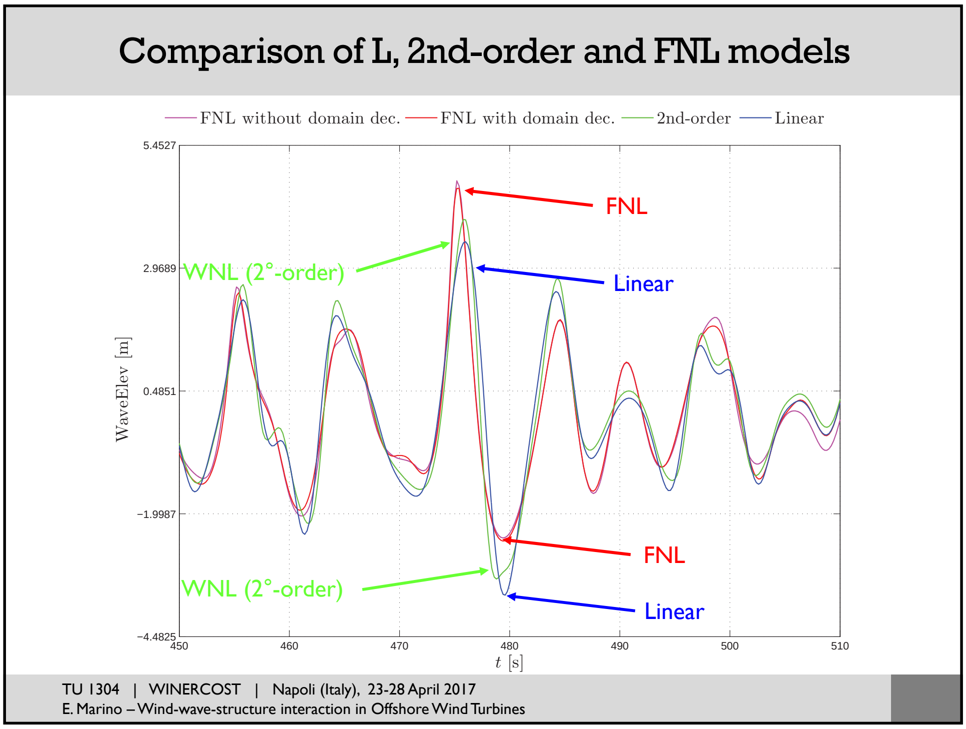
Linear wave theory

$$\eta_1(t) = \sum_{m=1}^{N} A_m \cos(\omega_m t - \phi_m)$$

II-order wave theory

$$\begin{cases} \eta_2(t) = \eta_2^-(t) + \eta_2^+(t) \\ \eta_2^{\pm}(t) = \sum_{m=1}^{N}\sum_{n=1}^{N}[A_m A_n\{B_{mn}^{\pm}\cos((\Psi_m \pm \Psi_n)\}] \end{cases}$$

where $\Psi_m = \omega_m t - \phi_m$ and $\Psi_n = \omega_n t - \phi_n$. A_m, A_n, ω_m and ω_n are, respectively, the amplitude and the circular frequency of the m–th and n–th wave components. B_{mn}^- and B_{mn}^+ are the second order transfer functions [16]. Similarly, the second–order velocity potential is obtained as a sum of a first order and a second order term $\Phi(t) = \Phi_1(t) + \Phi_2(t)$. $\Phi_2(t)$ is defined by differences and sums of frequencies: $\Phi_2 = \Phi_2^- + \Phi_2^+$



Comparison of L, 2nd-order and FNL models

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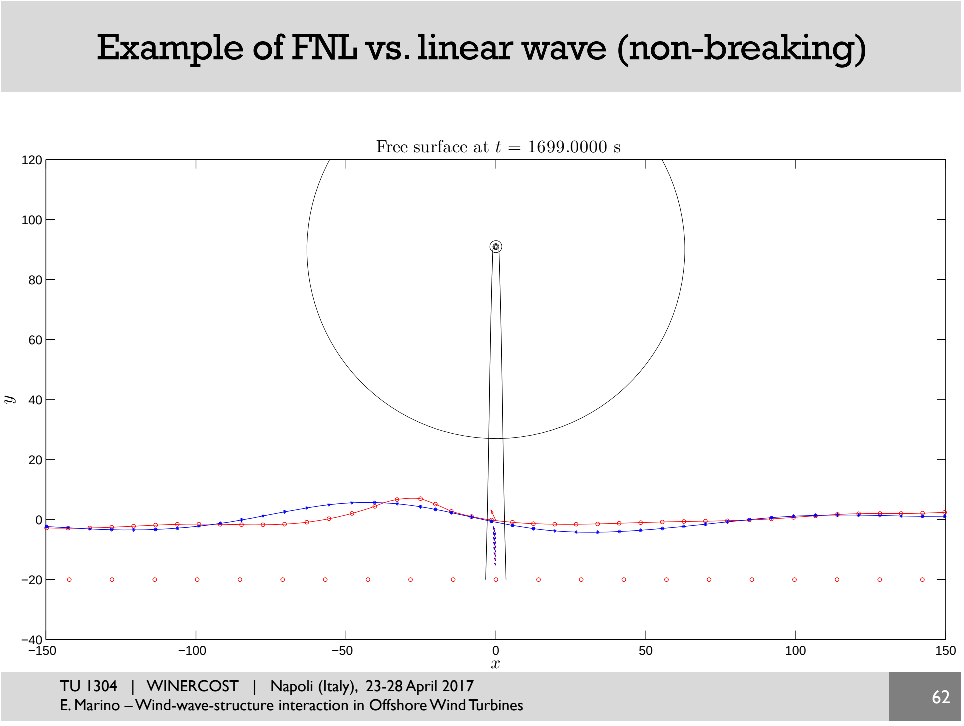
E. Marino – Wind-wave-structure interaction in Offshore Wind Turbines



Example of FNL vs. linear wave (non-breaking)

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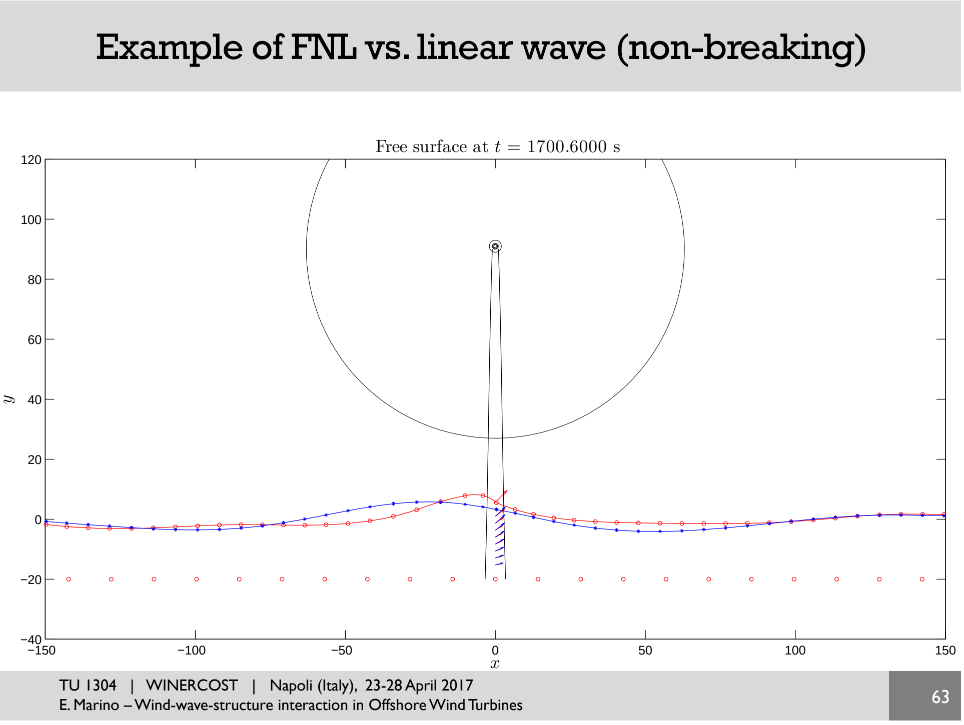
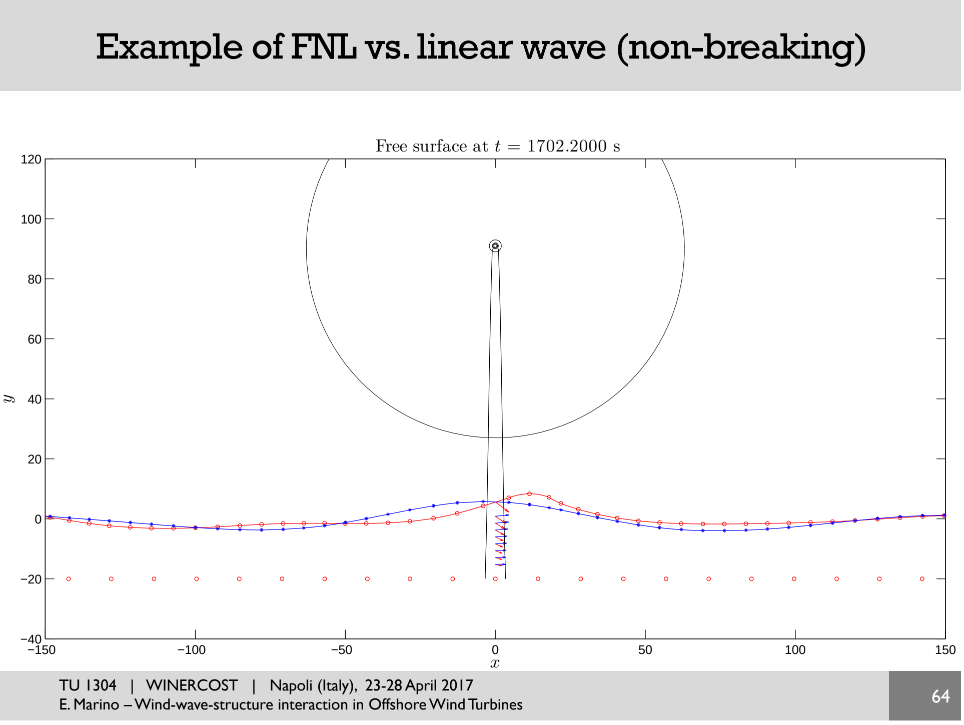
E. Marino – Wind-wave-structure interaction in Offshore Wind Turbines



Example of FNL vs. linear wave (non-breaking)

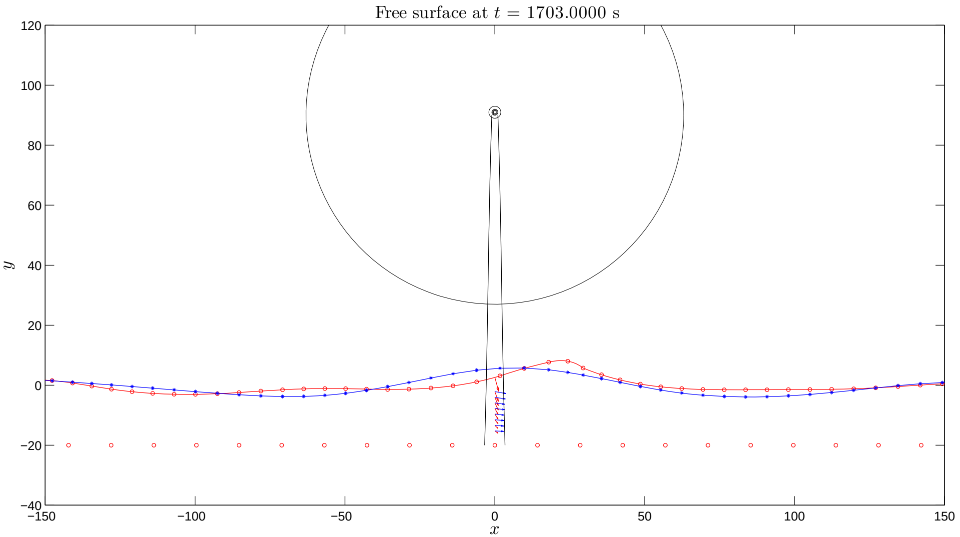
Free surface at t = 1700.6000 s



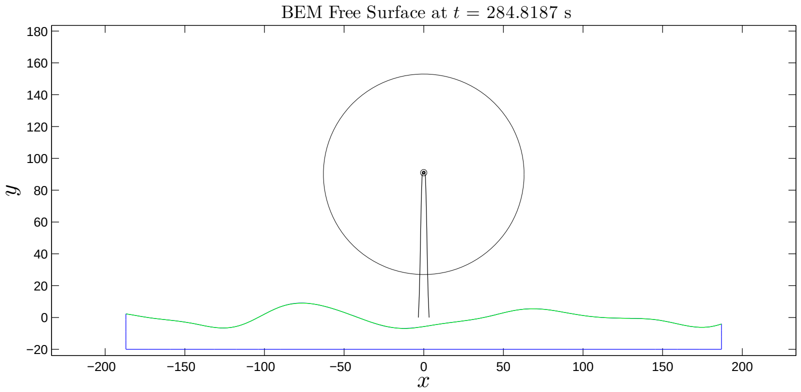
Example of FNL vs. linear wave (non-breaking)

Free surface at t = 1702.2000 s

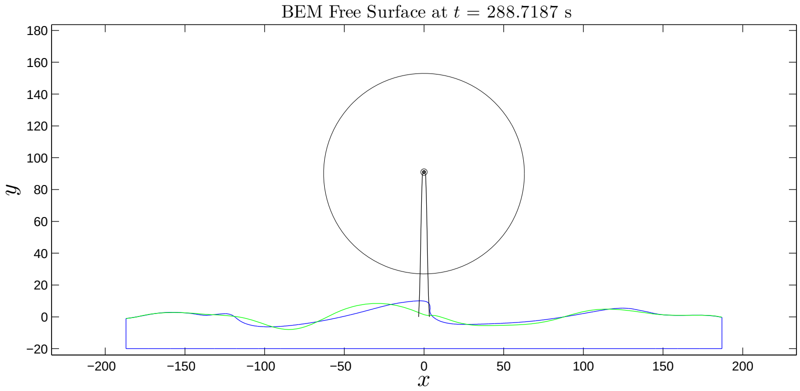
Example of FNL vs. linear wave (non-breaking)



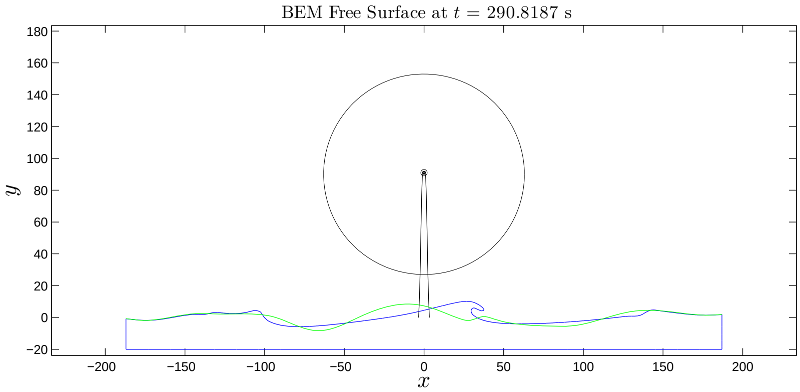
Example of FNL vs. linear wave (breaking)



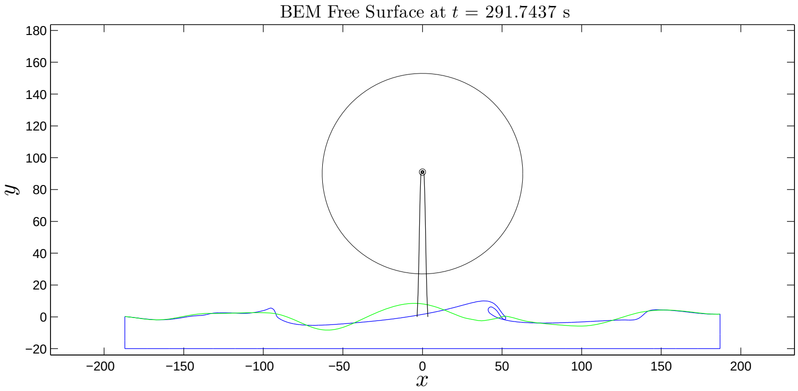
Example of FNL vs. linear wave (breaking)



Example of FNL vs. linear wave (breaking)



Example of FNL vs. linear wave (breaking)



Outline

- Aerodynamic model (basics)
- Linear, weakly and fully nonlinear wave models
- Hydrodynamic loading models
- Coupled simulations and effects of nonlinear waves
- References

Loading models

Loading Model

ULTIMATE

Extreme wind–waves

1. Extreme Turbulent Wind Model
2. Highly nonlinear waves
3. Breaking waves occur
4. Hydrodynamic Model:

$$F(t) = F_D(t) + F_M(t) + F_I(t)$$

(e.g. Wienke & Oumeraci, 2005)

FATIGUE

Operational conditions

1. Normal Turbulence Wind Model ($U_{in} \leq U \leq U_{out}$)
2. Linear waves are suitable
3. Hydrodynamic Model:

$$F(t) = F_D(t) + F_M(t)$$

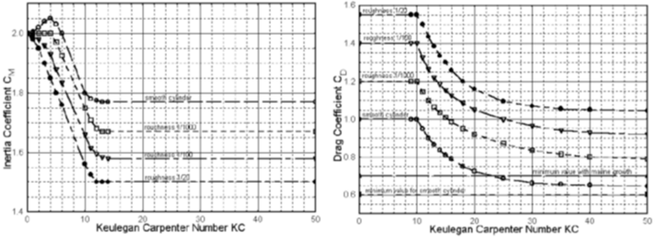
(Morison's equation, 1950)

Morison equation for a fixed cylinder

$$F(t) = F_{inertia}(t) + F_{drag}(t)$$

$$\boxed{F(t) = \frac{\pi}{4}\,\rho\,C_M D^2 \cdot \dot{u}(t) + \frac{1}{2}\,\rho\,C_D D\ \cdot u(t)\,|u(t)|}$$

Where C_M is the dimensionless inertia coefficient and C_D is the dimensionless drag coefficient. Both coefficient are obtained experimentally with several methods.



Suggested by DNV (Offshore Hydromechanics by J.M.J. Journée and W.W. Massie Delft University of Technology

	$Rn < 10^5$		$Rn > 10^5$	
KC	$\mathbf{C}_D$	$\mathbf{C}_M$	$\mathbf{C}_D$	$\mathbf{C}_M$
< 10	1.2	2.0	0.6	2.0
$\geqslant 10$	1.2	1.5	0.6	1.5

Clauss, 1992

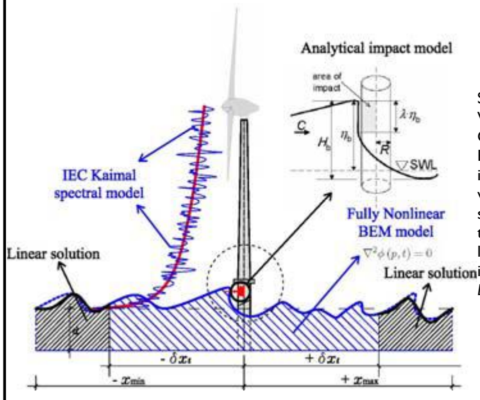
Where Rn is the Reynolds number: $Rn = \frac{u_a \cdot D}{\nu}$

u_a = flow velocity amplitude (m/s)
D = cylinder diameter (m)
ν = kinematic viscosity (m^2/s)

Where KC is the Keulegan-Carpenter number that in regular wave writes:

$$KC = \pi \cdot \frac{H}{D} = 2\pi \cdot \frac{\zeta_a}{D} \quad \text{(deep water only)}$$

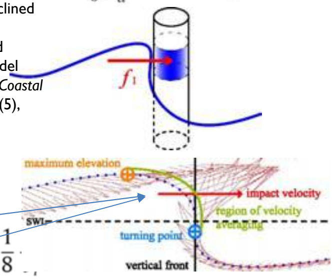
Impact force model



$$F_D + F_M = \int_{-d}^{\eta} \frac{1}{2} \cdot \rho \cdot C_D \cdot D \cdot u(z)|u(z)|dz$$

$$+ \int_{-d}^{\eta} \rho \cdot C_M \cdot \frac{\pi \cdot D^2}{4} \dot{u}(z)dz$$

Source:
Wienke, J., & Oumeraci, H. (2005). Breaking wave impact force on a vertical and inclined slender pile—theoretical and large-scale model investigations. *Coastal Engineering*, *52*(5),



$$f_I(t) = \rho R v_I^2 \left[2\pi - 2\sqrt{\frac{v_I}{R} t} \tanh^{-1} \sqrt{1 - \frac{1}{4}\frac{v_I}{R} t} \right] \quad \text{for } 0 \leqslant t \leqslant \frac{1}{8}$$

$$f_I(t) = \rho R v_I^2 \left[\pi \sqrt{\frac{1}{6} \frac{1}{\frac{v_I}{R} t'}} - \sqrt[4]{\frac{8}{3}\frac{v_I}{R} t'} \tanh^{-1} \sqrt{1 - \frac{v}{R} t' \sqrt{6 \frac{v_I}{R} t'}} \right] \text{ for } \frac{3}{32}\frac{R}{v_I} \leqslant t' \leqslant \frac{12}{32}\frac{R}{v_I}$$

where $t' = t - R/(32 v_I)$

Outline

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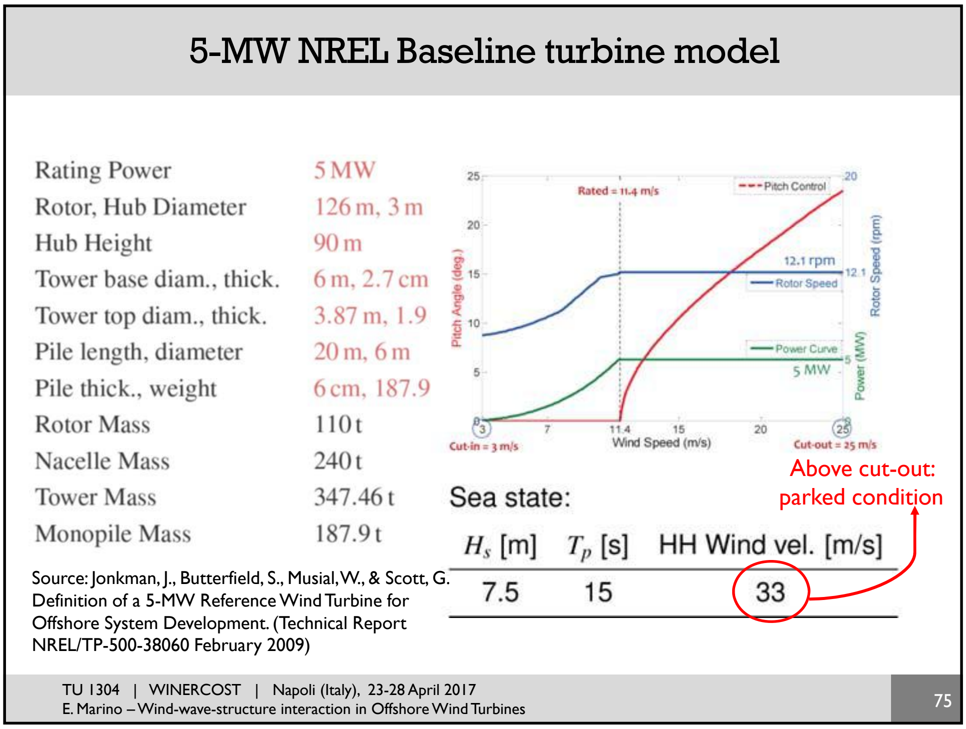


5-MW NREL Baseline turbine model

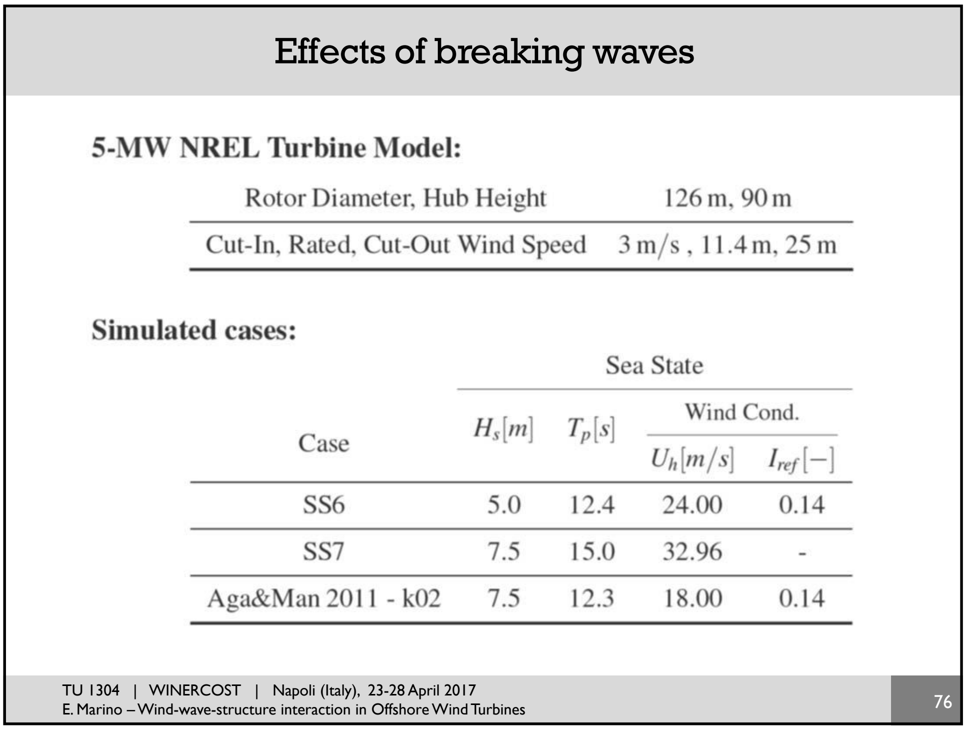
Rating Power	5 MW
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Tower base diam., thick.	6 m, 2.7 cm
Tower top diam., thick.	3.87 m, 1.9
Pile length, diameter	20 m, 6 m
Pile thick., weight	6 cm, 187.9
Rotor Mass	110 t
Nacelle Mass	240 t
Tower Mass	347.46 t
Monopile Mass	187.9 t

Source: Jonkman, J., Butterfield, S., Musial, W., & Scott, G. Definition of a 5-MW Reference Wind Turbine for Offshore System Development. (Technical Report NREL/TP-500-38060 February 2009)

Above cut-out: parked condition

Sea state:

H_s [m]	T_p [s]	HH Wind vel. [m/s]
7.5	15	33



Effects of breaking waves

5-MW NREL Turbine Model:

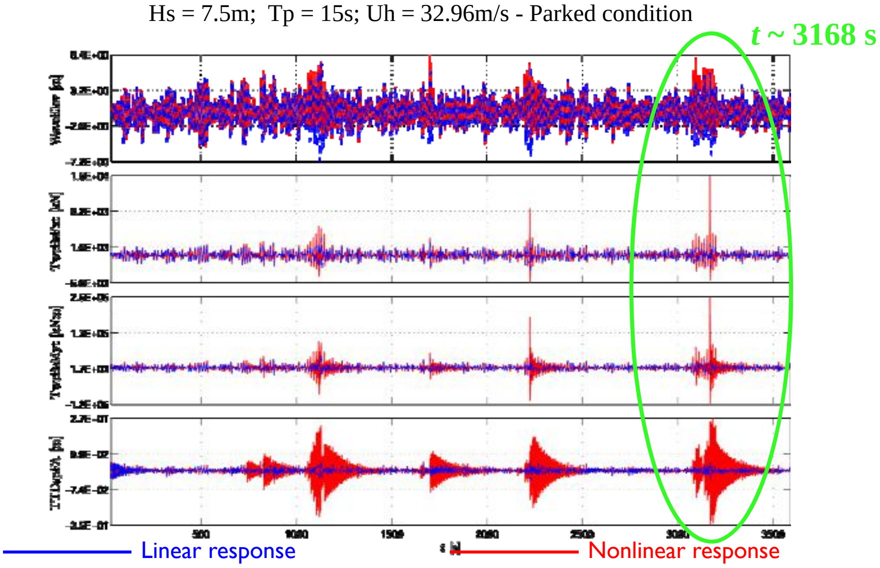
Rotor Diameter, Hub Height	126 m, 90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s , 11.4 m, 25 m

Simulated cases:

	Sea State			
Case	$H_s[m]$	$T_p[s]$	Wind Cond.	
			$U_h[m/s]$	$I_{ref}[-]$
SS6	5.0	12.4	24.00	0.14
SS7	7.5	15.0	32.96	-
Aga&Man 2011 - k02	7.5	12.3	18.00	0.14

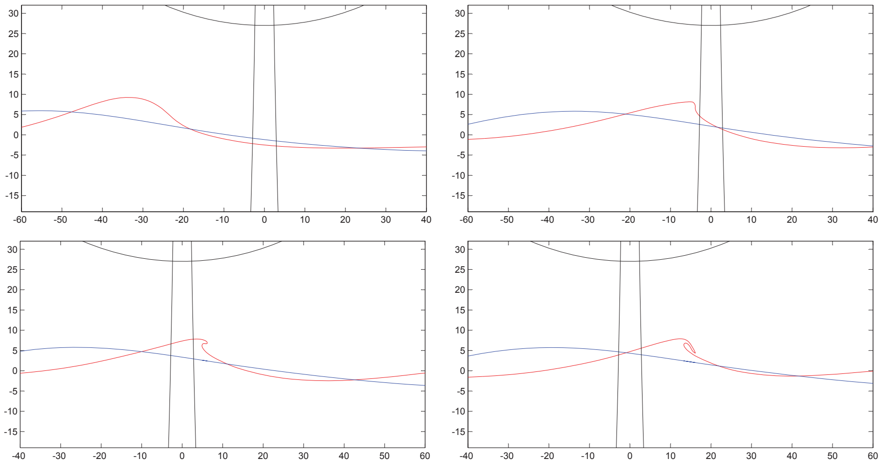
Linear vs. nonlinear tower response

Hs = 7.5m; Tp = 15s; Uh = 32.96m/s - Parked condition

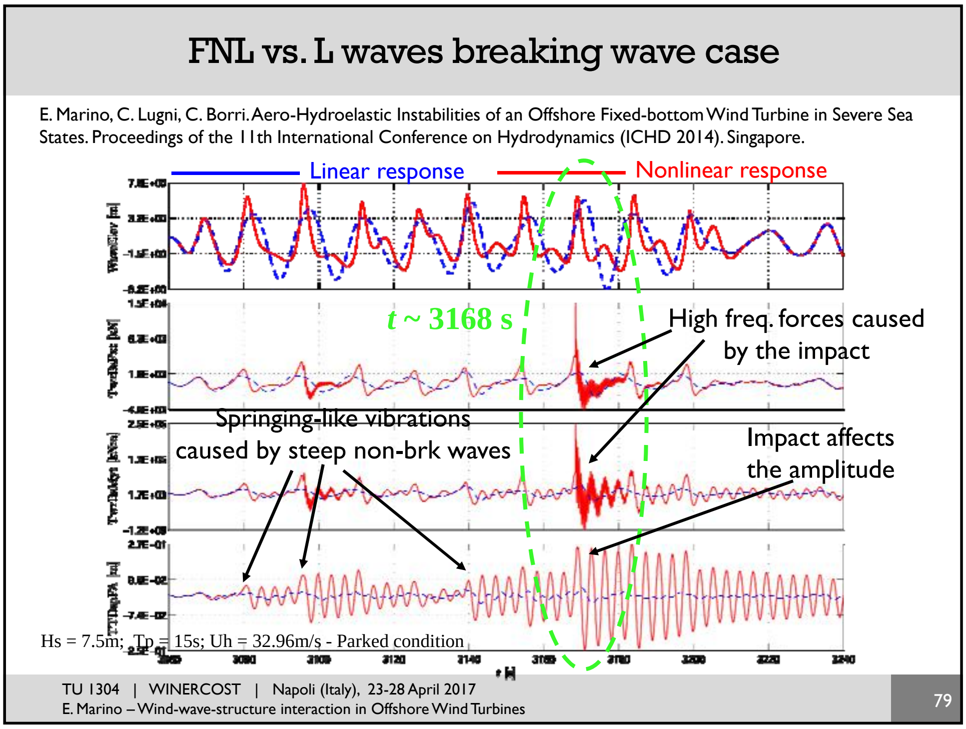


Impact occurring around *t* = 3168 s

Marino, E., Lugni, C., & Borri, C. (2013). A novel numerical strategy for the simulation of irregular nonlinear waves and their effects on the dynamic response of offshore wind turbines. Computer Methods in Applied Mechanics and Engineering, 255, 275–288.



$H_s = 7.5\text{m},\ T_p = 15\text{s}$



FNL vs. L waves breaking wave case

E. Marino, C. Lugni, C. Borri. Aero-Hydroelastic Instabilities of an Offshore Fixed-bottom Wind Turbine in Severe Sea States. Proceedings of the 11th International Conference on Hydrodynamics (ICHD 2014). Singapore.

Linear response
Nonlinear response

t ~ 3168 s

High freq. forces caused by the impact

Springing-like vibrations caused by steep non-brk waves

Impact affects the amplitude

Hs = 7.5m; Tp = 15s; Uh = 32.96m/s - Parked condition

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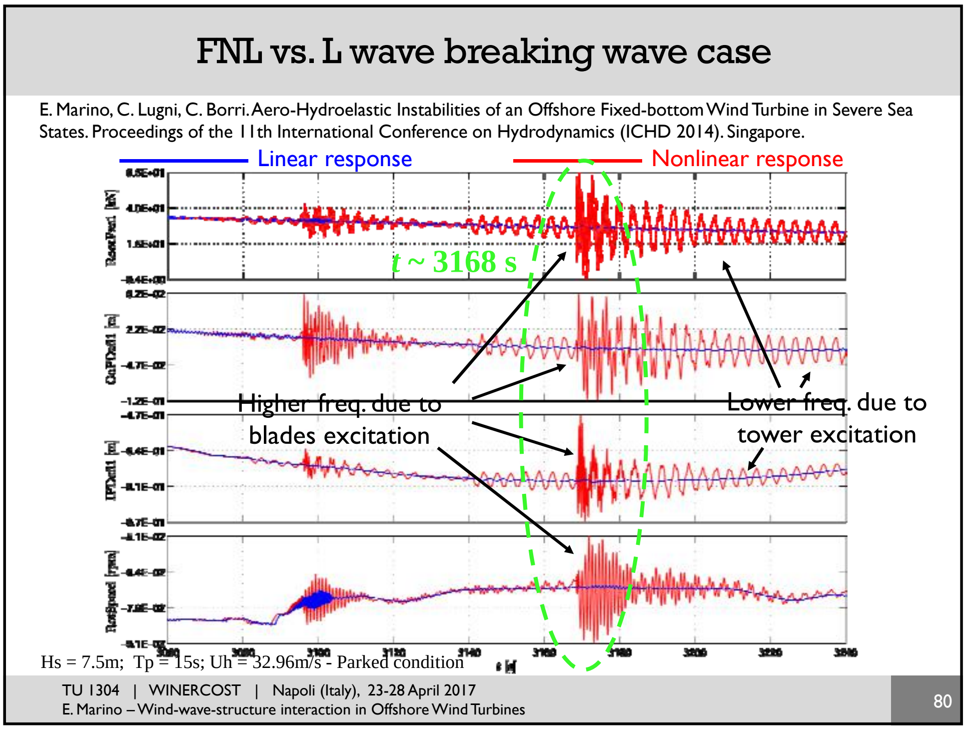
79



FNL vs. L wave breaking wave case

E. Marino, C. Lugni, C. Borri. Aero-Hydroelastic Instabilities of an Offshore Fixed-bottom Wind Turbine in Severe Sea States. Proceedings of the 11th International Conference on Hydrodynamics (ICHD 2014). Singapore.

Linear response
Nonlinear response

t ~ 3168 s

Higher freq. due to blades excitation

Lower freq. due to tower excitation

Hs = 7.5m; Tp = 15s; Uh = 32.96m/s - Parked condition

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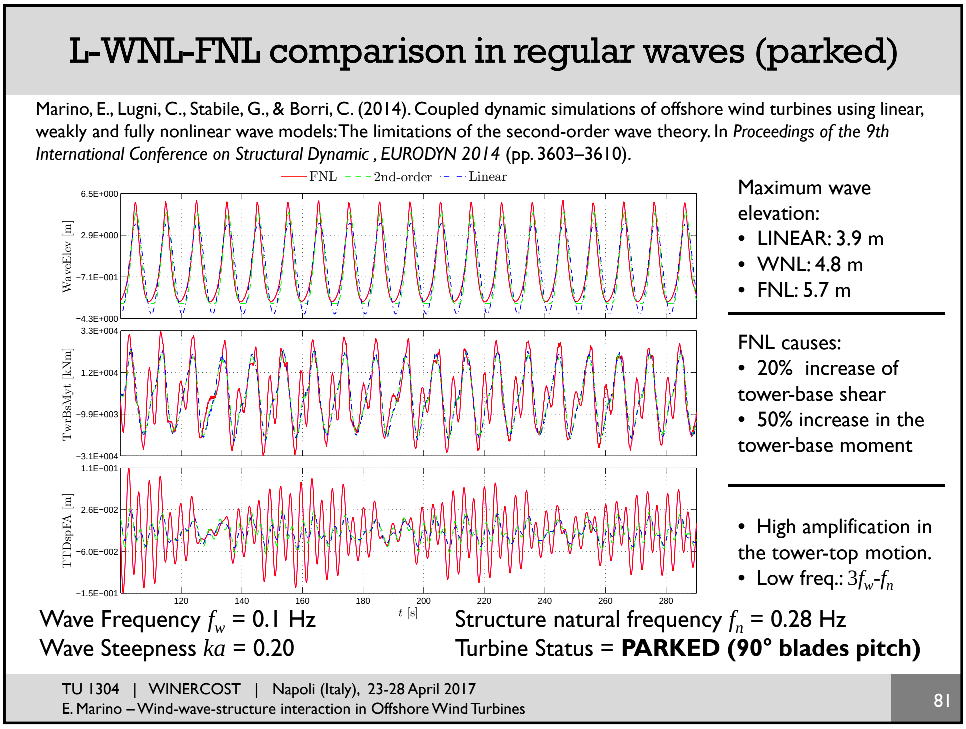
80



L-WNL-FNL comparison in regular waves (parked)

Marino, E., Lugni, C., Stabile, G., & Borri, C. (2014). Coupled dynamic simulations of offshore wind turbines using linear, weakly and fully nonlinear wave models: The limitations of the second-order wave theory. In *Proceedings of the 9th International Conference on Structural Dynamic , EURODYN 2014* (pp. 3603–3610).

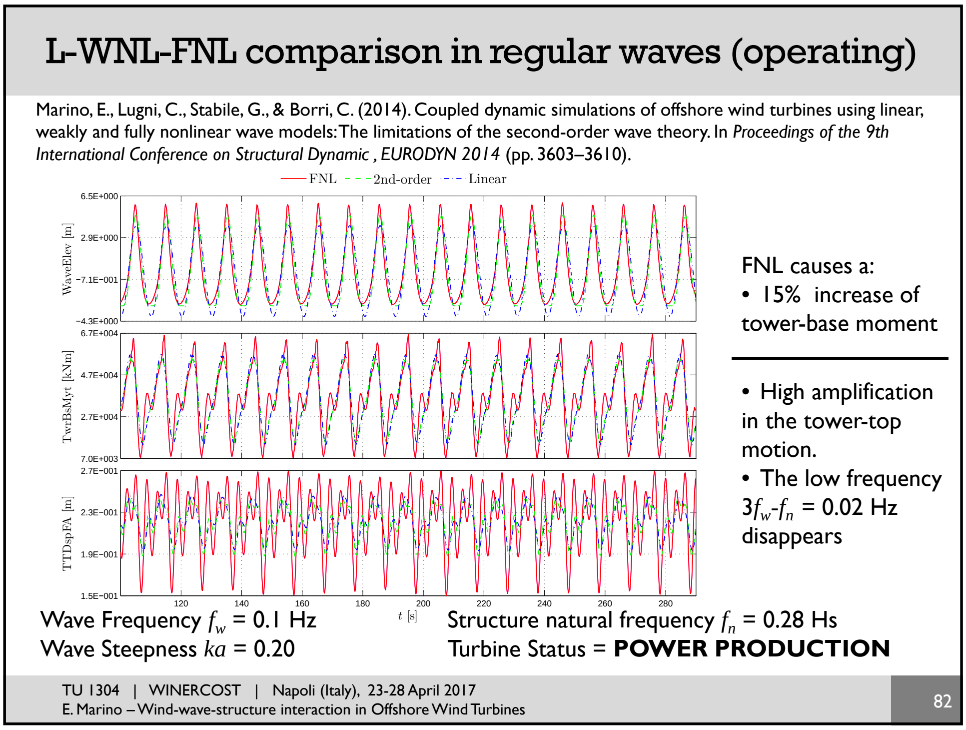
Maximum wave elevation:
- LINEAR: 3.9 m
- WNL: 4.8 m
- FNL: 5.7 m

FNL causes:
- 20% increase of tower-base shear
- 50% increase in the tower-base moment

- High amplification in the tower-top motion.
- Low freq.: $3f_w$-f_n

Wave Frequency f_w = 0.1 Hz
Wave Steepness ka = 0.20

Structure natural frequency f_n = 0.28 Hz
Turbine Status = **PARKED (90° blades pitch)**



L-WNL-FNL comparison in regular waves (operating)

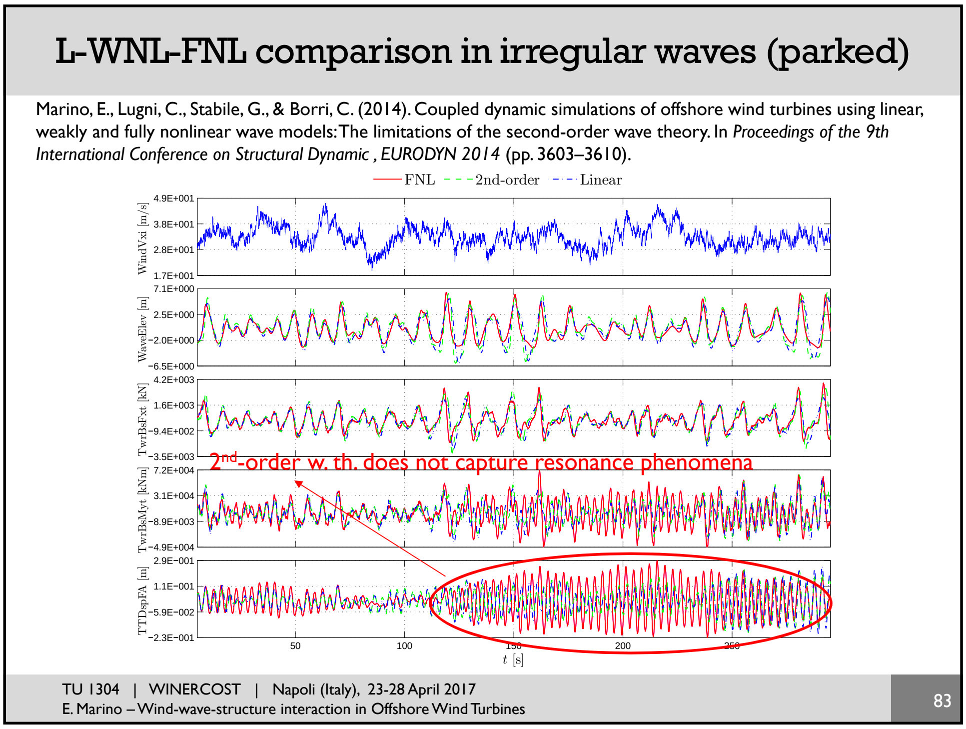
Marino, E., Lugni, C., Stabile, G., & Borri, C. (2014). Coupled dynamic simulations of offshore wind turbines using linear, weakly and fully nonlinear wave models: The limitations of the second-order wave theory. In *Proceedings of the 9th International Conference on Structural Dynamic , EURODYN 2014* (pp. 3603–3610).

FNL causes a:
- 15% increase of tower-base moment

- High amplification in the tower-top motion.
- The low frequency $3f_w$-f_n = 0.02 Hz disappears

Wave Frequency f_w = 0.1 Hz
Wave Steepness ka = 0.20

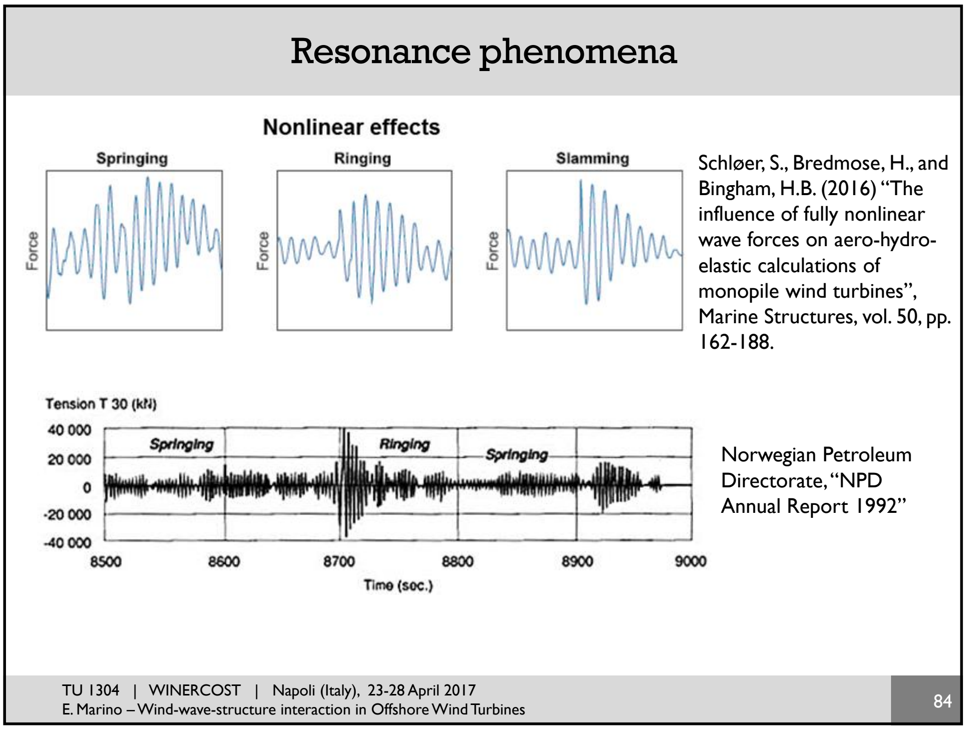
Structure natural frequency f_n = 0.28 Hs
Turbine Status = **POWER PRODUCTION**



L-WNL-FNL comparison in irregular waves (parked)

Marino, E., Lugni, C., Stabile, G., & Borri, C. (2014). Coupled dynamic simulations of offshore wind turbines using linear, weakly and fully nonlinear wave models: The limitations of the second-order wave theory. In *Proceedings of the 9th International Conference on Structural Dynamic , EURODYN 2014* (pp. 3603–3610).

2nd-order w. th. does not capture resonance phenomena

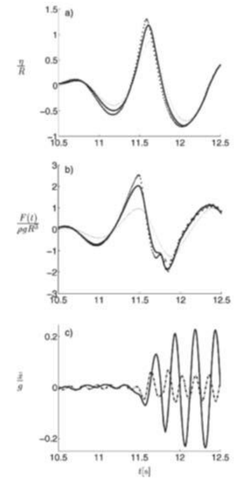


Resonance phenomena

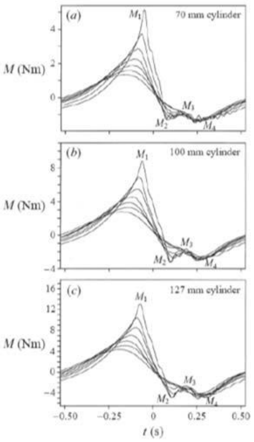
Schløer, S., Bredmose, H., and Bingham, H.B. (2016) "The influence of fully nonlinear wave forces on aero-hydro-elastic calculations of monopile wind turbines", Marine Structures, vol. 50, pp. 162-188.

Norwegian Petroleum Directorate, "NPD Annual Report 1992"

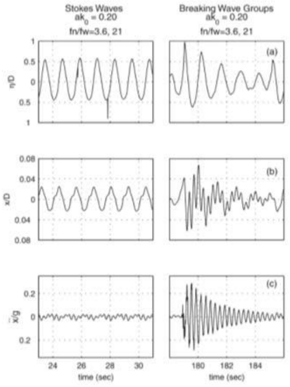
Some experiments from the literature



Grue & Huseby
Applied Ocean Research, 24(2002)



Chaplin, Rainey & Yemm
JFM.350(1997)



Welch, Fontaine & Tulin
Int. Jou. Off. Eng.9(4)(1999)

Basic definitions of accumulated damage D

Constant stress cycles:

$$D = NS^m/K$$

- m, K: material parameters ($m = 3$ for turbine tower - welded steel)
- N: number of cycles; S: stress amplitude

Variable-amplitude stress cycles:

$$D = \sum_i^N S_i^m/K$$

- S_i: individual stress cycle

Equivalent Fatigue Load (EFL):

Is the constant-amplitude stress range which would cause an equivalent amount of damage as the original variable-amplitude stress time series.

Basic definitions of accumulated damage D

Time-domain approach: Rainflow Cycle-Counting (RCC)

- Individual cycles S_i may be superimposed upon one another
- They are counted by means of the standard RCC Algorithm
- The EFL is given by: EFL $= \left(\sum_i^N S_i^m/N\right)^{1/m}$
- The damage is given by: $D = N\left(\text{EFL}\right)^m/K$

Frequency-domain approach: Dirlik's spectral method

- The ex. value of the stress range random variable is: $E[S^m] = \int_0^\infty S^m p(S)dS$
- $p(S)$: PDF of S
- The EFL is given by: EFL $= (E[S^m])^{1/m}$
- The ex. damage is given by: $E[D] = E[N]\left(\text{EFL}\right)^m/K$

Basic definitions of accumulated damage D

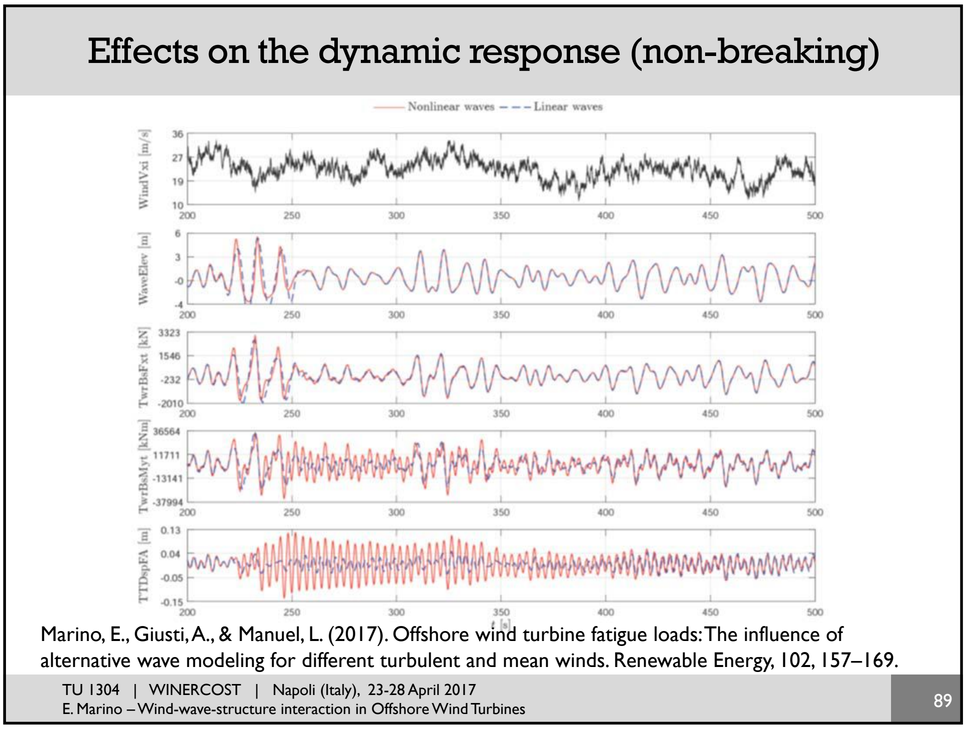
5-MW NREL Turbine Model:

Rotor Diameter, Hub Height	126 m, 90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m, 25 m

Simulated case:

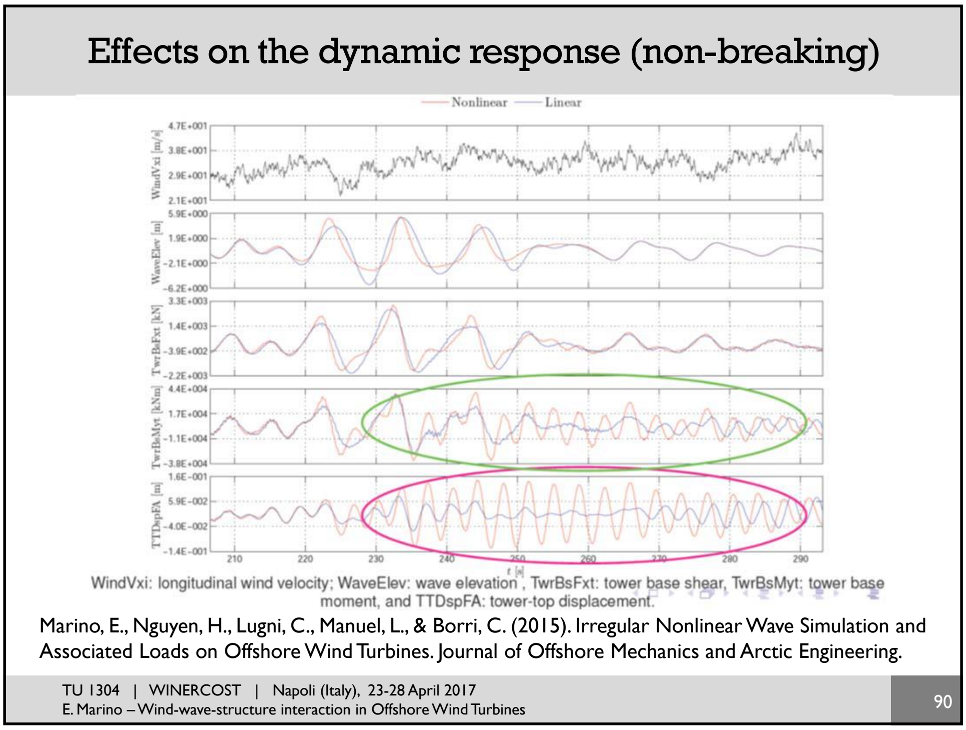
Case	Sea State		Wind Cond.	
	H_s [m]	T_p [s]	U_{hub} [m/s]	Turb. Int. [-]
U_{hub} at 0.9999 non-ex. fract. (1 to 2.5-year return period)	5.6	10.82	33.43	0.1

The turbine is assumed in parked condition. Wind shear: power law with exponent 0.2. Wind Turbulence: Kaimal power spectral density function; Sea spectrum: JONSWAP with $\gamma = 3.3$.



Effects on the dynamic response (non-breaking)

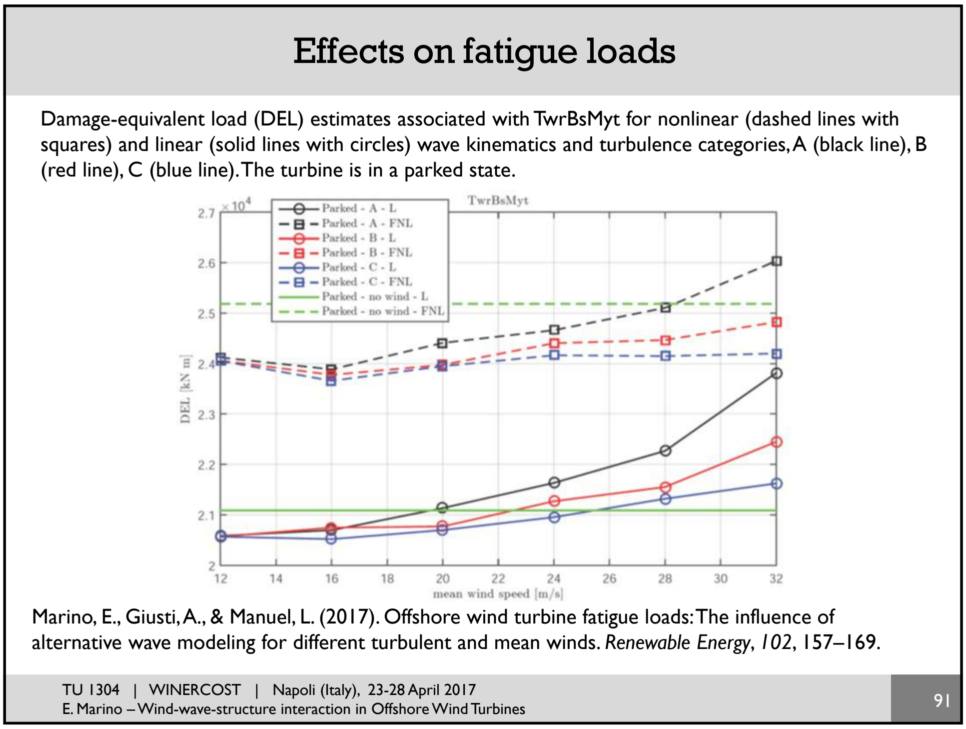
Marino, E., Giusti, A., & Manuel, L. (2017). Offshore wind turbine fatigue loads: The influence of alternative wave modeling for different turbulent and mean winds. Renewable Energy, 102, 157–169.



Effects on the dynamic response (non-breaking)

WindVxi: longitudinal wind velocity; WaveElev: wave elevation , TwrBsFxt: tower base shear, TwrBsMyt: tower base moment, and TTDspFA: tower-top displacement.

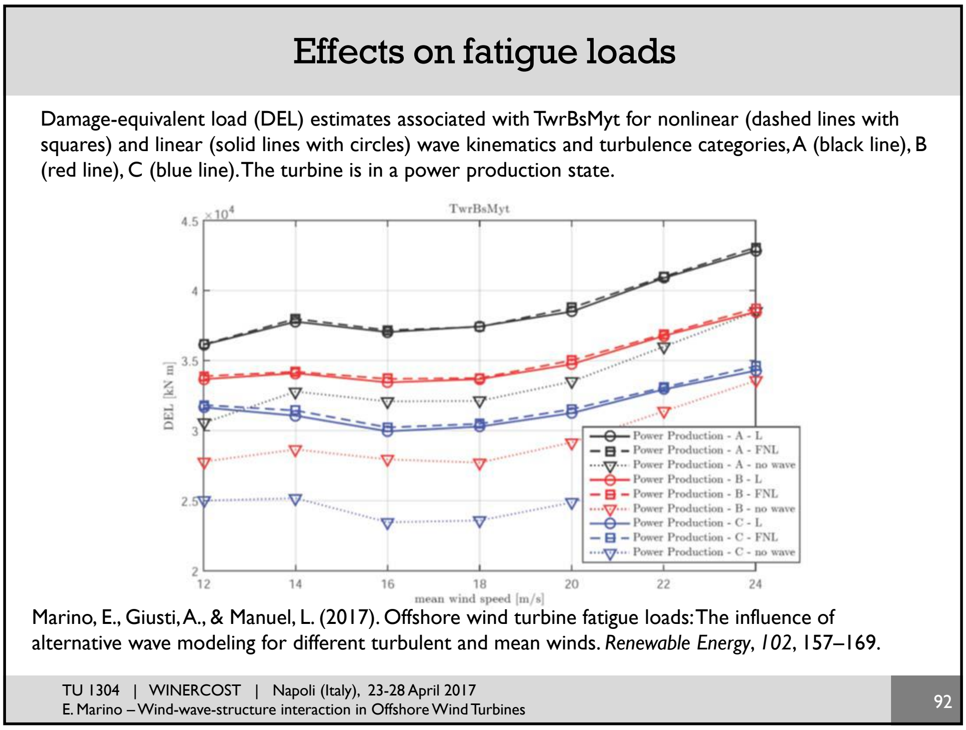
Marino, E., Nguyen, H., Lugni, C., Manuel, L., & Borri, C. (2015). Irregular Nonlinear Wave Simulation and Associated Loads on Offshore Wind Turbines. Journal of Offshore Mechanics and Arctic Engineering.



Effects on fatigue loads

Damage-equivalent load (DEL) estimates associated with TwrBsMyt for nonlinear (dashed lines with squares) and linear (solid lines with circles) wave kinematics and turbulence categories, A (black line), B (red line), C (blue line). The turbine is in a parked state.

Marino, E., Giusti, A., & Manuel, L. (2017). Offshore wind turbine fatigue loads: The influence of alternative wave modeling for different turbulent and mean winds. *Renewable Energy*, *102*, 157–169.



Effects on fatigue loads

Damage-equivalent load (DEL) estimates associated with TwrBsMyt for nonlinear (dashed lines with squares) and linear (solid lines with circles) wave kinematics and turbulence categories, A (black line), B (red line), C (blue line). The turbine is in a power production state.

Marino, E., Giusti, A., & Manuel, L. (2017). Offshore wind turbine fatigue loads: The influence of alternative wave modeling for different turbulent and mean winds. *Renewable Energy*, *102*, 157–169.

Outline

- Aerodynamic model (basics)
- Linear, weakly and fully nonlinear wave models
- Hydrodynamic loading models
- Coupled simulations and effects of nonlinear waves
- References

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IEC 61400-1 Wind turbines - Part 1: Design requirements 3rd ed.

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Urban Wind Energy: Social, Planning and Environmental Considerations

Ruben Paul Borg

TU 1304 – WINERCOST
International Training School
Napoli, Italy 23-28.04.2017

Lecture

Urban Wind Energy: Social, Planning and Environmental Considerations

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L-Università ta' Malta

Contents

- **Section 1**: A Review of Life Cycle Impact Analysis of Wind Turbines
- **Section 2**: LCA: Comparative Life Cycle Assessment: Structural Design & Life Cycle Assessment
- **Section 3**: Environmental Impacts of Wind Energy Projects
- **Section 4**: Challenges in the Implementation of Wind Energy Projects: Case Study Malta
- **Section 5**: Challenges in the Implementation of Wind Energy Projects / Urban Wind Energy: Survey

A Review of Life Cycle Impact Analysis of Wind Turbines

Section 1

A Review of Life Cycle Impact Analysis

of Wind Turbines

Outline

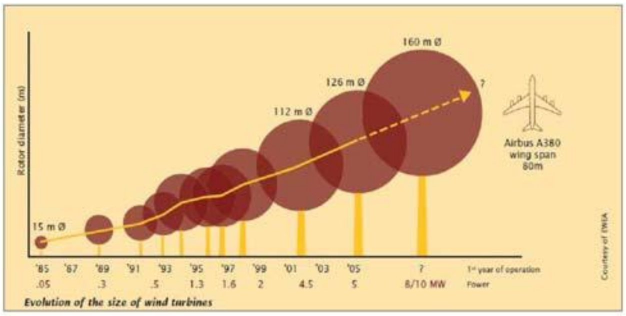
1. Introduction
2. LCA Methodology (the standard for LCA)
3. LCA for Wind Turbines
4. Comparison of Results
5. Discussion
6. Conclusions

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

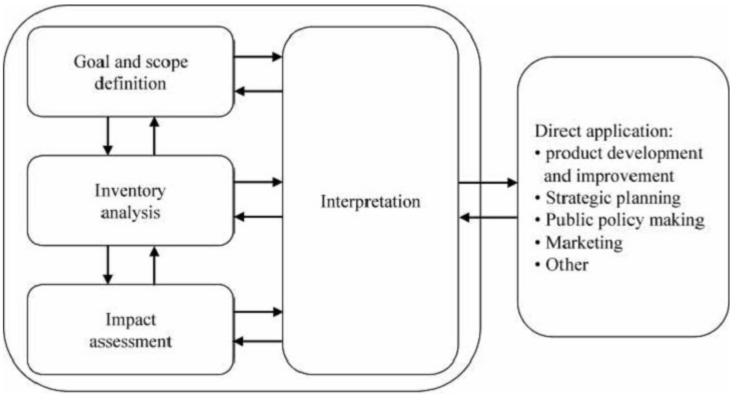
This increases the cost

- 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)



Goal and scope definition

Inventory analysis

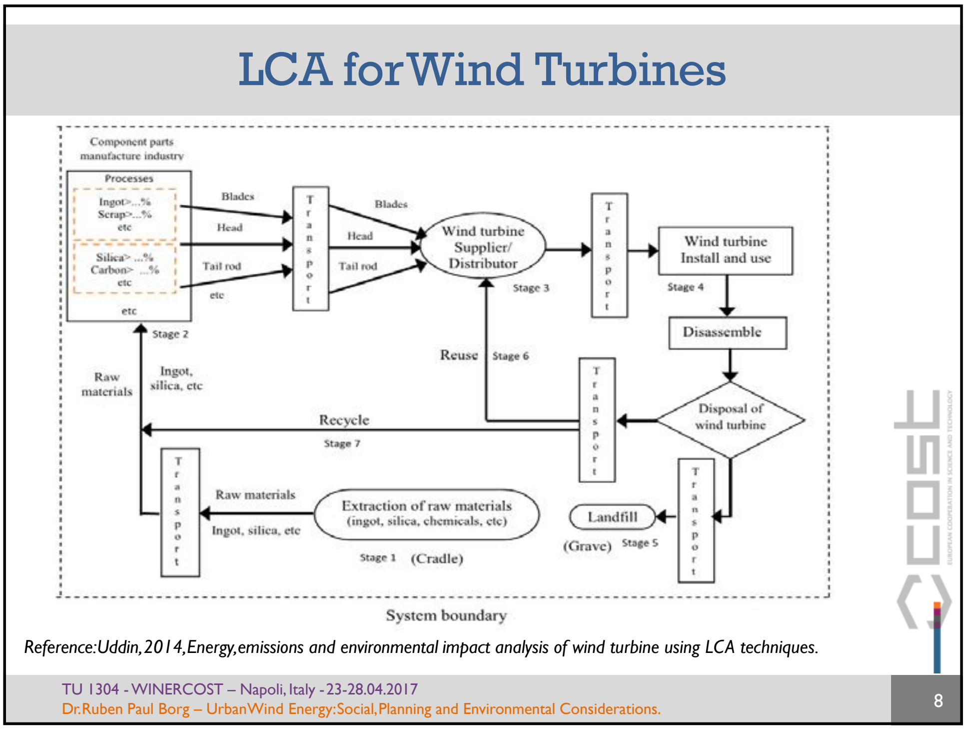
Impact assessment

Interpretation

Direct application:
- product development and improvement
- Strategic planning
- Public policy making
- Marketing
- Other

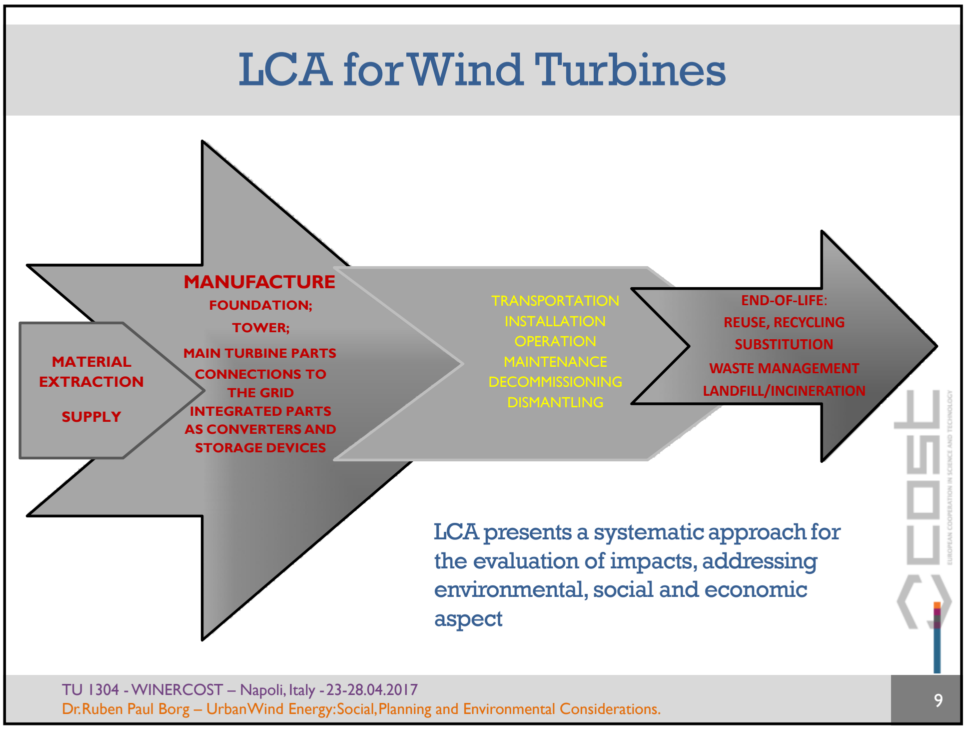
Life Cycle Analysis (LCA)

- 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

MATERIAL EXTRACTION

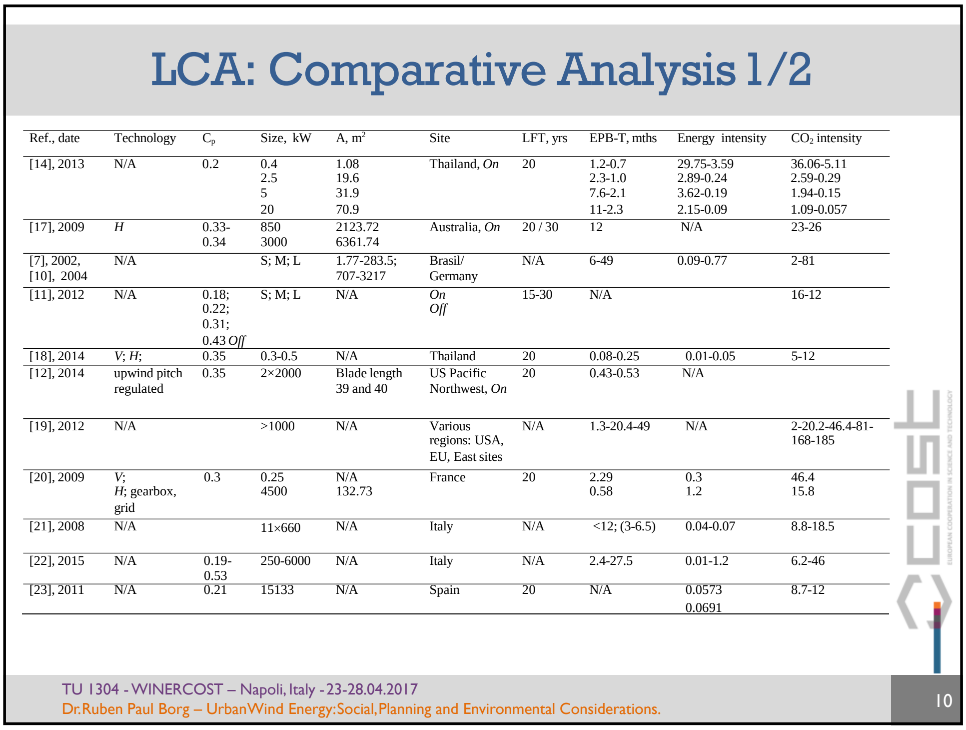
SUPPLY

MANUFACTURE
FOUNDATION;
TOWER;
MAIN TURBINE PARTS
CONNECTIONS TO THE GRID
INTEGRATED PARTS AS CONVERTERS AND STORAGE DEVICES

TRANSPORTATION
INSTALLATION
OPERATION
MAINTENANCE
DECOMMISSIONING
DISMANTLING

END-OF-LIFE:
REUSE, RECYCLING
SUBSTITUTION
WASTE MANAGEMENT
LANDFILL/INCINERATION

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

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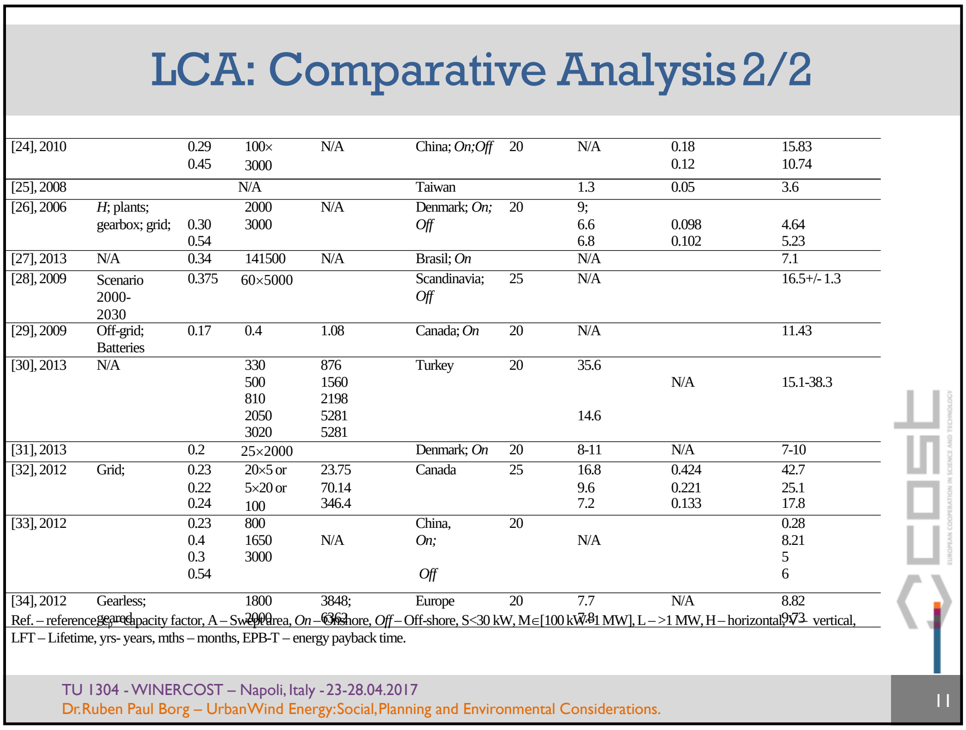

LCA: Comparative Analysis 2/2

[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.

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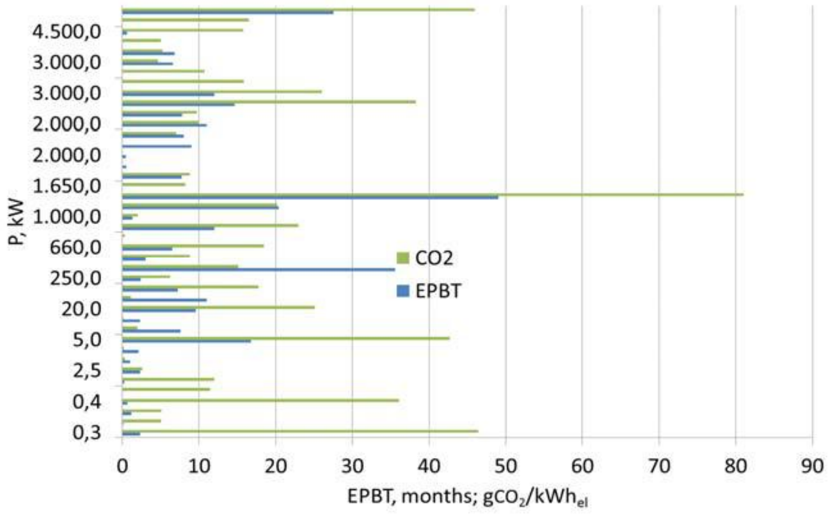
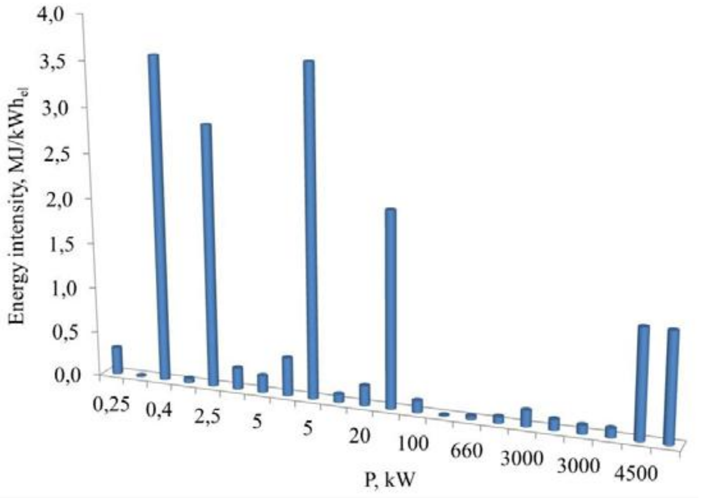
Key Environmental Indicators: Review 2002-2015



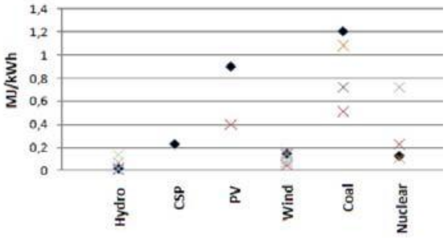
Comparative Analysis

- 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.

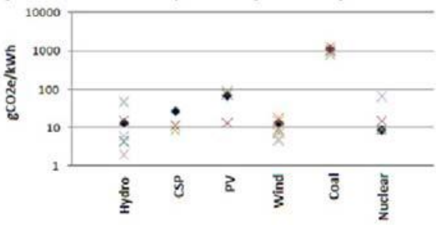
Key Environmental Indicators: Review 2002-2015



Comparative LCA



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.

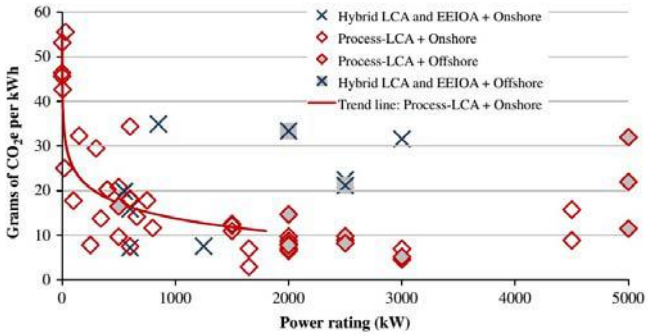
LCA Review

		Fixed cost at construction	Annual fixed cost	Variable 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

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

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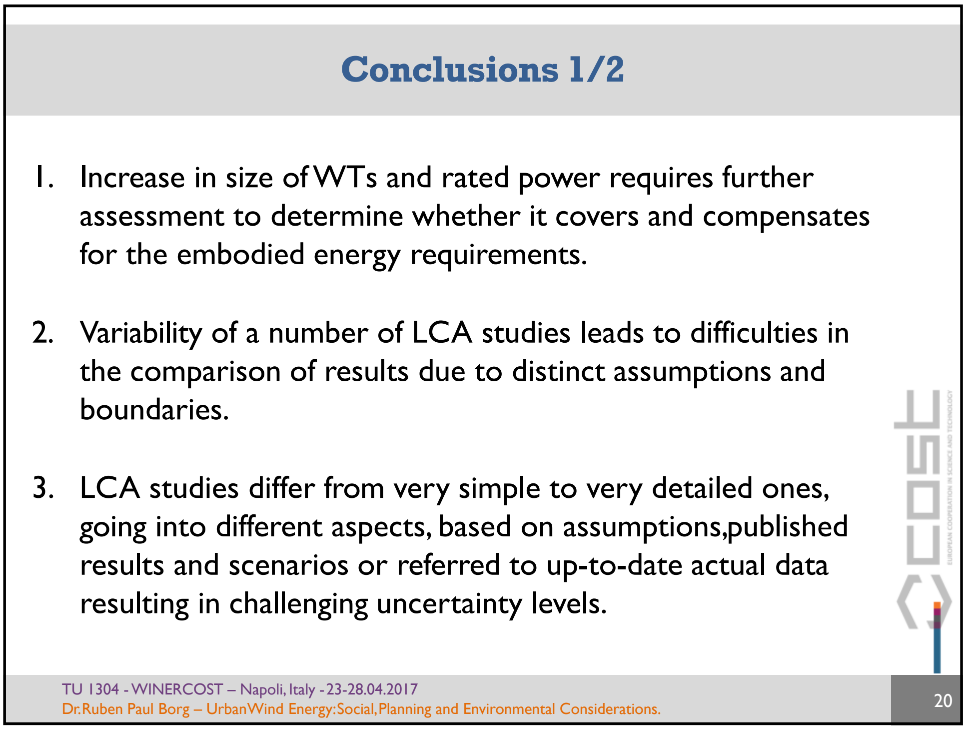
LCA Review

	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	

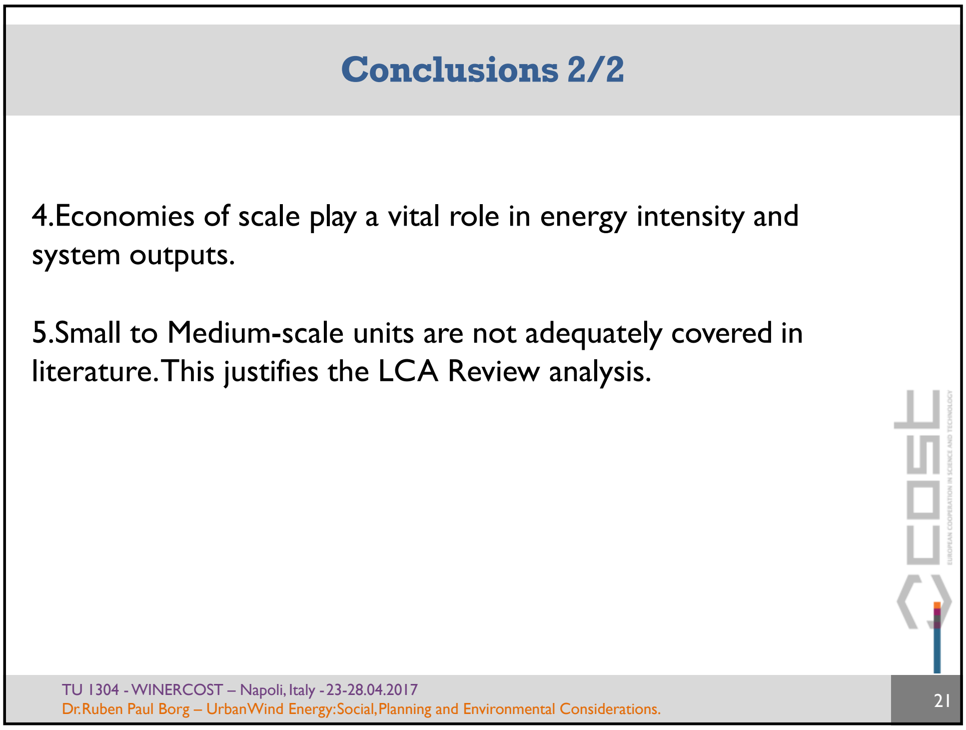
Drawbacks in quantitative and qualitative aspects of assessments and reports.

Ref: Price A Kendall, 2012, Wind Power as a Case Study. Improving life cycle assessment reporting to better enable meta analysis



Conclusions 1/2

1. Increase in size of WTs and rated power requires further assessment to determine whether it covers and compensates for the embodied energy requirements.
2. Variability of a number of LCA studies leads 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 referred to up-to-date actual data resulting in challenging uncertainty levels.



Conclusions 2/2

4.Economies of scale play a vital role in energy intensity and system outputs.

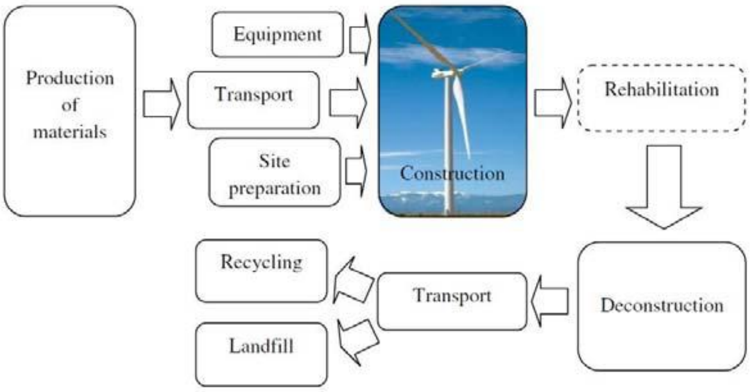
5.Small to Medium-scale units are not adequately covered in literature. This justifies the LCA Review analysis.

LCA: Comparative Life Cycle Assessment: Structural Design & Life Cycle Assessment

Section 2

LCA:Comparative Life Cycle Assessment:
Structural Design & Life CycleAssessment

Comparative Life Cycle Assessment

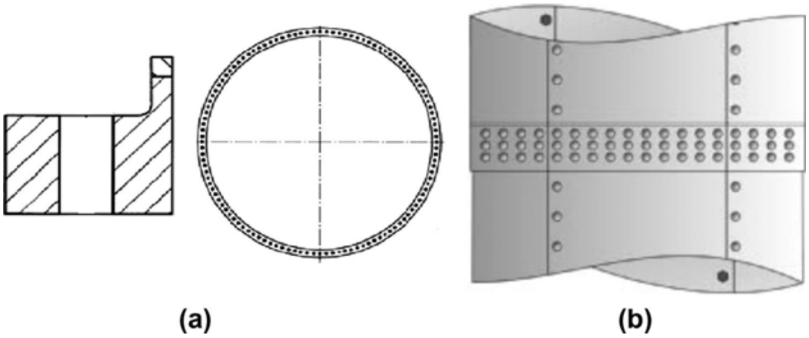


- Rebelo C et al. Comparative life cycle assessment of tubular wind towers and foundations – Part 1: Structural design. Eng Struct (2014), http://dx.doi.org/10.1016/j.engstruct.2014.02.040
- Gervásio H et al. Comparative life cycle assessment of tubular wind towers and foundations – Part 2:Life cycle 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.

Comparative Life Cycle Assessment


(a) (b)

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).

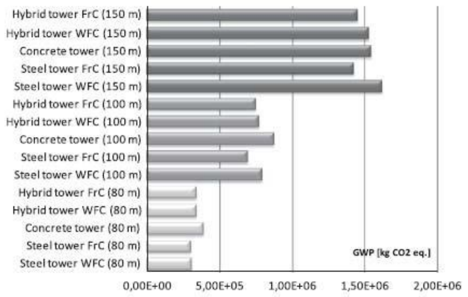
Scenario 3: after the initial period of 20 years, the structures are deconstructed, rehabilitated and reused in another place for another period of 20 years (scenario 40b).

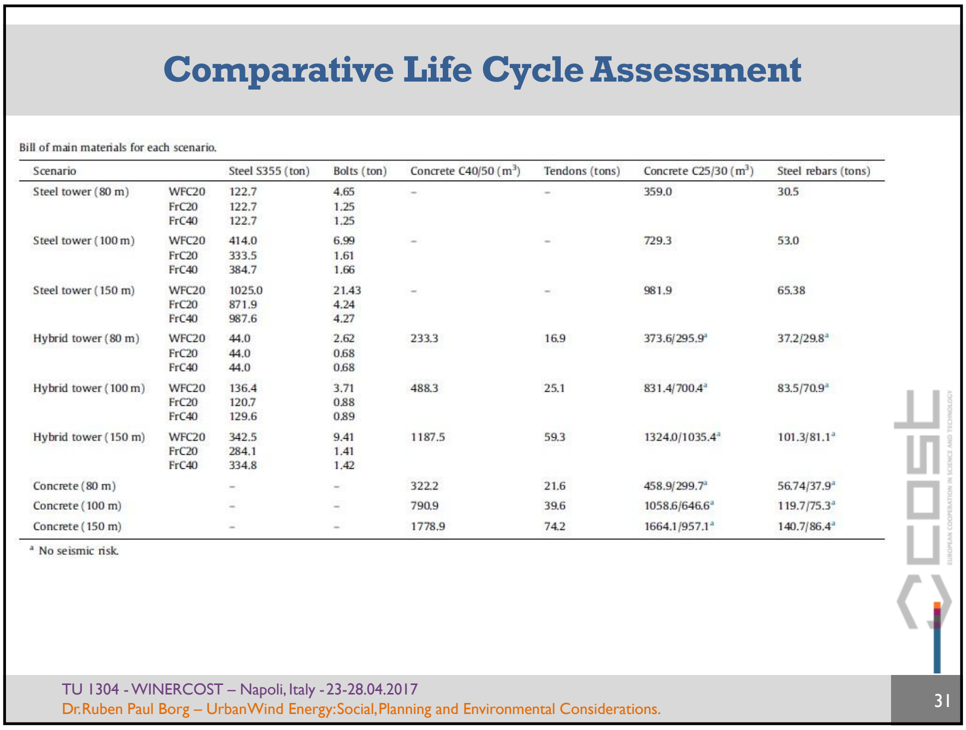
[In both cases, after the total period of 40 years the structures are then demolished and sent to their final destination according to Scenario 1].

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.



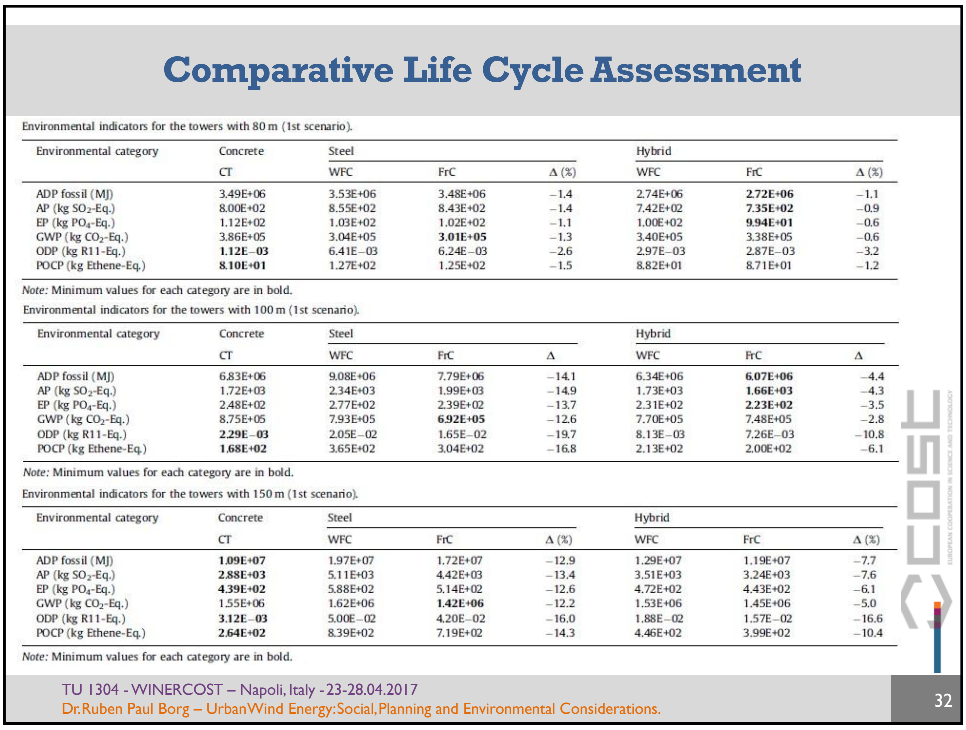


Comparative Life Cycle Assessment

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.



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).

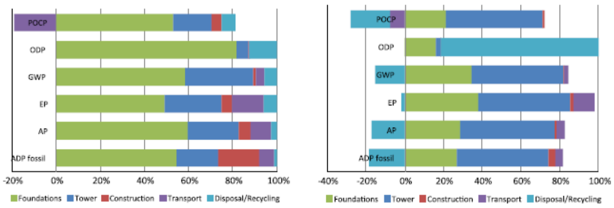
Environmental category	Concrete	Steel			Hybrid		
	CT	WFC	FrC	Δ (%)	WFC	FrC	Δ (%)
ADP fossil (MJ)	**1.09E+07**	1.97E+07	1.72E+07	−12.9	1.29E+07	1.19E+07	−7.7
AP (kg SO_2-Eq.)	**2.88E+03**	5.11E+03	4.42E+03	−13.4	3.51E+03	3.24E+03	−7.6
EP (kg PO_4-Eq.)	**4.39E+02**	5.88E+02	5.14E+02	−12.6	4.72E+02	4.43E+02	−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.

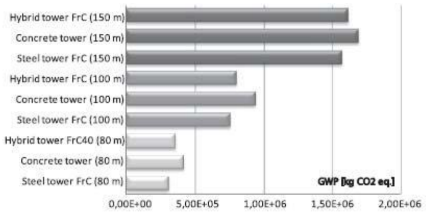
Environmental category	80 m 2.0 MW			100 m 3.6 MW			150 m 5.0 MW		
	Concrete	Hybrid		Concrete	Hybrid		Concrete	Hybrid	
	CT (%)	WFC (%)	FrC (%)	CT (%)	WFC (%)	FrC (%)	CT (%)	WFC (%)	FrC (%)
ADP fossil (MJ)	−15	−8	−9	−19	−6	−6	−18	−6	−6
AP (kg SO_2-Eq.)	−19	−9	−9	−21	−6	−7	−19	−6	−7
EP (kg PO_4-Eq.)	−18	−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



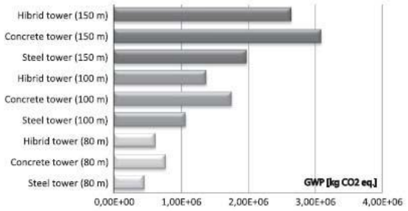
(a) concrete tower (100 m)

(b) hybrid tower (100 m)

Comparative Life Cycle Assessment



LCA of WindTurbines (Scenario 2)



LCA of WindTurbines (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

Section 3

Environmental Impacts of Wind Energy Projects

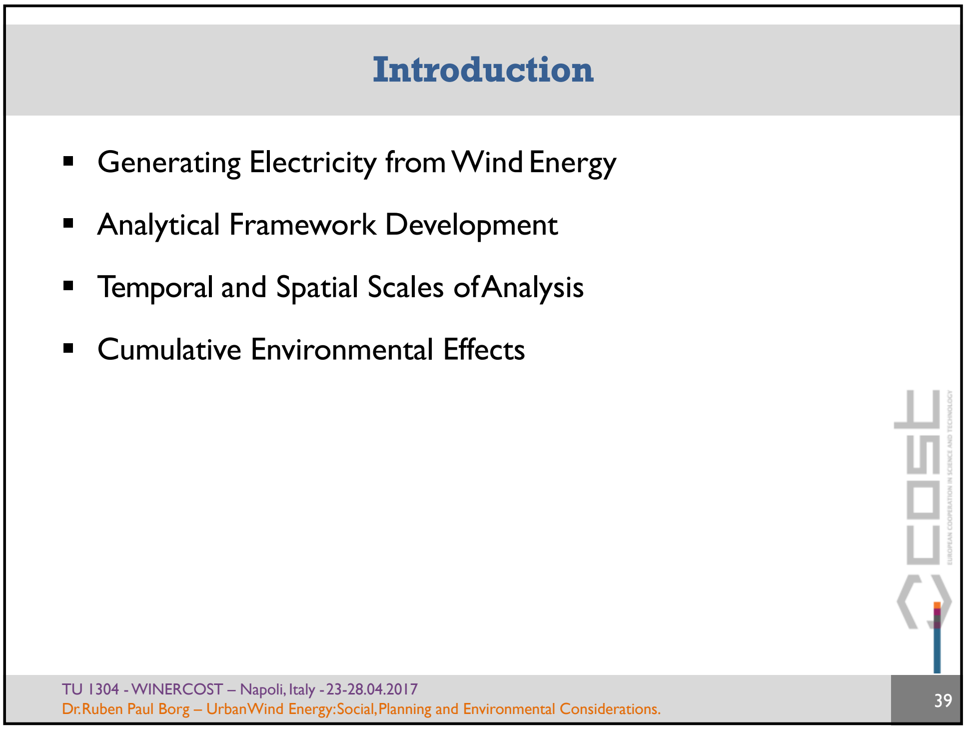
Outline

- 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

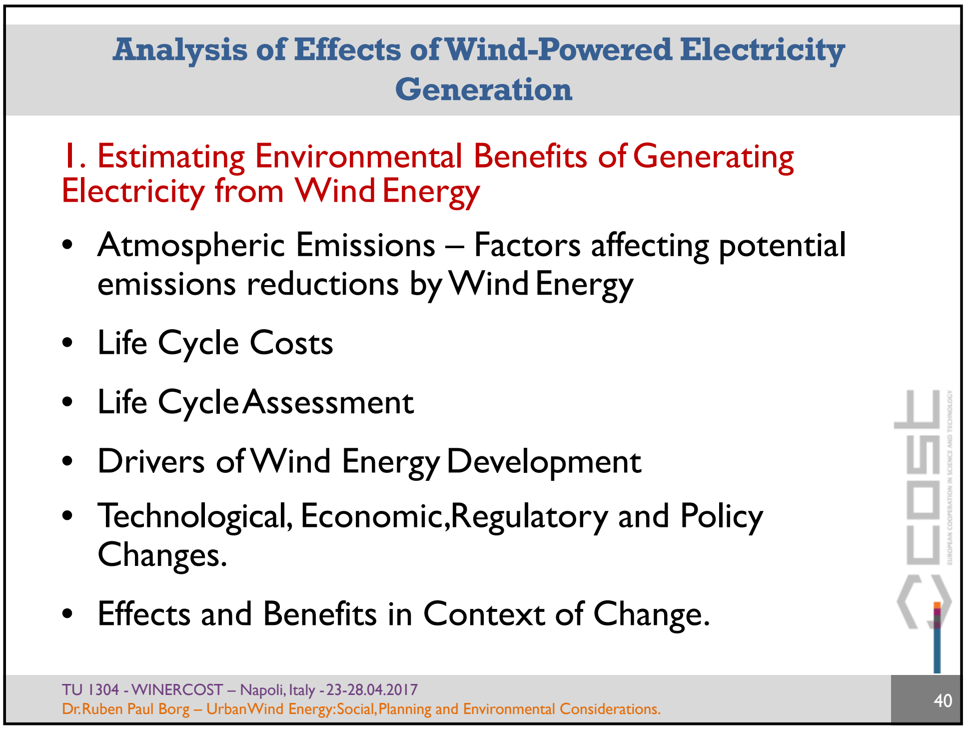
Guidance for reviewing Wind-Energy proposals

- Environmental benefits of Wind Energy
- Ecological Impacts
- Impacts on Humans
- Analysing Adverse and Beneficial Impacts in Contexts
- Framework for reviewing Wind Energy Proposals



Introduction

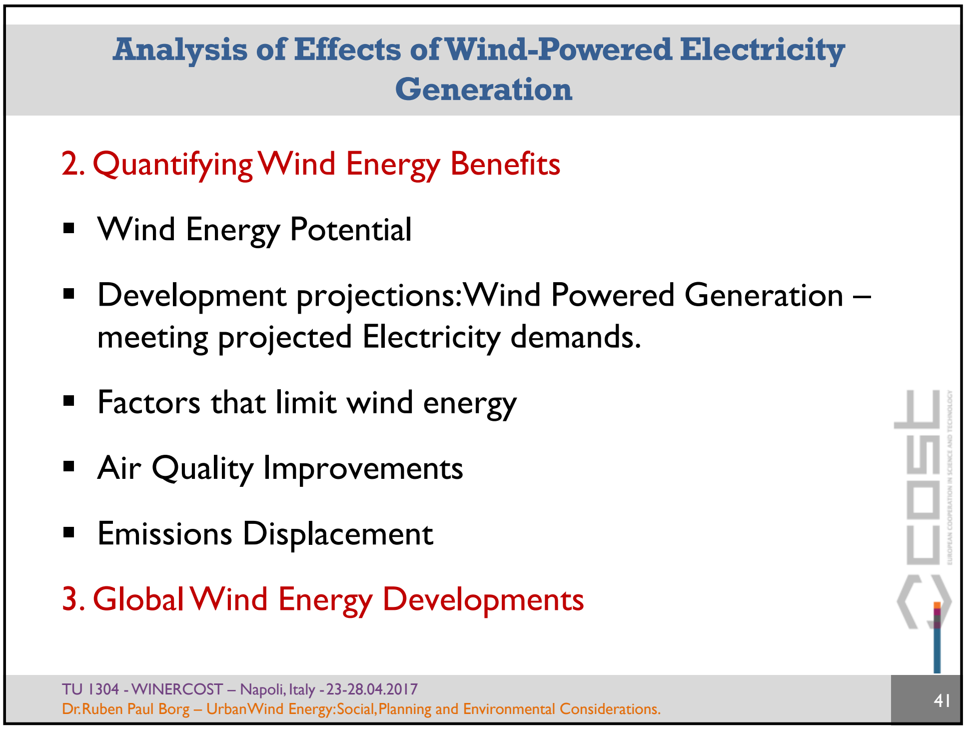
- Generating Electricity from Wind Energy
- Analytical Framework Development
- Temporal and Spatial Scales of Analysis
- Cumulative Environmental Effects



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.

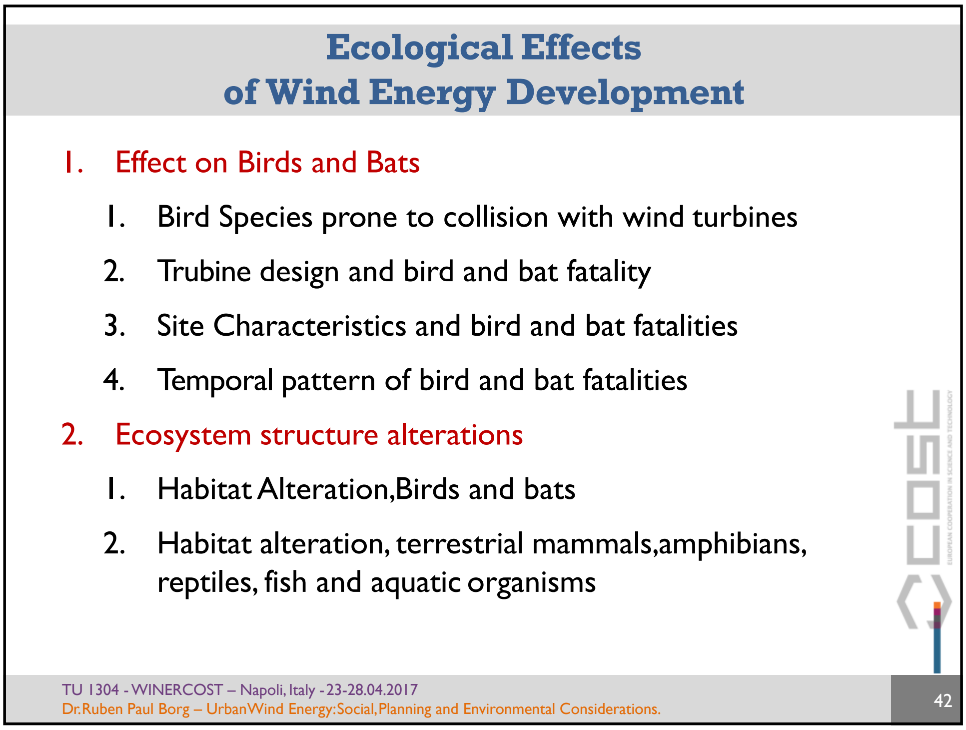


Analysis of Effects of Wind-Powered Electricity Generation

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

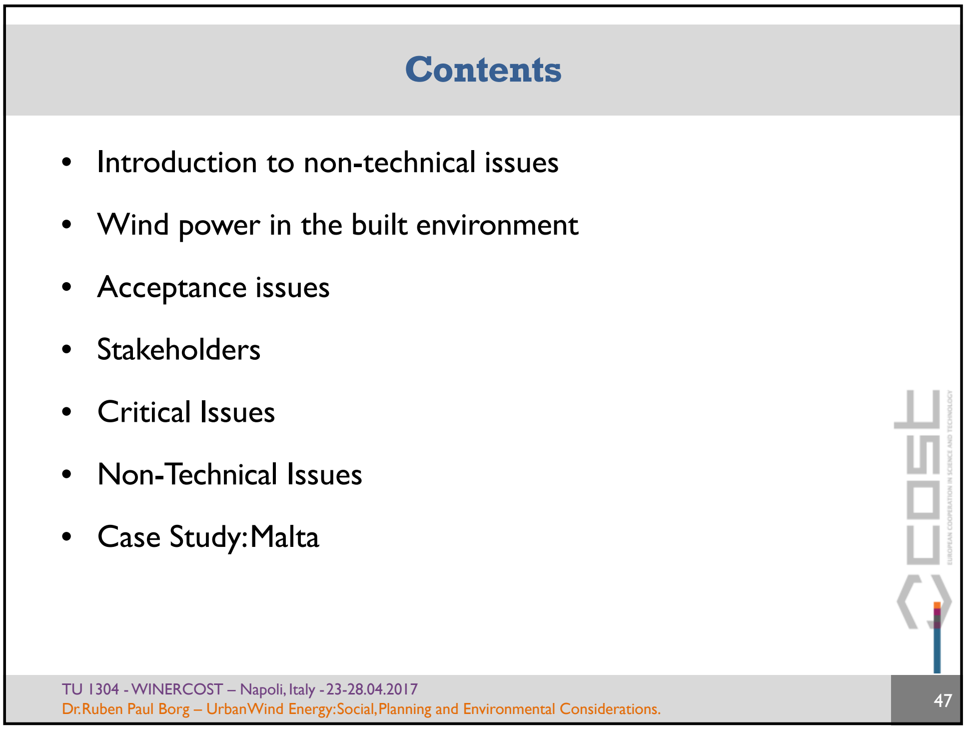
Challenges in the Implementation of Wind Energy Projects: Case Study

Section 4

Challenges in the Implementation

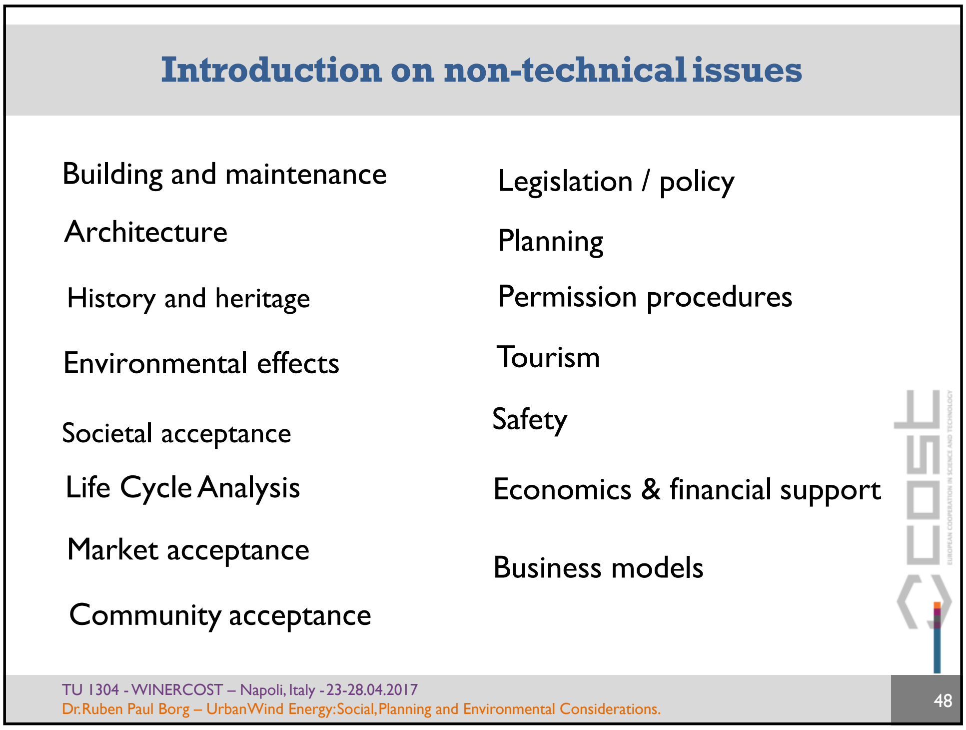
of Wind Energy Projects:

Case Study Malta



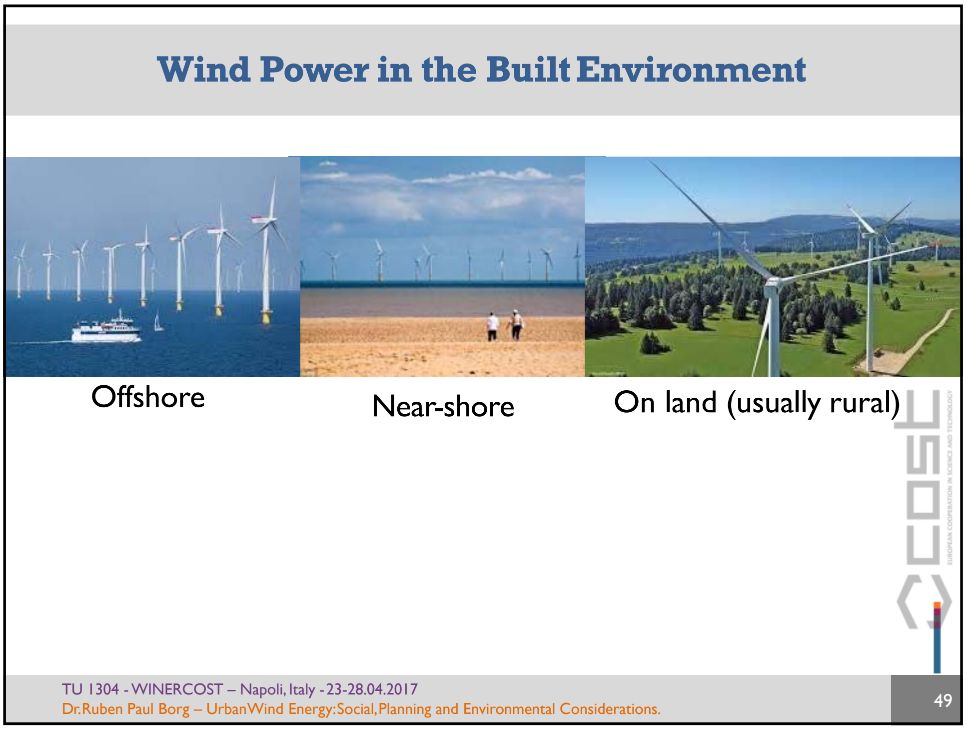
Contents

- 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	Legislation / policy
Architecture	Planning
History and heritage	Permission procedures
Environmental effects	Tourism
Societal acceptance	Safety
Life Cycle Analysis	Economics & financial support
Market acceptance	Business models
Community acceptance	



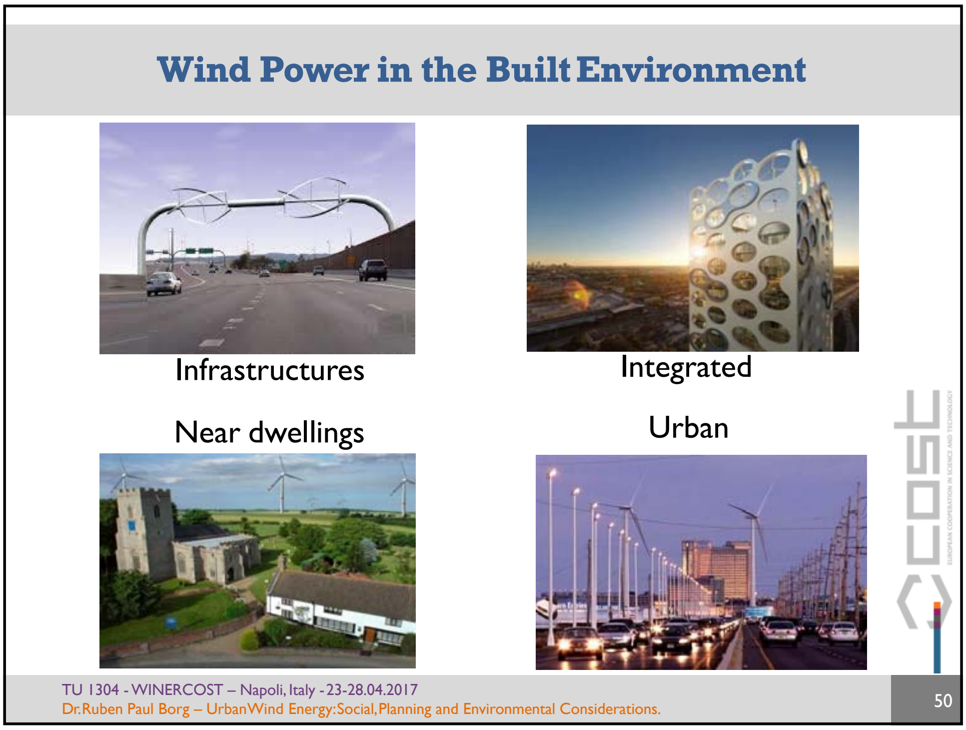
Wind Power in the Built Environment

Offshore

Near-shore

On land (usually rural)

TU 1304 - WINERCOST – Napoli, Italy - 23-28.04.2017
Dr.Ruben Paul Borg – Urban Wind Energy: Social, Planning and Environmental Considerations.



Wind Power in the Built Environment

Infrastructures

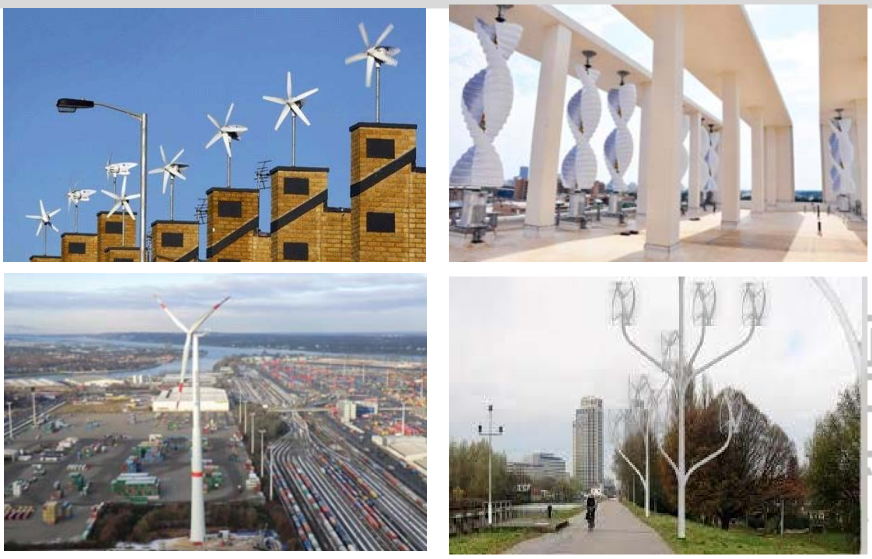
Integrated

Near dwellings

Urban

TU 1304 - WINERCOST – Napoli, Italy - 23-28.04.2017
Dr.Ruben Paul Borg – Urban Wind Energy: Social, Planning and Environmental Considerations.

Wind Power in the Built Environment



Wind Power in the Built Environment

Acceptance issues

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	Building Authority
Heritage protection	Architects
Media	Tourism agency
Politicians	Investors / banks
Health authority	Science
Police	Urban planners
Environmental NGO	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

Work of IEA Wind Task 28

www.socialacceptance.org

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

Task 28, Social Acceptance of Wind Energy Projects

August 2010
State-of-the-Art Report
IEA Wind Task 28
Social Acceptance of Wind Energy

Overview

Large-scale wind deployment, social acceptance

Robert Horbaty,[1]* Stefanie Huber[2]* and Geraint Ellis[3]*

The public is typically in agreement with the renewable energy targets established in many national states and generally supports the idea of increased reliance on

Task 28, Social Acceptance of Wind Energy Projects

Search

List of projects/publications

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

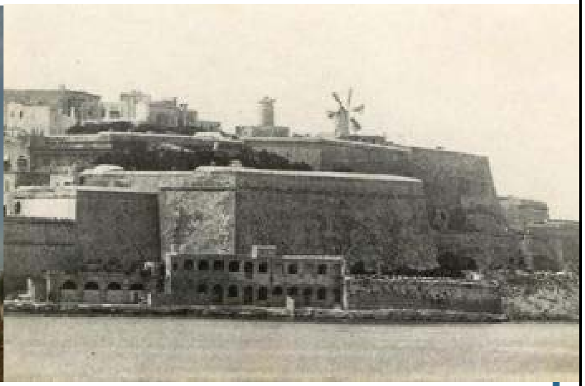
Case Study - Malta

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



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.

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.

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

Water pumps

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

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

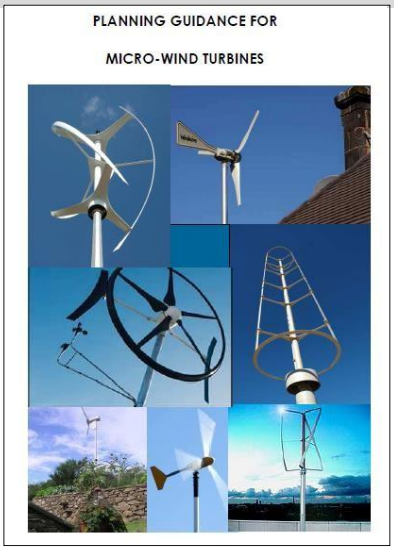
Guidelines: Micro Wind Turbines

- 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

- 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.

Challenges in the Implementation of Wind Energy Projects / Urban Wind Energy: Survey

Section 5

Challenges in the Implementation of

Wind Energy Projects / Urban Wind Energy:

Survey

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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(1) Stakeholders Survey

1. In your opinion, what are the main benefits of Urban Wind Technology?
2. How has Urban Wind Technology been delivered and managed so far in your region?
3. What are the main planning and environmental considerations relating to Urban Wind Technology in your region?
4. What are the main concerns and issues regarding social acceptance of Urban Wind Technology in your region?
5. Are you aware of any policies, guidelines or legislation relating to Urban Wind Technology in your region? If yes, please provide references.
6. Are you aware of any financial incentives to support Urban Wind Technology in your region? If yes, please provide references.
7. Are there any notable successes or failures in Urban Wind Technology in your region? If yes, please provide references.
8. Do you think that the implementation and adoption of Urban Wind Technology needs to be improved in your region? If yes, please provide details.

(2) Barriers and Limitations to Urban Wind Technology (A)

Preliminary:

- Define the **Scale** of urban wind turbine: Micrwind Trubine Limit of power set. Limit on size, how is it connected to the grid.
- Define the **Context** of Urban Wind Technology: Location including building integrated or at a defined distance from building/s.

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(2) Barriers and Limitations to Urban Wind Technology (B)

Points for Discussion:

1. How has Urban Wind Technology been delivered and managed so far in your region?
2. How do you rate the implientation so far of Urban Wind Technology in your Region?
3. In your opinion, what are the main benefits of Urban Wind Technology?
4. In your opinion what are the main limitations of Urban Wind Technology?
5. What are the main planning, environmental or other considerations relating to Urban Wind Technology implimentation in your region?
6. Are you aware of any policies (including incentives), guidelines or legislation relating to Urban Wind Technology in your region? If yes, please provide references.
7. Are there any notable successes or failures in Urban Wind Technology in your region? If yes, please provide references.
8. Is there room for improvement in the implementation and adoption of Urban Wind Technology in your region? If yes, please provide details.

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Thank you

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University of Malta

COST ACTION TU1304: WINERCOST

International Training School, Naples

Advances in Wind Energy Technology III

Accepting Winds of Change: Environmental Response Versus Social Perceptions

Neveen Hamza

TU 1304 –WINERCOST
Advances in Wind Energy Technology III
Napoli (Italy), 23 - 28April 2017

ACCEPTING WINDS OF CHANGE: environmental response versus social perceptions

Neveen Hamza (PhD, MSc, BSc)
Director: MSc Sustainable Buildings and Environments
School of Architecture, Planning and Landscape
Newcastle University
UK

http://www.protectwildscotland.org/wp-content/uploads/2013/06/wind-farm-protests

Social acceptance(SA)is interacting with the Energy Policy (EP), because:
1)Energy projects originate from an EP that seeks to secure energy supply and mix

2)SA influences the EP,as the implementation of the project results in either social acceptance or opposition that influences policy makers at the strategic level.

Direct influences on strategic decision-making are, the state of the environment, the economy and the society.

AEOLUS4FUTURE | Workshop on Sustainability and Life Cycle Assessment
Coimbra, 17-18 October 2016

Decentralized energy and theories of public perception

- Based on Devine-Wright (2012) and IEA task 28 reports,

Adopting decentralized energy systems

- Encourages energy citizenship
- Encourages engagement with energy systems
- altruistic values of caring about climate change will increase the appeal of engaging with micro generation
- The social rejection for the construction of nuclear plants
- That societies are less individualistic, lazy and passive and seek to be engaged and socially motivated to deal with the micro generation systems,
- and would allocate the necessary time to familiarize with the technology and be able to run it properly.

BUT ALSO

- While there is evidence on the ground that this is happening with PV and solar heating systems, this is not the case for urban wind generation.
- We need to instigate a cultural change: we cannot rely on this as lay people are usually used to the 'plug and forget' attitude they have with centralized energy supply

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Supranational influences

CLIMATE CHANGE AGREEMENTS
FREE MARKETS FLOW OF ELECTRICITY GENERATED FROM RENEWABLE ENERGY

The way in which supranational influences national wind energy objectives,
-The structure of the electricity market,
_the choice of development model or the choice of financial and legal instruments.

SOME QUESTIONS

LETS COMPARE CANADA To GERMANY……………………..
For example, the attitude of the Canadian federal government towards climate change and the significant presence of oil sands in Alberta do not help the various Canadian provinces to establish binding and ambitious Framework

This is in contrast to the situation in the European Union(EU), given that the EU has played the leading"climate" roles in the early 2000s by imposing RE guidelines and reference targets on each member state
Why Did it take 20 years within the same legislative framework to implement Wind Turbines between Demark and the UK?

11/10/2016

“Germany’s renewables revolution is making it harder to have a renewables revolution in Austria and other European countries,” Austria’s environment minister, Andrä Rupprechter, told Der Spiegel.

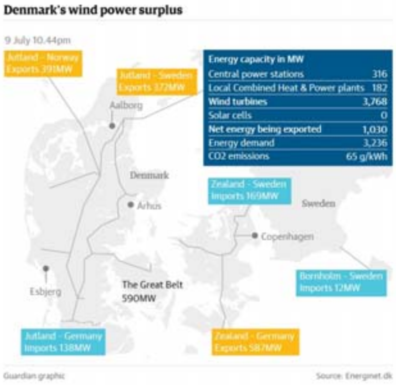
“Germany produces too much cheap energy, which countries like Austria then have to absorb.With the current prices for energy, investing in hydro or wind energy without state support is no longer competitive.”


theguardian

Renewable energy

Germany takes steps to roll back renewable energy revolution

The Conservative UK government has announced a withdrawal of support for onshore windfarms.(June 18th, 2015)


Denmark's wind power surplus

9 July 10.44pm

Energy capacity in MW	
Central power stations	316
Local Combined Heat & Power plants	182
Wind turbines	3,768
Solar cells	0
Net energy being exported	1,030
Energy demand	3,236
CO2 emissions	65 g/kWh

Guardian graphic

Source: Energinet.dk

Wind power generates 140% of Denmark's electricity demand

https://www.theguardian.com/environment/2015/jul/10/denmark-wind-windfarm-power-exceed-electricity-demand

The national Context

Top down approach
When the modes of action and preferred policy instruments are part of a ‘top-down’ tradition of state intervention based on large- scale infrastructure programs and large industrial conglomerates.

The existing energy mix
In Germany this led to wind energy being adopted in the 1980 while in France (nuclear energy) and Canada (Hydro power and oil availability) in the early 2000s (20 years apart)

- the perceived need for wind energy is less obvious, which strengthens opposition movements to projects and limits the political support for RE

The PUBLIC ISSUE- Perceptions versus implementation

The 89 % share of EU citizens who are in favour of wind power, according to a 2011 poll.

Survey in London, UK
90% of respondents expressed that renewable energy was a good idea,

however, only 20% of respondents indicated that it was at least fairly likely that they would install a renewable energy system, such as a wind turbine (Sauter and Watson, 2007).

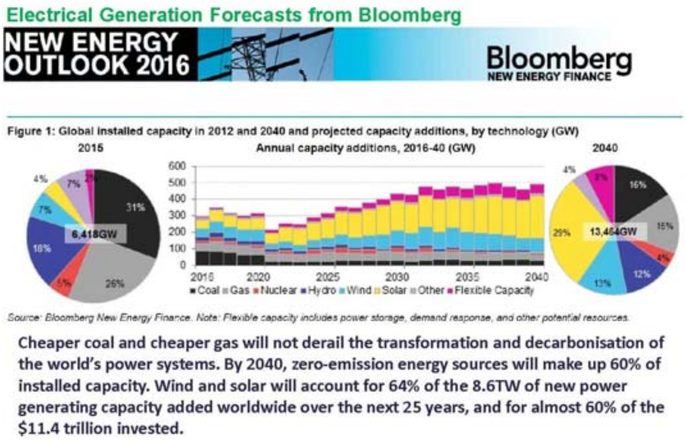
Research in other parts of Europe and the USA found similar results (Sims and Dent, 2007; Wolsink, 2007). These results suggest the social–political acceptance of RBSW is high, but it is not translating into high market acceptance.

Ref: Feurtey, E., Ilinca, A., Sakout. A., e,f,2, Saucier, C., (2016) Institutional factors influencing strategic decision-making in energy policy, Renewable and Sustainable Energy Reviews59, pp.1455–1470

While community members often express supportive attitudes towards wind energy, these attitudes are not usually exhibited behaviourally because of a reluctance to implement such projects locally (Energy Efficiency and Renewable Energy, 2008; Sauter and Watson, 2007; Sims and Dent, 2007).

What the public are told....

- 3.7% The percentage of global electricity supplied by wind power.
- Wind power installed more than any other form of power generation in Europe in 2015, accounting for 44% of total 2015 power capacity installations.
- It takes a wind turbine 3-6 months to recoup the energy that goes into producing, operating and recycling the wind turbine after its 20 to 25 year lifetime.



Electrical Generation Forecasts from Bloomberg

NEW ENERGY OUTLOOK 2016

Bloomberg
NEW ENERGY FINANCE

Figure 1: Global installed capacity in 2012 and 2040 and projected capacity additions, by technology (GW)

Source: Bloomberg New Energy Finance. Note: Flexible capacity includes power storage, demand response, and other potential resources.

Cheaper coal and cheaper gas will not derail the transformation and decarbonisation of the world's power systems. By 2040, zero-emission energy sources will make up 60% of installed capacity. Wind and solar will account for 64% of the 8.6TW of new power generating capacity added worldwide over the next 25 years, and for almost 60% of the $11.4 trillion invested.

The good, the bad! Earth is a finite resource

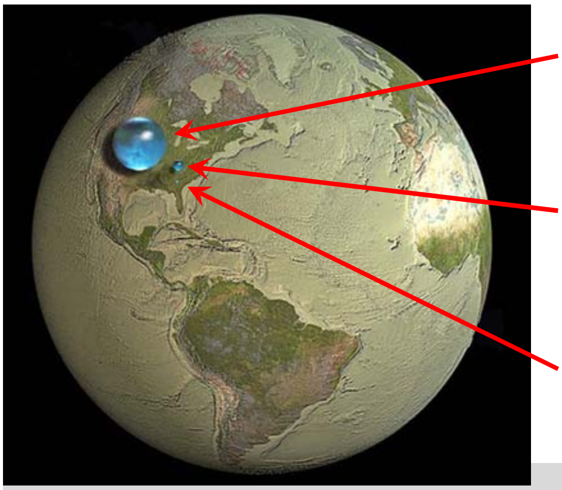
- The public agree on the fact that it is
- Clean technology

A farmer from Iowa who uses one tenth of a hectare for a wind turbine could earn about $USD 10,000 per year, compared to about$USD 300 using the same area to grow corn for ethanol. Source http://www.gwec.net/global-figures/wind-in-numbers/ (accessed October 2016)

Saving Water……

- 109 Amount in $billion invested in wind power globally, making it one of the fastest growing industrial segments in the world (source BNEF).
- 387 The amount of million cubic meters of water use avoided by wind energy in the EU, equivalent to the average annual household water use of nearly 7 million EU citizens (source:EWEA).
- 2,000 The amount of water in litres that wind power can save per MWh against other energy sources (source: US Department of Energy).

A graphical representation



All the earths water (860 miles in diameter)

Fresh liquid water in the ground, lakes, swamps, and rivers (169.5 miles in diameter)

Fresh-water lakes and rivers (34.9 miles in diameter)

Wind as an architectural form giver

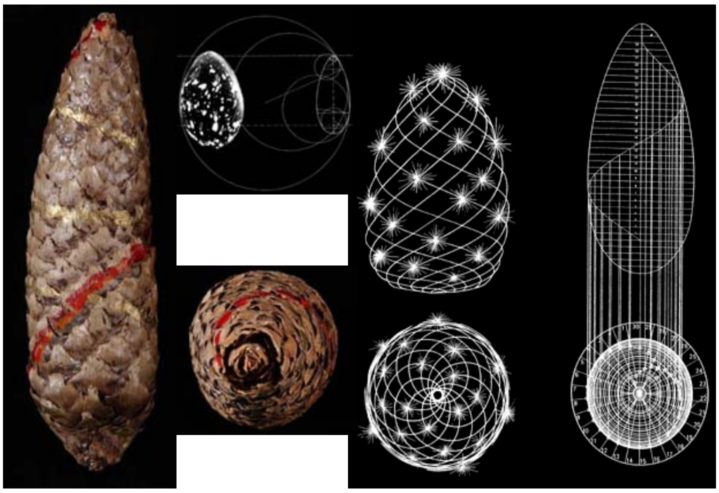
- Historically expressed as means to introduce fresh air for comfort

In Contemporary architectural forms

1- For maintaining air quality (fresh air intake)

2- A building form generator

3- For energy generation



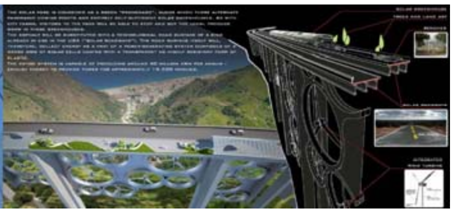
Let me mix you up

The dynamic profile of the tower is reinforced by a series of triangular air shafts that rotate through successive floor plates of the building, expressed in dark glass panels that resolve the exterior as an alternating series of spiraling bands.

Moving on to wind energy integration

Bahrain World trade Centre

Note: the arrow shape of the bridges holding the turbines….



“Solar Wind” bridge concept from Italian designers Francesco Colarossi, Giovanna Saracino and Luisa Saracino

Courtesy: http://www.gizmag.com/solar-wind-bridge-concept/17771/pictures#4

The questions….

- The public acceptance issue….
- Appreciation as a reliable technology or a mere symbol for urban sustainability
- A supporting energy generation technology to urban living! How much visual engagement do the public tolerate?

Wind Power within Urban Contexts

- Generally there are three methods of integrating wind turbines into the built environment;

-The first is the building integrated wind turbines, where a separate wind turbine is located on a free-standing tower away from the building itself;

-The second is the building mounted wind turbines, where the wind turbine is installed onto the building structure

-The third is the building augmented wind turbines where the building form is shaped to concentrate wind flow and is shaped towards the wind turbine.

Intentions, reality and the media

© Image courtesy of
Jane Coltman, Northumberland Gazette , 12th of January Saturday 11 February, 2012
http://www.windbyte.co.uk/northumberland.html and Northumberland Gazette,.

DEFRA Lion House Northumberland

What went wrong!

- *‘Much-criticised wind turbines on the edge of Alnwick have been out of action for almost half the time they have been installed, according to figures released following a Freedom of Information Act request by the Gazette. The statistics, provided by the Department for Environment, Food and Rural Affairs (Defra), show that the three generators at its flagship Lion House were offline for a total of 494 days since they went live on March 2, 2009. By comparison, they were working for 581 days during the same period.*
- *‘The problems arose after a world-wide recall by the turbine manufacturer, Proven Energy, which discovered a fault with its P-35 model in 2009. Proven finally went bust last September, but was sold by receiver KPMG to Irish renewables firm KingspanWind*

©
Jane Coltman, Northumberland Gazette , 12th of January Saturday 11 February, 2012
http://www.windbyte.co.uk/northumberland.html and Northumberland Gazette,.

What went wrong!

Left:The Green Building in Temple Bar,Dublin

- Anderson et al.(2008) studied the Green Building inTemple Bar,. *The application resulted in excessive noise, vibration, and eventual cracking of the turbine blades.The wind turbines were determined to be uneconomical and were eventually replaced by photovoltaic cells*

What went wrong!

The Kirklees council building (civic centre 3) in the town centre of Huddersfield,UK

The view of a wind turbine that doesn't rotate or even worse that is known to rotate without yield; increases public scientism of these systems (Kirklees Environment Unit Report,2006).

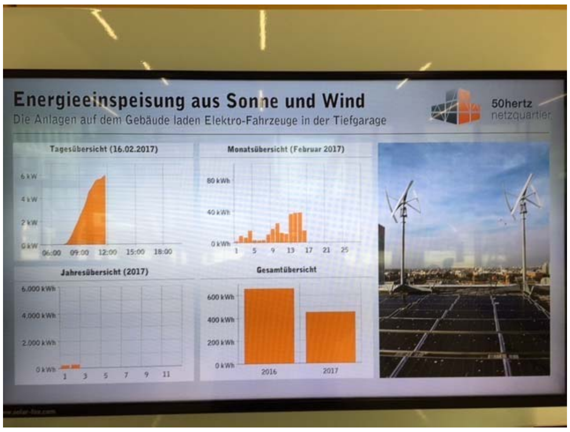
*'It seems that the posh folks living in the upper floor penthouses objected to the noise and vibration of the spinning blades, prompting project director Ian Bogle to suggest that they should be turned off between 11pm and 7am each night (*Londonist*, March 2010).*

Although local press blamed it on the vibration,Tom Hawkins commented (http://www.urban75.org/blog/)

'Its not so much the noise or vibration that has shut the turbines off, more like the £54,000 + vat a year maintenance costs for generating hardly anything that is the real factor. I know, I was involved in the second year budget for that building.'

The strata voted 'one of Britain's ugliest buildings'

50 Herz Building-Berlin-2016



Energieeinspeisung aus Sonne und Wind

Die Anlagen auf dem Gebäude laden Elektro-Fahrzeuge in der Tiefgarage

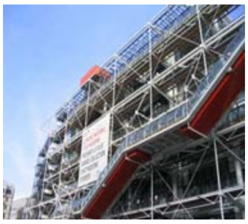
Hexham Abbey and community rejection for a wind turbine

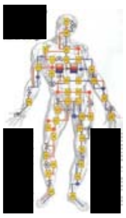
Focus groups with community leaders
Interviews with a random sample of residents
Interviews with Church clergy

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
Neveen Hamza-Accepting winds of change

http://www.ibispower.eu/products/powernest-2/

TU 1304 | WINERCOST | Napoli (Italy), 23-28 April 2017
Neveen Hamza-Accepting winds of change





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Sheerwind's ducted wind turbine prototype.

While all the ethical theories of public participation and awareness point out to strategies that may improve engagement with micro generation such as of citizenship.

What is the tolerance for the length of visual and noise exposure to urban wind turbines?

This draws on the analogy of visualizing the human body as a set of valves and pumps or do we prefer to see it the way we are used to?

Would ducted wind turbine with their huge structure offer a visually less intrusive model

How much of it do we want to see?

Images courtesy of SOM

Pearl River Wind Tower-China-SOM

Building augmented wind turbines: Exposing the statement hiding the technology

Qingdao Tower: Four ducted vertical-axis wind turbines (VAWTs) will be installed in the building's angular crown.
Image courtesy of SOM

Both towers exploit air accelerating through the vents by placing power-generating wind turbines hidden in the building structure
.The power satisfies only a small percentage of the towers' consumption needs and will take a relatively long 10 years to pay for themselves,. **Luke Leung, SOM's director of sustainable engineering services**,says : ***'clients see value in the ideas the turbines communicate and the questions they provoke.'***

- The societal acceptance of urban wind generation has been affected by experience and media exposure.
- Building augmented wind turbines are for performance reasons **only integrated in towers and one off iconic structures**. Still being seen by the public and design teams alike as a token gesture to sustainability and environmental values
- Although research suggests that public perceptions and acceptance of micro wind generation maybe supported by **value believes and excitement in participation in new forms of technology**, there is no evidence found that this is the case on the ground
- Public perceptions and their engagement with the market **dictates growth patterns and can underpin incentivization** schemes and government policy. Similarly this also affects building regulations.
- Architectural styles and the integration of renewables are directly affected by all of the above factors. It is interesting to see the discourse on **how much of micro renewable energy should be seen and heard by the public.**
- This in its wake will lead to raising questions on how to advance other **forms of micro generation from wind** such as the ducted systems and the possible involvement of artists to improve the aesthetic of these systems.

Conclusions