INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems
ANNEX XI

35th IEA Topical Expert Meeting

Long Term R&D Needs 2000-2020

The Netherlands, March 2001

Organised by: ECN

Scientific Coordination:

Sven-Erik Thor
FOI, Aeronautics Division, FFA, Sweden

CONTENTS

INTRODUCTORY NOTE TO IEA R&D WIND EXPERT MEETING ON LONG TERM R&D NEEDS, 2000 -2020

Sven-Erik Thor

The benefit of the R&D to the wind energy sector has been clearly demonstrated by increasing sizes and lower prices per installed unit of production capacity. Production costs have been reduced by a factor of four from 1981 to 1998. The dawn of R&D was technologically driven whereas, when it later became more mature other topics emerged, related to noise, public attitudes and the environment.

Wind energy is presently cost competitive on locations with a good wind resource. The present cost level is around 4.7 USD cent/kWh. The projected cost of wind energy in 2020 is 2.5 USD cent/kWh. This projection is based on an installed capacity of 80 GW year 2010 and 1 200 GW year 2020.

The wind energy market is in a state of rapid development; it is growing faster than the personal computer industry, and almost as quickly as the cellular phone market. In the last three years a number of growth studies have been presented. In a study called Wind Force 10 almost 3000 TWh electricity will be produced by year 2020, this corresponds to around 11% of the expected world consumption of electricity in that year. The annual investment requirements to achieve this goal will be USD 3 billion in 1999 reaching a peak of 78 billion in 2020. This will increase employment in the wind industry and supplying sector from 82,000 in 2005 to 180,000 in 2020. The environmental benefit from this scenario will be an annual reduction of CO_2 emissions by year 2020 of 1,780 million tons.

In order to make this deployment come true, it has to be supported by extensive R&D and Development actions. Future R&D will support incremental improvements in e.g. understanding extreme wind situations, aerodynamics and electrical machines. But, the challenge is to try to find those evolutionary steps that can be taken to further improve wind turbine technology, for example in large scale integration incorporating wind forecasting and grid interaction with other energy sources.

The objective the meeting is to try to identify needed future results from R&D both in the 5 to 10 and the 10 to 20 year time frames. The Executive Committee of IEA R&D Wind will use the resulting overview of R&D needs to plan mutual beneficial activities in the coming years.

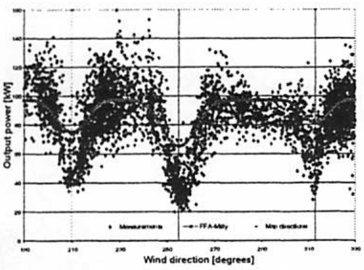
Reference

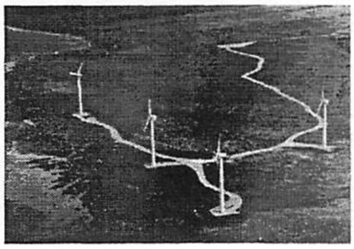
IEA R&D Wind Expert Meeting no 27, 1995
Current R&D needs in Wind Energy Technology

IEA R&D Wind

Topical Expert Meeting #35

Long Term R&D Needs 2000-2020





International
Energy
Agency
R&D
Wind

Agenda Thursday

9:15	**Meeting starts**	
	ECN Introduction,	**Bert Janssen**
	Recognition of participants	
	IEA Introduction,	**Sven-Erik Thor**
	Introductory note	
Break		
	Presentations	
Lunch		
	Presentations	
Break		
	Presentations	
End day one		

International
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Agency
R&D
Wind

Agenda Friday

9:15 **Meeting starts**

IEA work on Long Term R&D, Jaap 't Hooft

Presentations

Break

Discussion

Lunch

Discussion

End of meeting

International Energy Agency R&D Wind

IEA REWP Organization

- IEA Renewable Energy Working Party, REWP
  - IEA R&D Wind
    - Executive committee
      - XI - Base Technology Information Exchange
      - XV - Annual review of progress in the implementation of wind energy
      - XVI - Wind turbine round robin test program
      - XVII - Database on wind characteristics
      - XVIII - Enhanced field rotor aerodynamic database

International Energy Agency R&D Wind

XI - Base Technology Information Exchange

- Joint Action Symposium
  - Aerodynamics
  - Fatigue
  - Wind Characteristics
  - Offshore wind systems
- Topical Expert Meetings
  - Latest meeting was on Noise Immission (#34)

International Energy Agency R&D Wind

Previous meeting

- 1995
- ECN
- 22 participants

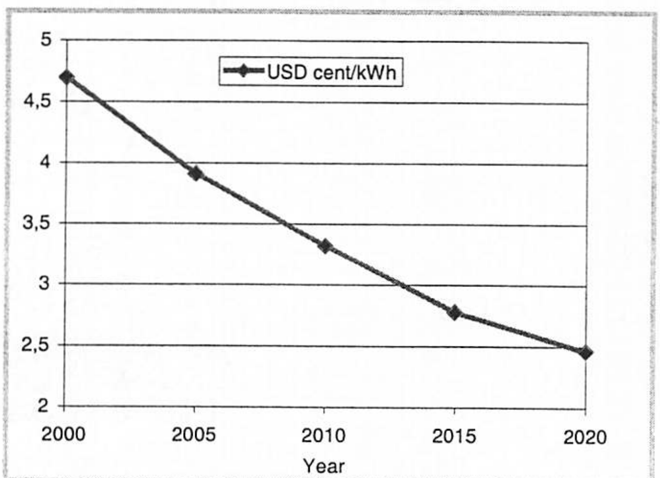
International Energy Agency R&D Wind

Why continue long term R&D?

- **Continue cost reductions**
- **Enable large scale use**
- **Minimize environmental impacts**

International Energy Agency R&D Wind

Declining cost of wind electricity



Source: BTM 99 cost scenario

Cost calculations are based on Wind Force 10 projections for installed capacities

2000	14 GW
2010	180 GW
2020	1200 GW

International Energy Agency R&D Wind

Sources of cost reductions 2000 - 2004

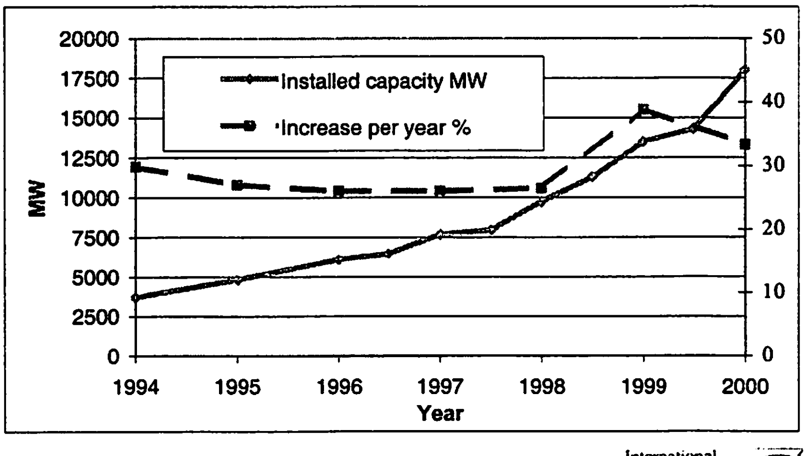
Source	%
• Technology improvements (weight and efficiency)	40
• Economy of scale (manufacturing improvements)	50
• Other contributions (foundations/grid connection/O&M cost)	10

Reduction in energy cost is 4.7 to 4.0 USD cent/kWh

Source BTM 1999

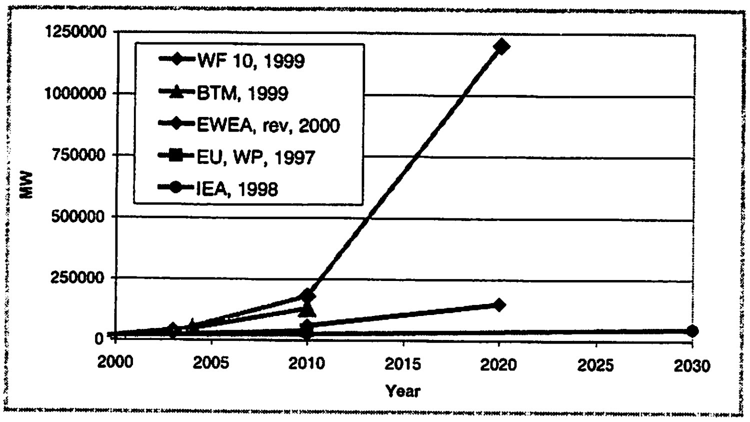
International Energy Agency R&D Wind

Cumulative installed capacity



International Energy Agency R&D Wind

Projections of wind market



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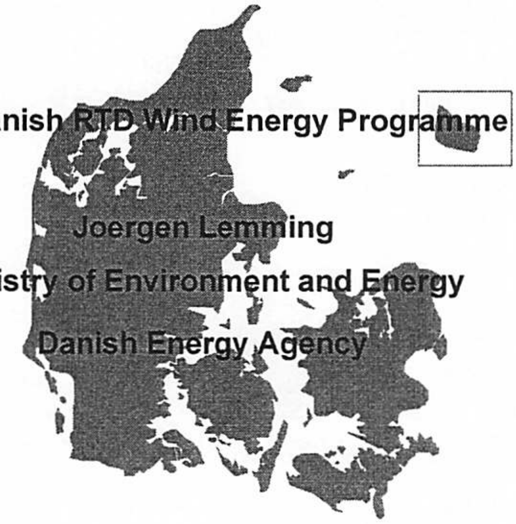
Wind

20-03-01



The Danish RTD Wind Energy Programme

Joergen Lemming

Ministry of Environment and Energy

Danish Energy Agency

20-03-01

Energy 21
The Danish Governments Plan of Action

Main Targets in Energy 21

- 20% reduction of CO_2 - emissions from 1988 to 2005
- 50% reduction of CO_2 - emissions before 2030

- 12 - 14 % of renewable energy in 2005 (100 PJ)
- 35% of renewable energy by 2030 (235 PJ)
- 20% renewable of elec. 2003

- http://www.ens.dk/stat/eindex.htm

Targets for Wind Power

- 1500 MW wind power in 2005 (200 MW off-shore)
  12% of electricity consumption
- 5500 MW wind power in 2030 (4000 MW off-shore)
  40-50% of electricity consumption

Energy 21

The Danish Government's Action Plan for Energy

- http://www.ens.dk/e21uk

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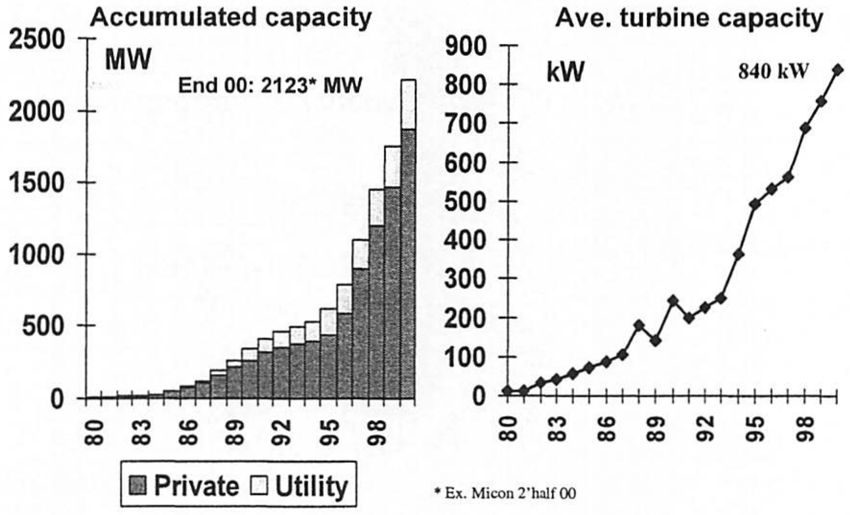
Status

Installed capacity in Denmark



20-03-01

Expected deployment of windpower end of 2000 i Denmark

• Number of turbines installed	6200
• Capacity installed	2340 MW
• Capacity offshore	50 MW
• Production 2000	4,242 GWh
• Electricity consumption 2000	34,870 GWh
• Share of Wind in 2000 (95.4% wind)	12.2 %

20-03-01

Danish Wind Turbine Industry

some key figures

- Sales in 1997: 5.0 billion DKK
- Sales in 1998: 7.0 billion DKK
- Sales in 1999: 11.0 billion DKK
- Sales in 1999: 13.0 billion DKK
- Export: 70 - 90%
- Global market share in 2000: approx. 45%.
- Employment in DK: approx.. 12,000 persons

1 EURO ~ 7.4 DKK

20-03-01

World Market

- 20 years track record for commercial wind turbines
- Average annual growth of 40% between 1991 to 1998
- Wind turbines in more than 50 countries
- Increasingly more countries adopts favourable policy for wind power
- World capacity growth from 18,450 MW in 2000 to 57,000 MW in 2005 (BTM Prognose)

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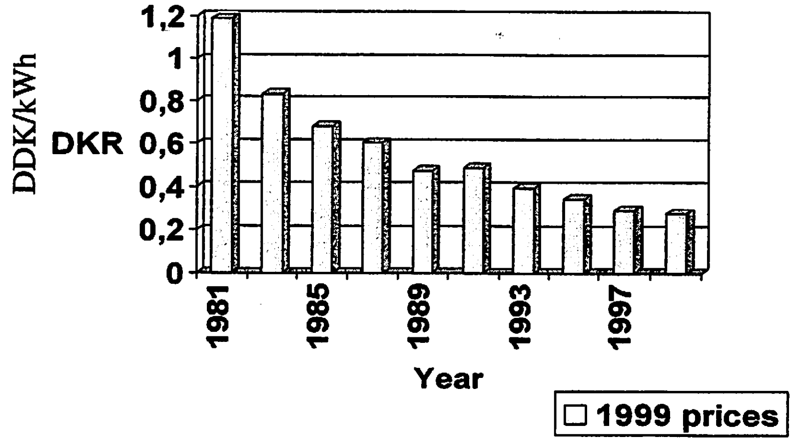
Production cost at Danish Wind Power Plants



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Estimates for future price reductions up to 2004

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Demand pull instruments and 'Back-up' policies

- Fixed price system
- Subsidies for installation and production
- Agreements with Utilities
- Grid-related issues
- Spatial planning
- 'Green Marked'

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Certificate in stead of electricity subsidy

'Old' system:
Electricity price + fixed subsidy.
Subsidy = administratively fixed.
Problem: Oversubsidiation.

'New' system:
Electricity price + certificate.
Certificate = market-set premium.
Certificate market starts 2002.

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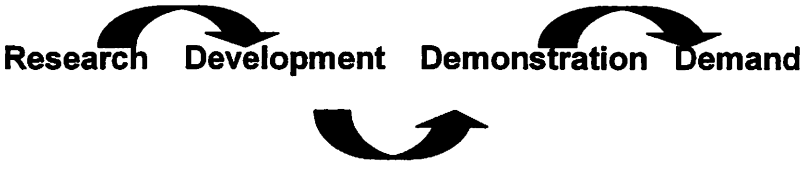
RTD Programme
The Innovation Chain



- **R&D is necessary - but not sufficient**
- **Market incentives are crucial**

20-03-01

Danish programmes
for Wind Energy RTD

- Ministry of Environment and Energy's RTD programmes (EFP & UVE)
- Test station programme at Risoe
- DANCED and DANIDA aid programmes for developing countries
- Utility sector PSO-programme (Public Service Obligation)

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Strategies for the RTD-Programme for Wind Energy

- Economic and technological development
- Wind Resources and climatic conditions
- Integration of Wind Power
- Environmental and society aspects

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Economic and technological development

- Aerodynamics, structure and materials
- Designbasis for offshore wind turbines
- Materials in wind turbine technology
- Further development of aeroelastical models
- New tools for validation of wind turbine constructions and components

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Wind Resources and climatic conditions

- Enhanced basis for short term wind prognoses and long term prediction of energy production
- Enhanced knowledge of wind structures an statistics for load calculations
- Climatic data for waves, current and ice for offshore installations

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Integration of Wind Power

- Storage
- The wind turbines as powerstation
- Stability of the grid
- Power electronics

20-03-01

Environmental and society aspects

- Lifecycle projects and recycling of materials
- Noise and infrasound
- Visual impact of large turbines

20-03-01

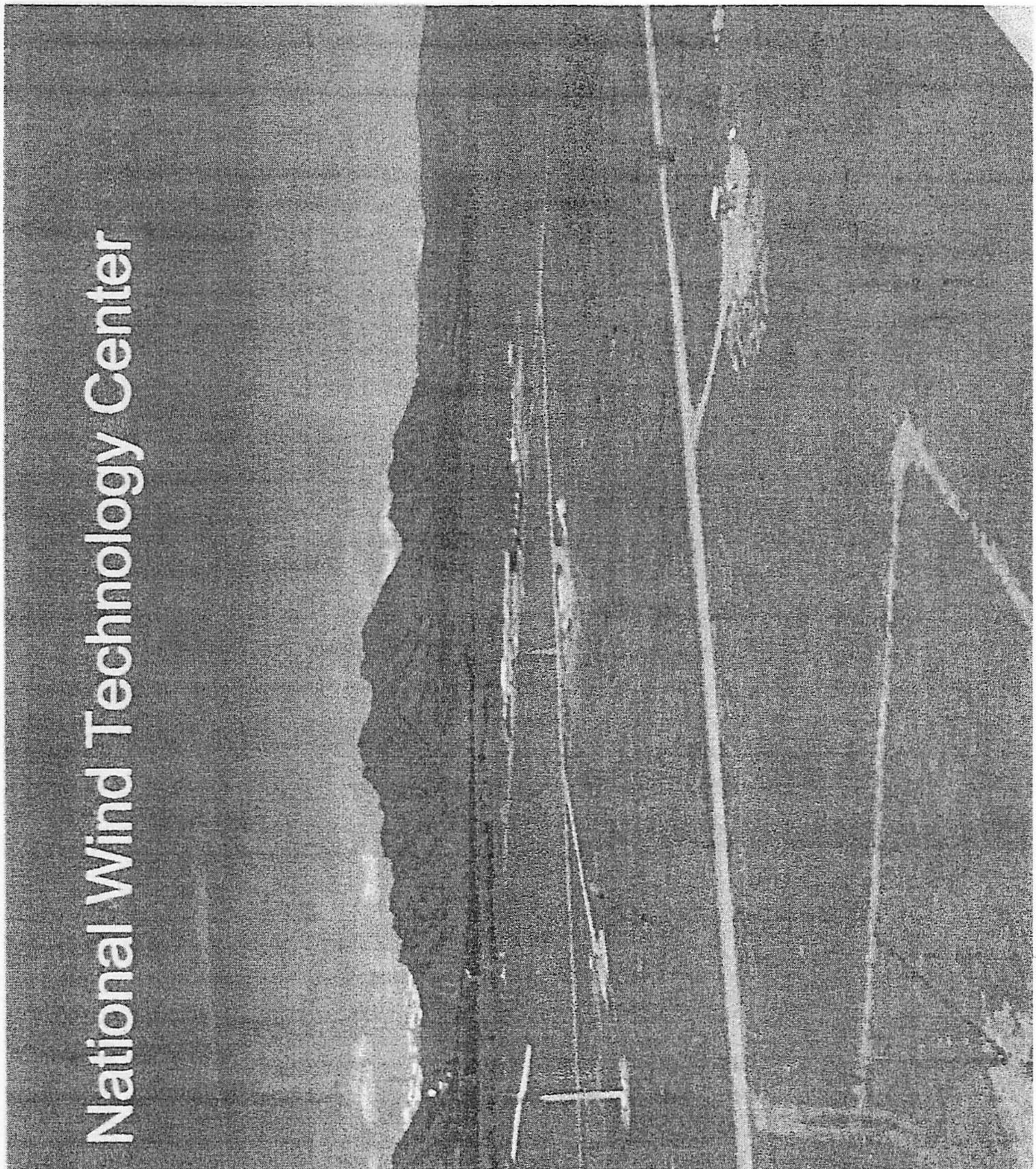
Projects under the EFP-2001 Programme

- Aeroelastic Research Programme 2001-2002
- Turbine dynamics and gear loads
- 3-D simulator for determination of extreme and fatigue loads
- Improved design basis for large wind turbine blades made of composites
- Electrical design and control - a simulations platform for modelling, optimisation and design of wind turbines

20-03-01

Future challenges

- Reduced public budgets for RTD
- Long-term RTD
- Public/private partnership in a context of globalisation

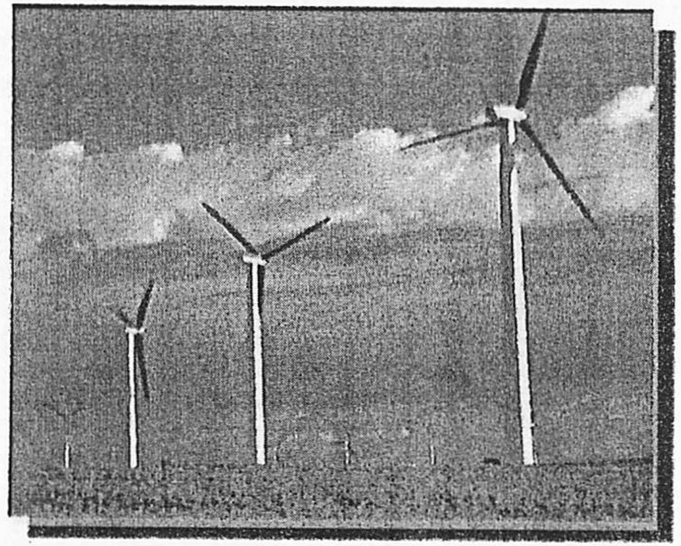

National Wind Technology Center

NREL

Cost of Energy Trend

1979: 40 cents/kWh

**2000:
4 - 6 cents/kWh**

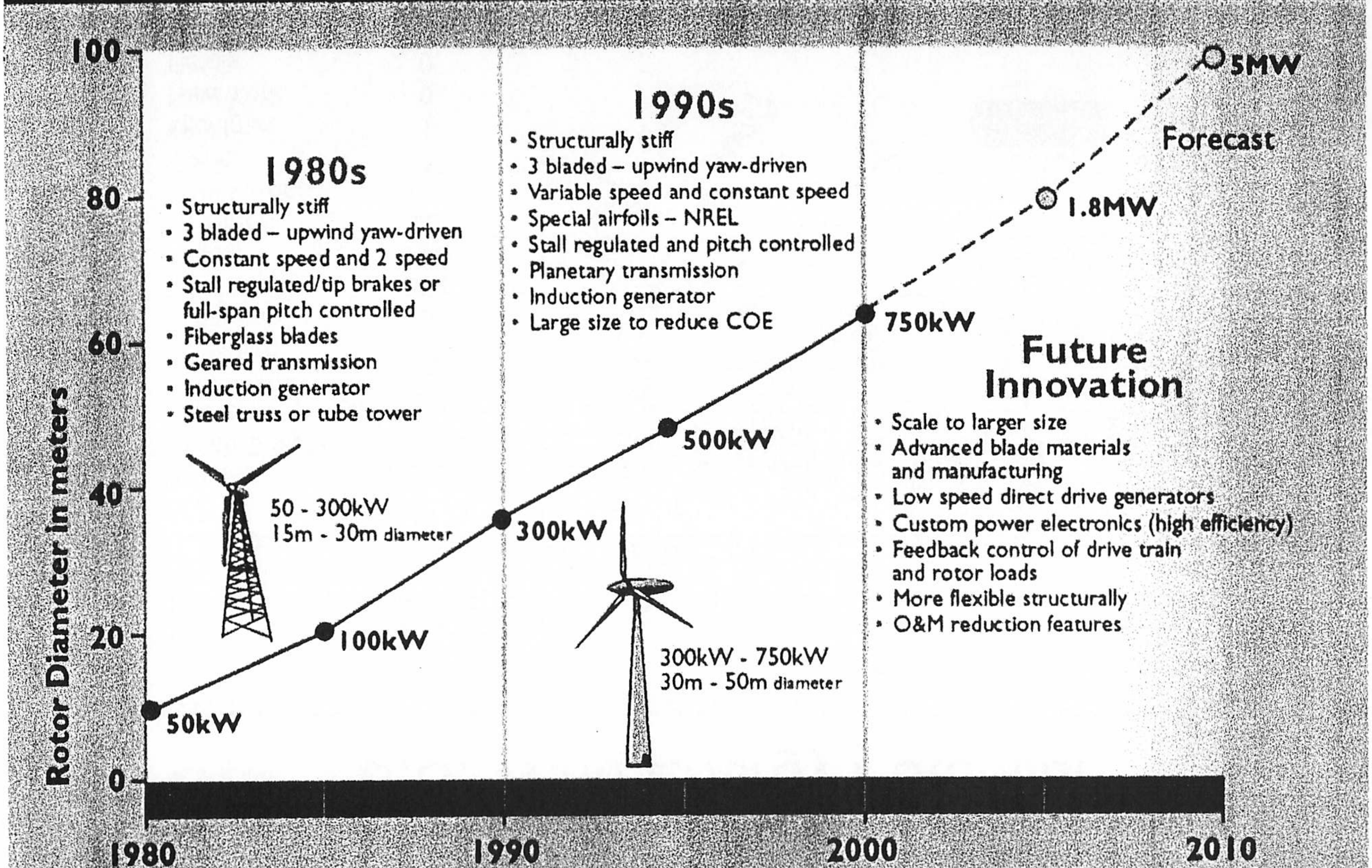


NSP 107 MW Lake Benton wind farm
4 cents/kWh (unsubsidized)

- Increased Turbine Size
- R&D Advances
- Manufacturing Improvements

**2003:
2.5 - 4.5 cents/kWh**

THE EVOLUTION OF COMMERCIAL U.S. WIND TECHNOLOGY

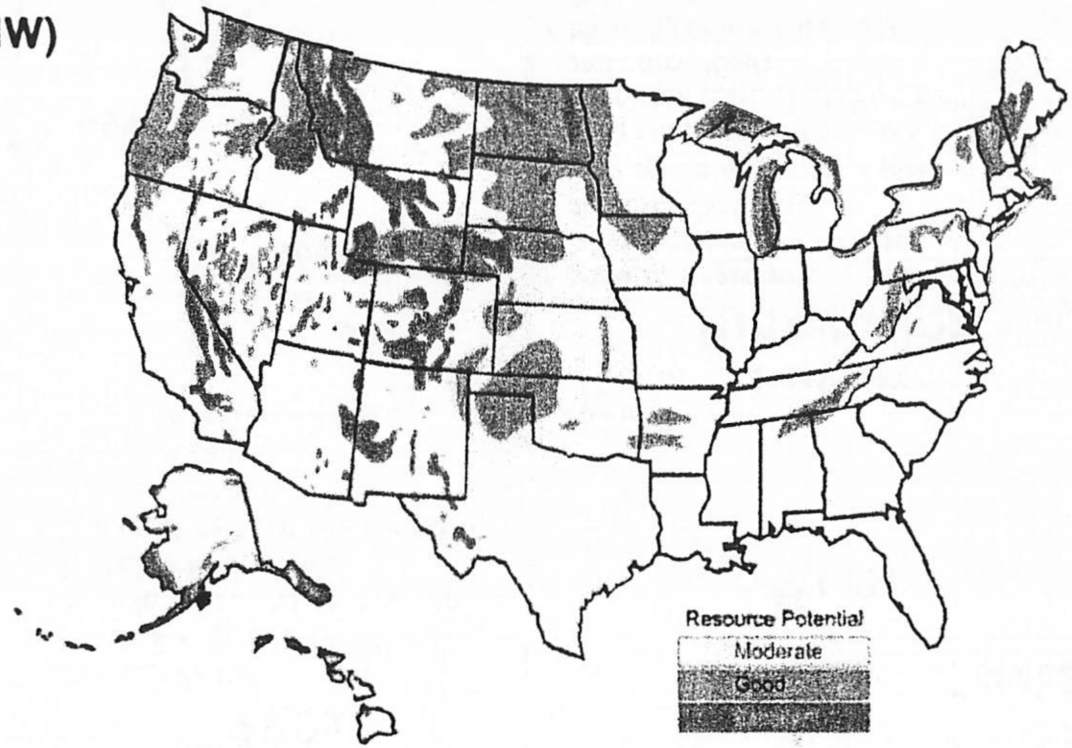


Source: Thresher & Dodge, Wind Energy Journal 1998

U.S. Wind Energy Potential

Rank	State	Installed Capacity (MW)
1	North Dakota	1
2	Texas	188
3	Kansas	2
4	South Dakota	0
5	Montana	0
6	Nebraska	3
7	Wyoming	73
8	Oklahoma	0
9	Minnesota	272
10	Iowa	242
11	Colorado	22
12	New Mexico	1
13	Idaho	0
14	Michigan	1
15	New York	0
16	Illinois	0
17	California	1599
	Other	96
	Total	2500

Source: AWEA



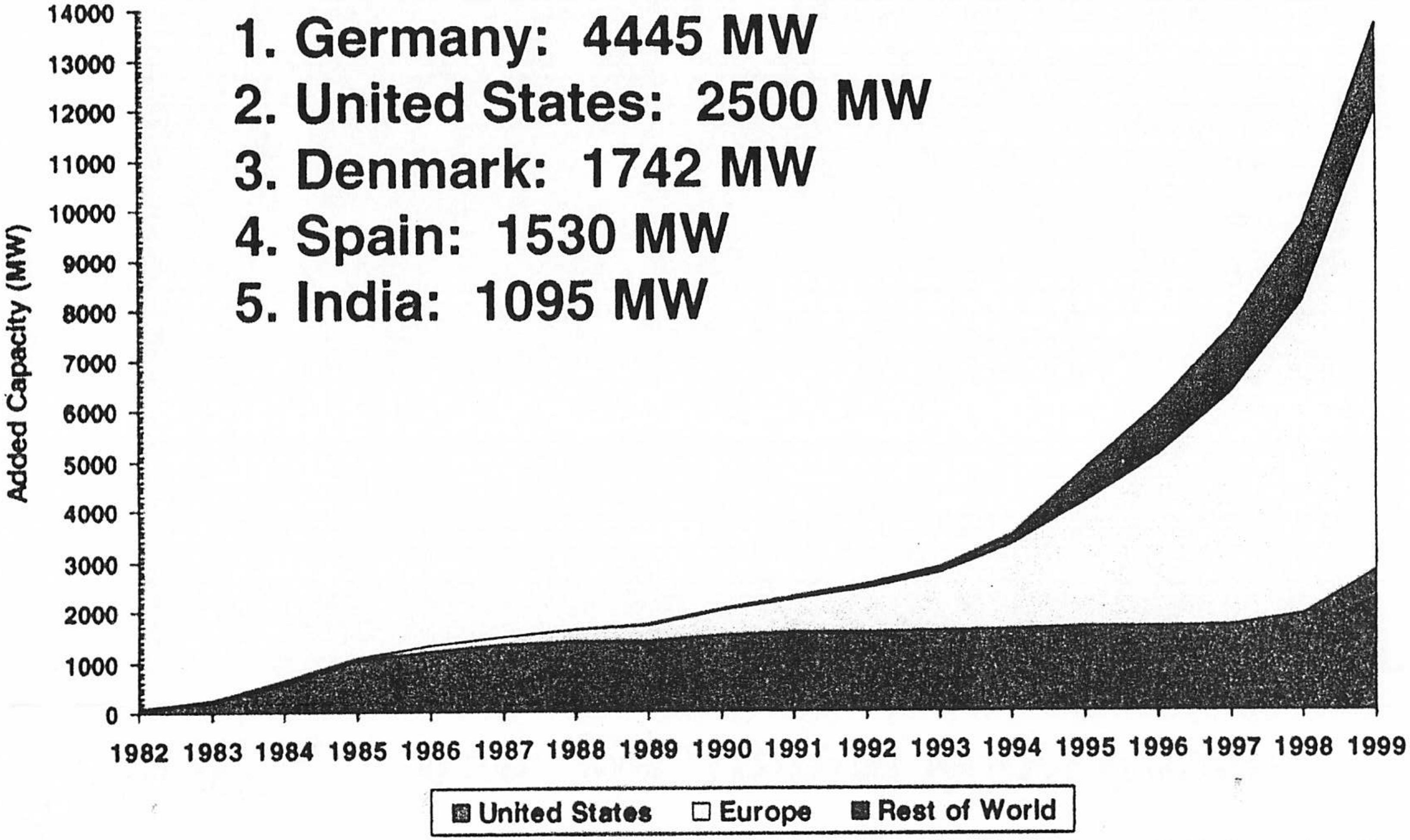
World Class Wind Potential

Germany's Potential: 100 GW

North Dakota's Potential: 250 GW

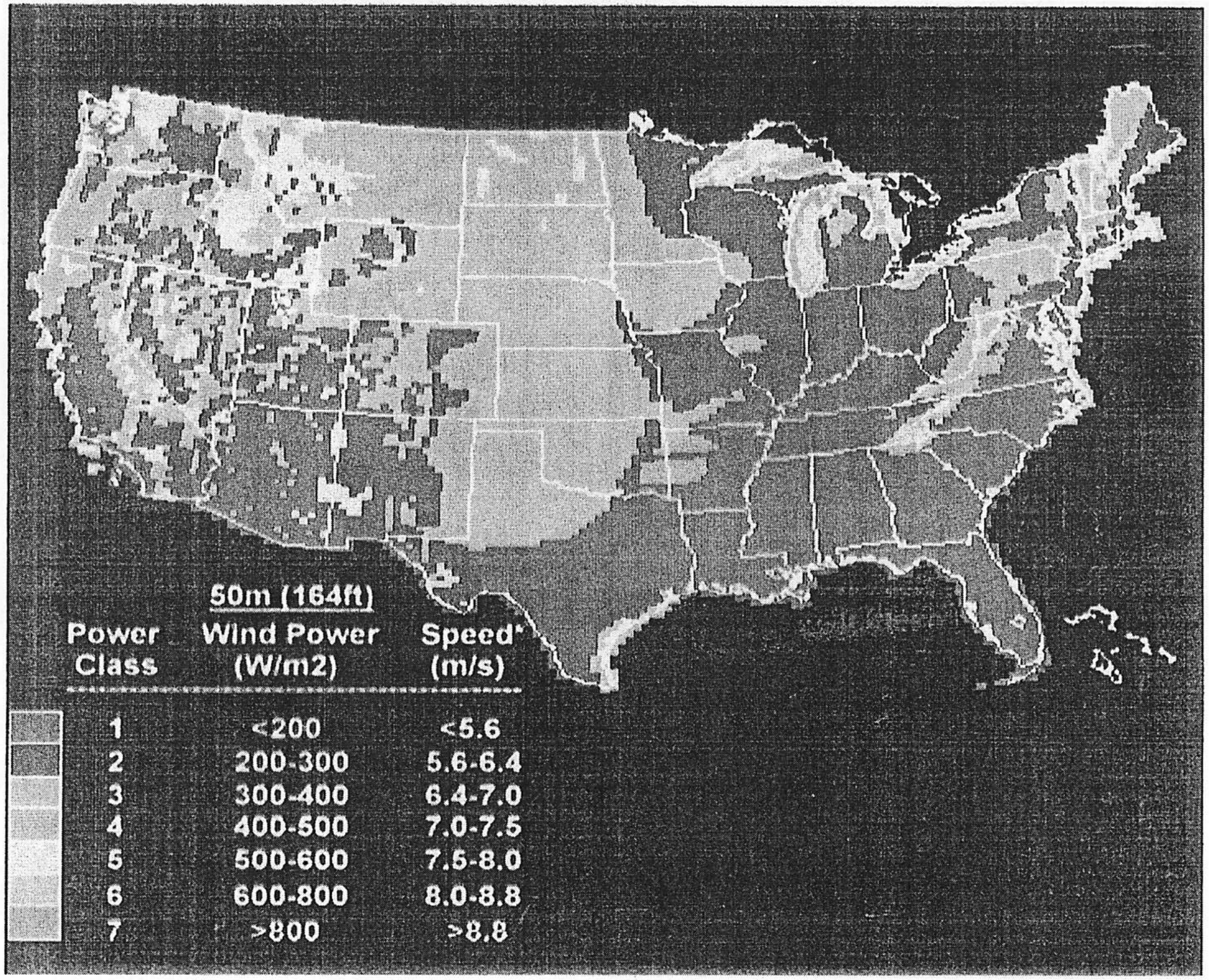
Taking Off Worldwide

1. Germany: 4445 MW
2. United States: 2500 MW
3. Denmark: 1742 MW
4. Spain: 1530 MW
5. India: 1095 MW

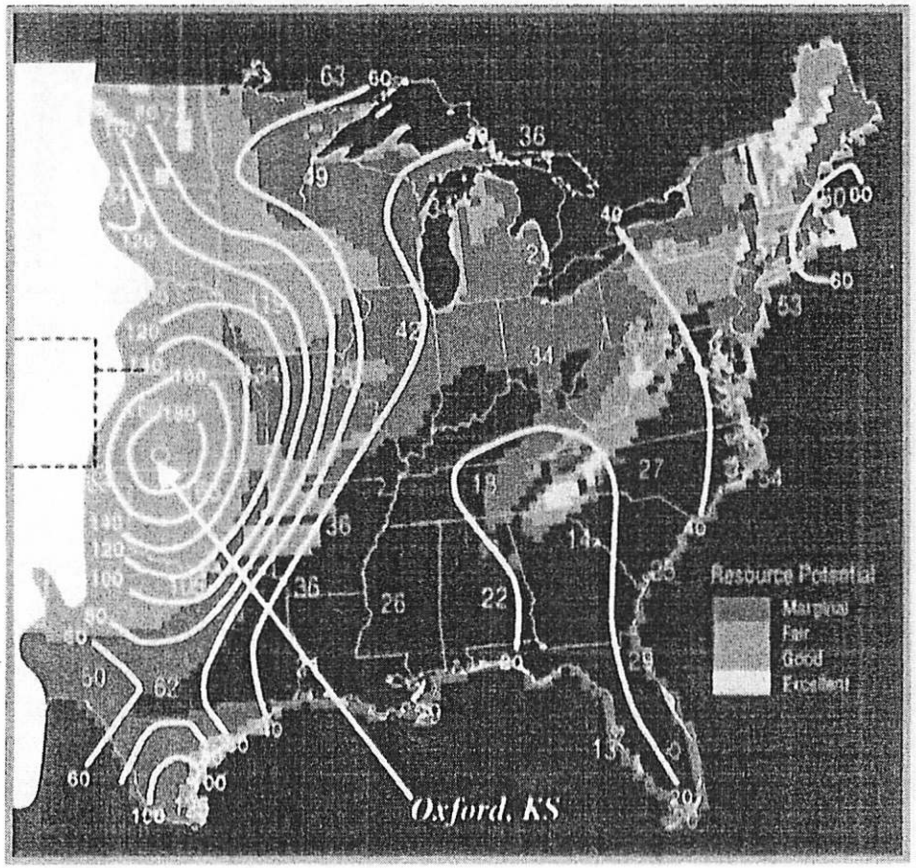


Based on information supplied by International Energy Agency.

Average Annual Wind Power



Bi-Annual Frequency of Great Plains Low-Level Jet and Its Relationship to Wind Resource Potential

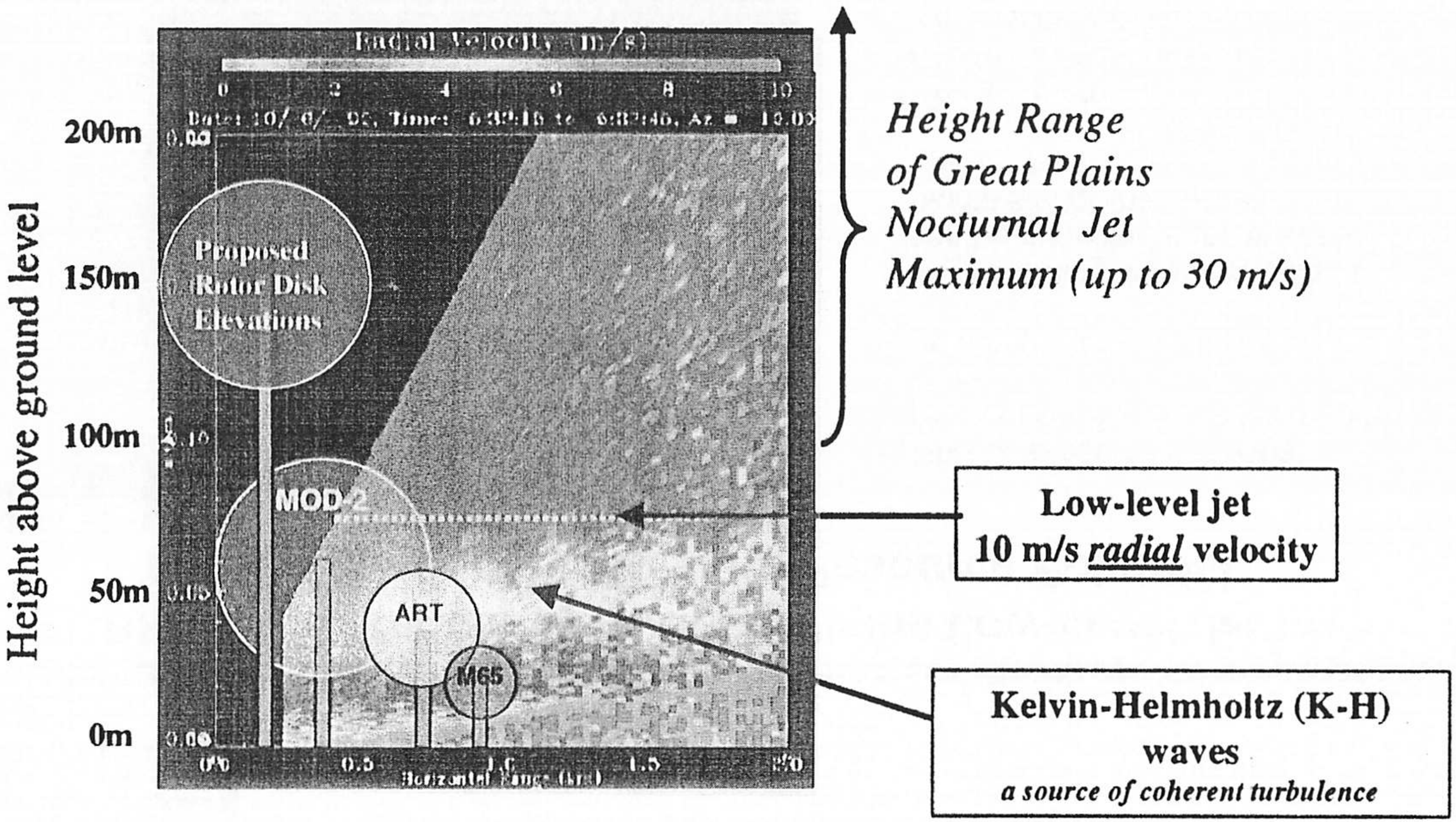


LLJ Source: Bonner, MWR, Dec 1968

- Shows expected bi-annual frequency# of a low-level jet below 3 km with a peak wind speed of 16 m/s or more
- A jet meeting these conditions can be expected once every 4 nights along the border of Oklahoma and Kansas
- The southern tip of Texas and New England also experience these jets
- There is a strong correlation between the good to excellent wind resource and the low-level jet in the Western Great Plains

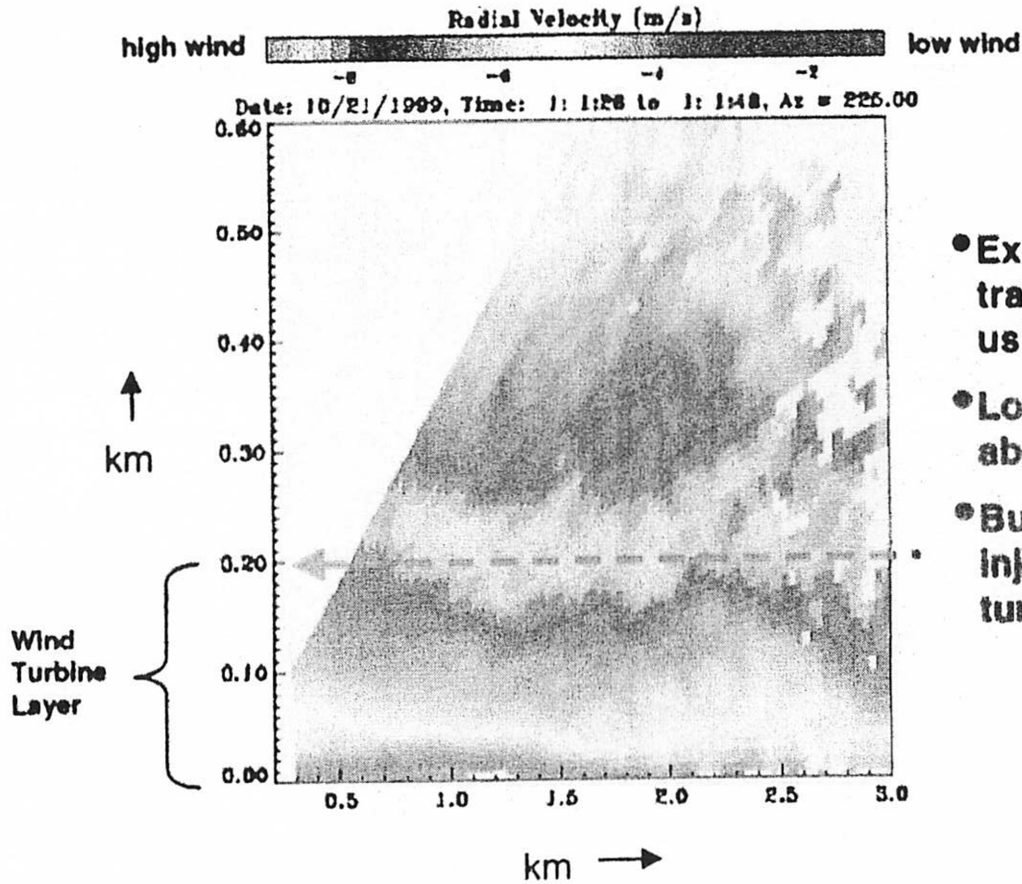
#frequency of jet occurrence is likely to be underestimated

Example of Nocturnal LIDAR-measured Low-Level Jet over Southern Kansas with Current and Proposed Turbine Heights



LIDAR measurements courtesy of Dr. Robert Banta, NOAA/ETL

Day-Night Transition of Boundary Layer Produces Organized Turbulence Structures



- Example of boundary layer day-to-night transition *(6:28 to 6:48 pm local time)* using LIDAR observations
- Low-level jet forms about 200 meters above ground
- Bursts of organized turbulent energy are injected into region occupied by wind turbines

LIDAR Measurements courtesy: Dr. Robert Banta, NOAA/ETL

Windpower – Research, Development and Demonstration in Sweden

Susann Persson
The Swedish National Energy Administration
Department for Power Technologies

Energimyndigheten

www.stem.se

Windpower Research

- ✓The Windpower programme, VKK
  - ✓100 % financed by the state
  - ✓MSEK 15,6
- ✓Elforsk Windpower programme
  - ✓50 % financed by utilities
  - ✓MSEK 2
- ✓Certain specific research projects

Energimyndigheten

VKK Research areas

1. Meteorology and performance
2. Aerodynamics and structural dynamics
3. Loads and design
4. Electrical systems and control systems
5. Noise issues
6. Sociotechnical aspects
7. Resources

Energimyndigheten

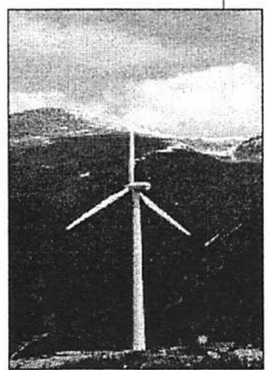
Development projects at present

✓Nordic Windpower – specific technology development projects

Energimyndigheten

Demonstration

- A demonstration plan will be made during spring 2001
- At present:
  - 2 projects in arctic climate
  - 2-3 offshore projects
  - Helicopter construction phase
  - Näsudden III (ABB:s Windformer)
  - Nordic Windpower technology



Energimyndigheten

Present research programmes

- Last through june 2001
- Evaluation has been performed in the winter
- Seminars have been arranged with researchers and the wind power business

- Aim:
  - To start a new programme with the most important research areas
  - To get more financing from the exploiters, developers and utilities

Energimyndigheten

Evaluation of wind research

- Goal has been reached
- Good relations with the industry
- Recommended to increase budget
- Material research recommended
- Socio-technical research must be closely linked to other research
- Try to involve the industry as much as possible

Energimyndigheten

The most serious problems

- Economic conditions uncertain
- Difficulties getting permits
- Environmental problems
  - ✓Visual impact
  - ✓Animal consequences

More windpower – the animals worse or better off?

Energimyndigheten

Seminar – Future wind research programme

- Knowledge aquiring and compilation
- Research on environment and permit processes
- Technology is important!
- Forecasting models
- Grid connection issues
- Local benefits – Bring it forward!

Energimyndigheten

Ongoing research that continues…

- **Structural dynamics**
- **Electric machinery and control technology**
- **Meteorology (bounday layer phenomena, simulation methods)**
- **Socio-technical aspects**
  - **Permission**
  - **Acceptance**
  - **Animal**
- **Mainly information, planning targets, changed regulation needed.**

Energimyndigheten

Other important areas

- The grid (integration)
- Foundation methods
- Meteorology (forecasting)
- LCA

Energimyndigheten

LONG TERM R&D NEEDS FOR OFFSHORE WIND ENERGY

Ian Fletcher
UK

Thinking Positively

- 5 MW machines
- wind farms of 0.5 to 1 GW
- developments outside territorial waters
- split ownership within site, sharing costs and spreading risk
- highly customised offshore turbine technology
- dedicated installation and maintenance vessels

Thinking Positively

COST

- 5 MW machines
- wind farms of 0.5 to 1 GW
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Thinking Positively

COST

RELIABILITY

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Thinking Positively

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RELIABILITY

COST

PUBLIC ACCEPTABILITY

Thinking Positively

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- highly customised offshore turbine technology
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RELIABILITY

COST

PUBLIC ACCEPTABILITY

GRID INTEGRATION

Cost

RESULTS NEEDED

- Match current onshore costs by 2005-2010
- Competitive in open market place by 2020 (equating to ~2-3 US cents today, but could increase)

Cost

RESULTS NEEDED

Performance measure
Capital costs
O&M costs
Availability

Cost

RESULTS NEEDED

Performance measure	Target 2005-2010
Capital costs	£ 750/ kW installed
O&M costs	0.75p/ kWh
Availability	95+% by 2010

Cost

RESULTS NEEDED

Performance measure	Target 2005-2010	Target 2020
Capital costs	£ 750/ kW installed	£ 500/ kW installed
O&M costs	0.75p/ kWh	0.5p/ kWh
Availability	95+% by 2010	99%

Cost

R&D areas:

- Improved understanding of design loads
- Foundation design
- Installation methods
- Installation and maintenance vessels
- Development of large blades (Manufacturing and materials technology)
- Large array loss calcs and design

Reliability

R&D areas:

- Improved accessibility
- Condition monitoring
- Application of failure modes and risk analysis techniques

Public acceptability

EDUCATION AND OUTREACH

- Needs and benefits, international perspective
- Technology awareness
- Quantification and amelioration of environmental effects
- Production and dissemination of information
- International best practice guidelines

Grid Integration

R&D Needs:

- Grid stability studies
- Regional potential and infrastructure requirement studies
- Control and mitigation measures for high wind penetration
- Development of large energy storage technologies

Divergence from onshore technology

- Lack of limitations on size and weight
- Increased need and cost benefit in reliability
- Reduced noise problem
- Integration of installation and maintenance methods into turbine/tower
- Possibly higher voltages
- Even higher emphasis of track record

Long Term R&D Needs for Wind Energy

Wind Resources & Forecasting

Ignacio Marti

Questions to solve in the field of Wind Resources

- High uncertainty of wind resources studies in complex terrain. Financial risk.
- Wind turbine failures due to turbulence in complex terrain.
- Expensive evaluation methods for isolated systems.
- Unpredictability limits wind energy grid penetration, may cause grid problems and it is an obstacle when one tries to combine wind energy with other energy sources.

Wind Resources. R&D needs

- Improvement of wind field models: (5-10 years)
  - Better spatial resolution in complex terrain.
  - Simulation of turbulent parameters.
  - Vertical profile in complex terrain.
- Low cost wind resources studies for isolated systems. (5-10 years)
- Satellite information. Development of accurate techniques to estimate the wind with satellite images in any kind of environment (10-20 years).

Wind Energy Production Forecasting. R&D needs I.

- Improvement of the existing prediction models performance: (5-10 years)
  - Increase of the Numerical Weather Prediction (NWP) models spatial resolution, especially for complex terrain areas.
  - Development of new statistical techniques to adapt NWP predictions to wind energy requirements.
- Extreme conditions forecasting, including gusts, turbulence, vertical profile changes,... (10-20 years).
- Low cost forecasting models for isolated systems. (5-10 years).

Wind Energy Production Forecasting. R&D needs II.

- Availability of the forecasts for a wide variety of users (utilities, energy planners, wind farm owners, ...) (5-10 years).
- Improved use of wind forecasting by the final user. Better combination of wind energy with other energy sources (5-10 years).
- Use of satellite information for wind forecasting in combination with NWP models. Cost reduction and wider availability of the predictions. (10-20 years).

RISØ

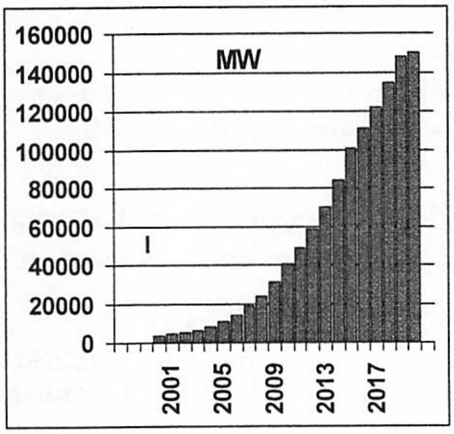
Long-Term Research Needs
Some thoughts on long term Research Lines

Flemming Rasmussen

Wind Force 10 EWEA, FED, Greenpeace Int.

A Blueprint to achieve 10% of the World's Electricity from Wind Power by 2020

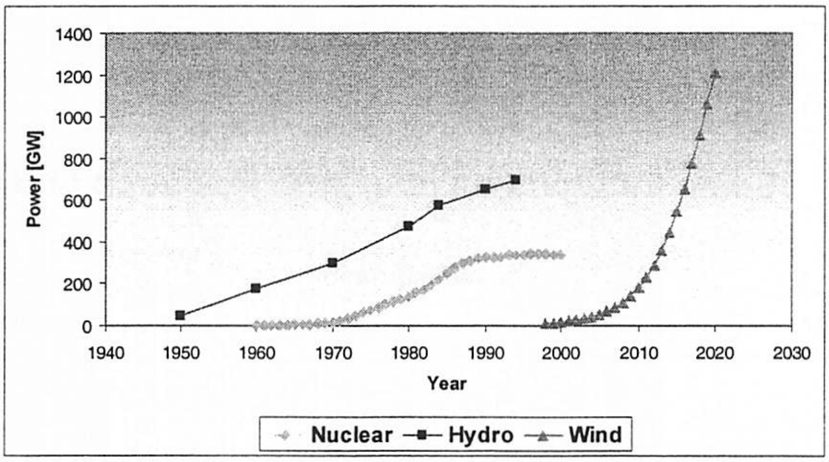
RISØ



Preconditions:
- World electricity need doubled by 2020
- 10% = 3000 TWh
- 20-30% yearly growth
- Progress Ratio: 0.85-1
- Turbine size: 0.7-2 MW
- World wind energy resources = 53.000 TWh/year

Accumulated Power

RISØ



RISØ

Development Lines for Wind Turbines 2000-2020

- **Multi-MW (app. 5 MW) wind turbines for large power stations off-shore or remote areas, own variable grid, DC transmission to shore (super conductor).**
- **Medium-size wind turbines (app. 1MW) for grid connection, single turbines or farms, landscape, environment.**
- **Smaller wind turbines (app. 30 kW) for electrification in developing countries, stand-alone, combined with solar energy and possibly hydrogen production for storage and transportation.**

Research Needs

RISØ

Research Area	5 MW	1 MW	30 kW
• Meteorology	2	3	1
• Aerodynamics and aeroacoustics	2	3	2
• Aeroelasticity and loads (wind, water, ice)	3	2	2
• Structure and system dynamic	3	2	1
• Concept and component studies	2	3	2
• Materials and production methods	2	1	3
• Design and safety	3	2	1
• Operation and maintenance (logistics)	3	2	3
• Control	3	2	2
• Electricity quality, grid-connection and transmission	2	3	1
• Energy storage	2	1	3
• Test and measurement methods	2	2	1

New related research areas

RISØ

- New dedicated materials and production methods
- Energy storage technologies
  (hydrogen, chemical, super conductor)
- Transmission by super conductor
- Integration in the energy system
- Combined energy systems (solar, wave, bio mass)
- Electro mechanical components
- Sensor development
- Artificial muscles (flow control, adaptive blade structure)
- Plant fibres with cellulose matrix (gene technology)
- Recycling and ecology

Research Areas with Wind Energy Perspectives

RISØ

- Solar power
- Wave energy
- Transportation based on hydrogen

Development 2000-2020

RISØ

- Flexibility and new principles
  - structural flexibility
  - coupling between deformations
  - flexible transmission system
  - multi-adjustment
- New types of generators
- Artificial muscles
- Hydrogen production for storage and transportation
- Combined energy systems
- Transmission of electricity (super conduction)

Future Wind Power Plants integrated into the Power System

RISØ

Nature
•Resourced
•actions/loads
•prediction

Wind turbine
•koncept
•nervous system
•production/materials

Wind Power Vision 2020

System
•integration
•controls, monitoring, diagn.
•Supply security/ power quality

Society
•market
•planning
•balancing interests

Contribution to the IEA – Wind Energy Experts Meeting on
Long Term R&D needs, 22 & 23 march 2001, ECN

The interaction between wind turbine (technology) development and long term research goals & efforts

Gijs van Kuik

DUWIND
DELFT UNIVERSITY WIND ENERGY RESEARCH INSTITUTE

Delft University of Technology

History of interaction technology&market – R&D

Start with a strong technology push:	Start with strong market push:
Sweden, UK, Germany, the Netherlands, USA, Canada	Denmark, California, (later:) Germany, Spain
2-bladers, teeters, vertical axis, flexible	3-bladers, 'danish concept', stiff

DUWIND

Market was driving, not technology

- Innovative designs did not succeed, except DD
- R&D focus on wind field, aerodynamics, blade material and construction, electric conversion, control, siting
- In the 'technology push' countries: more R&D results than industry could absorb: technology development did not exploit R&D to full extent

Current situation

- Things have changed: technology is a success factor, besides market position
- Major manufacturers are 'vertically integrated' to cover all technology aspects
- Rapid increase in turbine size
- R&D, design tools, lag behind turbine- and market development
- Stability problems increasingly important
- Offshore is to start; two technologies have to merge, which is not yet commonly accepted

Future (1)

Statement:

wind energy can compete with fossil energy within 10 years, without subsidy.

This opens opportunities for other design drivers than maximal yield at minimum cost

IEA R&D, march 2001, GvK

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Future (2): two lines of market development

- (Large) wind power stations, unit size some hundreds of MW   offshore, remote areas
- Decentralised wind power, as part of mix of renewables   densely populated areas with fine-meshed grids

IEA R&D, march 2001, GvK

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1st development: Wind power stations

Max value becomes more important than min cost

- increased capacity factor is possible, if required
- peak shaving, power control and grid control possibilities
- combined with hydro(gen) storage: guaranteed renewable power

Choice depend on (free) market, customer, and turbine qualities

Turbine qualities

- high requirements on controllability of individual turbines and power station: power level, type of power, moment of delivery
- High requirements on condition monitoring, self-maintenance, integration of maintenance in operation
- Reliability becomes extremely important

  - the design procedure (will the turbine act as designed, including aeroelastic stability)
  - the turbine (offshore: order of magnitude better than now)

2^{nd} development Decentralised power production

- Wind energy as part of mix of renewables and other small generators. Size will be small to medium scale.
- Grid control and operation not yet clear. Regional stand alone grids with 'weak' connections are possible. Will have impact on voltage, power conversion system.
- Requirements for controllability are probably similar as in 1st development, but for smaller units
- Important: aesthetics, noise level, controllability of noise level., availability, perfect operational track record

Implications for future turbines

Two major objectives, for large and small scale:

- Continuous demand for lower loads & stable behaviour, lower weights, less structural components.
- Significant improvement of reliability and controllability of wind turbine and wind power station

Both are strongly related by turbine control

1. Loads and components

- Less structural components. Integration of hub with DD generator?
- Merging of offshore technology and turbine technology: integrated design methodology
- Re-introduction of controlled flexibility (active systems instead of passive), specifically for off-design load cases, development of smart structures.
- Aeroelasticity must be understood and solved

2. Performance and Reliability

- Control techniques will be much more sophisticated, based on sensors and actuators, to optimise quality of power and performance, and to add stability and alleviate loads: control by cyclic pitch ➔ individual pitch ➔ part-span
- Design process will be more detailed: system and structural reliability methods, probabilistic methods for incorporation of extreme load cases, monitoring- and maintenance driven design

Difficulties to be expected

- Control equipment is nowadays major cause for maintenance & repair actions (ISET database)
- Specifications of electronic and control equipment must be on higher level (military specs or space specs). Problem: sometimes this is not available
- This will increase ex-factory costs, but lowers O&M costs

IEA R&D, march 2001, GvK

DUWIND

Offshore

- Completely new concepts are possible (see Dewind picture, see old Swedish designs of vertical turbines)
- Interaction with support structure will lead to new nacelle lay-outs
- Turbine costs have limited impact on energy costs, so there is room for improvement

IEA R&D, march 2001, GvK

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Consequences for R&D (1)

Fundamental research :

- Aerodynamics and aeroelasticity
- Combined wind & wave loading
- Meteorology: short & long term wind forecasting
- Integration of time domain and frequency domain models
- New electrical conversion systems
- ....

DUWIND

Consequences for R&D (2)

Applied research :

- Validation of engineering rules in design codes
- Dynamics of turbine / support structure
- 'Smart structure' blades
- Blade material/construction/manufacturing
- Reliability and maintainability as design driver
- Integrated design and system engineering
- Interaction (free) market aspects and turbine technology
- ....

DUWIND

Consequences for R&D (3)

Development :

- New concepts (offshore)
- Support structures
- Nacelle and drive train construction
- Databases for winddata, wave data, reliability of components, micrositing data, ……, …
- ………………

RISØ

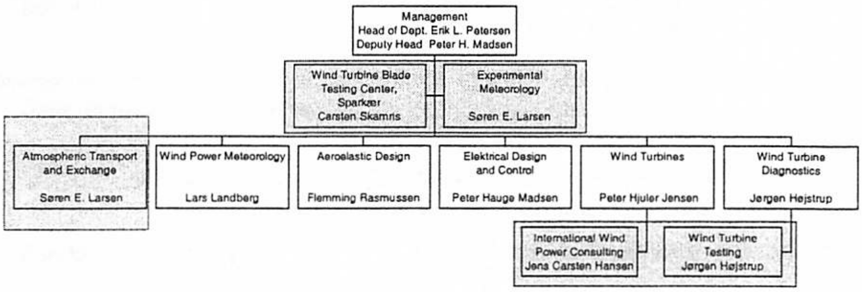
Long-Term Research Needs
Mid Term Goals for Wind R&D at Risø

Peter Hauge Madsen/Flemming Rasmussen

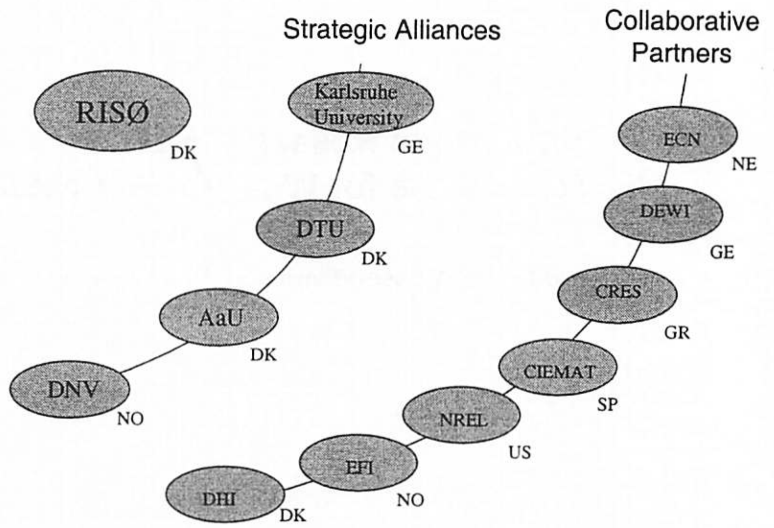
Risø Wind Energy Department

RISØ

R&D within boundary layer meteorology, fluid dynamics, structural mechanics, power and control engineering as well as loads and safety of wind turbines. Aim to meet the needs for new knowledge and consultancy assistance in relation to Wind energy, including technological development, manufacturing, testing, operation, approval and export of wind turbines as well as solution of the technical problems in connection with the application of wind energy.



RISØ - A networking wind energy centre



Aeroelastic Design

<u>Objective:</u> To develop new knowledge and models within aerodynamics, structural dynamics, aeroelasticity and design loads for application in design and optimisation, description of design basis and analysis of existing and new wind turbine concepts.

<u>Mid-term goals:</u> Through a long-term strategic and applied research and development in the fields of experimental and numerical aerodynamics as well as aero-acoustics (OFD and CAA), structural dynamics, stability and design basis to develop:

- an analytical and numerical tool, "the numerical wind tunnel", for aeroelastic design and optimisation of wind turbines as well as an experimental wind tunnel facility for verification;
- basis for a new generation in the MW-class of the traditional concept for three-bladed with turbines with control;
- basis for determination of the cost efficiency and competitiveness for new MW-class flexible wind turbine concepts.

Electric Design and Control

RISØ

Objective: To contribute with new knowledge and computational models for analysis and development of wind turbines with respect to electric and control characteristics as well as grid integration.

Mid-term goals: In co-operation with Aalborg University, to

- develop new control concepts for optimisation of wind turbine loads, production and power quality;
- assess and test possible applications of alternative electromechanical components for wind turbines including new advanced generators and power electronics;
- develop methods and concepts for electrical integration of large shares of renewable energy, especially wind energy, in centralised and decentralised energy systems.

Wind Power Meteorology

RISØ

Objective: To contribute with new knowledge on wind climatology, atmospheric flow and turbulence as a basis for development and application of methods and models to predict wind resources as well as wind loads on wind turbines and structures in all kinds of natural terrain.

Mid-term goals: Through a long-term research effort within boundary-layer meteorology including wind climatology, atmospheric flow on meso- and micro scale, atmospheric turbulence and experimental meteorology to

- further develop models and to extend the area of geographical application of the wind-atlas method for wind resource studies and models for short-term prediction of wind farm production;
- develop and combine the wind-atlas method and models for atmospheric turbulence and extreme events with regard to wind load calculations and an estimation of extreme wind conditions in natural terrain,
- develop models for off-shore wind flow including resources and extreme wind loads and to support these models by measurements.

Wind Turbines

RISØ

Objective: To develop new knowledge and methods to verify load and safety for wind turbines; develop new opportunities within structural design, technical and economical application and opportunities with regard to electric grids and hybrid energy systems.

Mid-term goals:

- *Load and safety:* to establish a rational and empirical basis for a reliable and economic design of wind turbines with models based on probability theory
- *Structural design:* to develop methods for modelling and optimal structural design of wind-turbine components including development of new testing methods for blades
- *Wind power implementation:* to develop methods for verification of the technical/economical risks in wind-turbine projects; to verify the output of a wind turbine and to develop methods illustrating the technical/economical application and opportunities in relation to the electric grid and hybrid energy systems.

Wind Turbine Diagnostics

RISØ

Objective: Through a long-term and strategic research effort to develop methods for an experimental determination of wind-turbine characteristics, including testing methods for use by industry.

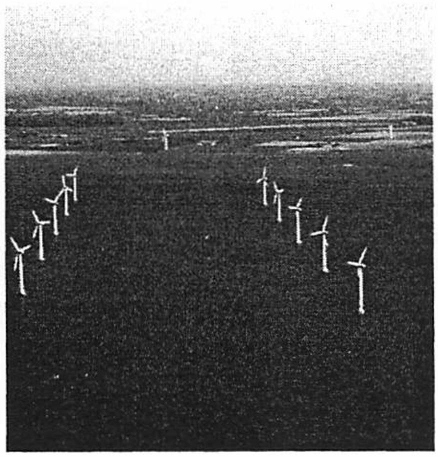
Mid-term goals: Development of experimental methods to determine:

- performance and interaction with the energy system
- loads, dynamics and stability
- aerodynamic flow conditions on full-scale rotors

Offshore Trends

RISØ

- Increase in size (due to expensive foundations)
- Very high reliability
- Advanced maintenance schemes based on monitoring
- Advanced wind farm control



Wind Farms

RISØ

- Increase in size (150-200-?MW)
- Extended control of the total wind farm also from dispatch centres
- Power plant requirements
  - Control active and reactive power
  - Control signals can be local voltage or frequency or from dispatch centre
  - Robustness to certain grid faults
- Combination with Storage ?
  - Saved hydro
  - Pumped storage
  - Electrochemical

Technological options - Tools

RISØ

- Wind resource assessment codes (WAsP)
- Wind climate codes
- Short term prediction
- Aerodynamic codes: Profile design, Numerical wind tunnel
- Aeroelastic codes e.g. HAWC or Flex5
- Electrical and control models
- Grid integration models

Development Trends

RISØ

- **Generic Development**
  - Improved aerodynamics
  - Flexible and Controllable
  - Optimal Design and Materials
  - Extended monitoring
  - Improved grid integration
  - Concurrent design of aerodynamics, structure, electrical system and controls
  - Reduction of project economic uncertainties (Prediction)
  - Site specific optimisation and operation
- **Application Specific Development**
  - Wind climate
  - Off-shore
  - Weak grids

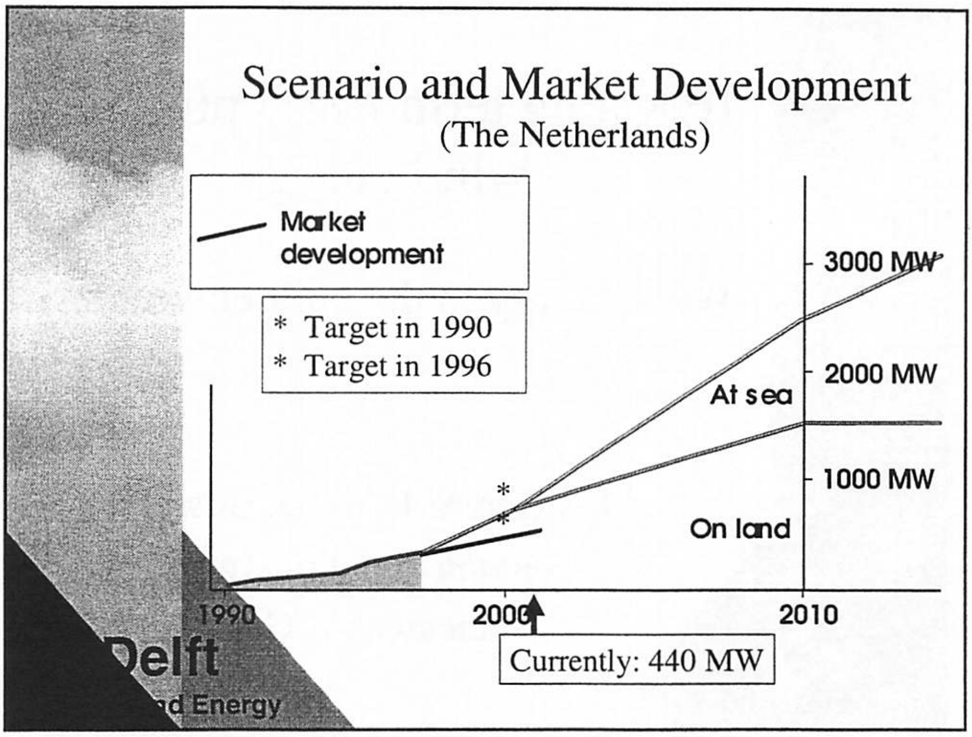
IEA long term R&D program wind energy

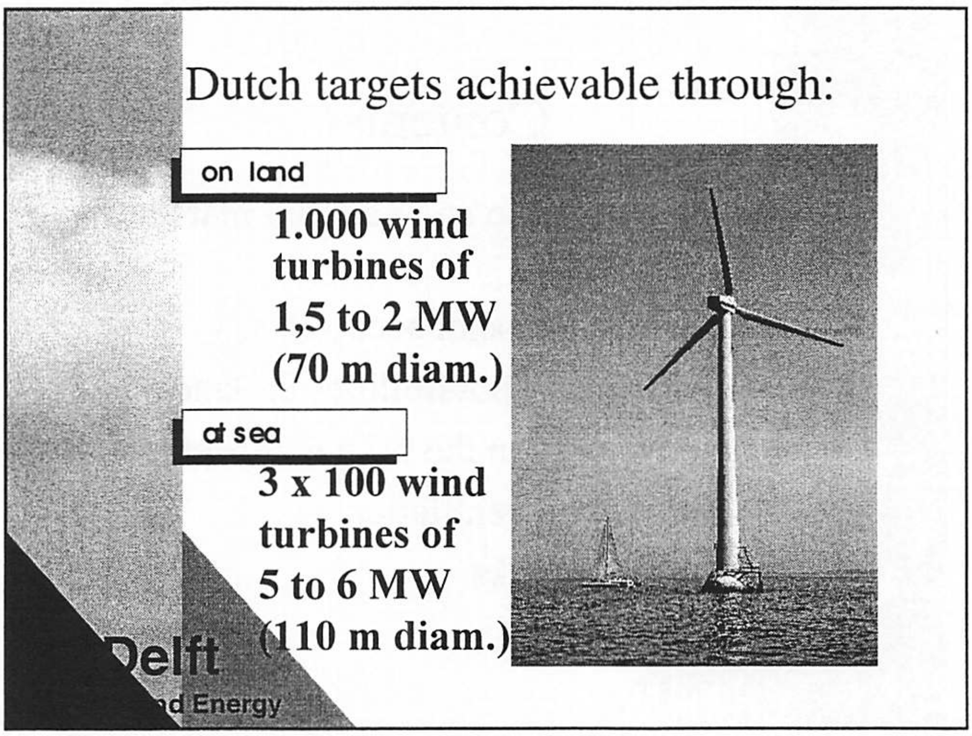
Wind energy in the built environment

Dr. Gerard J.W. van Bussel
section Wind Energy
faculty CiTG

Contents

- Dutch scenario and national market development
- re-establish social acceptability
- creating new possibilities on land
- wind energy in the built environment
- wind driven ventilation
- closing remarks


Scenario and Market Development
(The Netherlands)
Market development
* Target in 1990
* Target in 1996
3000 MW
2000 MW
1000 MW
At sea
On land
1990
2000
2010
Currently: 440 MW


Dutch targets achievable through:
on land
1.000 wind turbines of 1,5 to 2 MW (70 m diam.)
at sea
3 x 100 wind turbines of 5 to 6 MW (110 m diam.)

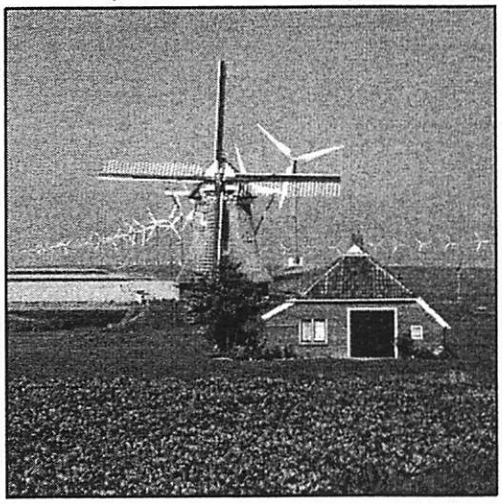
Social acceptance (Netherlands)

Mid 19th century

10.000 windmills
300 MW

End 20th century

1.200 wind turbines
400 MW



New possibilities on land

multi-functional use

- **on industrial estates**
- **along railways**
- **at high voltage masts**
- **near civil engineering works and dikes (?)**
- **etc etc**

use (existing) buildings

- **as foundation/tower**
- **as wind accelerator**
- **use differential (wind)pressures**
- **wind driven building ventilation**

New possibilities on land (2)

multi-functional use

But….

still rather limited possibilities

- **legislative limits (planning, noise, hazards)**
- **image of "classical" wind turbine (visual impact on landscape)**

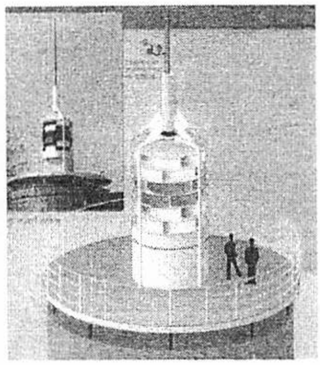
New social and economic **policy** on land

targets

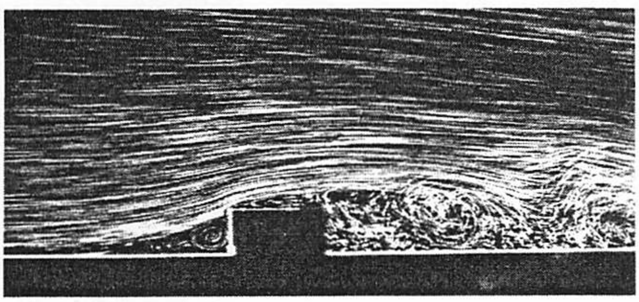
- **integration of Renewable Energy Sources**
- **decentralised (Distributed) Generation**
- **increased reliability of energy supply**
- **different economics**

Building as foundation

Rijkshogeschool IJselland Deventer

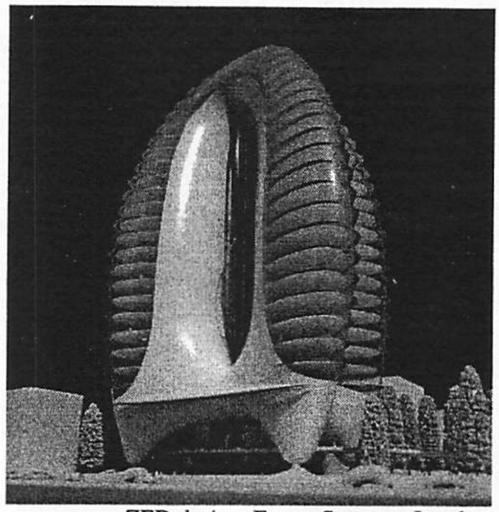


Building as wind accelerator



Flow around building visualised in a wind tunnel

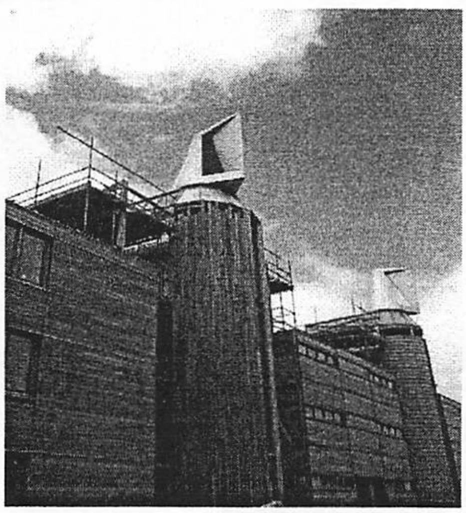
Integrated design (uses pressures and accelerations)



ZED design, Future Systems, London

Wind driven ventilation

- **Malcaf on the roof**
- **Large ventilation channels:**
  - corridors
  - stair cases
- **Atrium as a buffer**



Nottingham University Business School

R&D needs

- Wind in a very complex environment (town, buildings)
- Dedicated (vertical axis) wind turbines
- Ducted wind turbines
- Extreme low noise and vibrations
- Integration in (RE) elect. networks with (intermitted) grid connection
- Integrated design of wind turbine and building
- Wind driven ventilation

Closing remarks

- Market development in NL is lagging
- Quest for new possibilities on land
- Integration of wind turbines in buildings, (a technological and architectural challenge)
- New prospects for VATs, and ducts
- Perspectives for wind driven ventilation

R & D Areas for Wind Energy Autonomous Systems

Author: I. Cruz,
Departamento de Energías Renovables

The market of Wind Energy Autonomous Systems

- **Scattered market**
- **Small enterprises working in the field**
- **Handmade manufacturing, and without access to design codes and test centers**
- **Technical complexity of the technology**
- **Lack of adequate R&D projects**

REVIEW OF THE STATE OF THE ART FOR SMALL WIND TURBINES AND AUTONOMOUS SYSTEMS.

- **MARKET PROMISING**
- **TECHNOLOGY NEED TO BE IMPROVED**
- **LOW RELIABILITY ON EXISTING SYSTEMS**
- **COST HAS TO BE REDUCED**
- **LACK OF STANDARDS**
- **LACK OF CO-ORDINATED RESEARCH**

OBJECTIVES OF DEVELOPMENT

- RELIABILITY IMPROVEMENT
- COST REDUCTION
- MODULAR DESIGN
- LOW MAINTENANCE AND EASY TO OPERATE SYSTEMS

R&D AREAS

- WIND ASSESMENT
- TECHNOLOGY OF SWT
- STORAGE
- TESTING CENTERS
- STANDARS

WIND ASSEMENT

- EASY AND CHEAPER PROCEDURES TO ESTIMATE THE RESOURCE FOR THIS TYPE OF INSTALLATIONS

TECHNOLOGY IMPROVEMENT

SMALL WIND TURBINES		
Aerodynamic	**Electrical System**	**Control**
- Low Reynolds Number Advanced Airfoils **- New Blade Designs**	**- Super-magnet generators** **- Axial PMG** **- Switched Reluctance Generators**	**- Passive regulation systems for power and speed.** **-Passive yaw** **- Smart Power Electronics**

R&D NEEDS: STORAGE

- BUFFER STORAGE:
  - **FLYWHEELS**
  - **SUPERCONDUCTIVITY COILS**
  - **HYDRAULIC**
  - **AIR COMPRESSED**
  - **SUPER CAPACITORS**

STORAGE R&D NEEDS FOR AUTONOMOUS WIND SYSTEMS

Short term	Medium term	Large term
Flywheels	Hydrogen	Batteries
Hydraulic	Batteries	Minihydro
Air compressed	Air compressed	Hydrogen
		Biofuels

R&D NEEDS: TESTING CENTERS

- The lack of testing procedures, is one of the main limitations detected for the development of an effective technology
- Availability to the access to these centres for manufacturers and developers

R&D NEEDS: STANDARS

- DEVELOPMENT OF ACCEPTED STANDARS, NORMS AND GUIDELINES AND CERTIFICATION PROCEDURES

CONCLUSIONS

- **R&D PROJECTS IN CO-ORDINATED DEVELOPMENT PROGRAMS ARE CLEARLY NEEDED TO IMPROVE THE TECHNOLOGY**
- **TEST CENTERS HAVE TO BE AVAILABLES**
- **NORMS AND STANDARS MUST TO BE ELLABORATED**
- **DEMOSTRATION PROGRAMS HAVE TO BE PLANNED**

IEA R&D Wind

Long term R&D needs in Wind

presented by

Jaap 't Hooft

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at

IEA REWP Workshop in Paris 11 Oct. 2000

International Energy Agency R&D Wind

Long term energy scenarios

- IEA World Energy Outlook
  - first time RE technologies quantified
  - wind low 63 GW, high 124 GW in 2020
- EU Green paper
  - Towards a European strategy for the security of energy supply
  - Looks at 30 years, RE is important

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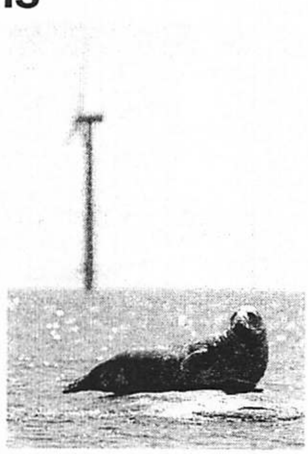
REWP Workshop

- clarifying renewable energy R&D issues
- long term results needed in 5-10 or 10-20
- identify uncovered areas in technlogy
- identify gaps and overlaps between technologies
- identify cross cutting and enabling technologies
- final report available

International Energy Agency R&D Wind

Main conclusions

- Mid term 5 - 10 years
  - forecasting techniques
  - grid integration
  - public attitudes and visual impact
- Long term 10 - 20 years
  - adding intellegence to structures and grid interaction
  - storage and hybrid systems



International Energy Agency R&D Wind

Why wind energy?

- Energy portfolio
  - diverse energy supply
- Economic development
  - domestic and international
- Environment
  - minimal impact of generation

International
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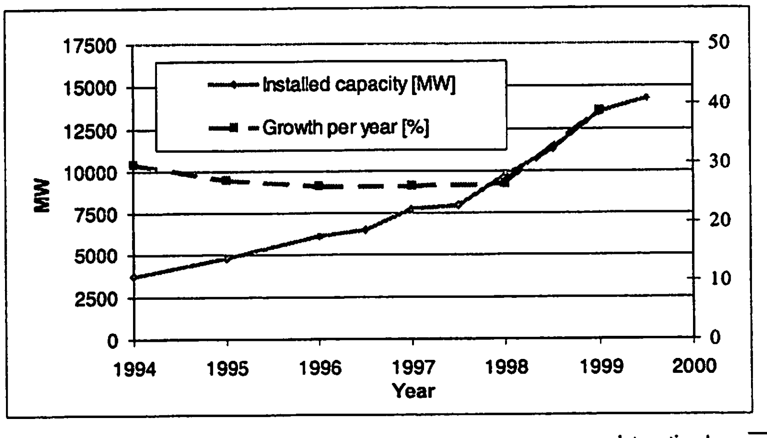
Wind

Cumulative installed capacity



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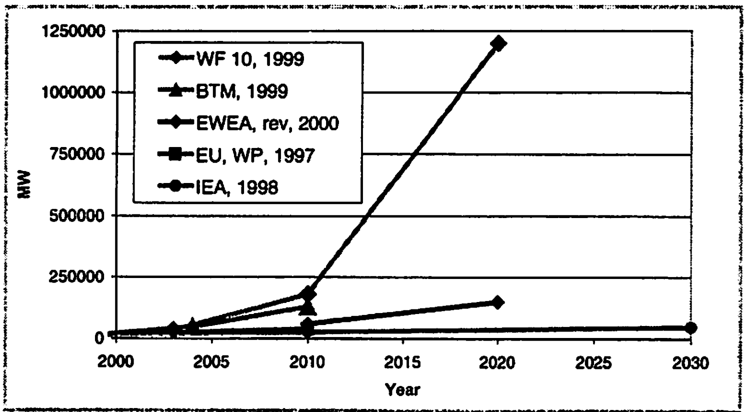
Projections of wind market



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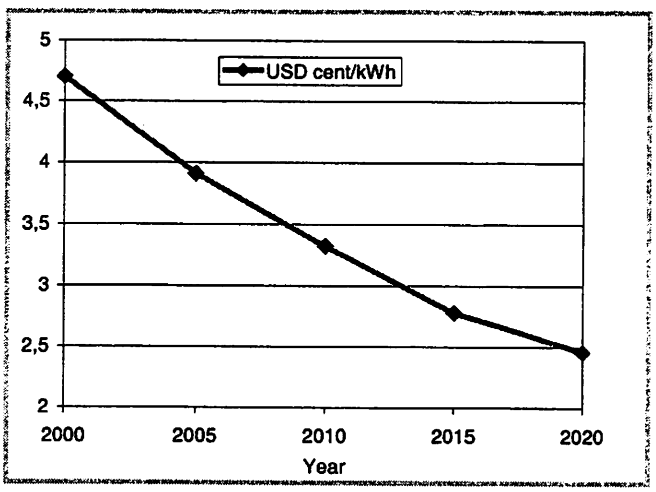
Declining cost of wind electricity



Source: BTM 99 cost scenario

Cost calculations are based on Wind Force 10 projections for installed capacities

2000	14 GW
2010	180 GW
2020	1200 GW

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Sources of cost reductions 2000 - 2004

Source	%
• Technology improvements (weight and efficiency)	40
• Economy of scale (manufacturing improvements)	50
• Other contributions (foundations/grid connection/O&M cost)	10

Reduction in energy cost is 4.7 to 4.0 USD cent/kWh

Source BTM 1999

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Why continue long term R&D?

- Continue cost reductions
- Enable large scale use
- Minimize environmental impacts

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Continue cost reductions

- Improved resource assessment and siting, new locations
- Better models for aerodynamics/aeroelasticity
- New intellegent structures/materials and recycling
- Reduce uncertainties in mechanical loads,
- Improved standards
- More efficient generators, converters
- Improved reliability and maintainibility

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Enable large scale use

- Forecast power output to increase the value of electricity
- Electric load flow control and adaptive loads
- Inproved power quality
- Hybrid systems for other energy carriers
- New storage techniques for different time scales

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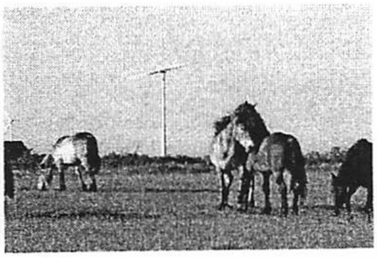
Minimize environmental impacts

- Compatible use of land
- Esthetic integration
- Reduced noise from turbines
- Increased knowledge of effects on flora and fauna



International Energy Agency R&D Wind

Main conclusions

- Mid term 5 - 10 years
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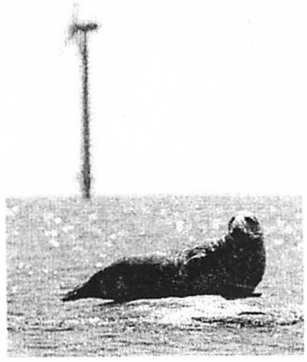


International Energy Agency R&D Wind

Info sources

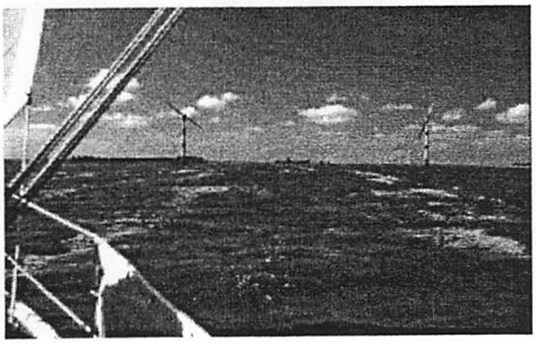
- IEA Agreement electrical storage
  - Newsletter: electricalenergystorage@egroups.co.uk
  - IEAElectricalStorageAnnex15Draft.pdf
  - IEAElectricalStorageAnnexIXFinalReport.pdf
- IEA REWP documents
  - www.iea.org/cert/rewp/index.htm (password needed, ask your local R&D Wind rep)

International Energy Agency R&D Wind

WIND ENERGY

Current Situation, Future Development and R&D Needs

Jos Beurskens c.s.



Presented by
Bert Janssen

EWEA

EUREC

ECN

CONTENT

- Targets
- Technological development
- Strategic goals
- R&D needs and priorities
- Conclusions

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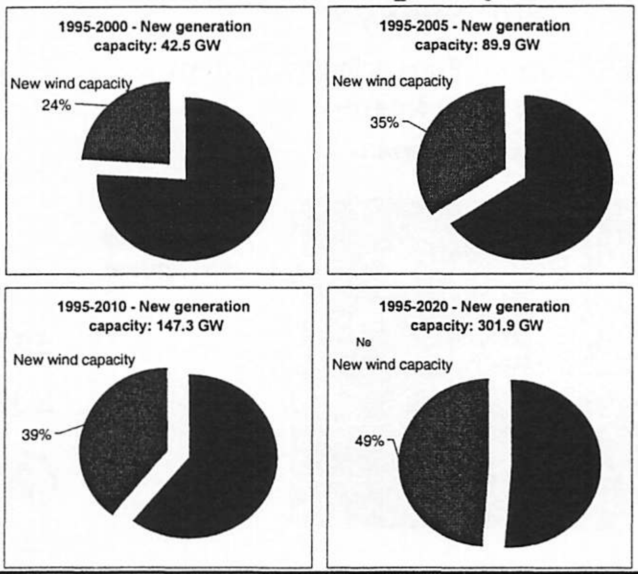
New Wind Capacity as a Percentage of New Generation Capacity 1995-2020



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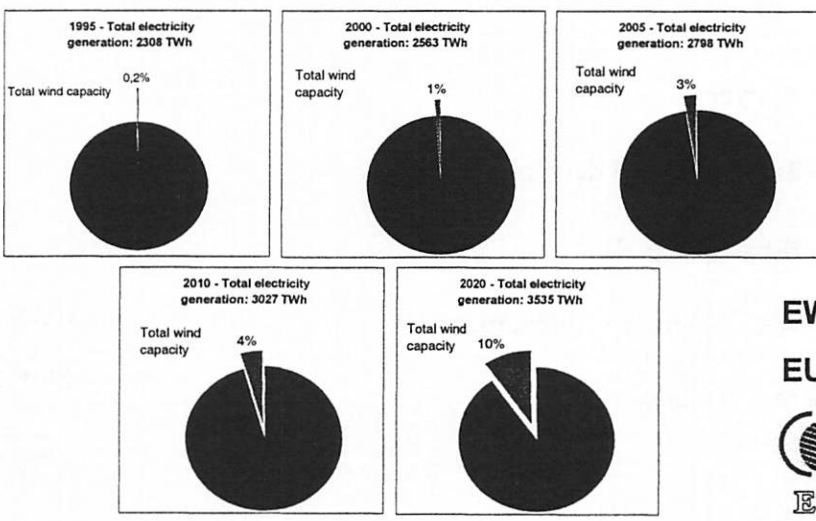
Wind Electricity Generation as Percentage of Total Electricity Generation 1995-2020



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Technology Development

Key figures: market, economy & technology

- 82% of power in only 3 countries (D, DK, E) (World: 5 countries incl. USA and India).
- Growth during last 4 years: > 30 %/year.
- 'Progress' factor: 80 %.
- Manufacturing capacity almost completely based in Europe.
- Energy pay back time: 0.25 - 0.5 years.
- Technical life time: 20 years.

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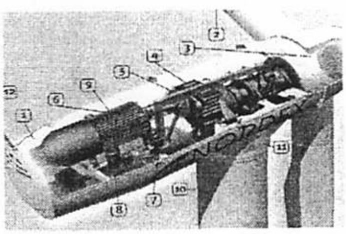
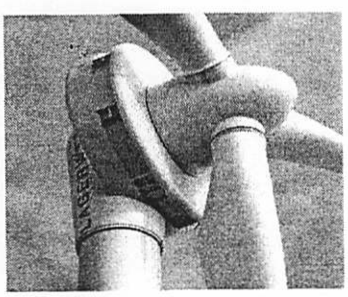
Technology Development





- **From classical drive trains to direct drives**
- **Introduction of power electronics**
- **Market share variable speed increases quickly**
- **Fixed blade angle to variable**
- **From 0.03 MW to 5 MW**
- **From 10 m to 120 m ø**

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Strategic Goals

- 12 % renewable energy in Europe by 2010
- 30 % new RE capacity in developing countries
- Maintaining industrial capacity & employment

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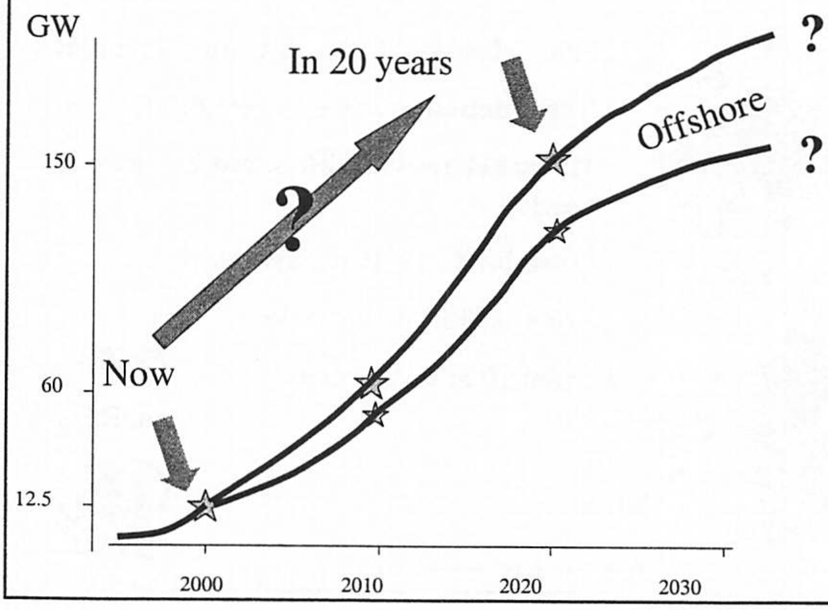
The Challenge



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Success Factors

- Decrease cost (Euro/kWh)
- Increase value of wind electricity (= price per kWh)
- Decrease uncertainties in application chain
- Develop new applications (offshore, weird sites, regions without electrical infrastructure (RAPS))
- System development
- Remove instititional bottle necks and increase public acceptance
- HR development
- Policy instruments

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R&D needs and priorities: Link Strategic Goals and success factors

Strategic goals Aspects	10% renewable energy in Europe	30% new RE capacity in developing countries	Maintaining Industrial capacity & employment
Cost reduction of wind energy	••	•••	•••••
Increasing the value of wind energy	•••	•••	•••
Finding new sites	••••	••	•
System development	••••	••••	•••
Reduction of uncertainties	••	•••••	•••••
Reduction of environmental effects and negative social impacts	•••	-	•
Education & human resource development	••	••	•••••
Development of policy and instruments	•••••	•••••	•••••

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R&D needs and priorities: specify for applications

- Large scale wind farms on and offshore (P > 1.5 MW)
- Distributed systems on land (P < 1.5 MW)
- Decentralised systems (P < 0.5 MW)

Now emphasis on P > 1.5 MW

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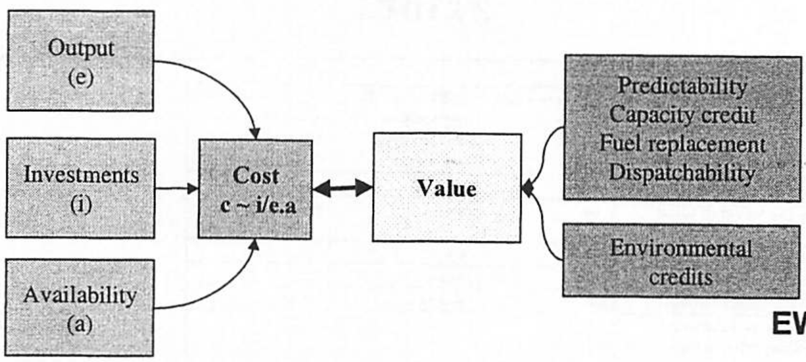
Cost and Value



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Cost reduction

- Design improvement (reliability of prediction, aero-elastic and performance stability of large rotors)
- Manufacturing technology
- Transport and installation techniques

EWEA

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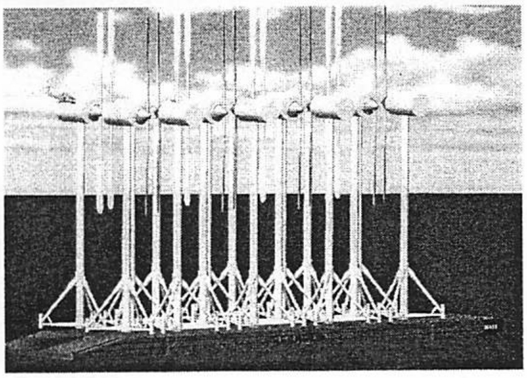
Manufacturers of turbines and components

ECN

Cost reduction: e.g. Offshore Transportation



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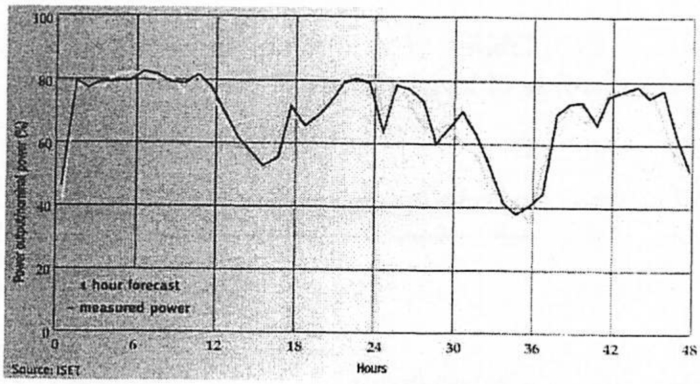
Offshore industry, turbine suppliers, project designers

ECN

Increase Value: forecasting/dispatchability

Correlation between one hour forecast and real time data



EWEA

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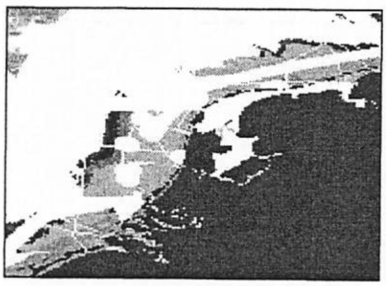
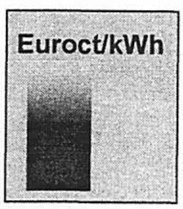
Wind farm operators

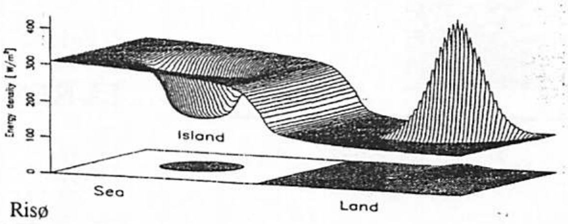
Siting and new Applications





Bron: Opti-OWECS studie (1998)

Project developers and Financiers



Risø

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System Development

- **Improvement of power quality by power electronics (reactive power controllable, wind farm ouput controllable)**
- **Control strategies (needed because of increasing plant size and adjustment to local atmospheric conditions)**
- **Large scale grid integration (500 MW offshore plants?)**
- **Large scale storage**

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Utilities, grid operators, wind farm operators, turbine manufacturers

ECN

Decrease Uncertainties in Application Chain

- **Long term output prediction (rotor and system optimisation, meteorology, reliability)**
- **Short term output prediction**
- **Technical lifetime (reliability, fatigue life determination)**
- **O&M cost (condition monitoring, early failure detection)**
- **Resource assessment (anemometry, site characteristics)**
- **Noise prediction (aero-acoustic modelling)**

EWEA

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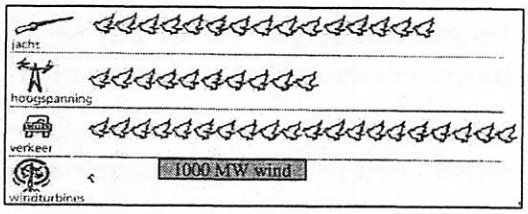
Project developers, Banks, Insurance Companies

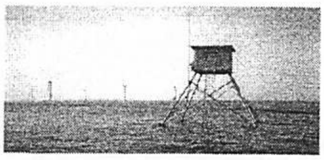
ECN

Reduce negative environmental effects and social impacts

Radar observation in the Netherlands



Cause of death for 1000 MW installed wind power



Observation of birds at Tunø Knob (DK)

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Regional governments, municipalities, general public, environmental pressure groups

Human Resource Development

- Training on all levels
- Repair unbalanced situation: more dedicated quality courses needed on all sub academic levels
- Target training (in particular energy policy) on high potential regions
- European (international) accepted degrees needed
- Prompt actions needed

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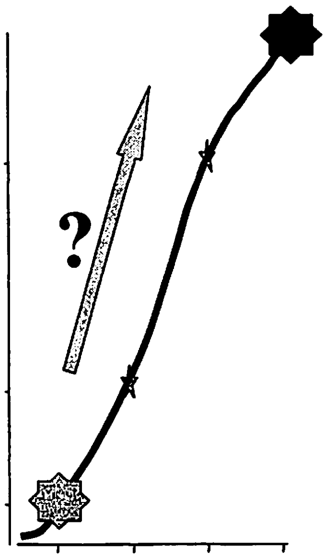
ECN

All actors

Conclusions (1)



- Full use of R&D results needed to achieve goals
- Reducing R&D efforts the moment Wind technology appears successful, is short sighted
- R&D to be intensified, but focused on problems which could hamper implementation speed

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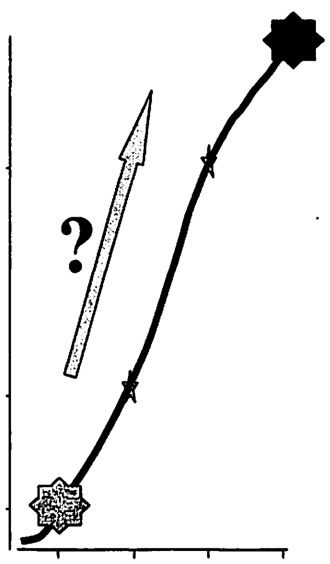
Conclusions (2)



- Specific targets per issue needed)
- Proper balance needed for land based, offshore and remote area applications
- HR-Development needed urgently

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Windenergie-Forschung, ein Auslaufmodell?

Wind Energy Research, a Run-Out Model?

J. P. Molly, DEWI

Zusammenfassung

Fünfzehn Jahre kommerzielle Anwendung der Windenergie in Deutschland und der Welt legen nahe, ein kritischen Rück- und Ausblick vorzunehmen, vor allem was technische und damit zusammenhängend, die wirtschaftliche Entwicklung angeht. In dieser Zeit fand eine vom Markt getragene Größenentwicklung der Windturbinen von etwa 50 kW auf heute 2,5 MW statt, wobei die größten Schritte in den vergangenen zehn Jahren erfolgten. Diese Entwicklung, meint man, könne nur mit einer umfassenden Forschung zur Lösung der Probleme verbunden gewesen sein. Leider war dies entgegen den Erwartungen allerhöchstens in Teilbereichen der Fall. Einerseits gelang es der Windenergie, sich als Energieträger in der Stromerzeugung zu etablieren, andererseits sind technik- und anwendungsorientierte Probleme weitgehend im Verborgenen geblieben, überdeckt vom vordergründigen Erfolg der Windenergie. Sie werden deshalb von der für die Forschungsmittel zuständigen öffentlichen Hand nicht im notwendigen Umfang wahrgenommen. Zwei Forschungsschwerpunkte sind festzuhalten. Forschung zur Verbesserung der Windturbine und deren technischen Eigenschaften und Forschung zur Klärung von Problemen, die aus der Anwendung resultieren. Beispiele hierfür sind die dringend notwendige Verbesserung der Kenntnis über die Betriebsbeanspruchungen und die Wirkungen des komplexen Geländes auf die Prognose des Energieertrags. An Windenergieanlagen müssen nicht nach zehn Jahren wesentliche Komponenten ausgetauscht werden. Wenn dies trotzdem heute angenommen wird, so mag das zur Zeit der Realität entsprechen, muss aber nicht so sein und ist schon gar kein grundsätzliches Kriterium zur Bewertung der Windenergie, sondern eher eine Folge ungenügender Auslegung infolge mangelnder Kenntnis.

Summary

After fifteen years of commercial application of wind energy in Germany and world-wide it seems reasonable to take a critical look back and also look forward, especially with regard to the technical and, related to it, the economic development. During this time, a considerable upscaling of wind turbines has taken place, which was supported by the market. Wind turbine size increased from 50 kW to 2.5 MW today, the biggest steps having been taken in the past ten years. One should think that this development had to be accompanied by extensive research activities to solve the technical problems. Against all expectations, however, this has only been the case in certain areas. On the one hand, wind energy managed to establish itself as a source of energy in electricity generation, on the other hand technical and application-related problems largely remained in obscurity, masked by the obvious success of wind energy. They are therefore not properly noticed by the authorities responsible for distributing research funds. Two main areas of research should be emphasized here: Research into the improvement of the wind turbine and its technical characteristics and research in order to solve problems resulting from the application of wind energy. For example, it is urgently required to improve the knowledge on operating loads and the effects of complex terrain on the energy output prognosis. In wind turbines, it is not necessary to replace major components after ten years. If this is generally assumed today, it may correspond to reality today, but it doesn't have to be so inevitably. In particular it is not a general criterion for assessing wind energy, but rather the consequence of inadequate design due to insufficient knowledge.

1. Vorbemerkung

Mit heute installierten rund 6100 MW und 9400 Windenergieanlagen erlebte die Nutzung der Windenergie in Deutschland einen unerwarteten Aufschwung. Möglich wurde dies durch positive politische Vorgaben, wie das in seiner Wirkung sehr erfolgreiche Stromeinspeisungsgesetz aus dem Jahr 1991, das nach langen und zähen Verhandlungen mit dem Erneuerbaren Energien Ge-

1. Preliminary remarks

With the 6100 MW capacity and 9400 wind turbines installed today, wind energy use in Germany again experienced an unexpected upswing. This was made possible by favourable political framework conditions, such as the very effective electricity feed-in law from the year 1991, which after long and tedious negotations was followed by the equally attrac-

tive Renewable Energies Law in the spring of 2000. The lasting success of wind energy in Germany is largely due to the various subsidy programmes of the Federal Government and the States and to a change in the building laws in favour of wind energy.

So everything should be fine. Sales figures rising every year, more and more countries copying the German model and so contributing to the uninterrupted impressive progress of wind energy. An industry with a turnover of 6 billion Euro world-wide that accounts for a respectable portion of the power engine market and has created about 200,000 jobs directly and indirectly. This result came as a surprise even to politicians, because it doesn't happen very often that subsidy measures are such a sweeping success.

It obviously has induced some decision makers responsible for the distribution of research funds to believe that wind energy is already fully developed and research no longer necessary. The best example, according to this view, are the prototypes developed in the past, heavily subsidised, which hardly lived through the duration of the research project, whereas today the industry is capable of putting large-scale wind turbines of the megawatt class on the market largely by their own efforts. So why put public money into it? The market is booming, companies' sales figures reach record highs, large companies join the business, and more and more investors invest their money in wind farms because even banks have discovered the wind as an investment object.

DEWI now exists for more than ten years. In the beginning we mainly did research, mostly in cooperation with other European research institutions. But an institute that has to earn money cannot exist on research alone. However, the change of DEWI from a research institute to a services company, didn't make life less exciting, quite on the contrary. If you take your job seriously, you cannot fail to notice that things are not running so smoothly as many seem to think. This already became obvious during the dispute over the amount of the feed-in tariff for the Renewable Energies Law. It was not easy to convince people that the premium feed-in tariff, which many regarded as too high, is necessary because technical problems do exist which in the end have a serious effect on the economic efficiency of wind energy. As a measuring institute we have a much more direct insight into reality, i.e. problems occurring are discovered at an early stage, and quite a few issues present themselves demanding for research. But how can research be setz im Frühjahr einen nicht minder attraktiven Nachfolger erhielt. Mit der Änderung des Baugesetzbuches zu Gunsten der Windenergie und den vielfältigen Fördermaßnahmen der Länder und des Bundes wurde der Erfolg der Windenergie erst möglich und anhaltend.

Eigentlich wäre doch damit alles in bester Ordnung. Jährlich wachsende Absatzzahlen, mehr und mehr Länder, die das deutsche Modell kopieren und damit zum ungebrochenen weiteren "Siegeszug" der Windenergie beitragen. Eine Branche, die mit einem Umsatz von weltweit über 6 Milliarden Euro einen respektablen Anteil am Kraftmaschinenbau verbucht und ca. 200.000 direkte und indirekte Arbeitsplätze geschaffen hat. Dieses auch für die Politik überraschende Ergebnis, selten hatten Fördermaßnahmen einen so durchschlagenden Erfolg vorzuweisen, scheint bei einigen für die Forschungsmittel verantwortlichen die Meinung geprägt zu haben, Windenergie sei ausgereift und benötige keine Forschung mehr. Bestes Beispiel seien doch die früher mit vielen Forschungsmillionen entwickelten Prototypen, die meist kaum die Dauer des Forschungsvorhabens überlebten, während doch heute die Industrie aus vorwiegend eigenen Mitteln in der Lage sei, Großanlagen der Megawattklasse erfolgreich in den Markt zu bringen. Also, weshalb sollte hier staatliches Geld hineingesteckt werden? Der Markt boomt, die Firmen erzielen ein Rekordumsatz nach dem anderen, Großkonzerne steigen in das Geschäft ein und mehr und mehr Anleger investieren ihr Geld in Windparks, weil auch die Banken den Wind als Anlageobjekt entdeckt haben.

Seit mehr als zehn Jahren gibt es das DEWI. Anfangs machten wir hauptsächlich Forschung, vorwiegend in europäischer Zusammenarbeit mit anderen Forschungseinrichtungen. Doch wer Geld verdienen muss, kann von der Forschung alleine nicht leben. Mit dem Wandel des DEWI zum Dienstleistungsunternehmen wurde das Leben aber nicht weniger spannend, ganz im Gegenteil. Nimmt man seine Berufung ernst, erkennt man sehr schnell, dass nicht alles so glatt läuft, wie viele denken. Deutlich wurde dies schon beim Gerangel um die Festlegung der Einspeisevergütung für das EEG. Es war nicht einfach zu vermitteln, dass die von vielen als zu hoch betrachtete Vergütung notwendig ist, da eben doch technische Probleme vorhanden sind, die sich letztlich gravirend auf die Wirtschaftlichkeit auswirken. Aber als Messinstitut besitzt man einen anderen Einblick in die Realität, d.h., auftretenden Probleme können frühzeitig erkannt werden, woraus sich so manche Forschungsaufgabe ergibt, die einer Lösung bedarf. Doch woher die Finanzierung nehmen, wenn die Geldgeber überzeugt sind, dass es beim Wind nichts mehr zu forschen gibt?

financed if authorities are convinced that wind energy does no longer need research? The solution of a problem may not always be what a manufacturer or project developer wants, therefore it does not make sense to demand that they should pay for research themselves. By arguing in this way people ignore the fact that in the industry short-term economic interests are often given priority over research, especially today where only "shareholder value" seems to be important. But who is protecting the wind energy investor against unsolved problems? He normally is not backed by an organisation allowing him to undertake his own research.

What if investors withdraw from wind energy because breakdowns and accidents let it appear too risky? It does not matter so much if some manufacturers have less problems than the others; the question is whether it is possible to maintain the overall positive image despite of breakdowns and accidents, and this surely is a matter of the quantity of negative examples.

Therefore, if we don't manage to solve certain problems of wind energy in such a way that all parties concerned benefit from the solutions, some areas of wind energy use may suffer severe setbacks. This cannot be in the interest of politics which has introduced a number of subsidy programmes and so helped the wind energy reach its current position. By employing only a fraction of the millions spent so far, achievements could be assured by specific research, and wind energy could establish itself as a safe and lasting option within the energy supply of mankind, rather than disappear again like a flash in the pan. The wind energy is a very young industry which does not have the experience and especially not the financial means to stand its ground completely on its own. The purpose of research is not only to find innovative ways, but also to secure what has already been achieved in order not to jeopardize the whole. I therefore appeal to those responsible to rethink their position and allow research to be carried out in the extent necessary.

2. General Situation

The average turbine size increased from 50 kW to over 1500 kW today, and the first 2.5 MW prototypes have already been built. Both types of power control, pitch and stall, are used even in the largest wind turbines, although pitch seems to prevail in the megawatt class. Direct grid coupling of the generator (constant rotor speed) and indirect grid coupling (variable

Nicht immer ist die Lösung des Problems im Sinne des Herstellers oder Projekt-entwicklers, so dass man sagen könnte, diese sollten es doch gefälligst selbst bezahlen. Hier verkennt der Geldgeber, dass in Firmen häufig ein eher den kurzfristigen wirtschaftlichen Interessen untergeordnetes Denken herrscht, ganz besonders heute, wo nur noch der "shareholder value" wichtig zu sein scheint. Aber wer schützt den Windenergie-Investor vor den nicht gelösten Problemen? Er besitzt in der Regel keine Organisationsform, die es ihm erlaubt, eigene Forschung zu betreiben. Nur, was ist, wenn er sich zurückzieht, weil ihm die Windenergie durch Pannen zu risikoreich wird? Dabei spielt es nicht so sehr eine Rolle, ob einige Hersteller weniger Probleme als die anderen haben, sondern mehr, ob trotz Pannen das positive Image gehalten werden kann und das ist sicher eine Frage des Umfangs an Negativbeispielen.

Wenn es also nicht gelingt, bestimmte Probleme der Windenergie übergeordnet zu lösen, damit alle Betroffenen davon profitieren, könnte es in manchen Anwendungsbereichen zu einem herben Rückschlag kommen. Dies kann eigentlich nicht im Sinne der Politik sein, die mit vielen Wirtschaftsfördermaßnahmen dafür sorgte, dass die Windenergie den heutigen Stand erreichte. Mit einem Bruchteil der bisher eingesetzten Millionenbeträge könnte das Erreichte durch eine zielgerichtete Forschung abgesichert werden, damit die Windenergie wirklich nachhaltig in die Energieversorgung der Menschheit eingebaut werden kann und nicht wie ein Strohfeuer verbrennt. Die Windenergie ist eine sehr junge Branche, die noch nicht die Erfahrungen und schon gar nicht die finanziellen Mittel hat, sich völlig alleine zu behaupten. Forschung dient nicht nur dazu innovative Wege zu finden, sondern auch bereits beschrittene abzusichern, um so das Gesamte nicht zu gefährden. Ich appelliere daher an die Verantwortlichen, umzudenken und eine Forschung im notwendigen Umfang zu ermöglichen.

2. Allgemeine Situation

Die durchschnittliche Anlagengröße stieg von 50 kW auf heute über 1500 kW mit ersten Prototypen von 2,5 MW. Beide Leistungsregelungsprinzipien, Blattverstellung (Pitch) und Strömungsabriss (Stall) werden bis in die größten Windturbinen hinein eingesetzt, auch wenn sich Pitch offensichtlich gerade bei den Megawattanlagen stärker durchsetzt. Auch die direkte (konstante Rotordrehzahl) und indirekte Kopplung (variable Rotordrehzahl) des Generators ans Netz findet sich bis in den Megawattbereich als grundsätzliches Prinzip wieder. 15 Jahre kommerzielle Anwendung und die Erfahrung aus weltweit betriebenen 18 000 MW haben einen Fundus an Wissen erbracht, dessen deutlichstes Zeichen die Entwicklung von Mega-

speed) are maintained as a general principle in the whole range of wind turbines up to the megawatt class. 15 years of commercial application and the experience from 18,000 MW installed world-wide have produced a store of knowledge, the most obvious sign of which is the development of megawatt turbines which only 10 years ago when the prototypes of the second or even third generation were developed, did not meet the expectations placed in them.

Up to now, wind energy has mainly been employed in flat areas, where the low turbulence of the air flow only slightly affects the loads acting on a wind turbine. In areas without such a low turbulence, the lifetime of the wind turbines is considerably reduced. This could be seen already during the eighties in California. A similar negative influence of the complex terrain can be observed in energy output prognoses. In flat areas the wind resources can normally be established by way of calculation with sufficient exactness. This is not the case in complex terrain, which is found in most countries with good wind resources. In complex terrain, wind prognoses can easily include an error rate of 10-50%.

How close may wind turbines be installed one behind the other without risking an adverse effect on the lifetime of the leeward turbine? This is another question repeatedly posed to DEWI by law courts, to which a well-founded answer backed up by research cannot yet be given. And what is the matter with anemometers? Why do they all behave in the same way when tested in the wind tunnel laboratory, but show large deviations when mounted outdoors? (see also on page 17 pp.)

These are only a few of the questions urgently requiring an answer. They show quite clearly that wind energy is still far from being in safe waters. Under this aspect, adequate subsidy measures for the operation of wind turbines, as provided by the Renewable Energies Law, but also for research programmes, are more than justified and necessary, if wind energy is to become a reliable addition to our electricity supply.

wattanlagen darstellt, die immerhin noch vor 10 Jahren in den damals entwickelten Prototypen der bereits zweiten oder gar dritten Generation nicht die in sie gesetzten Erwartungen erfüllten konnten.

Die Windenergie wurde bisher hauptsächlich im flachen Land genutzt, wo eine geringe Turbulenz der Luftströmung einen ebenfalls geringen Einfluss auf die Belastungen der Windenergieanlage zur Folge hat. Wenn diese geringe Turbulenz nicht vorlag, wie schon in den achtziger Jahren am Beispiel Kaliforniens ersichtlich, dann gab es erhebliche Probleme mit der Lebensdauer der Anlagen. Ähnlich negative Einwirkungen eines komplexen Geländes gibt es bei der Prognose der Energieerträge. Im flachen Land kann mit rechnerischen Mitteln das Windpotential meist mit ausreichender Genauigkeit ermittelt werden. Anders dagegen im komplexen Gelände, wie man es in den meisten Ländern mit gutem Windpotenzial antrifft, wo leicht Fehler in der Prognose von 10-50% auftreten können.

Wie nah dürfen Windenergieanlagen hintereinander stehen, ohne das ein wesentlicher Einfluss auf die Lebensdauer der im Windschatten stehenden Anlage auftritt? Ein andere, mehrfach von Gerichten an das DEWI gestellte Frage, auf die man heute eine fundierte Antwort schuldig bleiben muss. Und was ist mit den Anemometern los? Warum sind sie im Windkanal alle gleich im Verhalten, aber in Freien gibt es abweichende Messergebnisse? (siehe auch Seite 17 ff.)

3. Mistakes made in the past

Not everything that did not go well in the past is due to a lack of research. A few points should be mentioned here which are at least partly responsible for the cause of the technical problems noted. These are, referring to the Wind Turbine

- *insufficient continuity of knowledge in the industry,*
- *a rather aimless up-scaling of large wind turbines,*
- *uncontrolled slimming down for economic reasons resulting in a diminution of lifetime*
- *and insufficient knowledge of loads because costly load measurements are avoided.*

Many of the mistakes observed today could already be noticed during the eighties in Californian wind farms situated in complex terrain. Similarly, during the development and operation of DFVLR's DEBRA-25 wind turbine with a capacity of 100 kW, to which the author made a major contribution, deficiencies and failures could be observed which are documented and can be looked up, but nevertheless still occur today. These mistakes cannot come as a surprise or as something new.

In application, too, a lot of things could be improved. The following deficiencies can be observed in Application:

- *There is insufficient awareness of problems in the evaluation of energy resources,*
- *there are no quality standards for expert reports,*
- *the environmental influences on wind turbines are underestimated,*
- *there is no follow-up verification of the power output of wind farms.*

There are several reasons why these problems are not dealt with adequately. Pressure arising from tight time schedules and rising costs may be one reason, but also naïvety or the desire to

Dies sind nur einige der auf den Nägeln brennenden Fragen. Sie machen deutlich, dass die Windenergie noch ein gutes Stück davon entfernt ist, sich in sicheren Gewässern zu bewegen. Unter diesem Aspekt sind ausreichende Fördermaßnahmen für den Betrieb der Anlagen, wie sie das Erneuerbare Energien Gesetz bietet, aber auch für die Forschung mehr als berechtigt und notwendig, wenn die Windenergie nachhaltig unsere Energieversorgung ergänzen soll.

3. Fehler der Vergangenheit

Nicht alles was in der Vergangenheit nicht klappte, ist auf Mangel an Forschung zurückzuführen. So gibt es einige Punkte zu nennen, die zumindest teilweise zu den Ursachen der zu konstatierenden technischen Probleme führen. Dies sind bezogen auf die <u>Windenergieanlage</u>

- mangelnde Wissenskontinuität in den Firmen,
- nicht zielgerichtetes Up-scaling für Großanlagen,
- durch Kostendruck ausgelöstes unkontrolliertes Abspecken mit dem damit verbundenen Lebensdauerverlust
- und ungenügende Kenntnis der Belastungen durch Vermeiden der kostenintensiven Beanspruchungsmessungen

Viele der heute zu beobachtenden Fehler konnten schon in den achtziger Jahren an den Anlagen in Kalifornien im komplexen Gelände beobachtet werden. Auch die Entwicklung und der Betrieb der 100 kW leistenden DEBRA-25 der DFVLR zu Beginn der achtziger Jahre, an der der Autor maßgeblich beteiligt war, zeigte Unzulänglichkeiten und Vorgänge auf, die nachgelesen werden können und heute dennoch immer noch auftreten, also in diesem Sinne keine Überraschungen und Neuigkeiten sind. Auch in der Anwendung gibt es Verbesserungsmöglichkeiten im Verhalten der Beteiligten. So muss festgestellt werden, dass in der <u>Anwendung</u>

- bei der Ermittlung des Energiepotentials ein unzureichendes Problembewußtsein existiert,
- Qualitätsvorschriften bei Gutachten fehlen,
- die Umgebungseinflüsse auf Windenergieanlagen unterschätzt werden
- und keine nachträgliche Leistungsverifizierung der Windparks stattfindet.

Beim einen oder anderen ist es der Kosten- und Termindruck, der eine ausreichende Klärung der Probleme behindert, beim anderen die Blauäugigkeit und vielleicht auch das schnelle Geld. Es gilt zunächst die Probleme in den Griff zu bekommen, die das ungebrochene Größenwachstum der Anlagen mit sich bringt. Erst wenn dieses seine Grenzen erreicht hat, wird sich der Konkurrenzkampf auf dem Feld der Optimierung

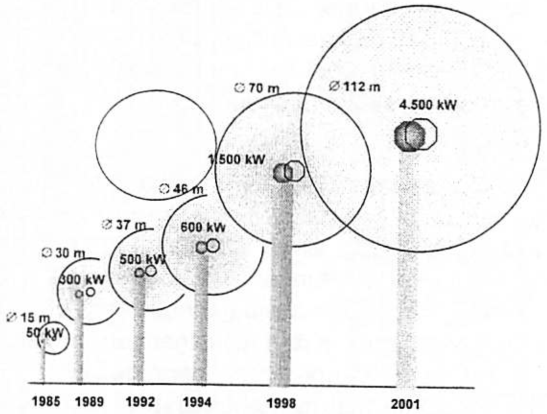


Abb. 1: Größenentwicklung der Windenergieanlagen während der letzten 15 Jahre
Fig. 1: Development of wind turbine size during the last 15 years

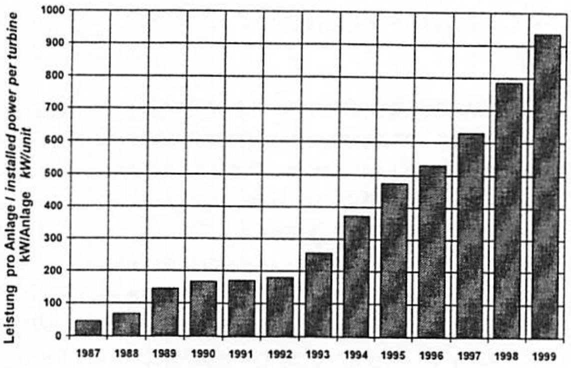


Abb. 2: Entwicklung der durchschnittlichen installierten Leistung der Windturbinen während der letzten Jahre
Fig. 2: Development of the average installed capacity of wind turbines during the last years

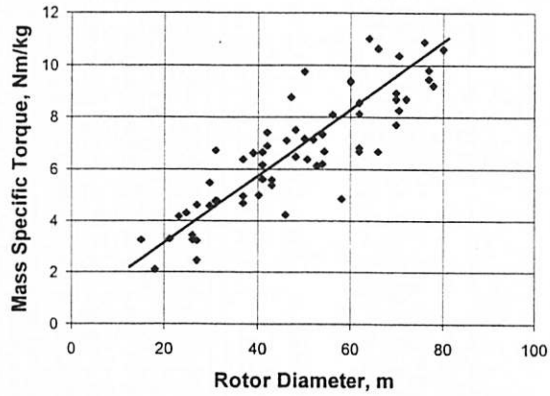


Abb. 3: Entwicklung des massenspezifischen Drehmoments mit dem Rotordurchmesser
Fig. 3: Development of mass specific torque with rotor diameter

der Anlagen abspielen, weil dann nur noch Qualität und Kosten als Unterscheidungskriterium zur Verfügung stehen.

4. Situation heute
4.1 Windenergieanlage

Der boomende Windenergiemarkt in den zurückliegenden Jahren verstärkte die Auffassung, Forschung und Entwicklung könne ausschließlich durch die Industrie abgedeckt werden. Sicherlich herrschte selbst in der Industrie einige Zeit diese Meinung. Bei den erreichten Größen der Windturbinen tun sich allerdings Unkenntnisbereiche auf, die zur Lösung der Probleme durchaus einer Vorlaufforschung bedürfen. Die heutige Entwicklung ist geprägt durch den Wettbewerb, wobei der Durchmesser und nicht Langlebigkeit oder geringste Herstellkosten die größte Rolle spielen, sondern es gilt, den berühmten Meter mehr Rotordurchmesser gegenüber der Konkurrenz zu besitzen. Deshalb ist es notwendig, zunächst die aus dem Größenwachstum resultierenden Probleme in den Griff zu bekommen. Dieser Konkurrenzkampf um die Größe lässt den Entwicklungsteams keine Zeit sich um eine wirkliche Detailoptimierung und Fehlerdiagnose zu kümmern. Erstes Firmenziel ist, die eigene, größere Anlage muss vor der der Konkurrenz im Betrieb sein und angeboten werden können. Wird die Entwicklung der letzten 15 Jahre betrachtet, so wird das nicht enden wollende Größenwachstum der Rotoren deutlich.

make money fast on the part of some parties concerned. It is necessary first to tackle those problems that are a consequence of the unbroken growth of the size of wind turbines. Only when this growth has reached its limit, competition will revert to the field of optimisation because then quality and costs will be the only distinguishing features.

4. Situation today
4.1 Wind turbine

The booming wind energy market in the past years confirmed the general opinion that research and development could be covered exclusively by the industry. This opinion may have been shared even by industry for some time. In view of the size of the turbines reached today, however, areas of ignorance become obvious, which definitely require predevelopment research. Today's development is characterised by competition, and rotor diameter rather than a longer lifetime or low production costs is the decisive criterion. Manufacturers strive to achieve the famous one meter more in rotor diameter than their competitors. Therefore it is necessary first to solve the problems resulting from upscaling. The competition in this field does not leave the design teams sufficient time to properly deal with detailed optimisation and fault diagnosis, because it is the prime target of manufacturers to have their

Abb. 1 macht eindrucksvoll klar, welche atemberaubende Entwicklung stattfand.

4.2 Anwendung der Windenergie

Weitgehend nicht als Forschungsthema im Bewusstsein sind die aus der Anwendung der Windenergie entstehenden Probleme. Dabei ist die Lösung der vorhandenen Fragestellungen für die weitere positive Entwicklung der Windenergie von genauso großer Bedeutung wie eine funktionierende und die Lebenserwartung erreichende Windenergieanlage. Die weltweite Verbreitung der Windenergie führte dazu, dass diese nicht nur mehr in flachem, von den Oberflächenformationen wenig beeinflussten Gebieten aufgestellt werden, sondern heute im überwiegenden Maße, im sogenannten komplexen Gelände, mit all seinen möglichen negativen Einflüssen auf Lebensdauer und Ertrag der Windturbine. Zusätzlich stellen sich Fragen der Wind- und Leistungsmesstechniken und zur optimalen Nutzung der Windenergie in vorhandenen Netzen, sowie die künftige Anwendung in anderen Energieverbrauchsbereichen wie Verkehr und Wärmemarkt.

5. Welches sind wichtigsten Forschungsziele?

Forschung in einem sich so schnell entwickelnden Bereich wie der Windenergie muss zielgerichtet und sehr praxisnah sein. Die Erfahrungen aus der Anwendung der Windenergie sind so umfangreich, dass sich leicht bestimmte Forschungsschwerpunkte definieren lassen. Generell gesprochen sollte das wesentliche Augenmerk bei der <u>Windenergieanlage</u>

- auf der Verminderung der spezifischen Herstellkosten,
- der Erhöhung der Komponentenlebensdauer
- und Verminderung der Wartungskosten

liegen. Dies gilt insbesondere für die Offshore-Anlagen, die ausschließlich gut getestet und mit hoher mechanischer Zuverlässigkeit in den schlecht zugänglichen Offshore-Bereich gebracht werden sollten, wenn sie dort im kommerziellen Betrieb bestehen sollen. Es sollte nicht vergessen werden, dass bei Windturbinen im mehr oder minder tiefen Wasser eine ganze Reihe zusätzlicher Belastungen durch beispielsweise Korrosion, Wellenbewegungen und Transport auftreten, die bisher nicht oder nur unzureichend bekannt sind.

own, larger turbine operating and on the market before their competitors.

Looking at the development of the past 15 years, the unending growth of the rotors becomes obvious. Fig. 1 gives an impressive view of this breathtaking development.

4.2 Application of wind energy

Problems arising from the application of wind energy are often not recognised as being a subject for research. The solution of these problems, however, is just as important for a further positive development of wind energy than the trouble-free operation and long lifetime of a wind turbine. As a result of the world-wide spread of wind energy, wind turbines are no longer installed in flat terrain only, but today mostly in so-called complex terrain, with all its potential negative influences on lifetime and energy output of the wind turbine. Additionally questions of wind and power measurement technology and of the optimum utilisation of wind energy in existing power supply grids, as well as the future application in other areas of energy consumption, such as traffic and heating, are waiting to be answered.

5. Which are the most important aims of research?

Research in an area developing as quickly as the wind energy has to be purpose-oriented and practical. From the vast experience gained in the application of wind energy, certain main topics of research can easily be identified. Generally speaking, these are the main areas, concerning the <u>wind turbines</u>

- *reduction of the specific production costs,*
- *increasing the lifetime of components*
- *reduction of maintenance costs.*

This is especially important for off-shore wind turbines which should only be deployed in the off-shore area, where access to them is difficult, if they have been properly tested and are mechanically reliable. Otherwise they will not be able to survive commercially. One should not forget that wind turbines installed in more or less deep water are subject to a number of additional loads, such as corrosion, waves and transport, which are not yet or not sufficiently known.

Natürlich sind genauso im Anwendungsbereich Schwerpunkte zu setzen. Es gilt die umfangreichen und theoretisch schwierig zu erfassenden Vorgänge des komplexen Geländes in den Griff zu bekommen und verbindliche Regeln zu schaffen, wie Messungen und Gutachten durchzuführen sind. Deshalb gilt, als Zielsetzung für die Anwendung:

- eine Erhöhung der Wirtschaftlichkeit
- und der Planungssicherheit,
- verbunden mit einer Verbesserung der Messtechniken
- sowie die Anwendung der Windenergie auf andere Nutzungsbereiche

zu realisieren. Schlecht geplante Windparks, sei es aus persönlicher Unkenntnis, Nachlässigkeit oder aus fehlenden wissenschaftlichen Erkenntnissen heraus, sind für die Windenergie genauso schädlich, wie mangelnde Lebensdauer der Windturbinen. Deshalb geht mein Appell an die für die Forschung zuständigen staatlichen Einrichtungen, sich nicht durch den oberflächlichen Erfolg der Windenergie von den Problemen dieser jungen Techniksparte ablenken zu lassen, sondern durch kräftige finanzielle Forschungsunterstützung die Wissensbasis der Windenergiebranche zu verbessern.

6. Erforderliche Forschung und Entwicklung

In den vorangegangenen Abschnitten sind viele F&E Themen schon angesprochen worden. Hier sollen nochmals die wichtigsten zusammengefasst werden, wobei auch der Hintergrund kurz angesprochen wird. Natürlich sollte aus der folgenden Aufstellung nicht der Schluss gezogen werden, es gäbe nur diese Forschungsthemen, um damit alles andere liegen zu lassen.

Windenergieanlage:

Größenwachstum:

Das schnelle Größenwachstum brachte eine Vielzahl von Schwierigkeiten mit sich, die zunächst völlig unterschätzt wurden. Einfaches Up-scaling zu immer größeren Rotordurchmessern ist nicht erfolgversprechend, da sich nicht nur die Belastungen aus dem Wind ändern, sondern auch die Reaktionen der Windturbine darauf. Können Windturbinen bei kleineren Größen noch mit dem dafür notwendigen Materialaufwand ausreichend steif gebaut werden, womit das eine oder andere Problem umgangen werden kann, so ist dies bei Megawattanlagen nicht mehr der Fall. Windturbinen sind in diesem Größenbereich hoch elastische Gebilde, die dynamisch beherrscht werden müssen.

In the area of application of wind energy it is also necessary to concentrate on certain main subjects. The problems encountered in complex terrain, which are extensive and difficult to grasp theoretically, have to be solved, and binding rules for carrying out measurements and evaluations are also required. Therefore the targets identified for application are:

- *Increasing the economic efficiency*
- *and planning security*
- *together with improved measuring techniques*
- *and the application of wind energy in other areas of utilisation.*

Wind farms planned badly for whatever reason, personal ignorance, negligence or insufficient scientific knowledge, can be just as damaging for the wind energy as a short lifetime of wind turbines. Therefore I would like to appeal to the Government institutions responsible for research not to be deceived by the superficial success of wind energy and so ignore the problems of this young technology. Wind energy still needs strong financial support for research in order to improve its store of knowledge.

6. Necessary Research and Development

In the previous paragraphs many R&D subjects were already mentioned. In the following the most important of them will be summed up and their background be discussed briefly. From this list one should of course not conclude that these are the only subjects of research and everything else could be neglected.

Wind turbine:

Upscaling:

The fast increase in size caused a lot of problems which at first were completely underestimated. Upscaling by simply increasing the rotor diameter again and again is not very promising because not only the loads caused by the wind will change, but also the reactions of the wind turbine. Whereas smaller wind turbines can be built with sufficient stiffness by using the amount of material necessary and so some of the problems can be avoided, this is no longer possible with megawatt turbines. In this range, wind turbines are highly elastic structures which have to be managed dynamically.

Operating loads:

As already mentioned, the knowledge about operating loads is unsufficient because the

Betriebslasten:

Wie schon oben erwähnt, sind die Betriebslasten wegen der sich mit der absoluten Größe der Windturbine ändernden äusseren Vorgänge und den heute üblichen Einsätzen im komplexen Gelände nur unzureichend bekannt. Zwar laufen die Megawattanlagen und beherrschen die prinzipiell auftretenden Betriebszustände, aber die auf die Lebensdauer einwirkenden Belastungen sind nur ungenügend bekannt. Es ist nicht nur notwendig, durch Messung eine bessere Wissensbasis zu schaffen, sondern auch die Belastungsannahmen durch Auswertung möglichst vieler gemessener Belastungsvorgänge zu modifizieren.

Lebensdauer:

Eng mit den Belastungen hängt die Lebensdauer zusammen. Fehlende Kenntnisse der während der Einsatzdauer einer Windturbine auftretenden Betriebslasten führen dazu, dass bestimmte Komponenten vorzeitig ausgetauscht werden müssen und so die Wartungs- und Instandhaltungskosten unnötig hoch werden. Im Klartext heisst das, Ro-torblätter müssen nicht nach 10 oder 12 Jahren ausgetauscht werden, wie das heute auf Grund der vorliegenden Erfahrungen angenommen werden muss. Rotorblätter müssen auch nicht doppelt so teuer werden, wenn sie doppelt so lang halten sollen. Sie müssen mit ihrer Struktur nur richtig ausgelegt sein. Die DEBRA-25 wird seit 16 Jahren betrieben und besitzt ein Rotorblatt, das auf halber Länge durchgesägt und wieder mit einer hochbelasteten Schraubverbindung zusammengefügt wurde. Hinzu kommt bei der DEBRA-25 eine fast doppelt so hohe zulässige Materialdehnung im GFK-Material der Blätter, als heute von den Zertifizierungsbehörden zugelassen wird. Ein 10% teureres Blatt das 20 Jahre hält ist mit Sicherheit wirtschaftlicher als ein Vollaustausch nach der halben Laufzeit. Gleiches gilt für die Getriebe. Sie gehören genauso wenig zu den Tauschkomponenten, sondern müssen nur den Belastungen entsprechend ausgelegt werden.

Regelungsqualität:

In der Regelungsqualität der Windturbinen gibt es deutliche Unterschiede. Bessere und schlechtere sind heute fast gleichberechtigt auf dem Markt, da ein starkes Netz keine besonderen Maßnahmen erfordert. Dies wird so nicht bleiben. Die schnelle Verbreitung der Windenergie führt in starken Netzen zu einem letztendlich doch großen Anteil der Windenergie und in vielen Anwendungsregionen sind die Netze von vornherein als schwach zu bezeichnen, so dass dort mit den heutigen Anlagen schnell die Grenze der Verträglichkeit erreicht wird. Es wird erforderlich sein, Windturbinen so netzverträglich wie möglich zu machen. Dies kann durch eine verbesserte Regelung geschehen, die beispielsweise Böen nicht sofort in Drehmomente und

external influences change with the absolute size of the wind turbine and because wind turbines are often installed in complex terrain today. Of course, megawatt turbines work, and they can cope with the operating states occurring normally, but little is known about the influence of loads on the lifetime of the turbine. It is not only necessary to get a better store of knowledge by carrying out measurements, but also to modify the load assumptions by evaluating as many load cycles measured as possible.

Lifetime:

The lifetime of a wind turbine is closely linked to the loads acting on it. Today, because of insufficient knowledge of the operating loads occurring during the service life of a turbine, certain components are replaced prematurely and so maintenance costs become unnecessarily high. In other words, it is not necessary to replace rotor blades after 10 or 12 years, as this is assumed today based on the experience gathered so far. Rotor blades also do not necessarily have to get twice as expensive if their length is doubled. It is merely necessary to design their structure accordingly. The DEBRA-25 has been operating for 16 years and is equipped with a rotor blade sawed through in the middle and joined together with a highly stressed screw connection. In the DEBRA-25 rotor blade the admissible strain in the GFP material is almost twice as high as allowed today by the certification authorities. A blade that costs 10% more, but will keep for 20 years, is certainly more cost effective than a complete exchange after half the time. The same applies to gears. They should not be among the exchange components either, if they were designed according to the loads.

Quality of the control system:

There are noticeable quality differences between the control systems of wind turbines. Today, better and worse control systems are on the market together, almost on an equal basis, because a strong grid does not require special measures to improve the power quality. This, however, will not remain the same in future. The fast spreading of wind energy will increase the share of wind energy and affect even strong grids, and in many areas of wind energy use the power supply grids are generally so weak that with today's wind turbines the limit of compatibility is quickly reached. It will be necessary to make wind turbines as grid-compatible as possible. This can be done by an improved control system which for damit in elektrische Leistungssprünge umsetzt. Drehmomentstöße führen nicht nur zu unerwünschten elektrischen Wirkungen sondern natürlich auch zu zusätzlichen Belastungen. Auch aus diesem Grund sind bessere Regelungsmöglichkeiten sinnvoll.

Fertigung & Material:

Ein noch großes Kostenreduktionspotenzial bietet die Fertigung der Komponenten und die Ausnutzung der Materialeigenschaften. Hier geht es nicht um die Serienfertigungseffekte, die so hoch nicht eingestuft werden können, wenn man davon ausgeht, dass immer nur Zehnerpotenzsprünge in der Fertigungsmenge wirkliche Kosteneinsparungen bringen. Die Schritte von 100 MW-Anlagen pro Jahr zu 1000 und dann auf 10000 sind groß und werden von den meisten Firmen nicht realisierbar sein, wenn von einer Anbietervielfalt im Markt ausgegangen wird. Aber, der Trend zeichnet sich ab, dass jeder Hersteller die wesentlichen Komponenten (bspw. Rotorblätter) selber baut und sie so auf seine Bedürfnisse optimieren kann. Beim Material sind gerade im Bereich der Blattstrukturen noch deutliche Verbesserungen zu erwarten. Es scheint möglich, die spezifischen Belastungen von Faserverbundwerkstoffen höher anzusetzen, als dies heute die Zulassungsinstitutionen erlauben. Voraussetzung sind ausrechende Kenntnis der Belastungen und der Materialeigenschaften.

example does not convert gusts into torques immediately and thus avoids sudden power variations. Torque peaks do not only have a negative influence on the grid, but of course also result in additional loads. This is another reason why it makes sense to develop better control systems.

Production & material:

The production of components and an effective use of material properties offer an even greater potential for cost reduction. We are not talking here about the effects of series production, which cannot be regarded as very high, because as a rule only an increase in production numbers by the power of ten really leads to a cost reduction. The step from 100 MW-turbines per year to 1000 turbines and then again to 10,000 is a large one and most companies will not be able to make it, as long as there is still a variety of suppliers on the market. But the trend is becoming apparent that each manufacturer is producing the main components (e.g. rotor blades) himself and so can optimise them according to his requirements.

With regard to material, distinct improvements are to be expected especially in the area of blade structures. It seems to be possible to allow higher loads in composite material than prescribed by the certification authorities today.

Anwendung

Energieprognose:

Die Genauigkeit der Energieprognosen für die Standorte von Windenergieanlagen muss im Bereich der komplexen Gelände deutlich gesteigert werden. Zwei Effekte kommen zusammen. Komplexes Gelände ist meist im Binnenland anzutreffen, wo die Windgeschwindigkeiten in der Regel auch niedriger sind. Eine geringere Genauigkeit verbunden mit niedrigerem Wind führt schnell dazu, dass ein Projekt unwirtschaftlich wird, obwohl es in der Planung ausreichende Verhältnisse versprach. Es gilt Methoden zu entwickeln, die auch im komplexen Gelände bessere Ergebnisse liefern als dies heute der Fall ist. Auch ist es notwendig, einheitliche Mindestqualitätsregeln für die Standortgutachten aufzustellen, damit der Kunde zumindest erkennen kann, ob sein Gutachter auch alles im Gutachten berücksichtigt hat.

Off-shore-Einflüsse:

Die Anwendung im Off-shorebereich erfordert noch sehr umfangreiche F&E, um alle vorhandenen dynamischen und umweltbedingten Einflüsse ausreichend genau in der Entwicklung von Offshoreanlagen berücksichtigen zu können. Im Gegensatz zu On-shore werden hier auch die Fundamente eine wesentliche Rolle spielen.

Kurzzeit-Prognose:

Je höher die Penetration der Windenergie im Netz ist, um so wichtiger wird es für den Betrieb des gesamten Kraftwerksparks des Energieversorgers, das zeitliche Angebot der Windenergie besser zu kennen. Diese Kurzzeitprognose verbessert die gesamtwirtschaftliche Situation der Energieversorgung und erlaubt die weitere Erhöhung des Windanteils.

Verifizierung, Messmethoden:

Heute scheint es für den Betreiber nur wichtig zu sein, ob der Windpark läuft und zumindest keine roten Zahlen produziert. Von untergeordneter Rolle ist, ob durch Nachvermessung der Anlagen eine Möglichkeit gefunden wird, eine Verbesserung der Energieausbeute zu erzielen oder nicht. Wird durch bessere Einstellung der Windturbinen nur 1% mehr Energieertrag pro Jahr erzielt, so wäre das bei einem Windpark von 25 MW Leistung immerhin rund 100000 DM pro Jahr, ein Wert, der die Kosten für eine solche Vermessung schnell wieder einbringt. Aber um solche Verifizierungen fundiert machen zu können, sind Methoden und Messverfahren zu entwickeln und zu verbessern, insbesondere auch die Anemometerkalibration, so dass die Ergebnisse von Betreibern und Herstellern anerkannt werden können.

This, however, requires sufficient knowledge of the loads and material properties.

Application

Energy output prognosis:

Energy output prognoses for wind farm sites must become a lot more precise as far as sites in complex terrain are concerned. The problem is a combination of two effects. Complex terrain is mostly found inland, where wind speeds are also lower as a rule. A reduced exactness in combination with lower wind speeds can easily make a project uneconomical, although during the planning stage the resources were considered to be sufficient. Methods have to be developed which will supply better results in complex terrain as is the case today. Furthermore standard minimum quality requirements for site evaluations have to be established so that the client at least can see if the institute commissioned by him has considered everything in its evaluation.

Off-shore influences:

Off-shore wind energy use requires very extensive R&D work to be able to consider all the existing dynamic and environmental influences with sufficient exactness in the development of off-shore wind turbines. Other than in on-shore installations, wind turbine foundations will be one of the major subjects here.

Short-term prognosis:

The higher the penetration of wind energy in the grid, the more important it will become for the operation of the entire generation system of the utility to have a better knowledge about the time variation of the wind energy available. The short-term prognosis improves the overall economic situation of electricity supply and allows to increase the share of wind energy even further.

Verification, measuring methods

Today most operators seem to be content if the wind farm is working and is not in the red financially. The possibility to find out by follow-up measurements if the energy yield could be improved seems to be of secondary importance. However, if by improving the adjustment of wind turbines the energy output could be increased by only 1%, this would amount to about 100,000 DM for a 25 MW wind farm, a sum which easily brings back the costs for such a measurement. Well-founded verifications can only be carried out if methods and measuring procedures are developed and improved, in particular the anemometer cali-

Erschließung anderer Anwendungsbereiche:

Neben der reinen Netzeinspeisung sind dringend Arbeiten im Bereich der Speicherung und Kombination mit anderen Energieerzeugern, wie beispielsweise Wind-Diesel-, Hybridsysteme, die Anwendung mit Brennstoffzellen im Verkehr und Wasserentsalzung intensiv aufzunehmen, damit die notwendige Vorlaufforschung rechtzeitig erledigt werden kann und die Systeme in die Anwendung gelangen können.

bration, so that results can be recognized by operators and manufacturers.

Development of other areas of application:

Apart from using wind energy for feeding it into the electricity grid, other areas e.g. energy storage and combination of wind energy with other electricity generators, such as wind/diesel systems, hybrid systems, the use of fuel cells in traffic and water desalination should be discussed intensively in order to begin the necessary pre-development research in time and put these systems to work.

IEA R&D WIND ANNEX XI
The Operating Agent

SUMMARY

35th IEA R&D Wind Annex XI Topical Expert Meeting on Long term R&D needs for wind energy. For the time frame 2000 – 2020

Prepared by Sven-Erik Thor (FOI) and Åsa Elmqvist (STEM)

1 Summary and conclusions

A similar meeting was held in Holland 1995. At that meeting the discussions mainly focused on technological issues. The meeting 2001 also focused on these things and in addition to that made reference to such areas as sociotechnical aspects (visual intrusion, acceptance etc.) and wildlife, flora and fauna. This seems natural in a stage when wind turbines are becoming a more common element in society.

There is a consensus on the view that there still is a need for generic **long term** research. The main goal for research is to support the implementation of national/international visions for wind energy in the near and far future. It was the opinion that it is possible to reach this goal for the near future with available knowledge and technology. However, large-scale implementation of wind energy requires a continued cost reduction and an improved acceptability and reliability. In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken. The technology of turbines, of wind power stations, of grid connection and grid control, the social acceptability and the economy of wind power in a liberalized market, all have to be improved in order to provide a reliable and sustainable contribution to the energy supply. It is for this objective that there is a need for long term R&D. Besides this, there is also a need for a short to mid term research that mainly is in the interest of utilities/manufacturing industries and to some extent to society.

The result of the meeting has given valuable information for updating the next version of the Strategic Document. Examples are the categorizing of the different research topics as well as an updated list of research areas, for example storage techniques, forecasting of production, autonomous systems and smart structures. Participants in the meeting "volunteered" to give comments and suggestions for improvement of the Strategy Document.

2 Background

The meeting was kindly hosted by ECN, Netherlands Energy Research Foundation, at Petten in Holland on the 22 - 23 of March 2001. The subject of the meeting was to identify Long-term R&D needs for wind energy, for the time frame 2000 – 2020. This meeting is an essential element in the process of developing a long term R&D strategy for the implementing agreement. Other activities to support the development of the document are:

- Meeting at the Kassel conference, Sept 2000
- Discussion at IEA ExCO #46 in Italy
- Presentation at the REWP meeting in Paris, Oct. 2000
- Ad hoc working group
- Discussion at IEA ExCO #47 in Norway

The meeting was attended by 16 persons, giving 10 presentations. The attendees represented seven countries and came mainly from national energy agencies or research organizations.

3 Summary of presentations

3.1 Categorization of needs

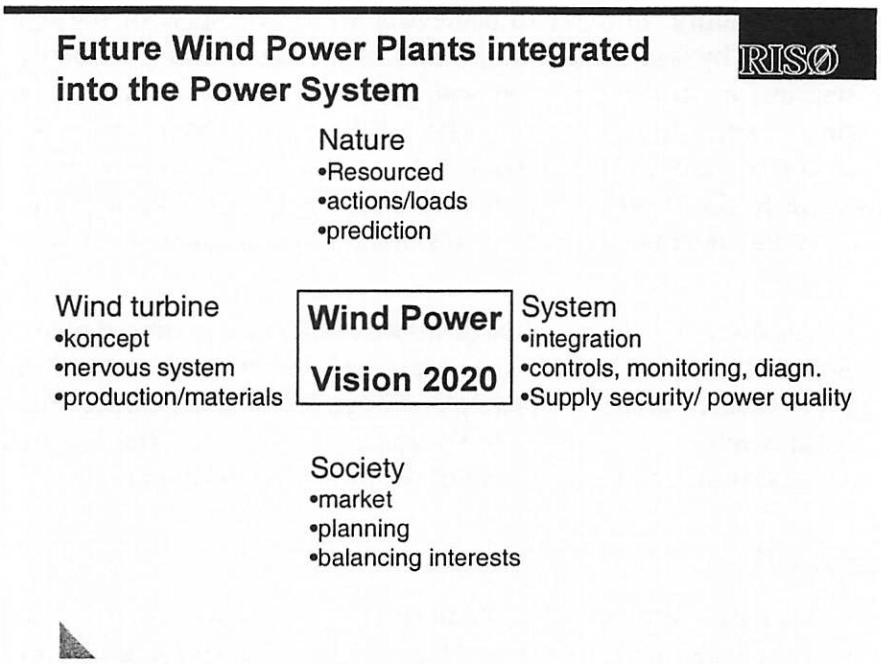
The presentations covered many aspects of wind engineering. Different approaches for sorting the R&D topics were given by the lecturers:

1. research topic oriented
2. overall view (holistic)
3. needs to achieve strategic goals.

An example of the first one is:

- Technology development
- Sociotechnical aspects
- Wildlife, flora and fauna

Another, holistic, way of presenting the subject was proposed by Rasmussen. This approach starts with the vision for future implementation of this energy source. The vision constitutes what we would like to achieve. Around this vision a number of interacting subjects are focused.



The presentation by Snel outlined R&D needs and priorities linked to strategic goals and success factors. The presentation was based on a recent survey made by EUREC/EWEA.

R&D needs and priorities: Link Strategic Goals and success factors

Strategic goals / Aspects	10% renewable energy in Europe	30% new RE capacity in developing countries	Maintaining Industrial capacity & employment
Cost reduction of wind energy	••	•••	•••••
Increasing the value of wind energy	•••	•••	•••
Finding new sites	••••	••	•
System development	••••	••••	•••
Reduction of uncertainties	••	•••••	•••••
Reduction of environmental effects and negative social impacts	•••	-	•
Education & human resource development	••	••	•••••
Development of policy and instruments	•••••	•••••	•••••

EWEA

EUREC

The last two ways take an overall view of the needs in different areas. This approach was considered to be the most suitable categorization to be used in the Strategy Document. However, the exact headings should be elaborated in more detail.

3.2 Research aiming at

In order to achieve visions many speakers mentioned that lowering the cost of generation as the main issue for R&D. In order to fulfill this, R&D should aim at:

- larger turbines
- offshore
- new concepts
- grid interaction and transmission
- reliability
- recycling
- free market aspects
- measures creating value and solutions to the energy supply

3.3 Turbine sizes

The size of turbines and related research was addressed. The general view is that there are three different categories of sizes:

1. multi MW size (≅5MW), wind turbines for large power stations off-shore or remote area
2. medium-size wind turbines (≅1MW) for grid connection, single turbines or farms
3. smaller wind turbines (≅ 30 kW) for electrification in developing countries, stand-alone, combined with solar energy and possibly hydrogen production for storage and transportation

The research needed is somewhat different for the different classes.

4 Round table discussion

The outcome of the discussion is summarized below.

4.1 Long term R&D –Research for whom? / Research for achieving what?

Main purpose of Long Term R&D is to create options. From them, the society can make the choices on direction of energy supply. The research is done for the whole society and the results will be used on a multi-national governmental level.

Short-term research is primarily for the manufacturers or the utilities. They are, together with R&D results, more like a helping tool to reach the existing political visions and goals for installed wind power. Progress ratio is only possible with a combination of manufacturers development and R&D.

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The time frame for research was touched upon. Three different horizons were proposed:

1.	Short term 0 – 5 years	system development, human resource development
2.	Mid term, 5 –10 years	mix of 1 and 3
3.	Long term 10 – 20 years	increasing the value of wind, supporting strategic goals

Research in all time scales should be in discussion with government, utilities and industry. Though industry is normally not involved in long term R&D and has usually not formulated their long term needs, it is possible to get ideas for the long-term research from the short and medium term R&D.

There is a consensus on the view that there still is a need for generic **long term** research. The main goal for research is to support the implementation of national/international visions for wind energy in the near and far future. It was the opinion that it is possible to reach this goal for the near future with available knowledge and technology. However, large-scale implementation of wind energy requires a continued cost reduction and an improved acceptability and reliability. In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken. The technology of turbines, of wind power stations, of grid connection and grid control, the social acceptability and the economy of wind power in a liberalized market, all have to be improved in order to provide a reliable and sustainable contribution to the energy supply. It is for this objective that there is a need for long term R&D. Besides this, there is also a need for a short to mid term research that mainly is in the interest of utilities/manufacturing industries and to some extent to society.

4.3 Topics

A similar meeting was held in Holland 1995. At that meeting the discussions mainly focused on technological issues. The meeting 2001 also focused on these things and in addition to that made reference to such areas as sociotechnical aspects (visual intrusion, acceptance etc.) and wildlife, flora and fauna. This seems natural in a stage when wind turbines are becoming a more common element in society.

A comparison of listed topics at the two meetings is shown in the figure below. Some of the 1995 topics were not mentioned at the 2001 meeting, they are marked in red/italic.

The total list of topics shall be interpreted as the sum of the two lists, except the red/italic bullets.

Comparison with 1995 meeting

1995

- Offshore
- Aeroelasticity and loads
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- Materials
- *Lightning protection*
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- Power conversion
- Recycling
- *Efficient park lay-out*
- *Certification*
- Public acceptability
- *Legal aspects*

New 2001

- Environment
- Storage
- Large scale introduction
- Forecasting
- Smart structures
- Autonomous systems
- HR development/training

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4.4 Cross cutting issues

The aim was to identify areas that were relevant not only to wind energy, but also to other energy sectors. A number of topics were mentioned:

- Micro turbines
- Hybrid systems
- Integration with other production sources
- Free market movement

IEA R&D Wind Topical Expert Meeting on Long Term R&D issues. ECN Holland, March 14 - 15 2001										
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IEA R&D WIND ANNEX XI
The Operating Agent

SUMMARY

35th IEA R&D Wind Annex XI Topical Expert Meeting on Long term R&D needs for wind energy. For the time frame 2000 – 2020

Prepared by Sven-Erik Thor (FOI) and Åsa Elmqvist (STEM)

1 Summary and conclusions

A similar meeting was held in Holland 1995. At that meeting the discussions mainly focused on technological issues. The meeting 2001 also focused on these things and in addition to that made reference to such areas as sociotechnical aspects (visual intrusion, acceptance etc.) and wildlife, flora and fauna. This seems natural in a stage when wind turbines are becoming a more common element in society.

There is a consensus on the view that there still is a need for generic **long term** research. The main goal for research is to support the implementation of national/international visions for wind energy in the near and far future. It was the opinion that it is possible to reach this goal for the near future with available knowledge and technology. However, large-scale implementation of wind energy requires a continued cost reduction and an improved acceptability and reliability. In order to achieve a 10 to 20% part of the worldwide energy consumption provided by wind, major steps have to be taken. The technology of turbines, of wind power stations, of grid connection and grid control, the social acceptability and the economy of wind power in a liberalized market, all have to be improved in order to provide a reliable and sustainable contribution to the energy supply. It is for this objective that there is a need for long term R&D. Besides this, there is also a need for a short to mid term research that mainly is in the interest of utilities/manufacturing industries and to some extent to society.

The result of the meeting has given valuable information for updating the next version of the Strategic Document. Examples are the categorizing of the different research topics as well as an updated list of research areas, for example storage techniques, forecasting of production, autonomous systems and smart structures. Participants in the meeting "volunteered" to give comments and suggestions for improvement of the Strategy Document.

2 Background

The meeting was kindly hosted by ECN, Netherlands Energy Research Foundation, at Petten in Holland on the 22 - 23 of March 2001. The subject of the meeting was to identify Long-term R&D needs for wind energy, for the time frame 2000 – 2020. This meeting is an essential element in the process of developing a long term R&D strategy for the implementing agreement. Other activities to support the development of the document are:

- Meeting at the Kassel conference, Sept 2000
- Discussion at IEA ExCO #46 in Italy
- Presentation at the REWP meeting in Paris, Oct. 2000
- Ad hoc working group
- Discussion at IEA ExCO #47 in Norway

The meeting was attended by 16 persons, giving 10 presentations. The attendees represented seven countries and came mainly from national energy agencies or research organizations.

3 Summary of presentations

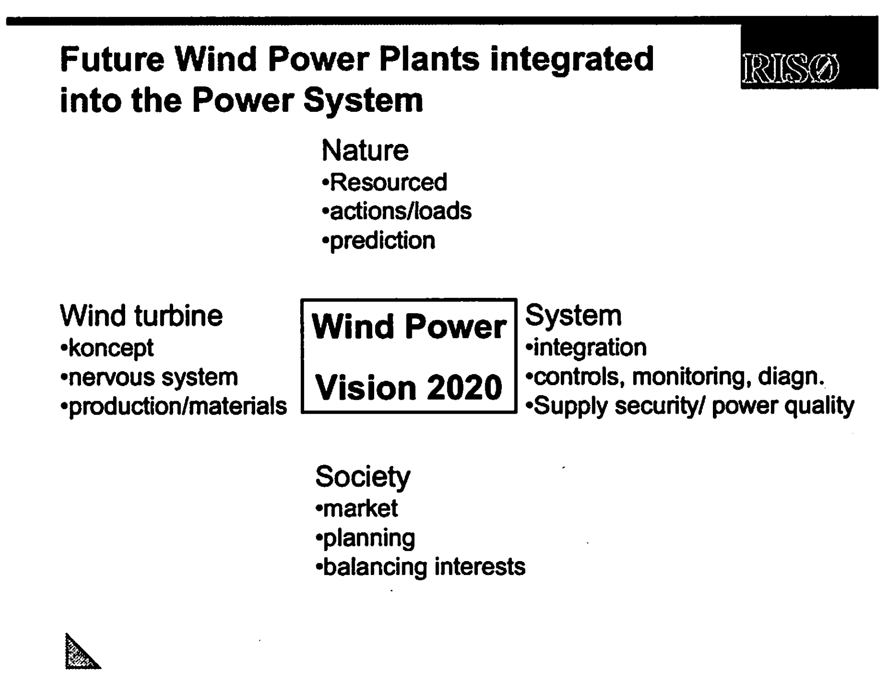
3.1 Categorization of needs

The presentations covered many aspects of wind engineering. Different approaches for sorting the R&D topics were given by the lecturers:

1. research topic oriented
2. overall view (holistic)
3. needs to achieve strategic goals.

An example of the first one is:
- Technology development
- Sociotechnical aspects
- Wildlife, flora and fauna

Another, holistic, way of presenting the subject was proposed by Rasmussen. This approach starts with the vision for future implementation of this energy source. The vision constitutes what we would like to achieve. Around this vision a number of interacting subjects are focused.



The presentation by Snel outlined R&D needs and priorities linked to strategic goals and success factors. The presentation was based on a recent survey made by EUREC/EWEA.

R&D needs and priorities: Link Strategic Goals and success factors

Strategic goals Aspects	10% renewable energy in Europe	30% new RE capacity in developing countries	Maintaining Industrial capacity & employment
Cost reduction of wind energy	••	•••	•••••
Increasing the value of wind energy	•••	•••	•••
Finding new sites	••••	••	•
System development	••••	••••	•••
Reduction of uncertainties	••	•••••	•••••
Reduction of environmental effects and negative social impacts	•••	-	•
Education & human resource development	••	••	•••••
Development of policy and instruments	•••••	•••••	•••••

EWEA

EUREC

The last two ways take an overall view of the needs in different areas. This approach was considered to be the most suitable categorization to be used in the Strategy Document. However, the exact headings should be elaborated in more detail.

3.2 Research aiming at

In order to achieve visions many speakers mentioned that lowering the cost of generation as the main issue for R&D. In order to fulfill this, R&D should aim at:

- larger turbines
- offshore
- new concepts
- grid interaction and transmission
- reliability
- recycling
- free market aspects
- measures creating value and solutions to the energy supply

3.3 Turbine sizes

The size of turbines and related research was addressed. The general view is that there are three different categories of sizes:

1. multi MW size (≅5MW), wind turbines for large power stations off-shore or remote area
2. medium-size wind turbines (≅1MW) for grid connection, single turbines or farms
3. smaller wind turbines (≅ 30 kW) for electrification in developing countries, stand-alone, combined with solar energy and possibly hydrogen production for storage and transportation

The research needed is somewhat different for the different classes.

4 Round table discussion

The outcome of the discussion is summarized below.

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