Technical University of Denmark

Nature's limit to the wind energy extractable for human use

Frandsen, Sten Tronæs; Hahmann, Andrea N.; Larsen, Søren Ejling; Hansen, Aksel W.

Publication date:
2009

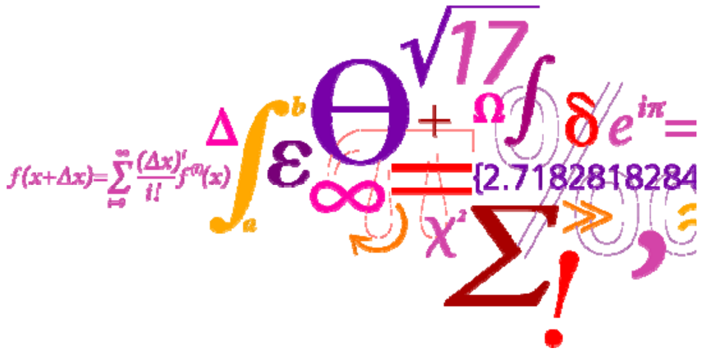
Citation (APA):
Frandsen, S. T., Hahmann, A. N., Larsen, S. E., & Hansen, A. W. (2009). Nature's limit to the wind energy extractable for human use [Sound/Visual production (digital)]. Risø International Energy Conference 2009, Roskilde, Denmark, 14/09/2009

UNIVERSITY OF COPENHAGEN

DTU

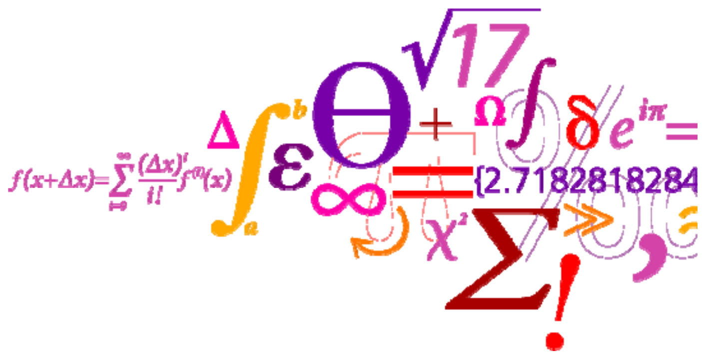
Nature's limit to the wind energy extractable for human use

Sten T. Frandsen, Andrea N. Hahmann, Søren E. Larsen
Risø DTU
Aksel W. Hansen
NBI Copenhagen University



Climate change mitigation
– what are the realistic options?

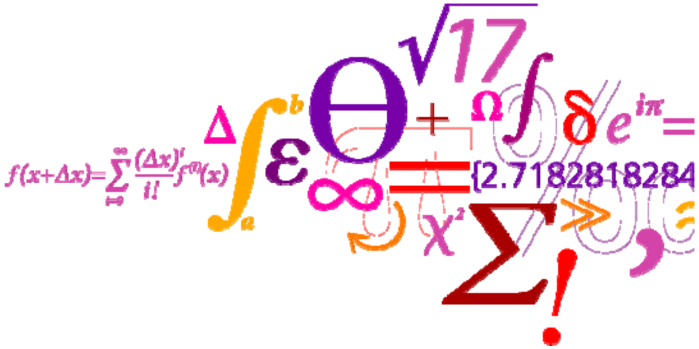
- Amongst the renewables, wind appears presently unchallenged, being much cheaper than the runners-up.
- Wind is known to be abundant – how abundant?
- It influences the climate marginally – how marginally?



Synopsis

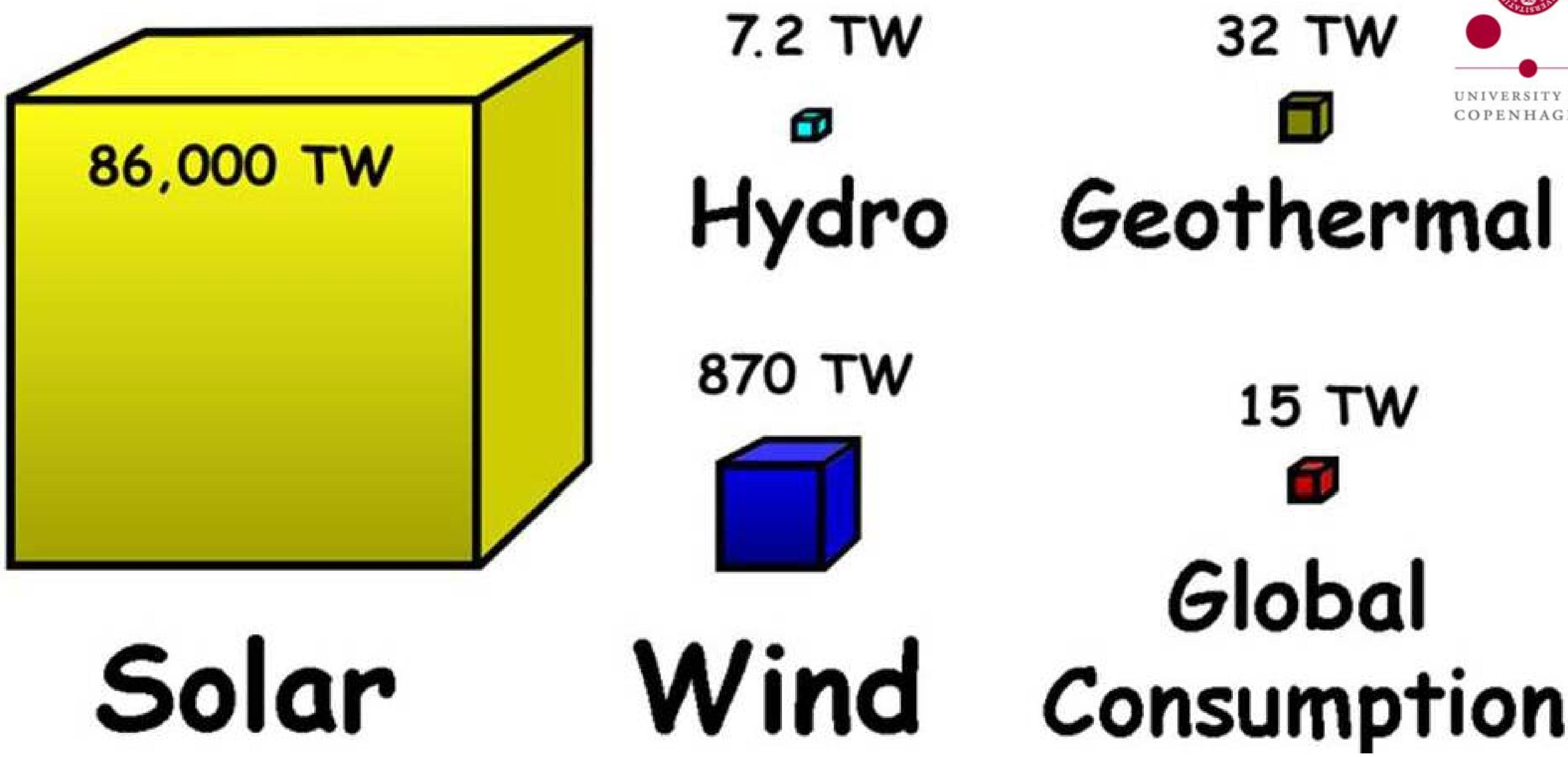
- Simple extrapolation of wind power contribution to world energy.
- Some uncertainties in predicting future availability of wind power from both technology and nature.

  Example from wind power over the North Sea Europe, including individual turbine wakes but not wind farm shadows and regional feed-back.
- Global atmospheric motion, upper limit to available energy and regional and global feed –back from the extraction.



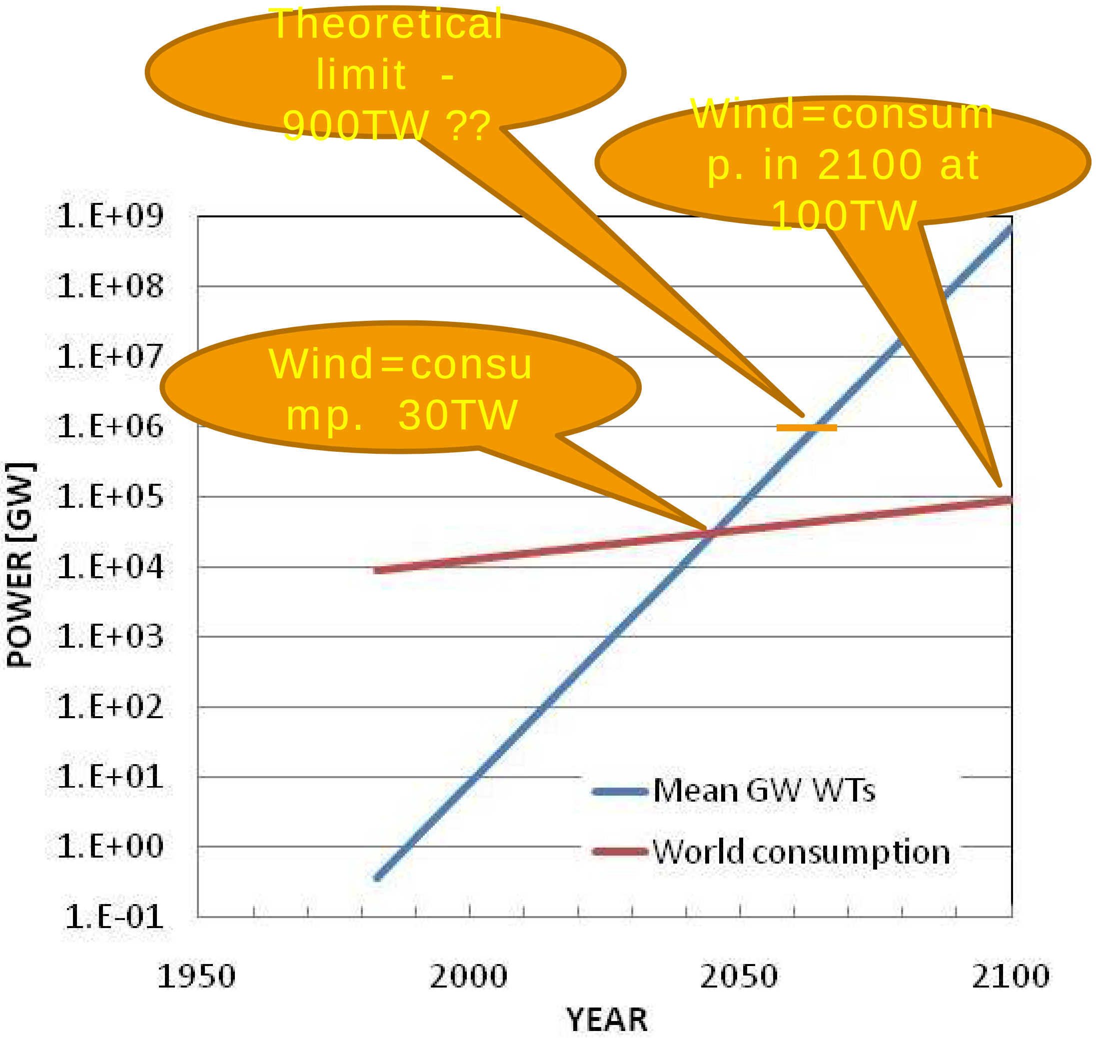
Renewable energies

How much is there? And how much is used already now? (annual mean power)



Prognoses: consumption and wind energy

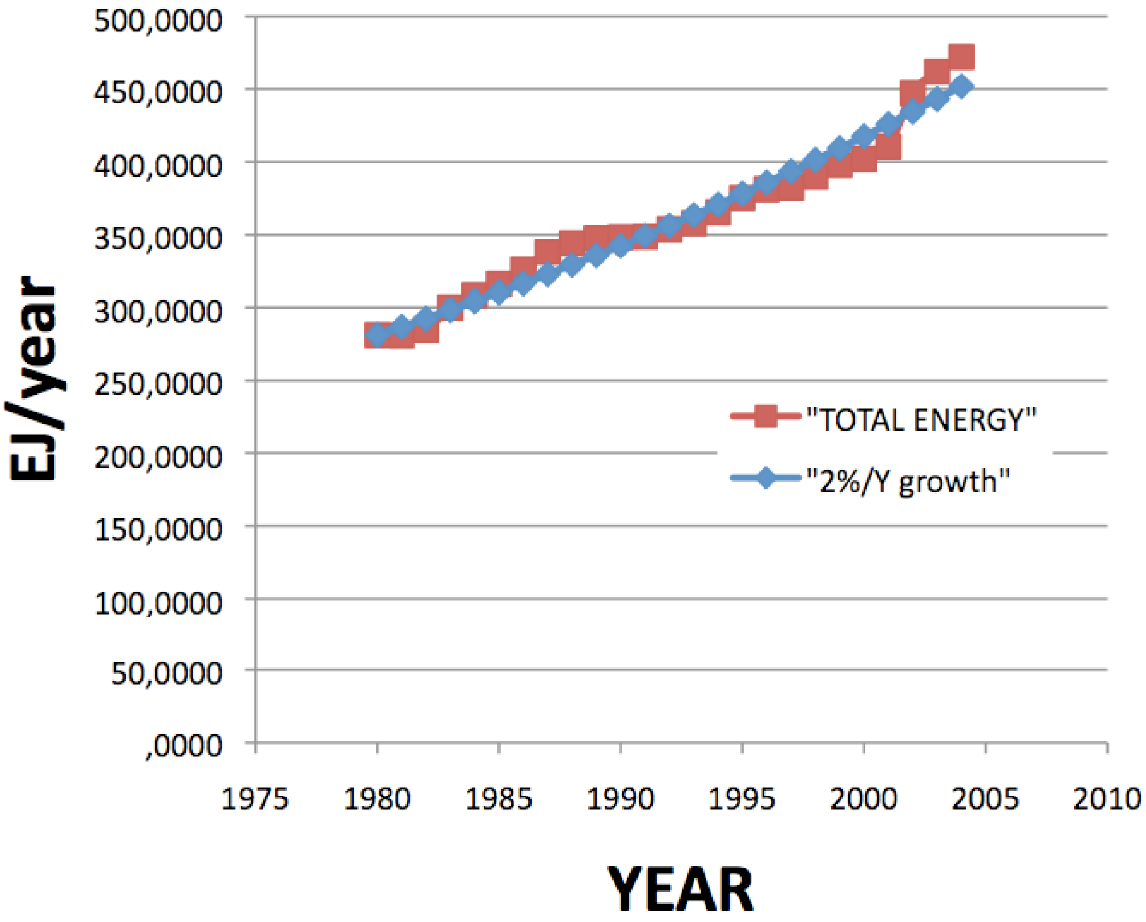
- Consumption growth rate: 2% per year
- Wind power industry growth rate: 20%
- **Wind=consumption in approx. 2050 at 30TW**

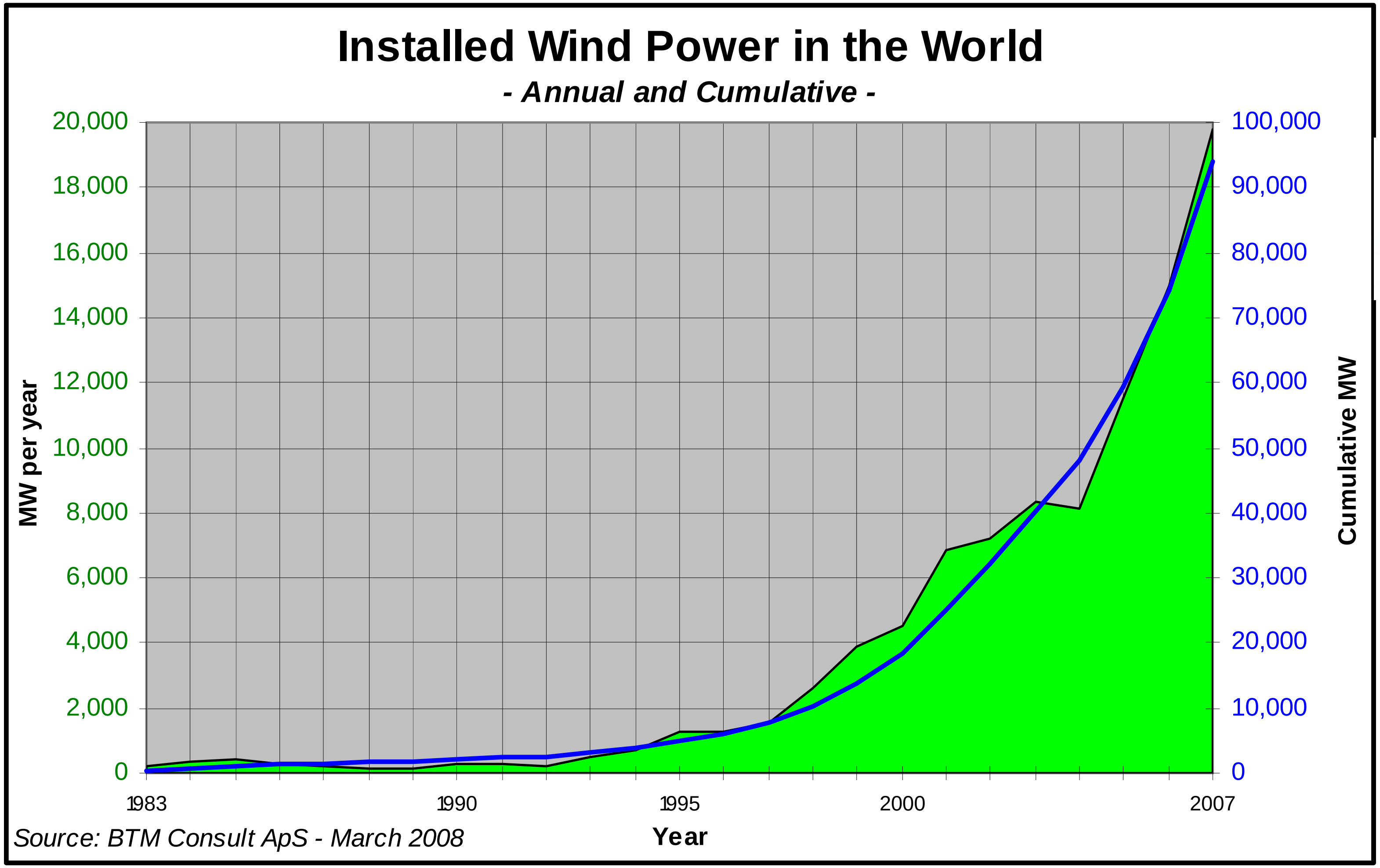


UNIVERSITY OF COPENHAGEN

Total energy consumption

Energy consumption is in fact growing at 2% pr year

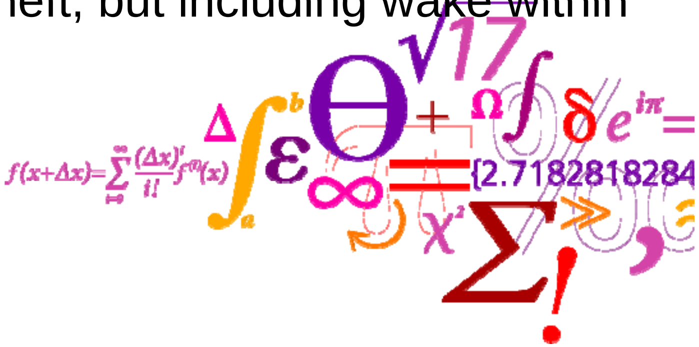




Installed Wind Power in the World
- Annual and Cumulative -
MW per year
Cumulative MW
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1983
1990
1995
2000
2007
Year
Source: BTM Consult ApS - March 2008

Development of wind energy and its uncertainties.

- Charateristics of wind energy: Variability.
- Reduction of output due to wake effects
  - a) between turbines.
  - b) wind shadowing and wind theft between wind farms(?).
- Future development of wind turbines
- The North Sea as a suitable area for a large wind power contribution to Europe's Energy consumption, based on the production from the Horns Rev Wind Farm, neglecting wind theft, but including wake within the farm area.

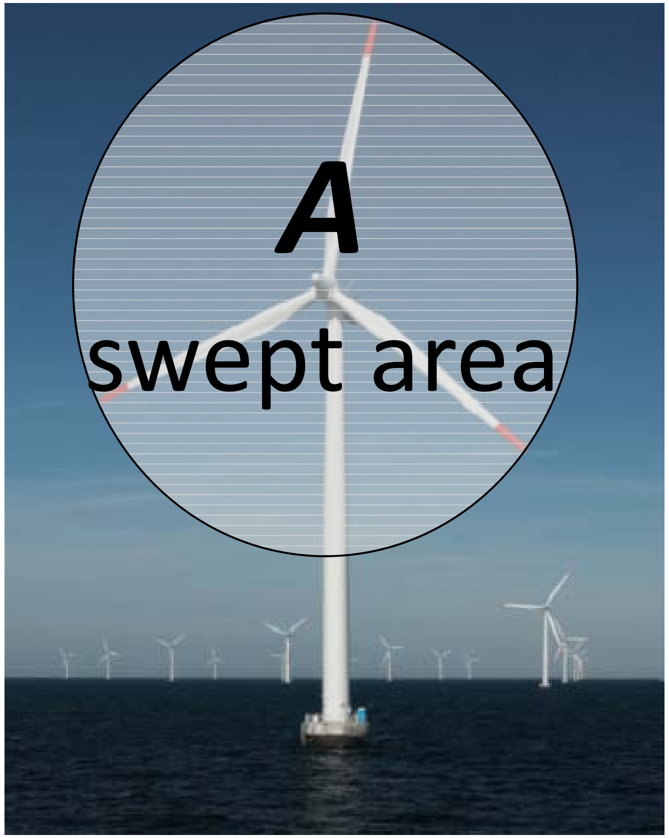


How does the wind turbine make electricity?

$$P_{available} = \tfrac{1}{2}\,\rho\, U^{3} A$$

wind turbine

wind



- Energy in the wind goes with **U*U*U**; therefore:
- **20% more wind-**
70% more energy

- **100% more wind-**
700% more energy!!

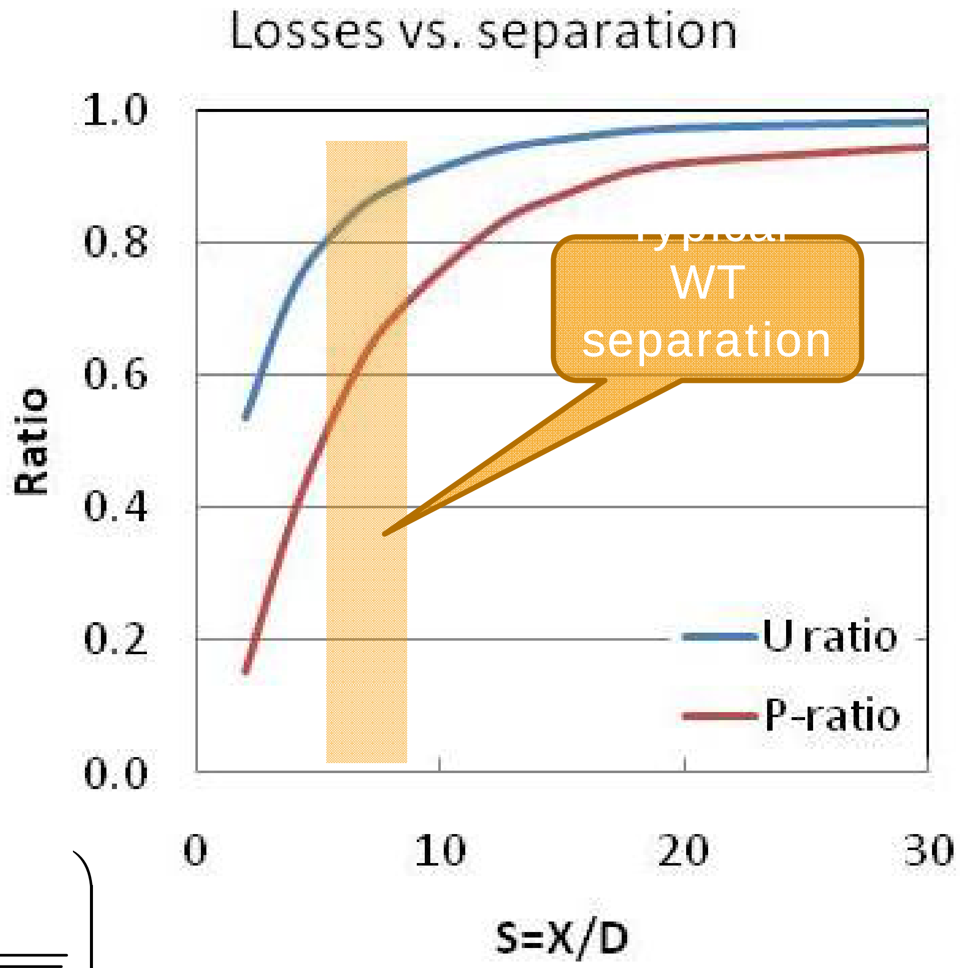
Wind turbines

..obstruct each other–

and interact with the atmosphere

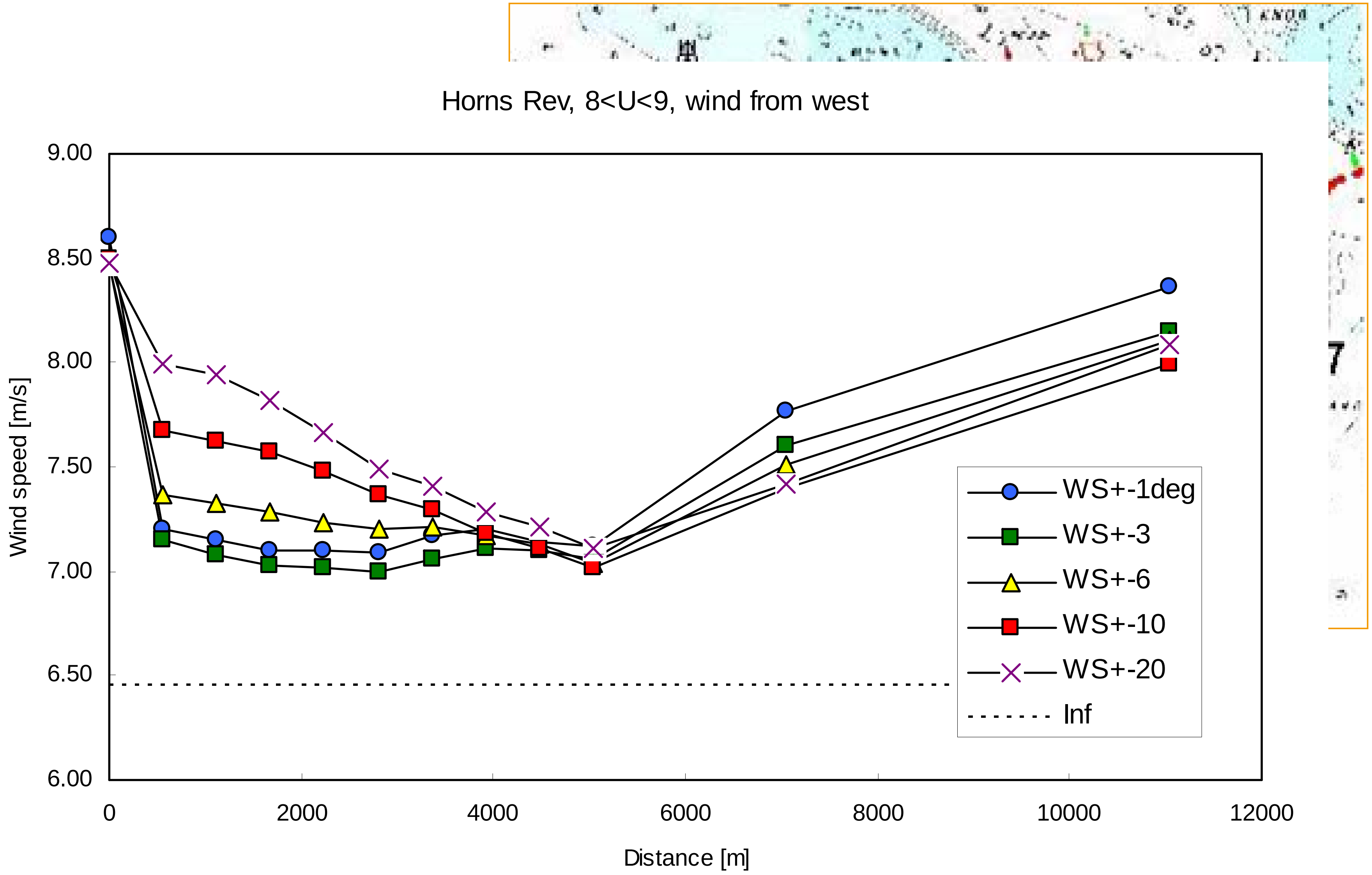
Wind farm losses relative to unobstructed wind turbines:
roughness boundary layer model

- Losses with present engineering tools small
- Disregarding global effects, but including feedback from wind farms to boundary layer, 40-50% losses may be seen with “standard” 7-8D separa-tions
- Wind turbines increase the surface roughness:



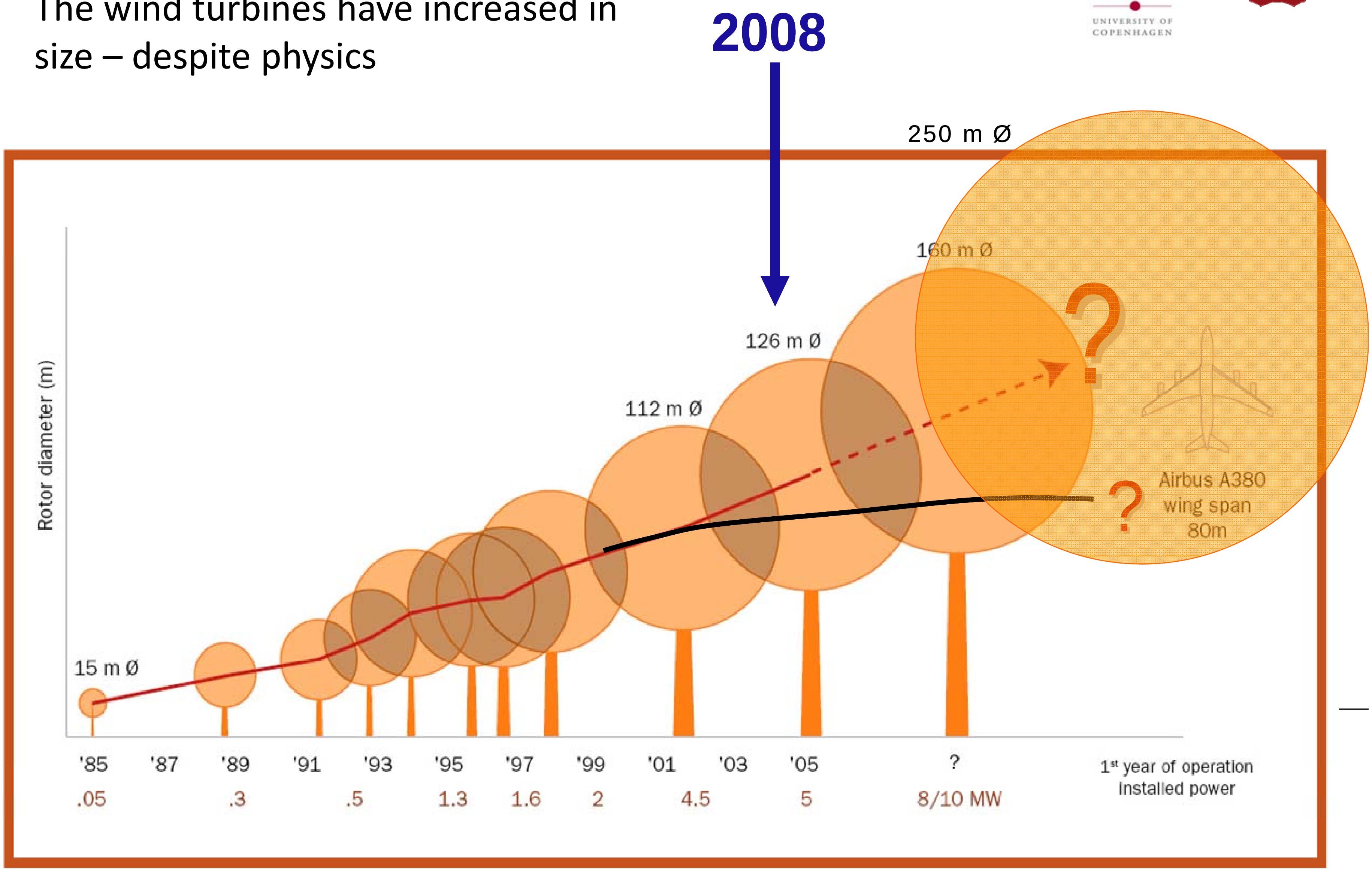
$$z_{00} = h_H \cdot \exp\left(- \frac{\kappa}{\sqrt{c_t + \left(\kappa / \ln(h_H / z_0)\right)^2}} \right)$$

Wind speed drop in wind farms - and recovery

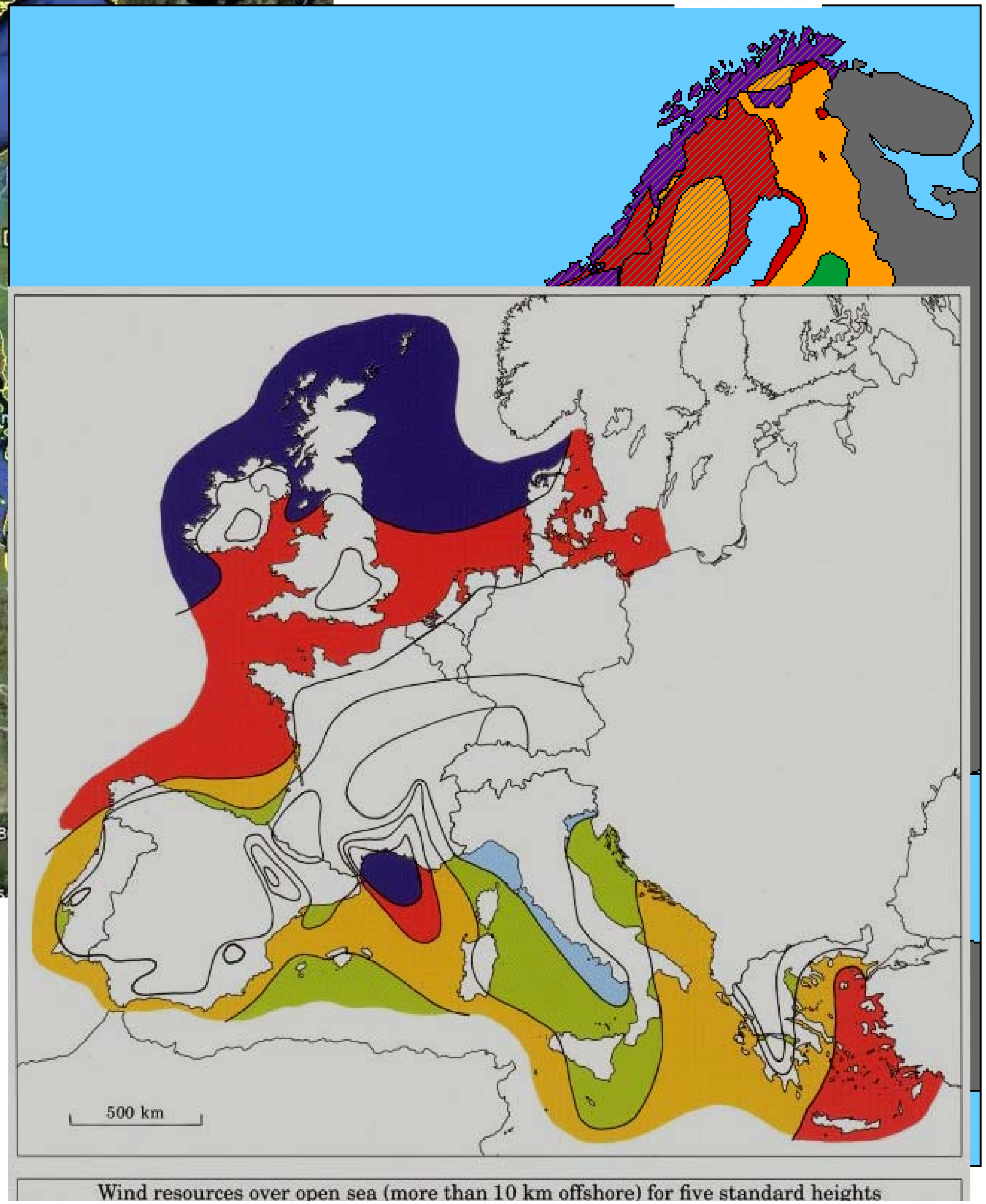


Up-Scaling

The wind turbines have increased in size – despite physics



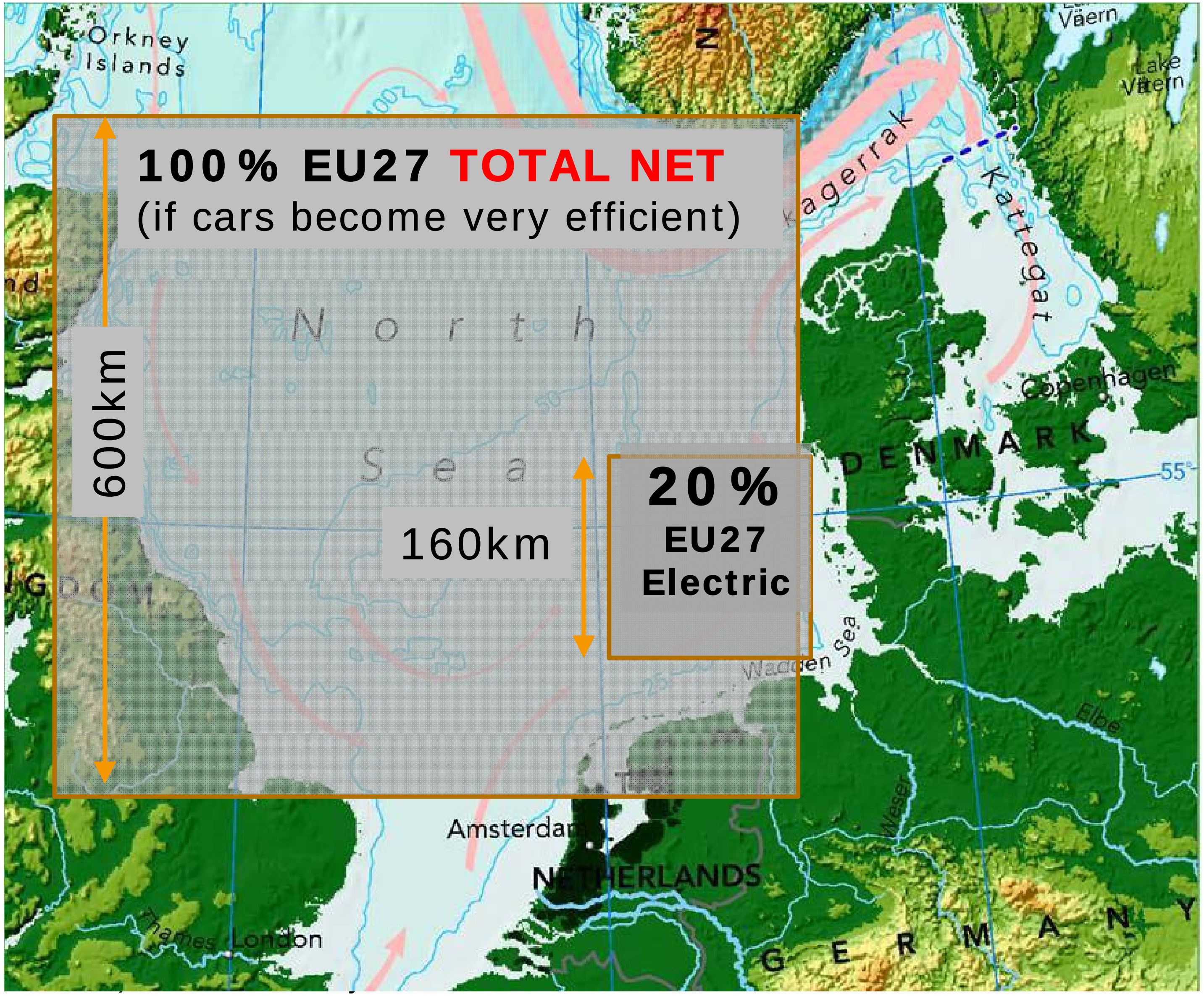
The wind in the northern seas



...**huge wind farm areas are needed** in the future and somehow wind farms affect the atmospheric flow also on the larger scale

Risø DTU, Technical University of Denmark

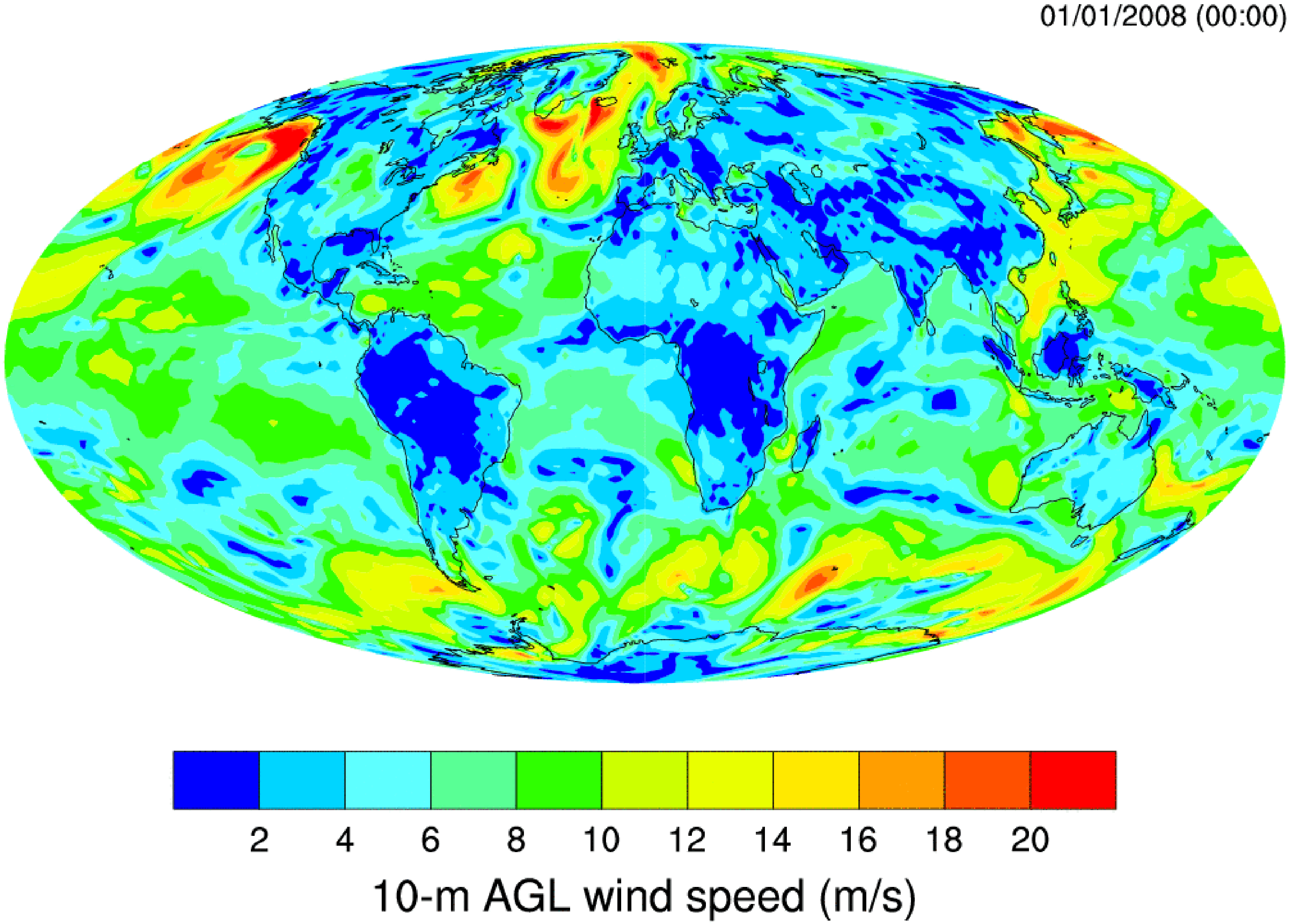
North Sea Wind (super Horns Rev farm)



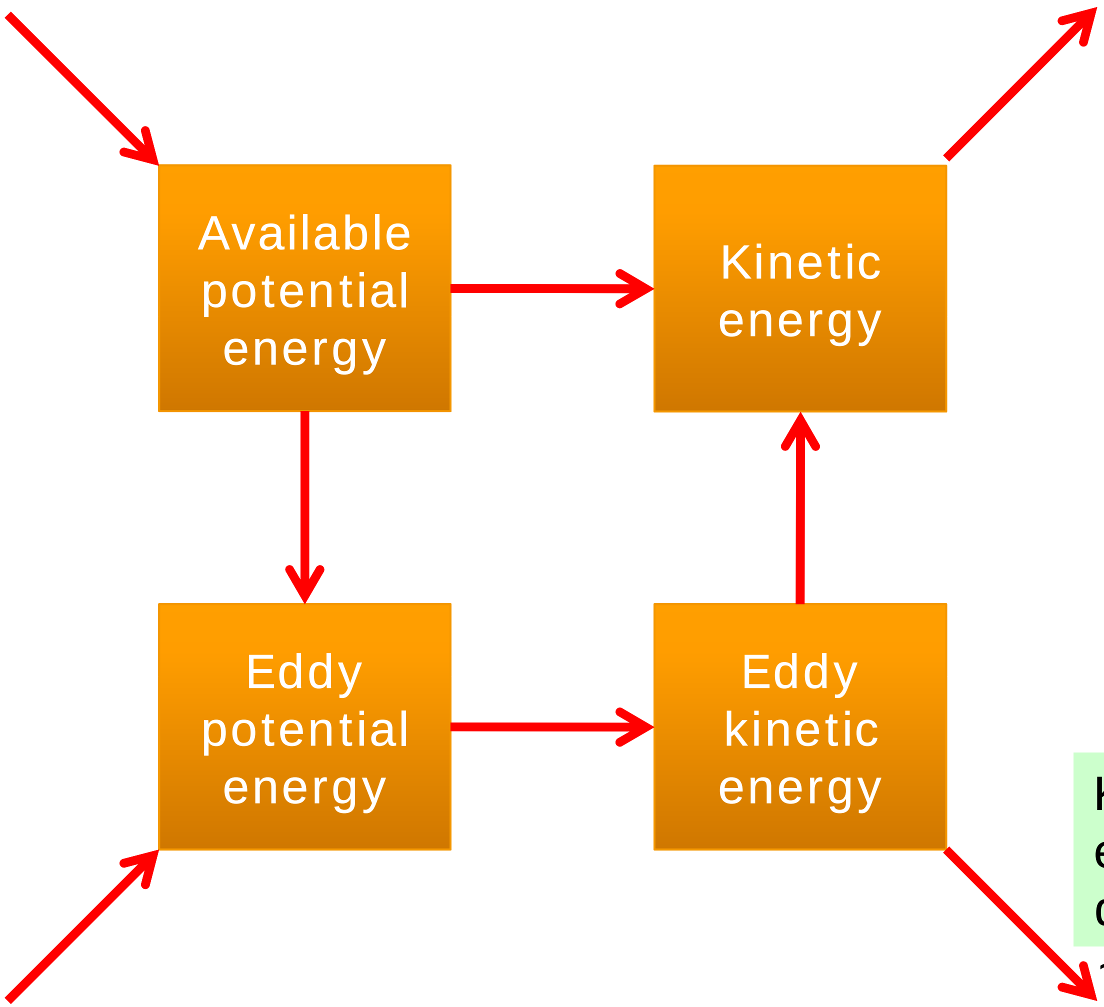
Large scale impacts.

- Global atmospheric motion, upper limit to available energy and feed – back from the extraction.
- The energy available extraction equals the energy that is dissipated in th Atmospheric Boundary Layer due to friction between the atmosphere and the ground. In a sense wind turbines are “just” a new dissipation mechanism in addition to “natural surface friction”.

Wind speed during January 2008



Global energy cycle (the Lorenz Cycle)



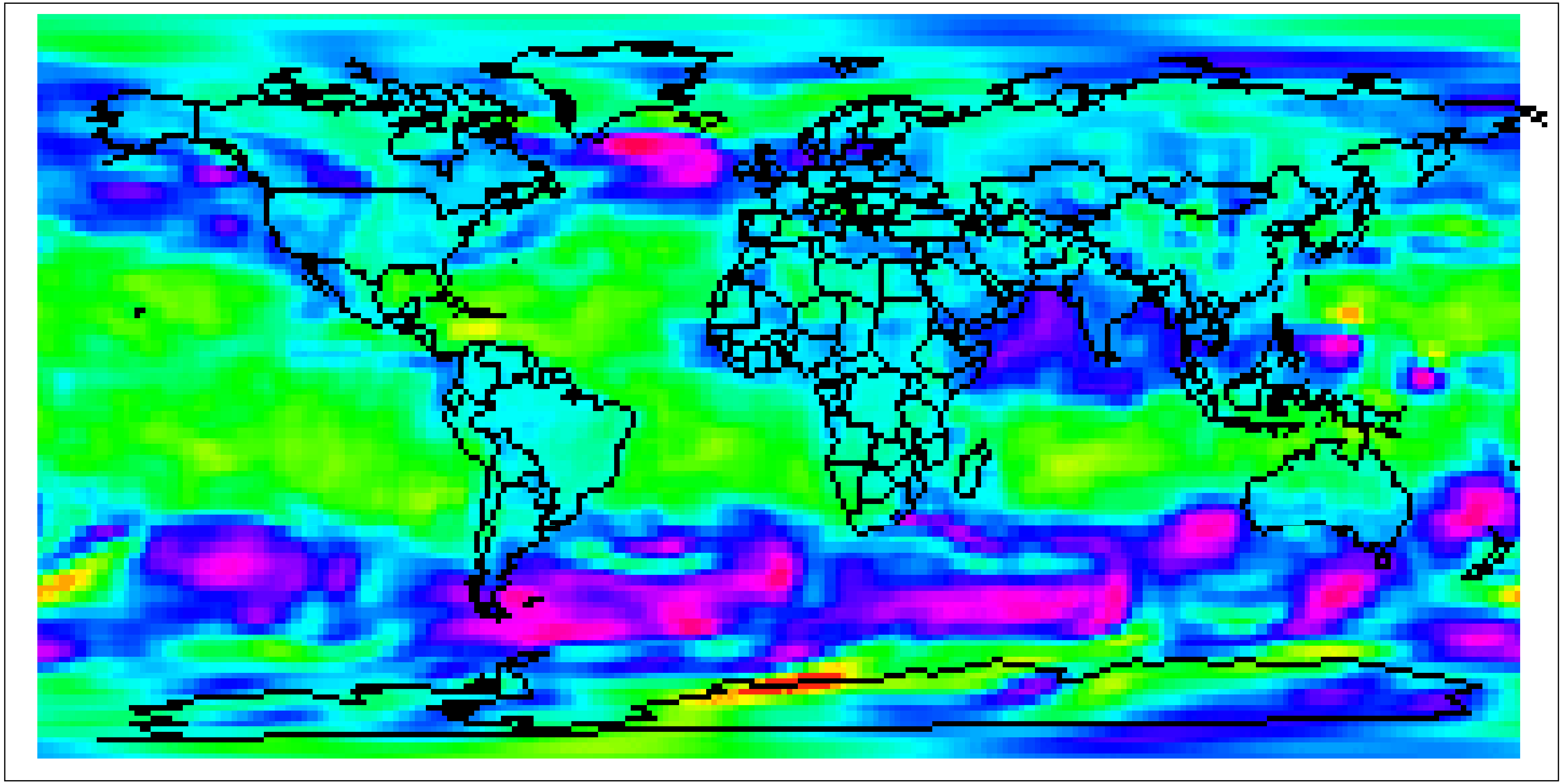
Energy “reservoirs”

Energy transformations

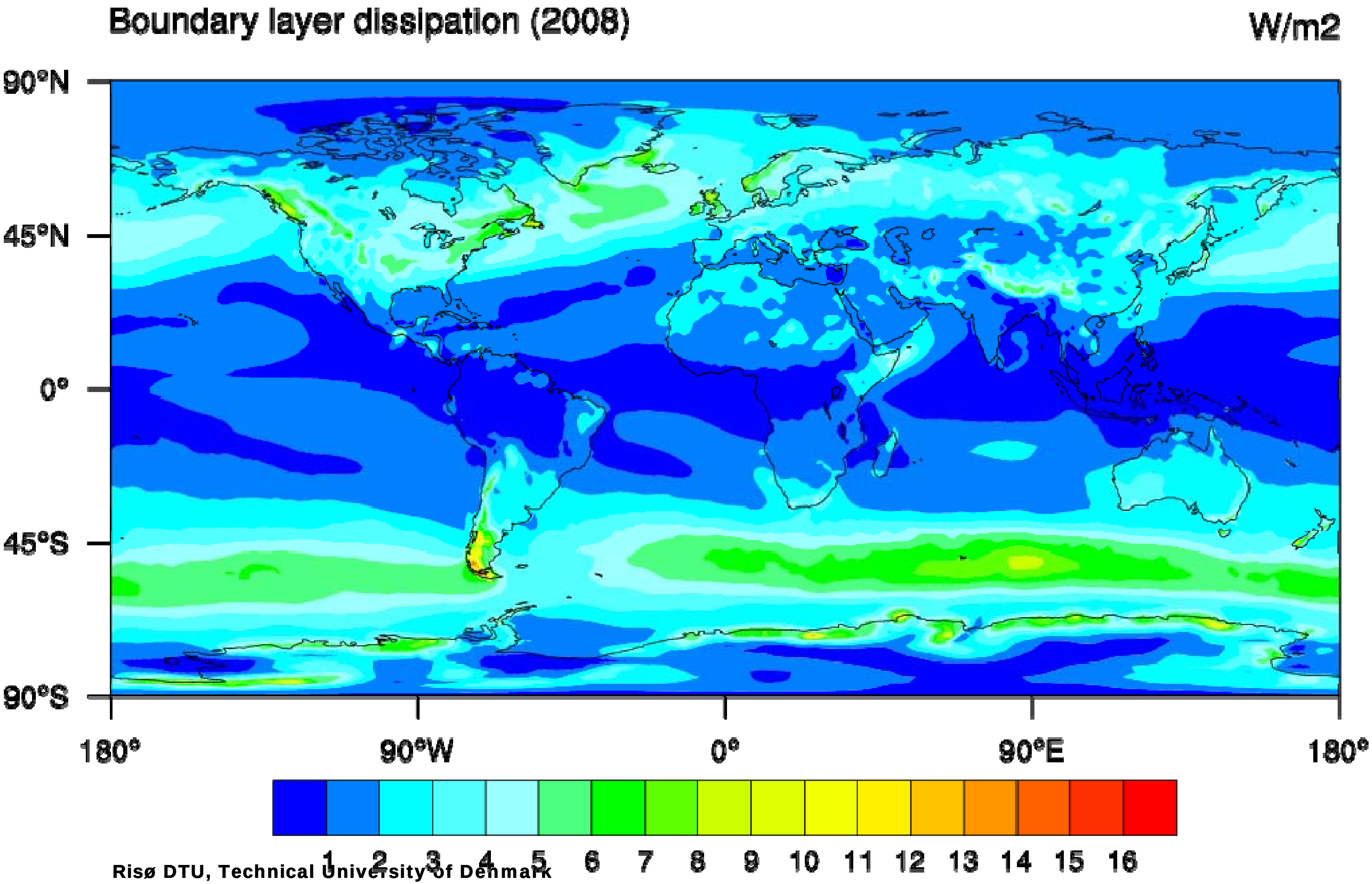
Kinetic energy dissipation $\sim 2\,W/m^2$

Is this the theoretical limit for wind power extraction?

The global wind systems



Boundary layer dissipation (W/m²) derived from ECMWF (European Centre for Medium Range Forecast) Reanalysis (ERA Interim, 1.5° resolution) for 2008



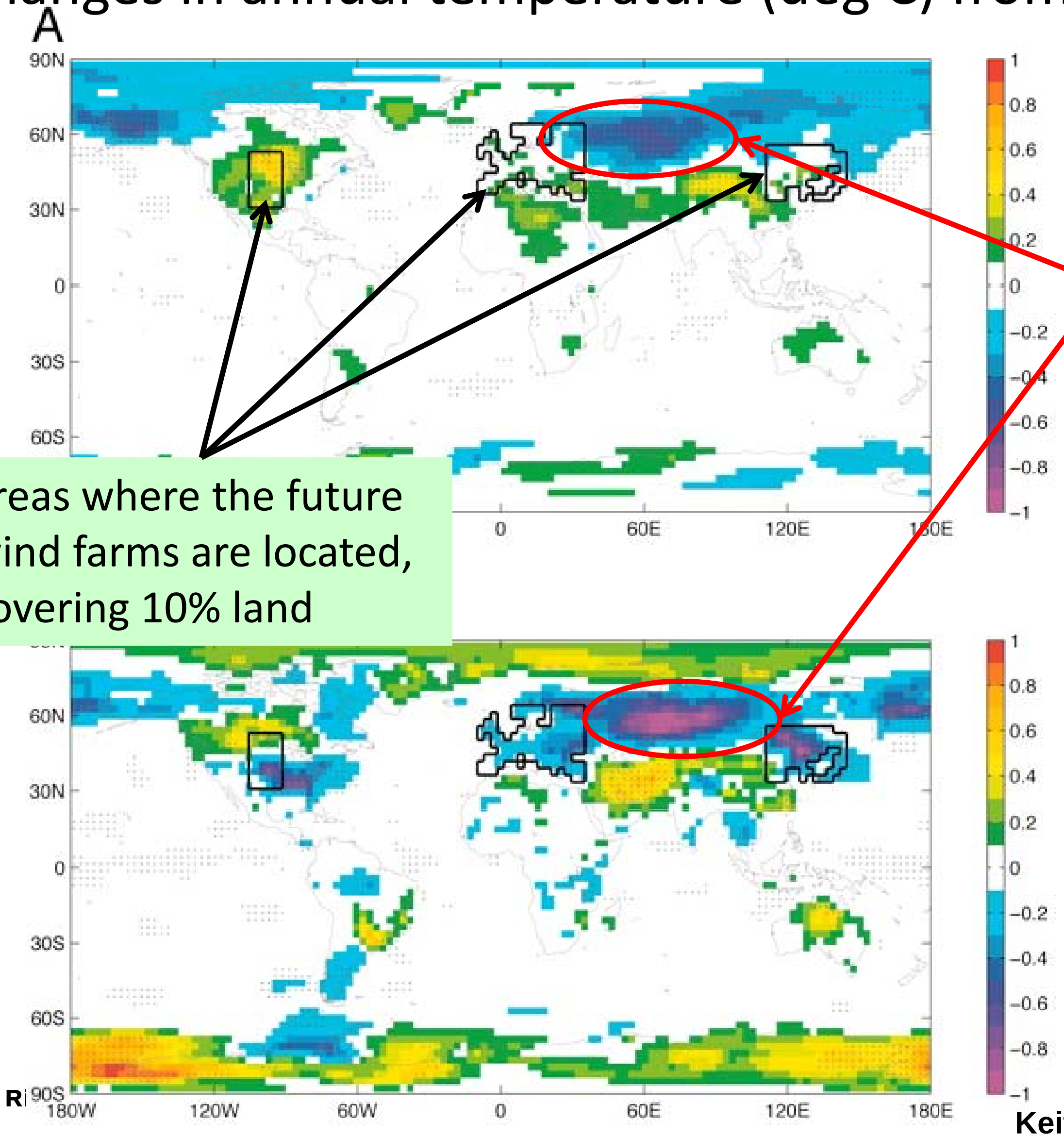
Risø DTU, Technical University of Denmark

Weather and Climate Impacts of wind farm installations?

- Under present day wind-power capacity, only a very small fraction of the available kinetic energy is extracted
- If the area were to increase, what would be impacts on weather and climate?
- Past studies have shown that:
  - Local meteorology: there are considerable changes within and downstream of the wind farm (winds slow down, increased turbulence, enhanced turbulent mixing of heat and water vapor) (Baidya Roy et al. 2004).
  - Effects can be seem from satellite imagery when large wind farms are offshore (Christiansen and Hasager 2005)
  - There is a potential for significant changes to surface climate as large-scale development approaches the limit of available kinetic energy (Keith et al 2004; Kirk-Davidoff and Keith 2008)

Climate impacts from general circulation model (GCM) experiments (Keith et al. 2004)

Changes in annual temperature (deg C) from two models



areas where the future wind farms are located, covering 10% land

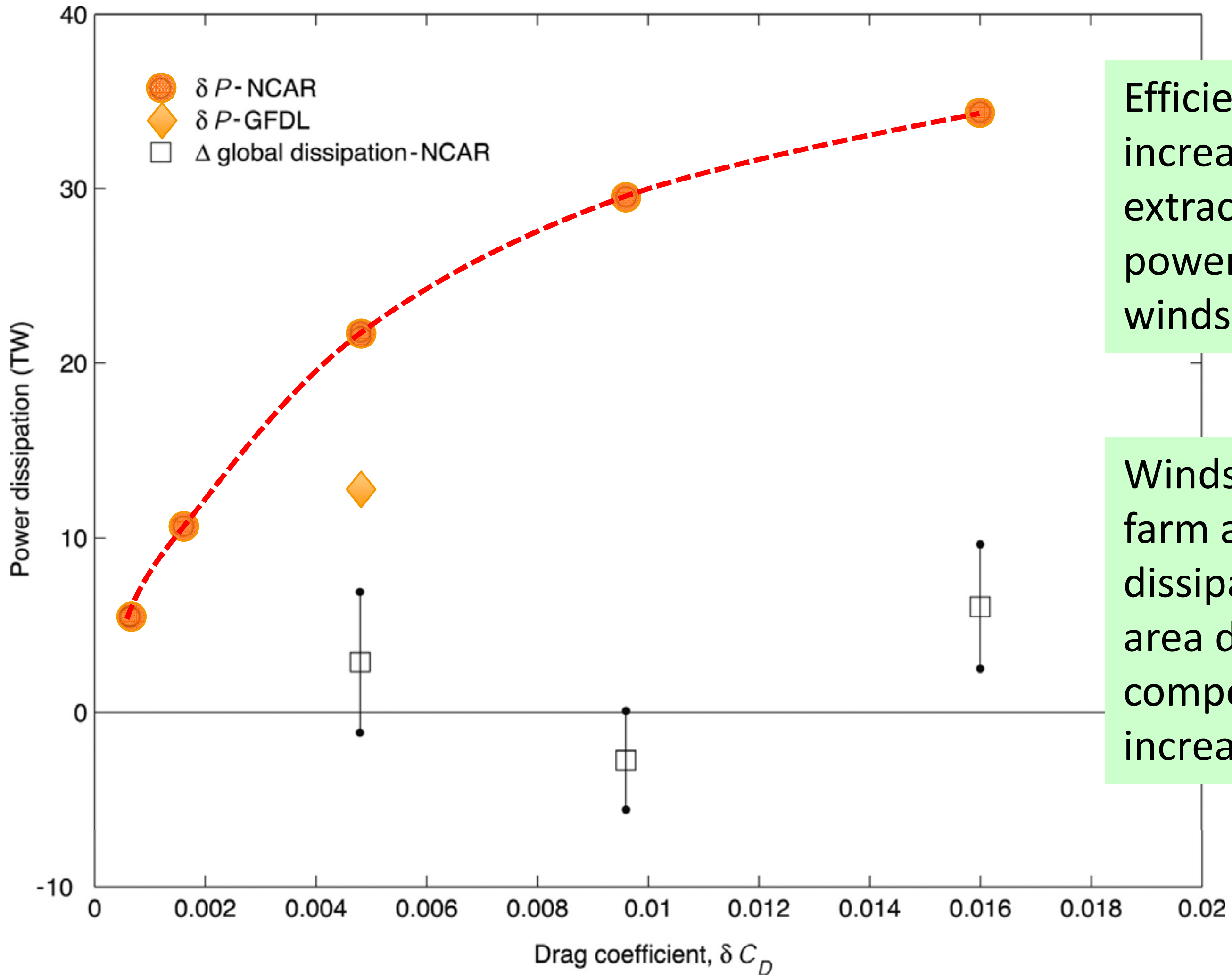
Colder over northern Europe and Asia

Warmer over N. America (sp winter)

Change in global-mean surface temperature is negligible, but regional responses exceed ±2° C.

Keith D W et al. PNAS 2004;101:16115-16120

Change of Energy dissipation versus change of drag



Efficiency by which increased surface drag extracts additional power declines because winds slow down

Winds outside the wind farm are slowed so that dissipation outside the area decreases to compensate for the increased dissipation

Keith D W et al. PNAS 2004;101:16115-16120

PNAS

Conclusions

UNIVERSITY OF COPENHAGEN

DTU

- The large-scale atmospheric dynamics (through the boundary layer dissipation) provide an upper bound on the power that can be extracted by large-scale wind power utilization.

- The extractable fraction depends on the wake structure of both individual turbines and of wind farms- and on regional scale wind climate feed-back.

- In present model experiments, the overall atmospheric structure is modified only slightly in response to the changes in surface drag, induced by installation of wind farms. Regional scale changes are noticed as well as some modification of other climate parameters.

Thank you for your attention

Thank you for your attention

RISØ, SEPTEMBER 2009

The world needs to replace fossil fuels because:

There is only fossil fuel energy for another century with present consumption

Burning carbon leads to more insulation and thereby a heating of the climate system

Burning all known carbon will DOUBLE/TRIPLE the current CO2 mixing ratio in the atmosphere

1300 – 1400 Gt C can be emitted, presently the atmosphere contains 750 – 800 Gt C

ESS Meeting, May 18, 2009

Energy production rate now: 16 TW eq. to 0,03 W/m^2
200 years from now we'll need: 1,5 PW eq. to 3 W/m^2 ?

	Present	Max rate	Remaining energy
NON-RENEWABLE			
inactive reservoir			
Fossil fuels	0,013 PW (0,400 ZJ/yr)	----	100 – 300 ZJ
Nuclear power	0,001 PW	----	???
active reservoir			
Geothermal	0,015 TW	0,025 PW	"infinite", but
Solar	0,003 TW	+ 120,000 PW	"infinite"
RENEWABLE			
(cycling or flow based)			
Biomass	0,001 PW	0,200 PW	----
Hydropower	0,001 PW	0,007 PW	----
Wind power	<0,120 TW	1,000 PW	----
Oceanic energy	zero	0,080 PW	----

Vil vi sige noget om forskellen mellem det teoretiske max og det praktisk opnåelige max?
Altså diskutere tallene på slide forud?

Vise en kurve med det stipulerede carbonfrobrug pr år, verdens krsv til energi, erstatningskildernes praktiske max-tal

Climate change mitigation
what are the realistic options?

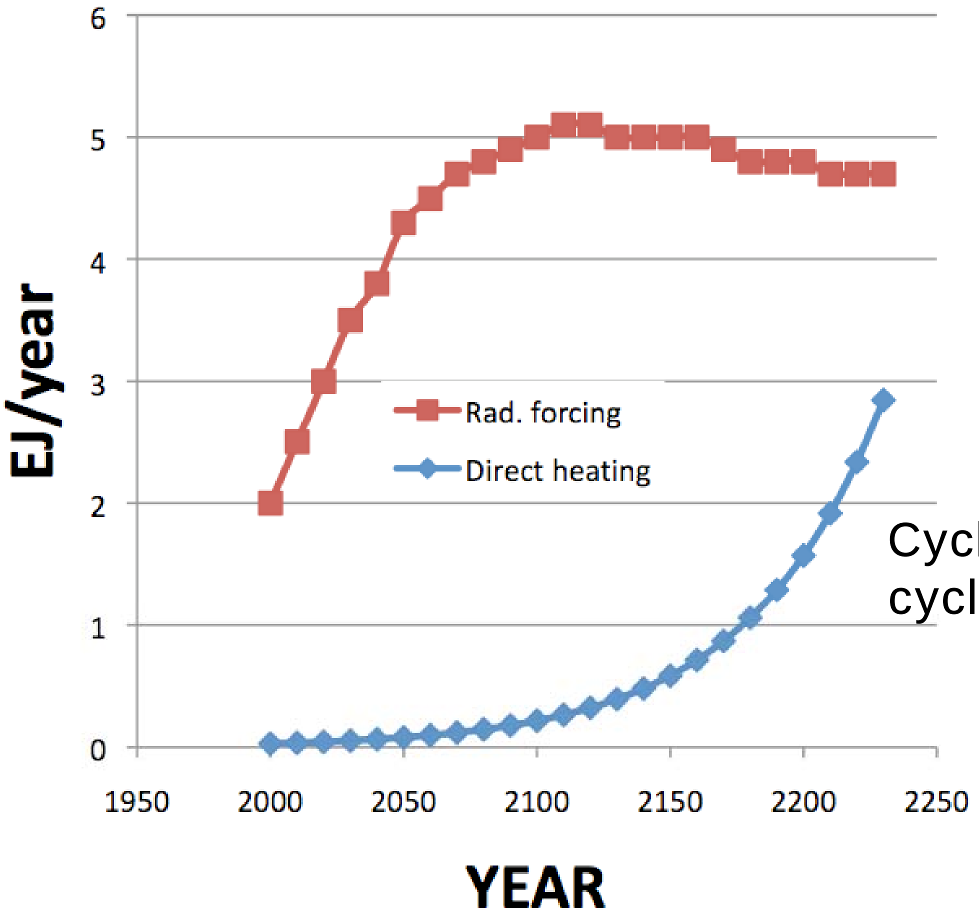
- Alternative energy sources for carbon:
  - Non renewable, but finite
    - Nuclear power comment
  - Infinite sources
    - Solar energy comment
    - Geothermal energy comment
  - Renewable
    - Hydropower comment
    - Biomass comment
    - Wind comment
    - Ocean power comment
- Amongst these substitutes for carbon wind appears presently unchallenged, being much cheaper PR GW? than the runners-up
- Wind is known to be abundant – how abundant?
- Wind energy dissipation affects the climate – how much?

- Answers to the two questions
  - Can we produce energy enough in the future?
    - Fossil fuel must abandoned (greenhouse effect)
    - And in fact, there is not enough coal, gas and oil
    - Solar energy can meet the demand, but should be dealt with very carefully
  - Will the climate/environment be affected adversely from 1,5 PW even with green technology?
    - Yes, probably

DTU

Greener technology versus growing demand for energy

$\Delta T_s = RF/\lambda$



Cycling or non-cycling sources?

UNIVERSITY OF COPENHAGEN

Offshore wind farms replacement scenarios

SCENARIO	Mean Power	Installed Wind Power	Area Needed	Square side	Investment costs
Denmark 40% of EL	3.2 GW	3.6 GW	530 km^2	23 km	3 billion €
EU27 20% of EL	80 GW	160 GW	27000 km^2	160 km	320 billion €
EU27 40% of EL	160 GW	360 GW	53000 km^2	230 km	640 billion €
EU27 50% of total	1300 GW	2600 GW	430000 km^2	660 km	2600 billion €
50% of Peak North Sea Oil (1998)	225 GW	450 GW	70000 km^2	270 km	440 billion €

World Market Growth rates 2002-2007

Year:	Installed MW	Increase %	Cumulative MW	Increase %
2002	7,227		32,037	
2003	8,344	15%	40,301	26%
2004	8,154	-2%	47,912	19%
2005	11,542	42%	59,399	24%
2006	15,016	30%	74,306	25%
2007	19,791	32%	94,005	27%
Average growth - 5 years		**22.3%**		**24.0%**

Source: BTM Consult ApS - March 2008

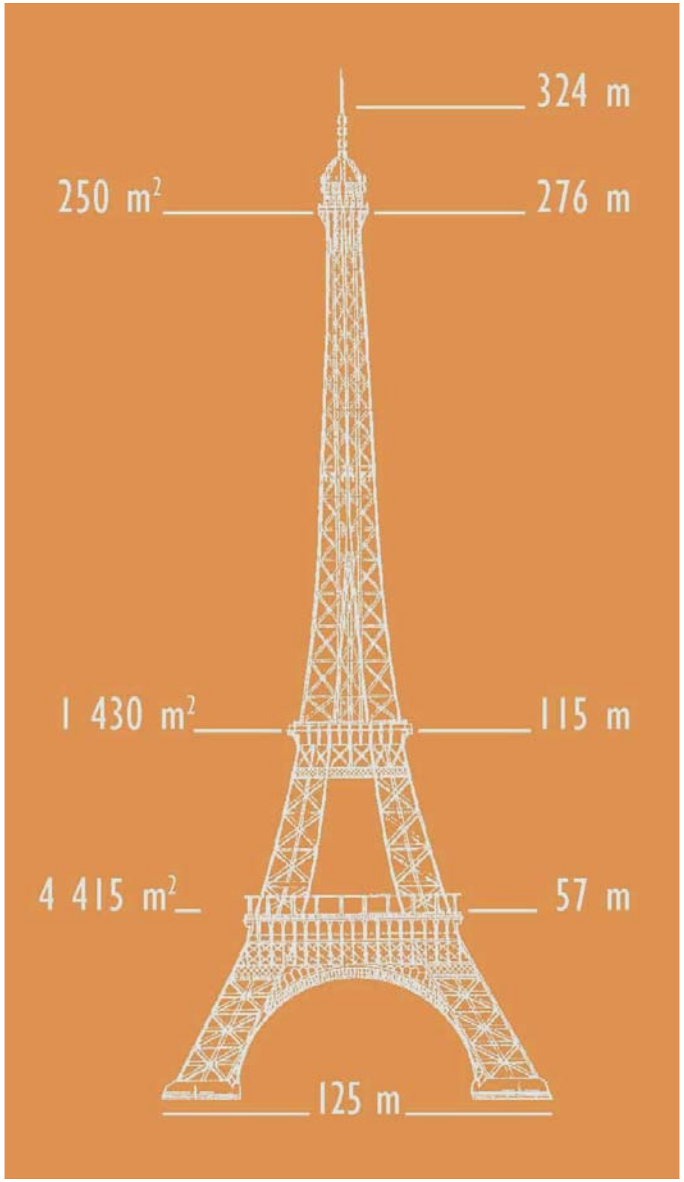
Installed capacity in 2006 and 2007 (Global)

	Installed MW 2006	Accu. MW 2006	Installed MW 2007	Accu. MW 2007	% of installed MW 2007
Total Americas	3,515	13,577	5,815	19,391	29.4%
Total Europe	7,682	48,627	8,285	56,824	41.9%
Total South & East Asia	3,220	8,963	5,010	13,973	25.3%
Total OECD-Pacific	491	2,628	597	3,220	3.0%
Total Africa	109	386	83	469	0.4%
Total other continents and areas:	0	124	3.0	127	0.0%
Annual MW installed capacity	15,016		19,791		
Cumulative MW installed in the world		74,306		94,005	

Source: BTM Consult ApS - March 2008

The future's 20MW wind turbine and Eiffel tower

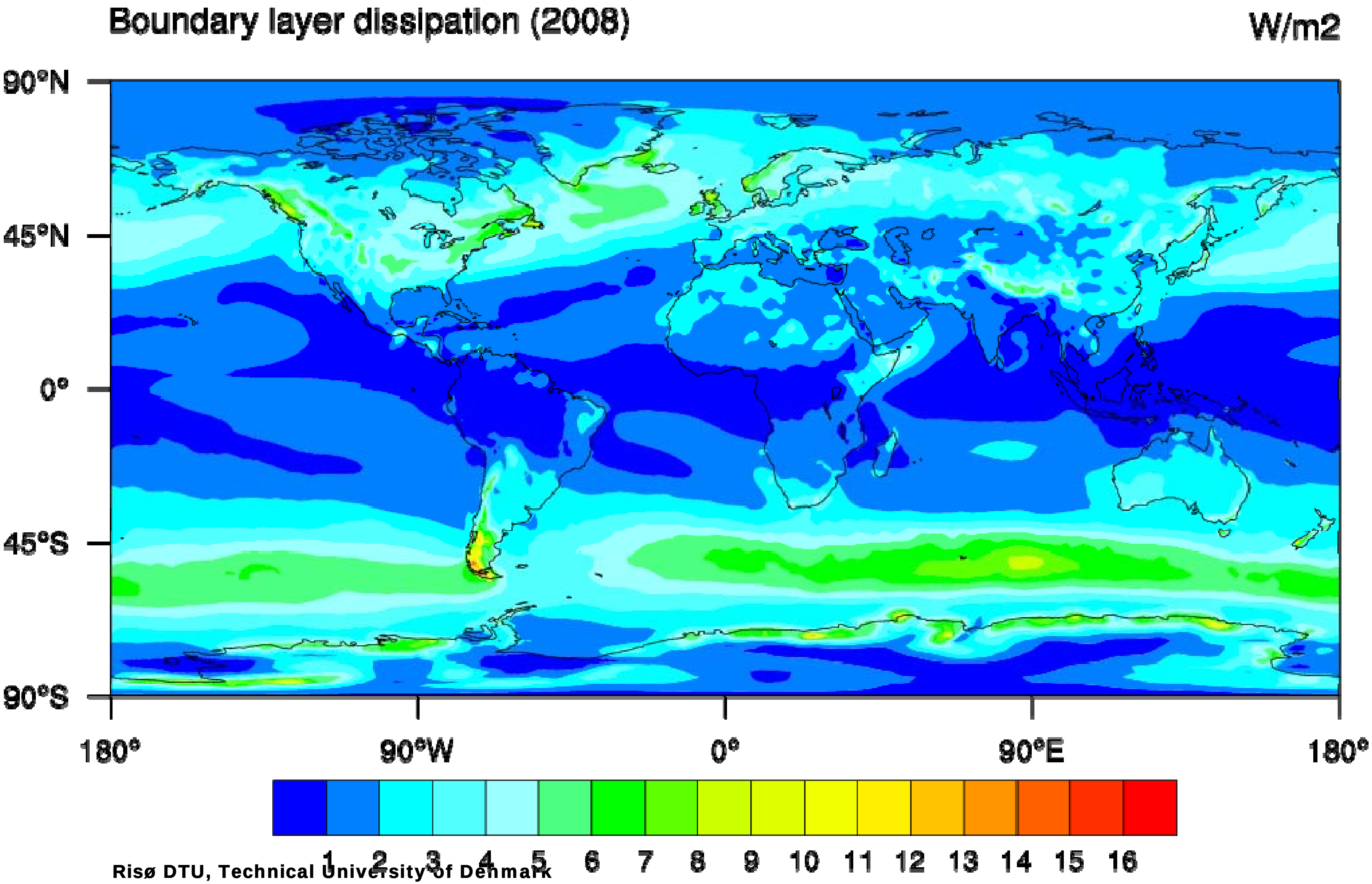
$$\approx 300m$$



Giant wind turbines – and houses

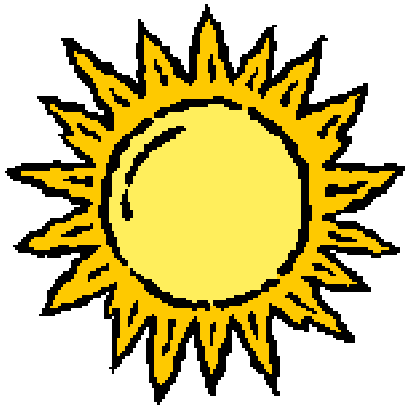
300m

Boundary layer dissipation (W/m²) derived from ECMWF (European Centre for Medium Range Forecast) Reanalysis (ERA Interim, 1.5° resolution) for 2008



Risø DTU, Technical University of Denmark

Global Energetics



Energy absorbed
by the Earth

latent heat (evaporation), 70.4%

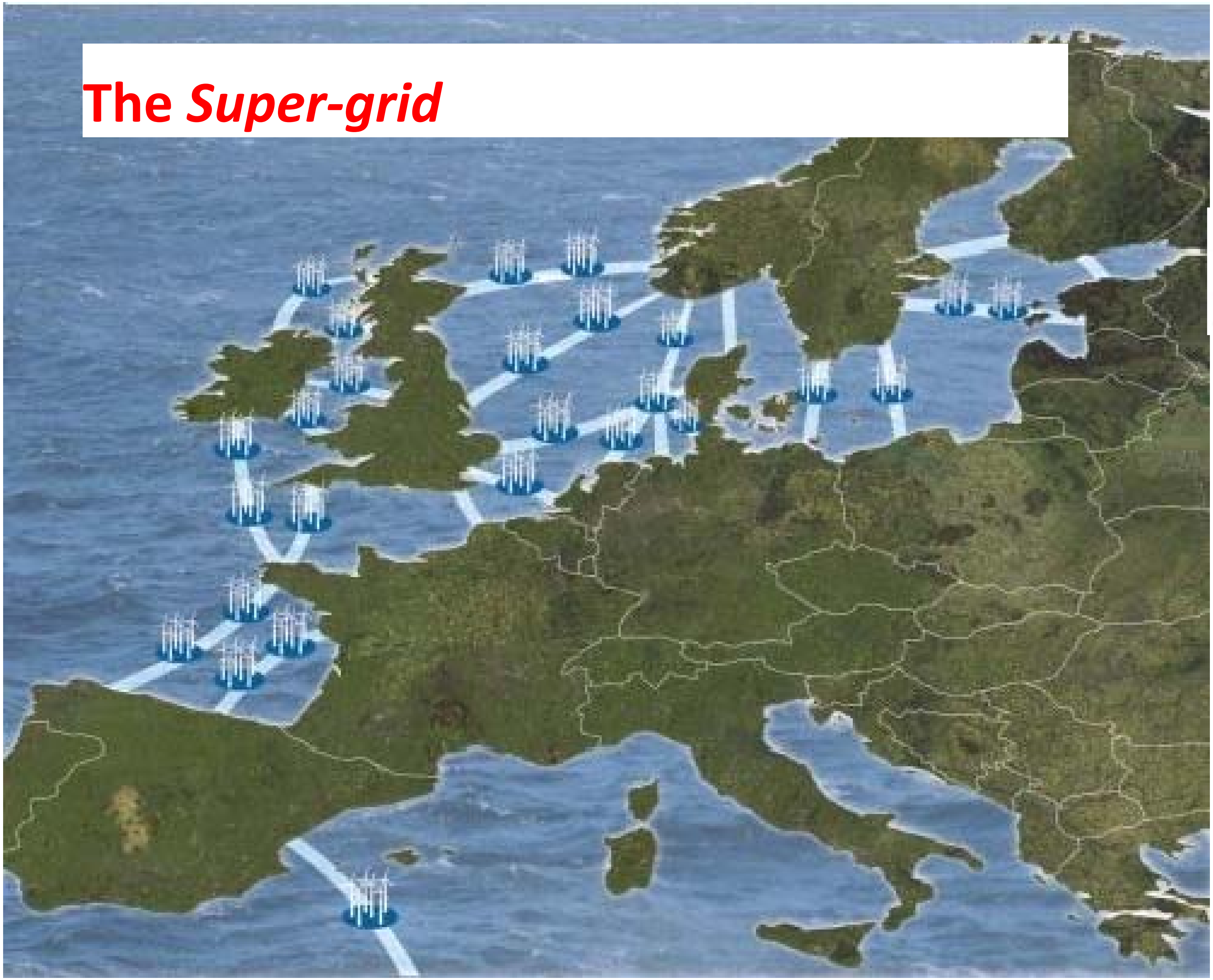
gravitational potential energy, 27.05%

internal energy, 2.5%

kinetic energy (winds), 0.05%

Only a small fraction of this
is available to be extracted
by wind farm installations

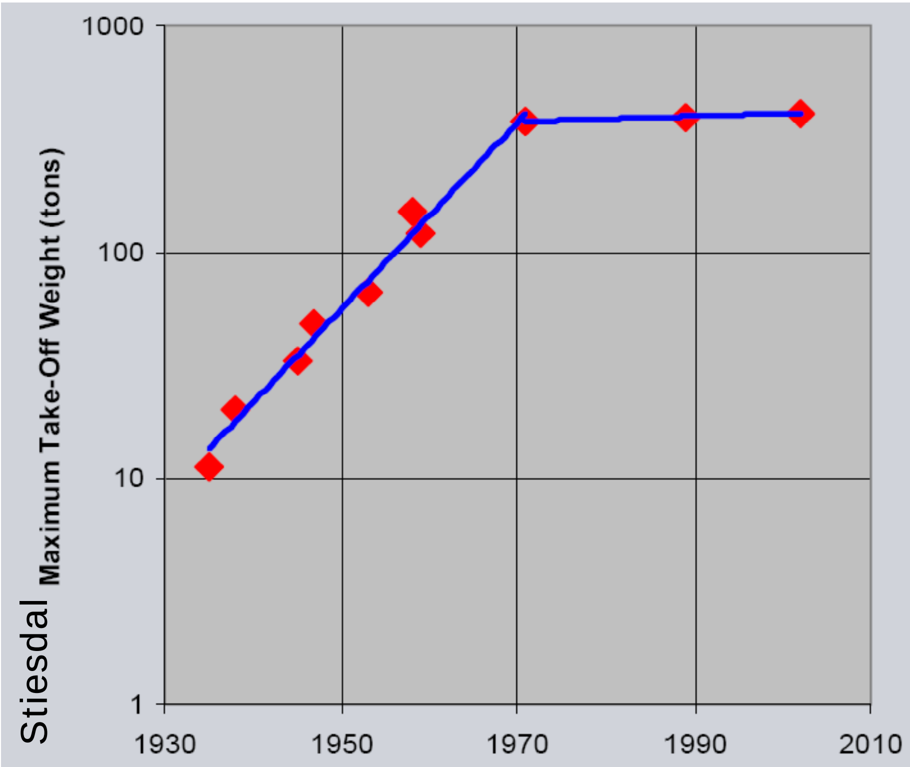
The *Super-grid*



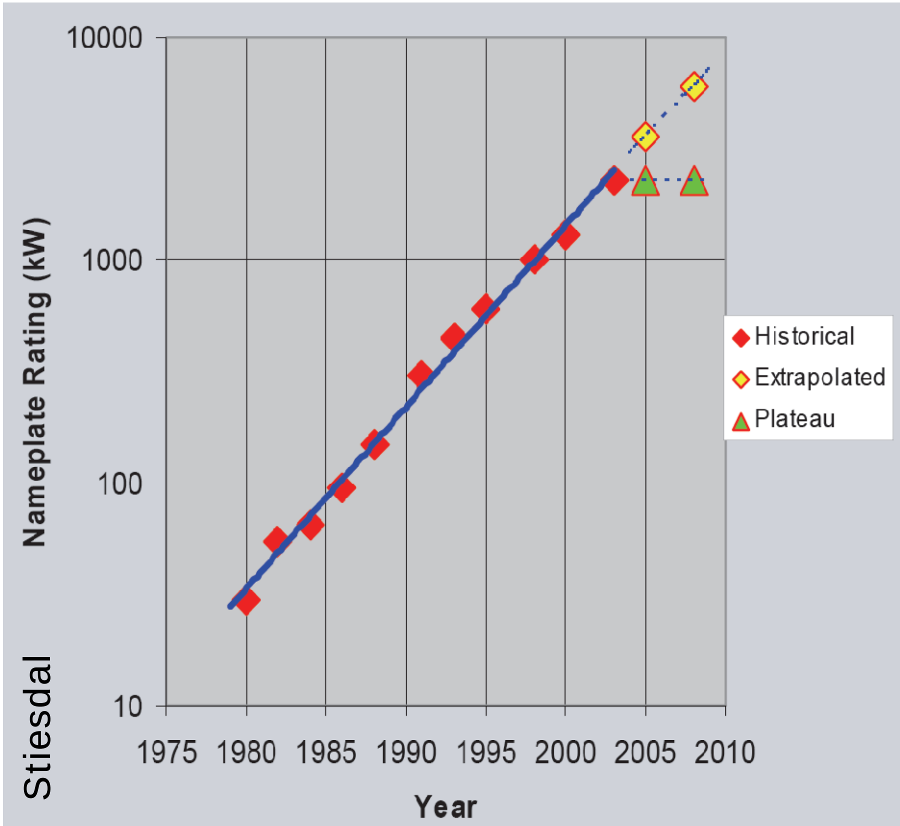
Large planes and wind turbines over time...

....shearing a problem with the bumblebee?

Airplanes



Wind turbines



The wind pits of Europe – The North Sea

- Excellent wind resources 10-11 m/s average
- Manageable water depths
- Large population densities around it
- Vast in size