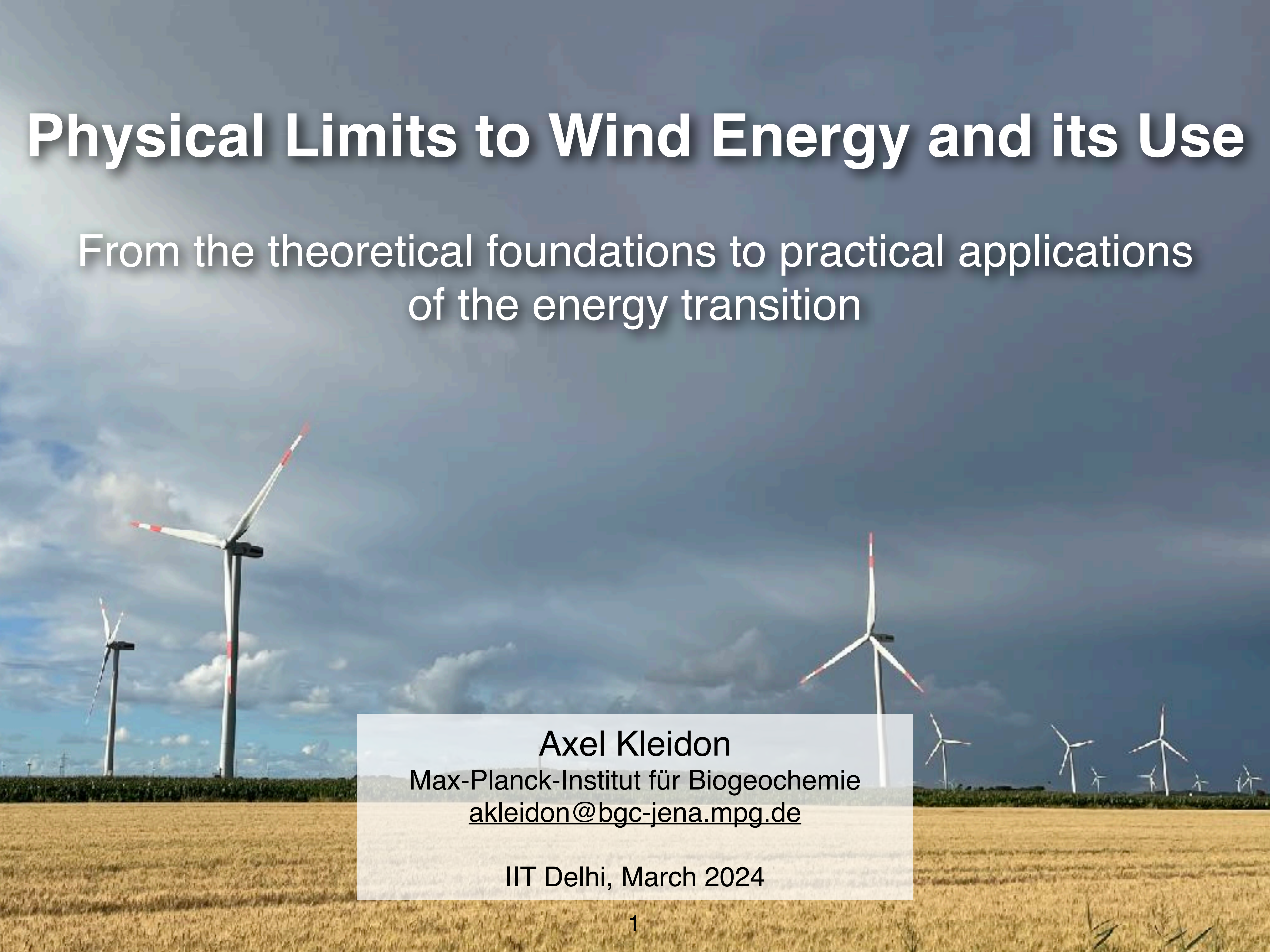
Physical Limits to Wind Energy and its Use

From the theoretical foundations to practical applications
of the energy transition



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IIT Delhi, March 2024

Science Denial by Populists

Source: https://facebook.com

Source: https://afd.nrw

“Planless Federal Government:
Energy efficiency looks different!
30,000 wind turbines cover only 3%
of our electricity needs!”

“Smashing!
Study finds out:
Wind farms cause
droughts!”

Estimating Wind Energy Limits and Impacts

<u>Understanding:</u>
As simple
as possible

Description
of the relevant
constraints

<u>Prediction:</u>
As detailed
as possible

Numerical
simulation models;
Machine learning/AI

compare

How does Earth generate wind energy?

And how much?

What does it mean for the regional scale (Germany)?

And for the energy transition?

What are the consequences?

Image: NASA

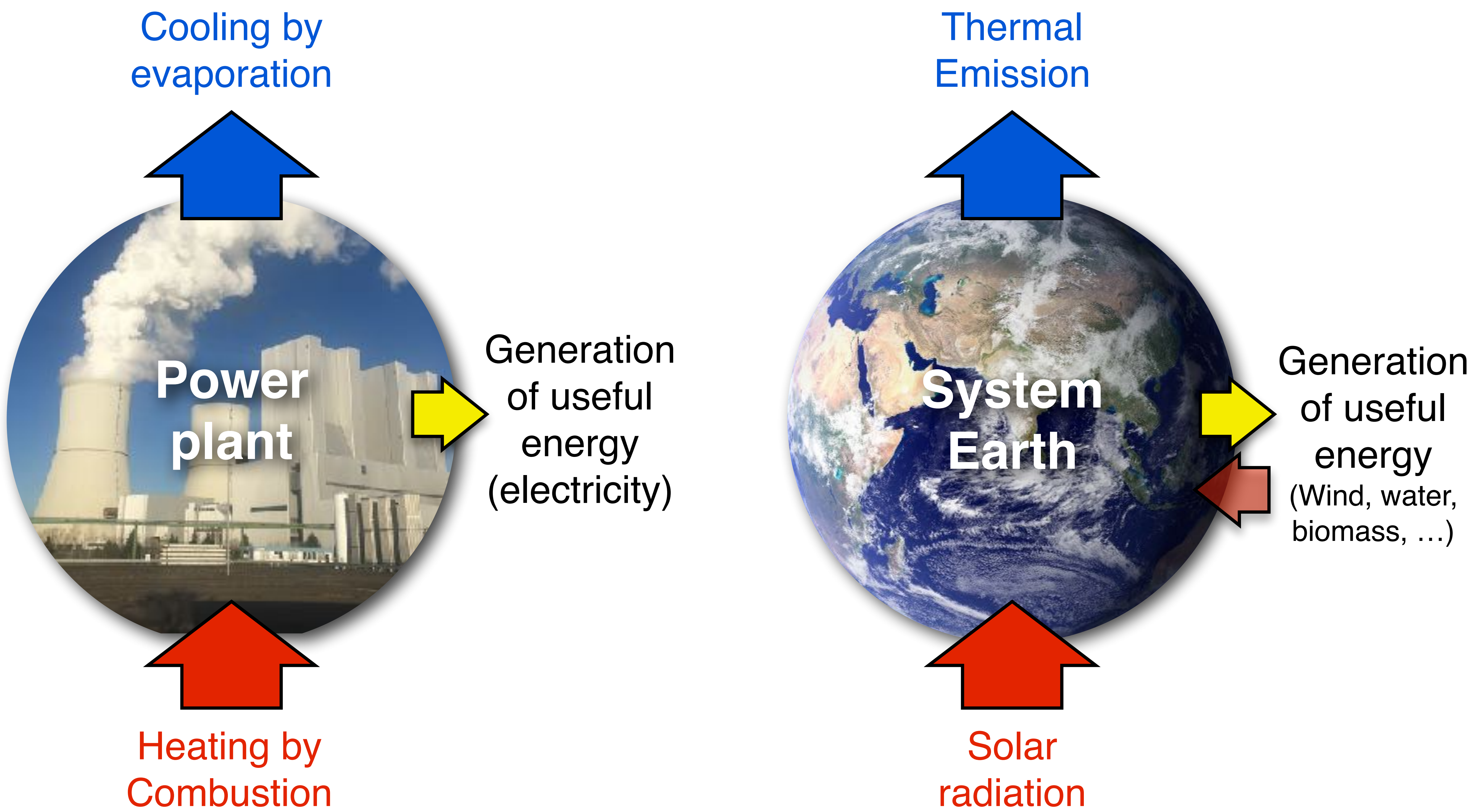
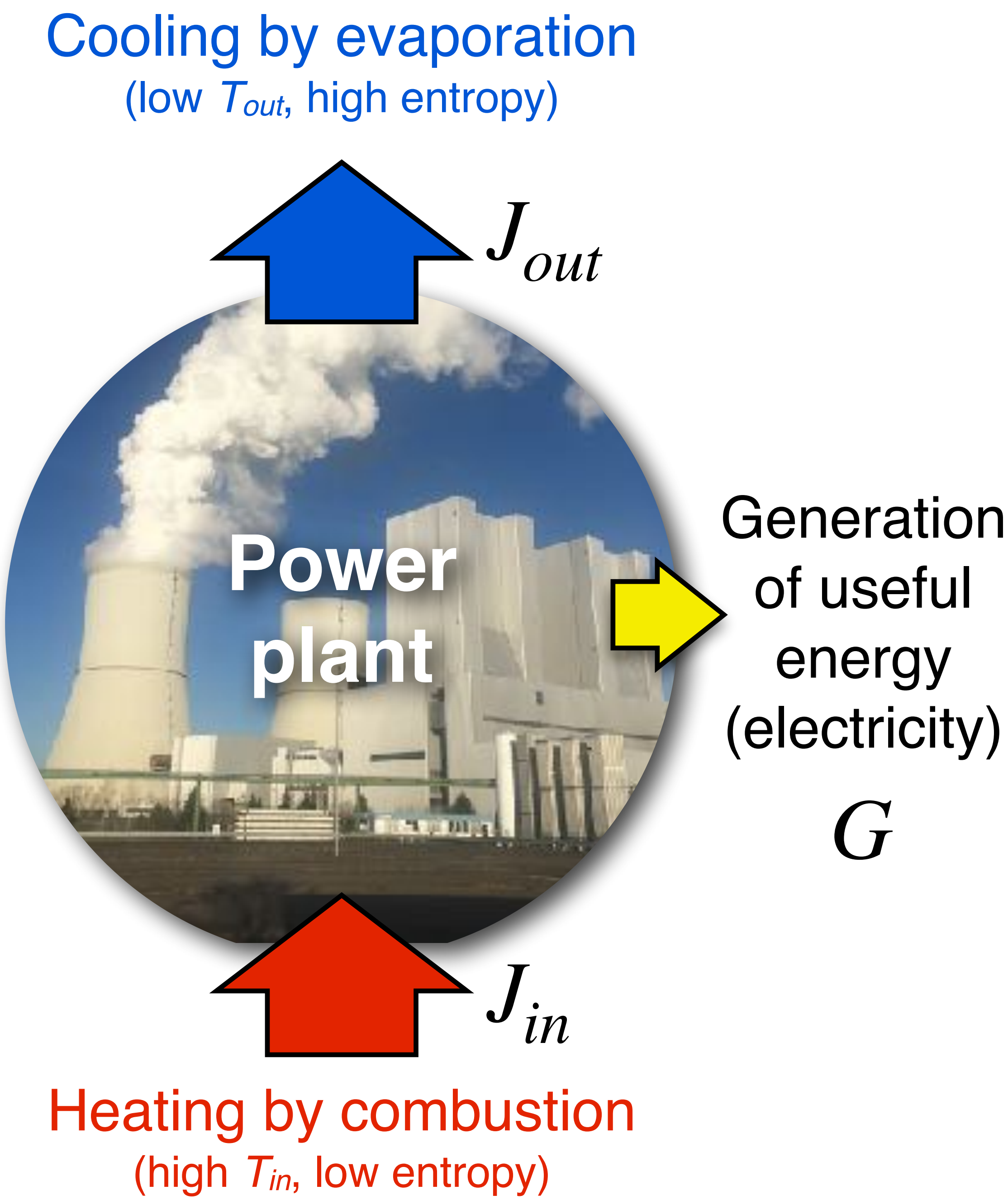

Cooling by evaporation
Power plant
Generation of useful energy (electricity)
Heating by Combustion
Thermal Emission
System Earth
Generation of useful energy
(Wind, water, biomass, …)
Solar radiation

Image: NASA



First law of thermodynamics:

$$J_{in} = J_{out} + G$$

Second law of thermodynamics:

Entropy exchange

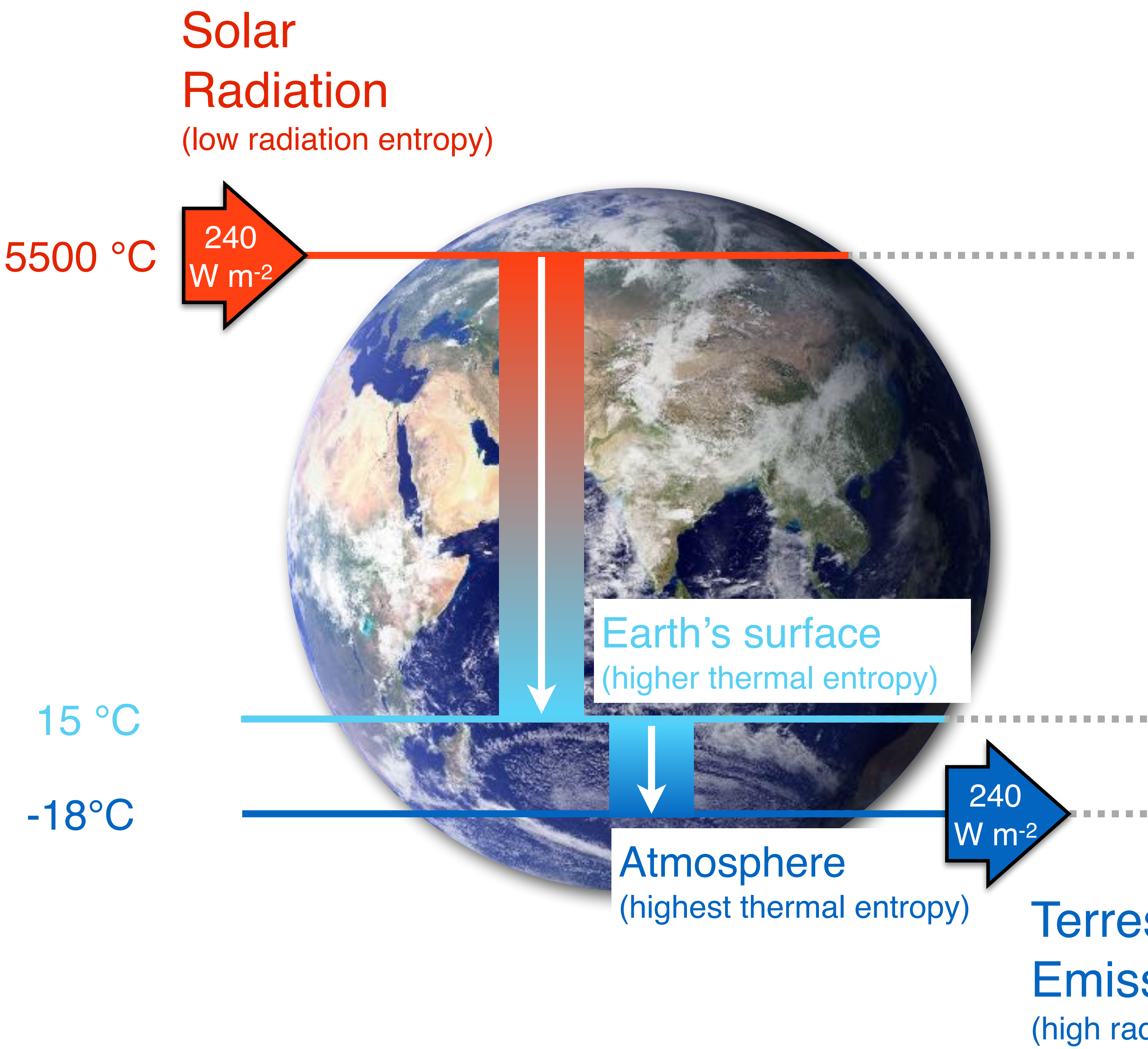
$$\frac{J_{out}}{T_{out}} = \frac{J_{in}}{T_{in}} + \sigma$$

Entropy production ≥ 0

Generation of useful energy
(no entropy, best case, σ = 0):

$$\boxed{G \leq J \cdot \frac{T_{in} - T_{out}}{T_{in}}}$$

Generating Power



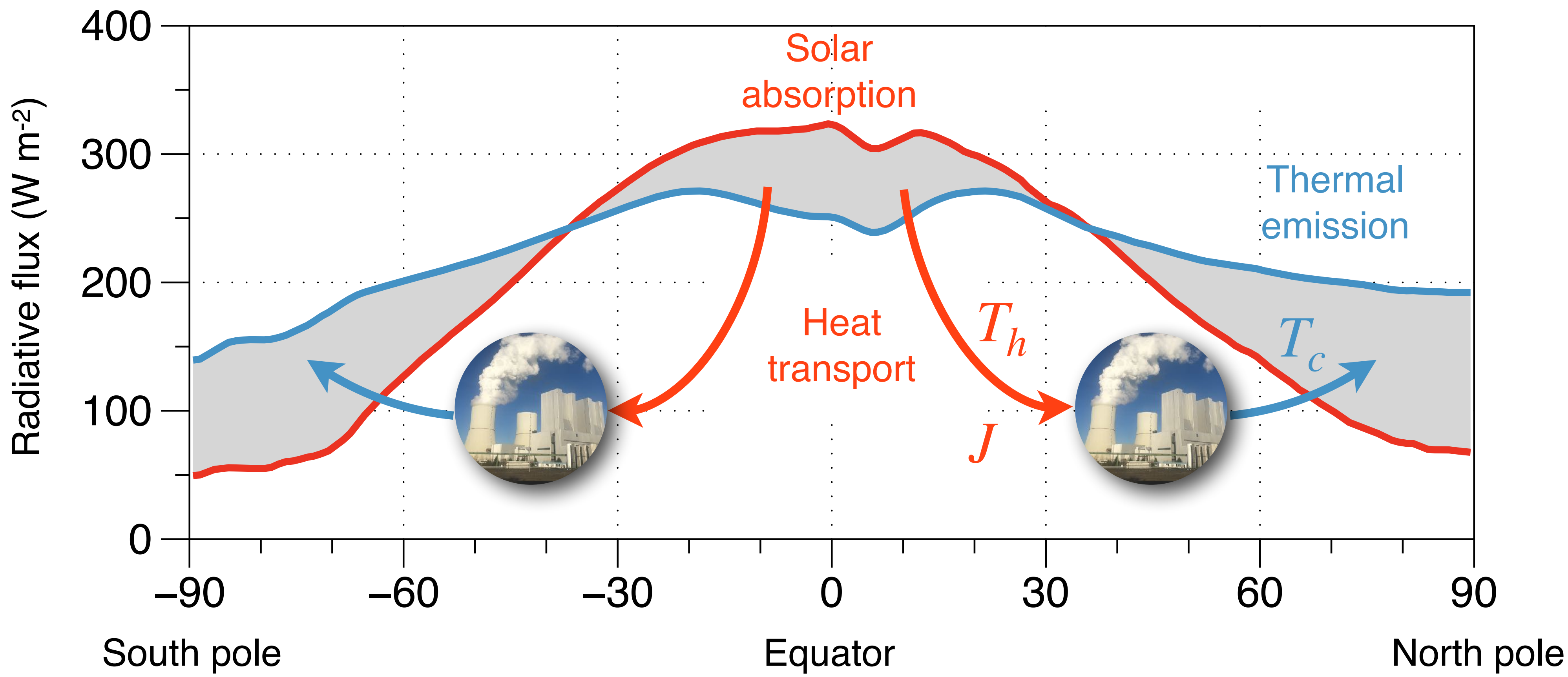
Photovoltaics
➔ Anthroposphere

Photosynthesis
➔ Biosphere

"Power plants"
➔ Atmosphere

Image: NASA

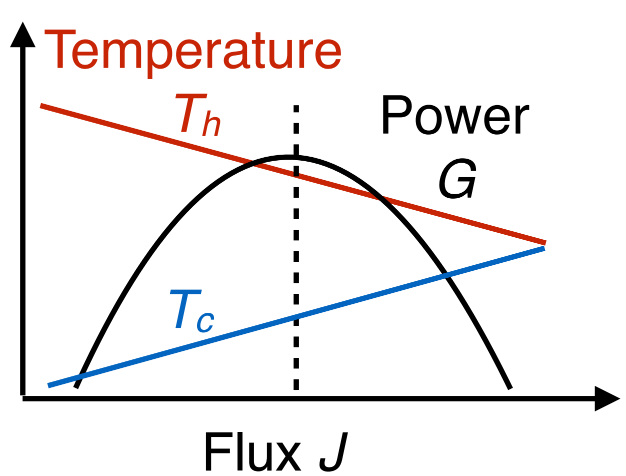
Generation of Large-scale Wind Energy



Thermodynamic limit:

$$G = J \cdot \frac{T_h - T_c}{T_h}$$

More transport ➔ less efficiency:

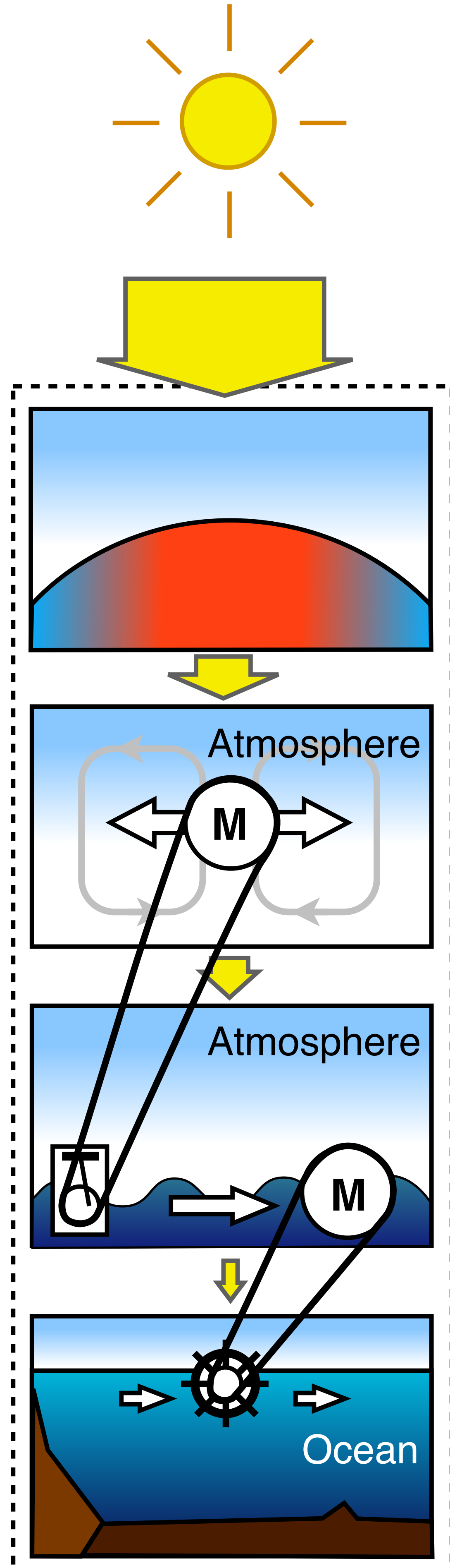


Maximum power:

Heat flux:	50 W m^{-2}
T_h - T_c:	≈ 30 K
Power:	**0.5 x 50 x 10%**
	≈ 2.5 W m^{-2}
Global:	≈ 1000 TW
Efficiency:	**≈ 1%**

Kleidon (2021) Met. Z.; Data: NASA-CERES

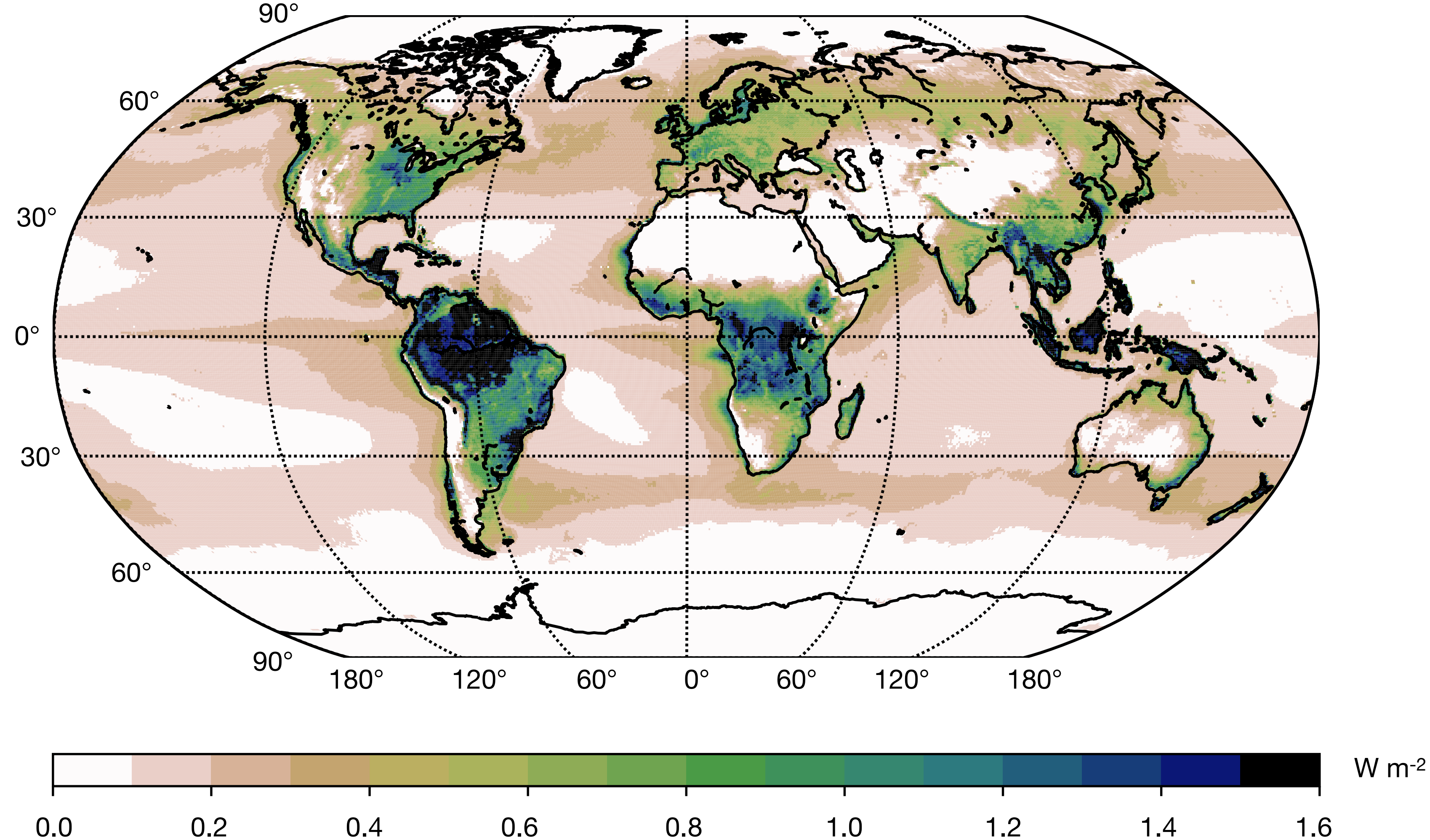
Earth system process				Renewable energy
Solar irradiation		≈ 175000 TW	→	Solar power
		Absorption 70% *Differential heating* 40%		
Absorption generates heating		≈ 49000 TW		
		Conversion (maximal) 2%		
Heating differences cause motion		≈ 1000 TW	→	Wind energy
		Conversion (observed) 6%		
Motion generates waves		≈ 60 TW	→	Wave energy
		Conversion (observed) 8%		
Waves generate ocean currents		≈ 5 TW	→	Energy from ocean currents
		≈ 20 TW		Human societies



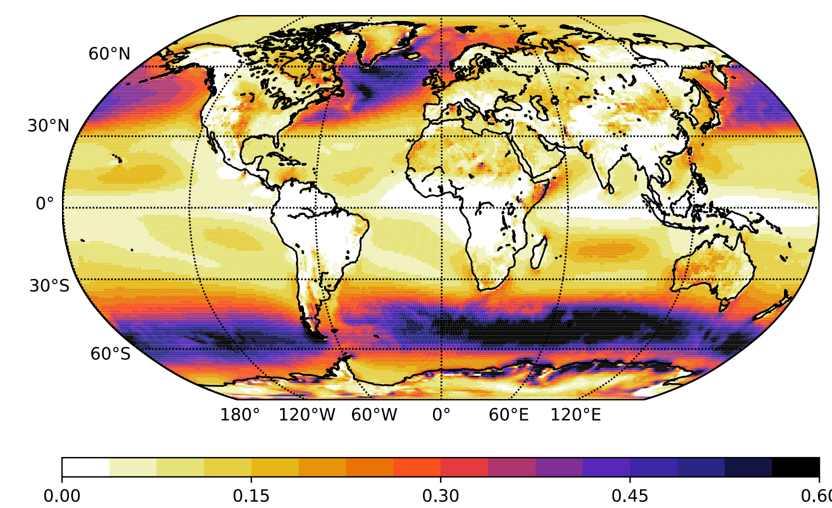
Kleidon (2019) PhysIUZ

Power from Photosynthesis

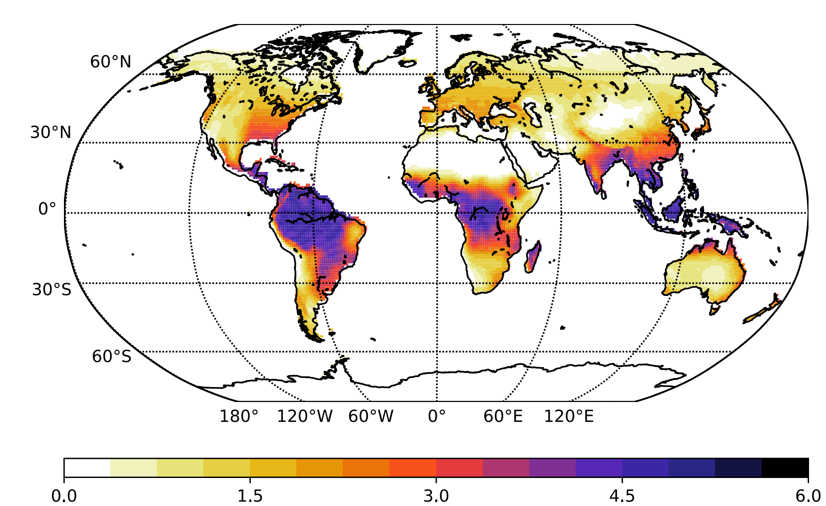
Biomass production ("NPP")



Ocean: mixing



Land: gas exchange



Land: 152 TW (≈ 1%)

based on Field et al. (1998) Science, 281: 237-240
updated using MODIS Daten

Wind energy

Efficiency: < 1%
Power: 1 000 TW

Photosynthesis

Efficiency: < 1%
Power: 152 TW

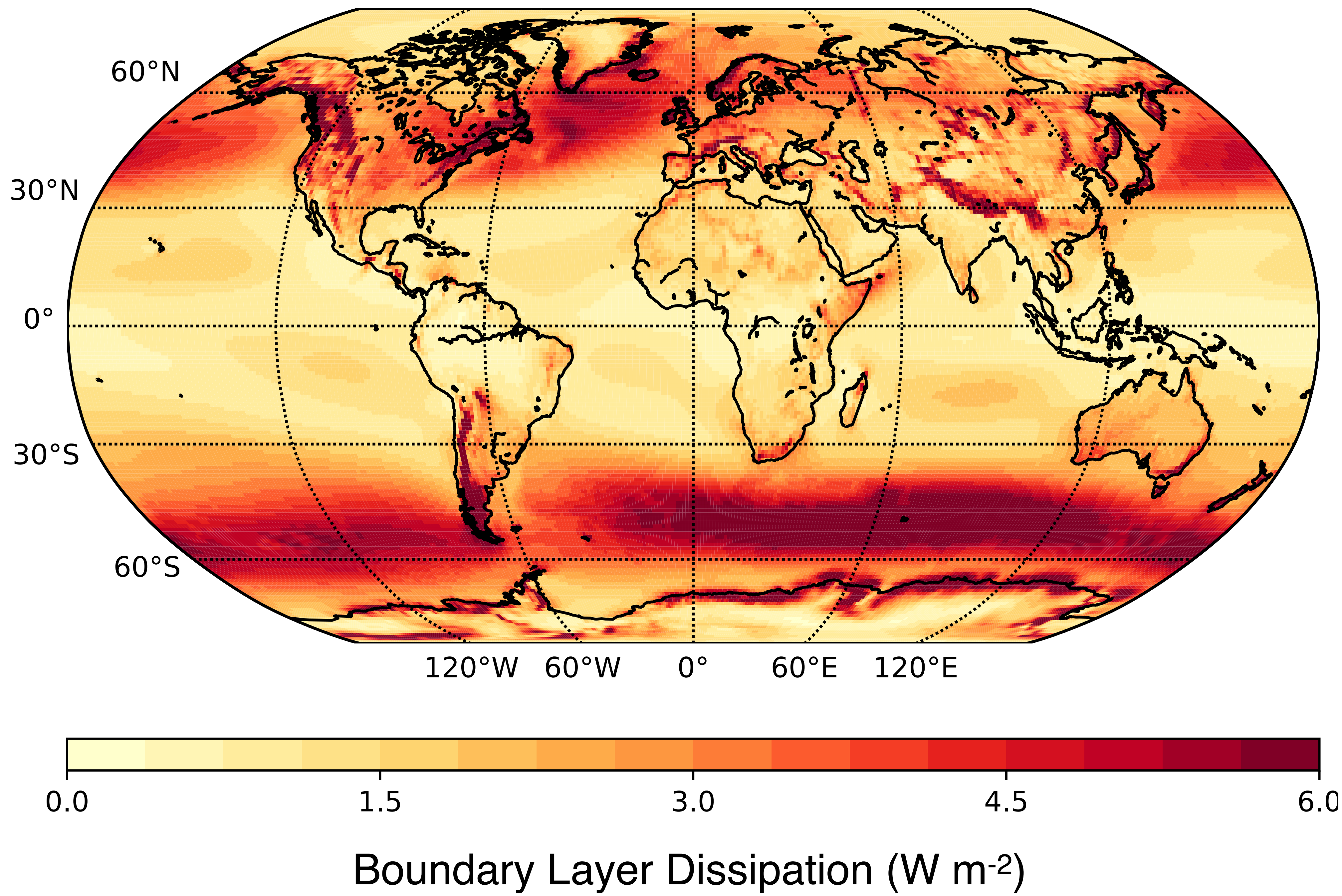
Photovoltaics

Efficiency: ≈ 20%
Power: 35 000 TW

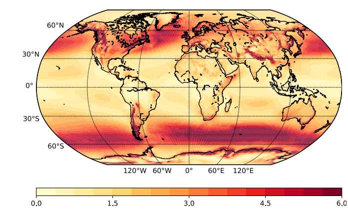
Limits to Using Wind Energy

Frictional Losses by the Atmosphere

Conversion of kinetic energy ➔ heat



Data: ERA-5



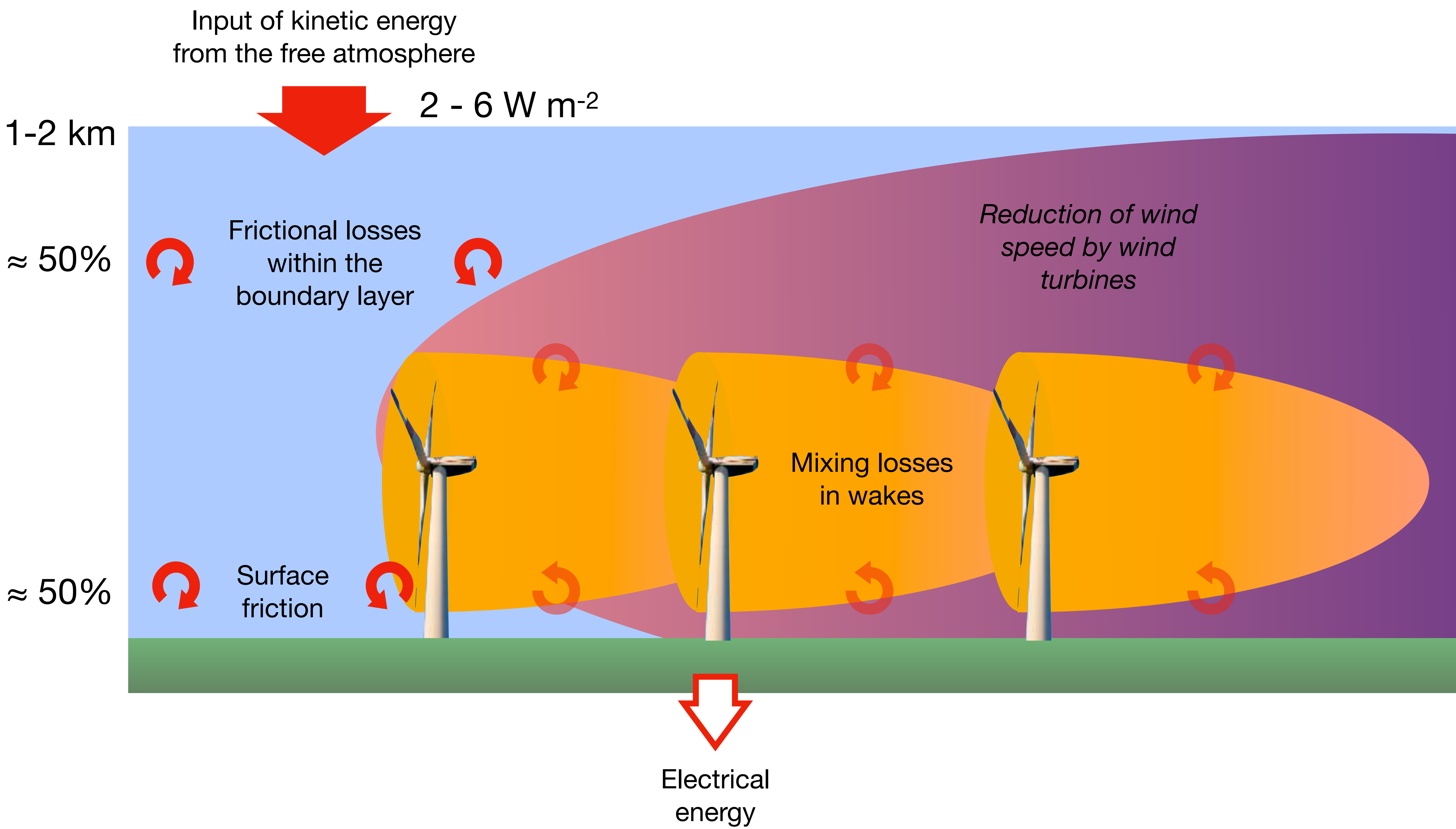
Absorption — Generation — Friction

Solar irradiation → Heat → Kinetic energy → Heat

Conversion by turbines

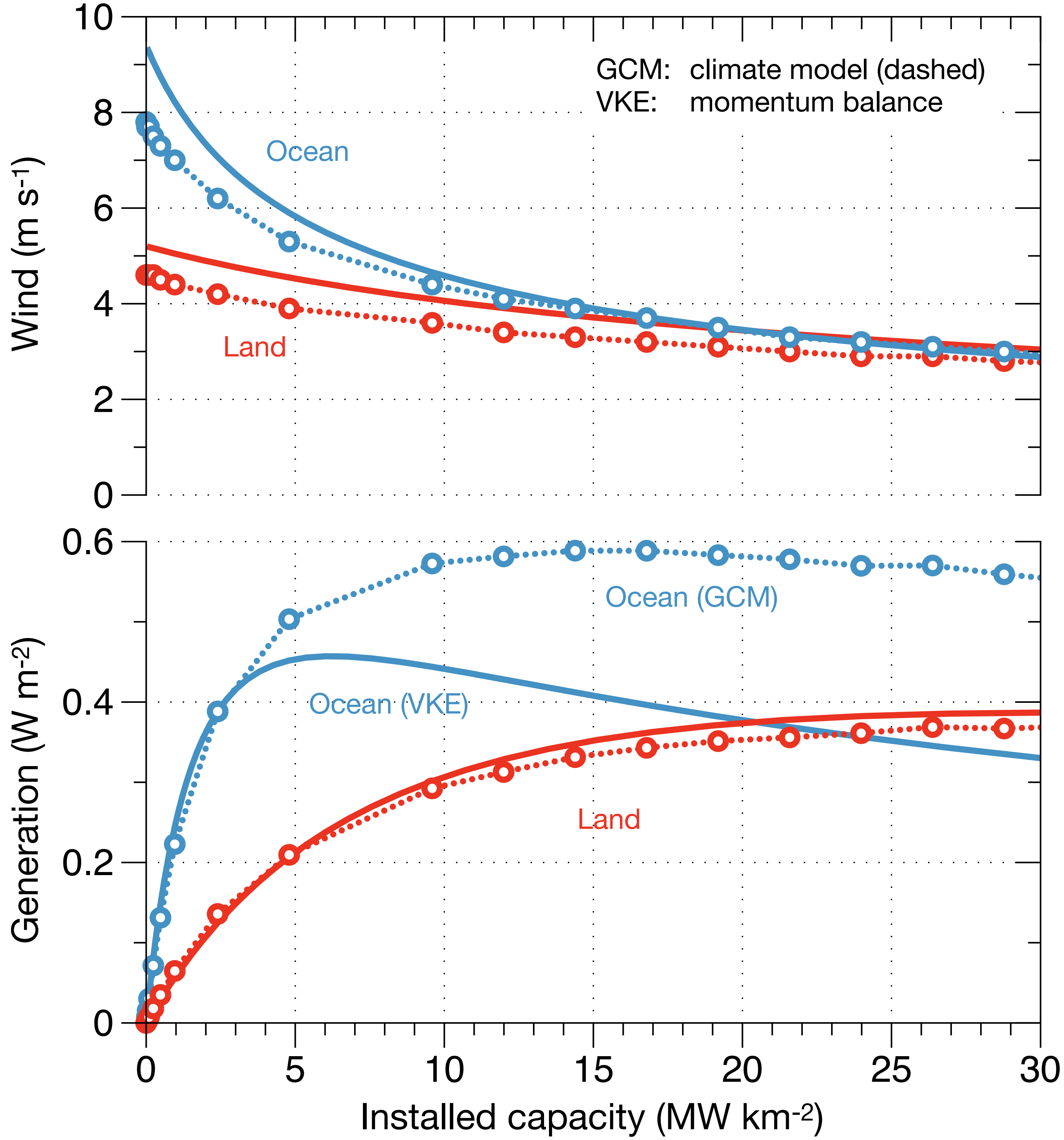
Electrical energy → Heat

Consumption



Kleidon (2023)

Global climate models



"VKE" Estimate

1. Momentum conservation:

$$J_{m,in} = \tau + F_{turb}$$

2. Frictional loss near the surface:

$$\tau = \rho C_d v^2$$

3. Momentum flux to turbines:

$$F_{turb} = n \cdot \eta \cdot A_{rotor} \cdot \frac{\rho}{2} \cdot v^2$$

4. Wind speed:

$$v = v_0 \cdot \sqrt{1 - \frac{n\eta A_{rotor}}{2C_d + n\eta A_{rotor}}}$$

5. Generation by turbines:

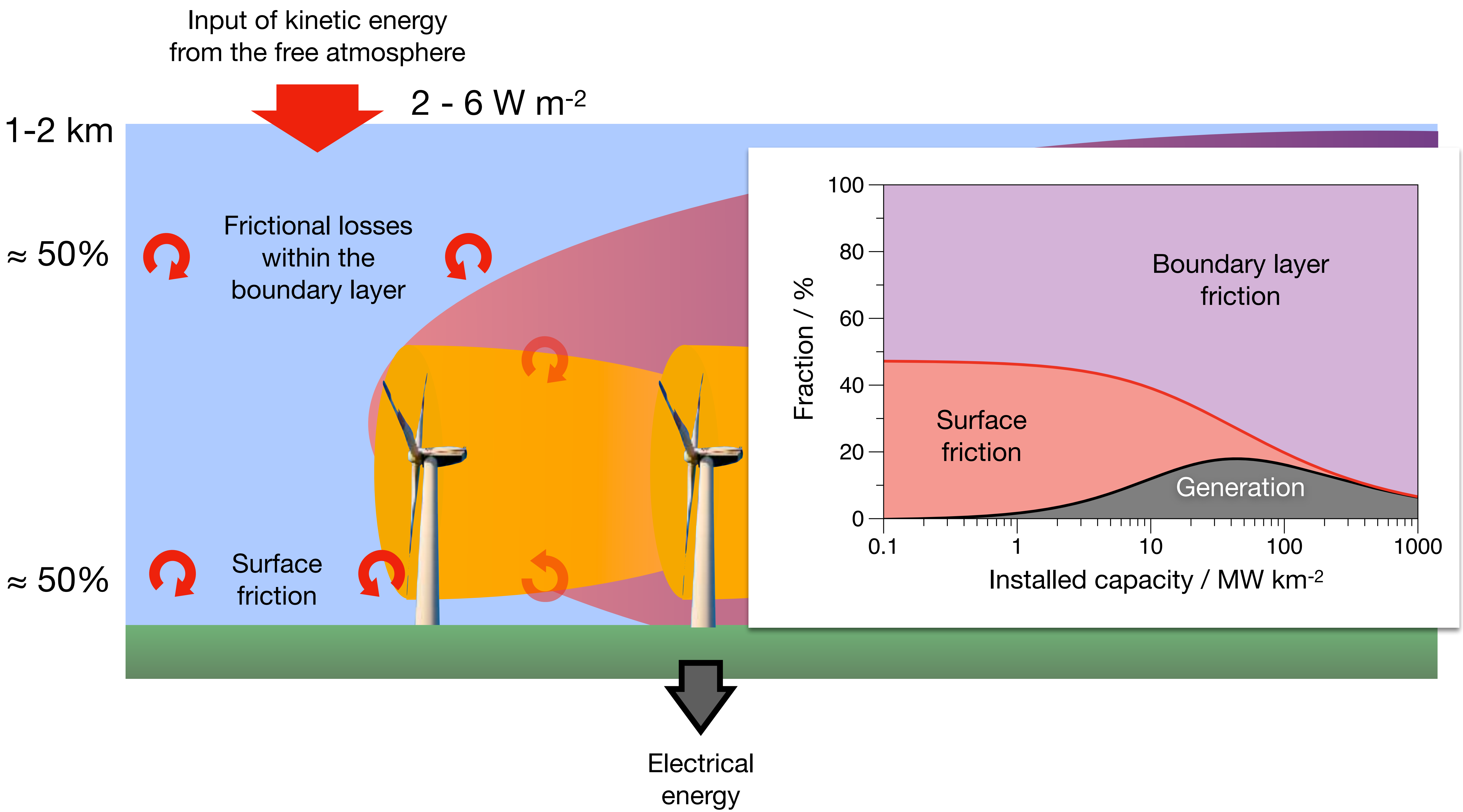
$$G_{turb} = F_{turb} \cdot v$$

6. Maximum generation via $dG_{turb}/dn = 0$:

$$v_{opt} = \frac{1}{\sqrt{3}} \cdot v_0$$

$$G_{turb} = \frac{2}{3^{3/2}} \cdot J_{ke} \qquad (\approx 38\%\ D_{fric})$$

Miller and Kleidon (2016) PNAS, Kleidon (2021) Met. Z.



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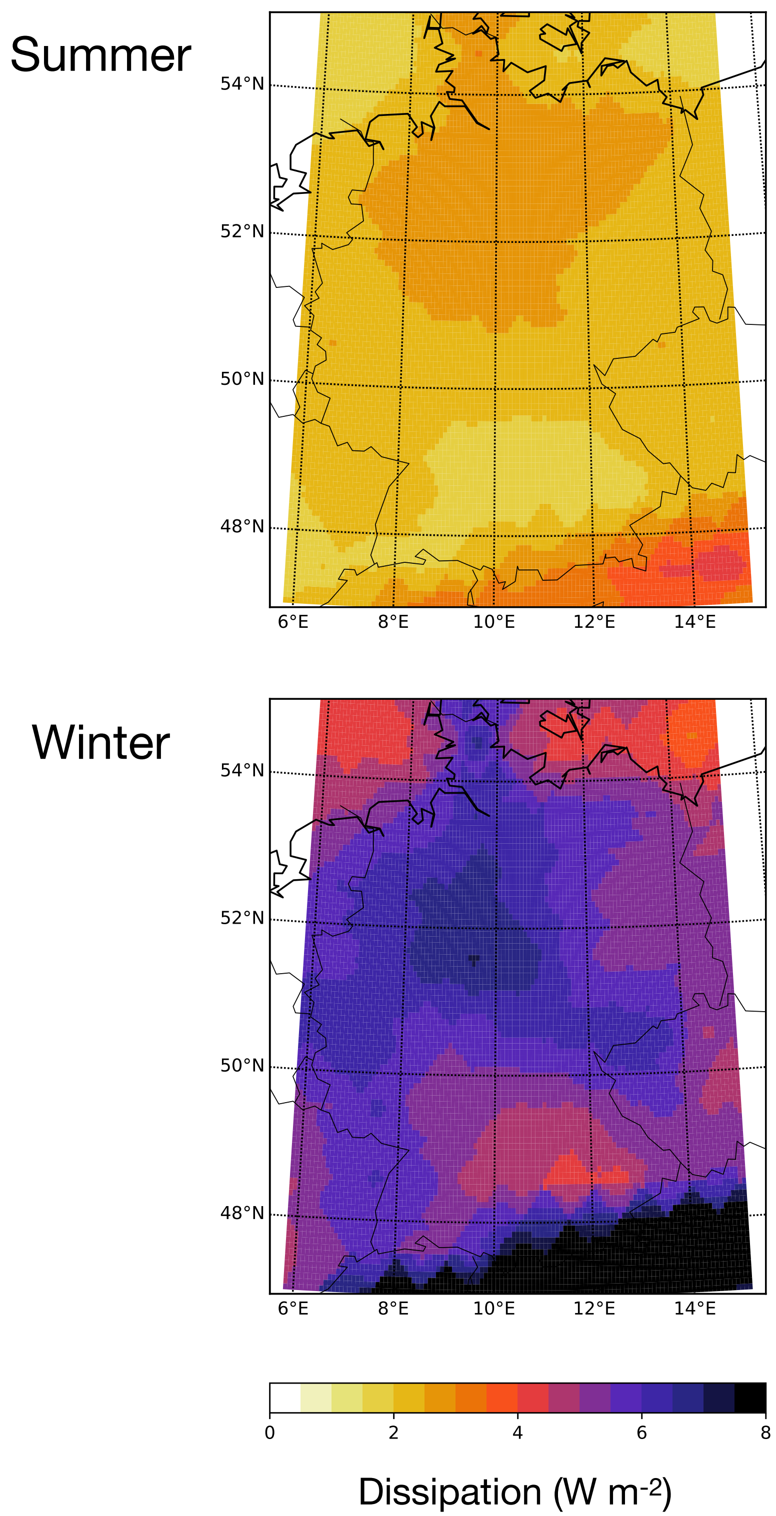
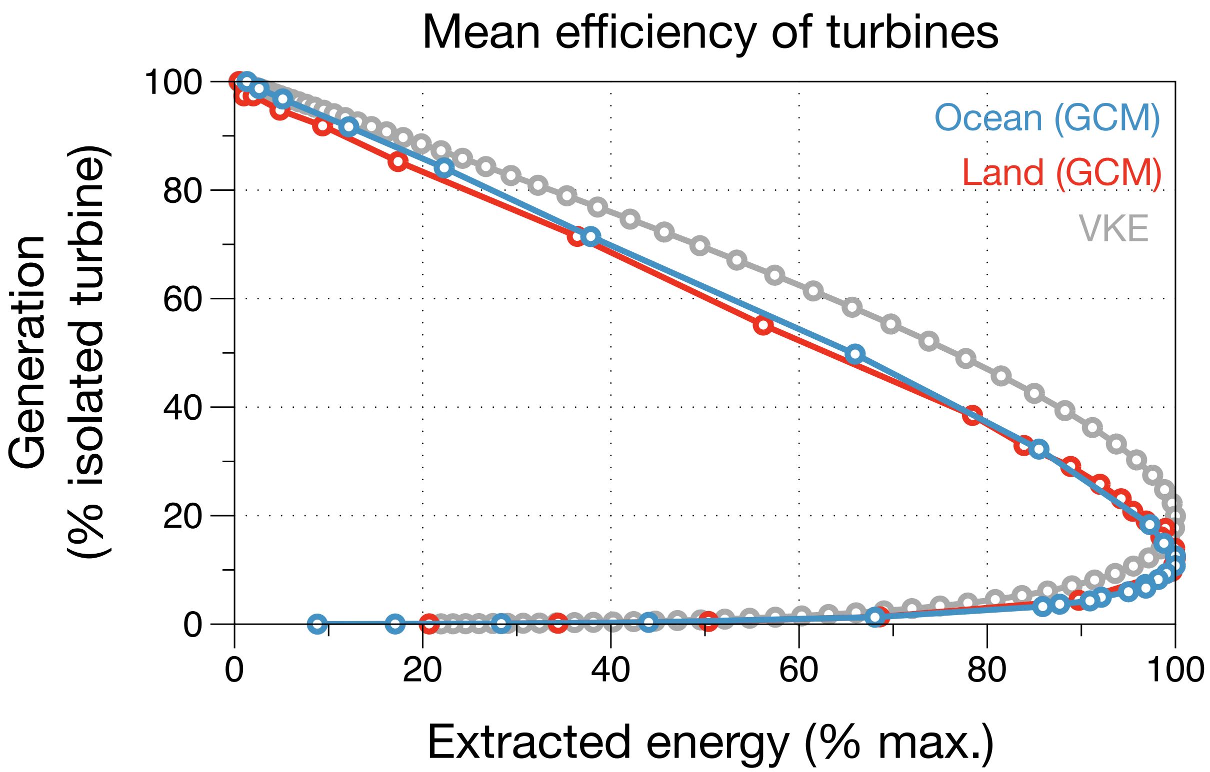
Application to 200 GW in Germany





$$f_{cap} \approx f_{cap,max} \cdot \left(1 - \frac{1}{\sqrt{3}} \cdot \frac{Y_0}{Y_{max}}\right)$$

Comparison:
Absorption of solar radiation
120 W m^{-2}

Kleidon (2023)

Estimating yield reductions

$f_{cap,max} \approx 20\%$

$Y_0 \approx 0.2 \times 200$ GW ≈ 350 TWh/a

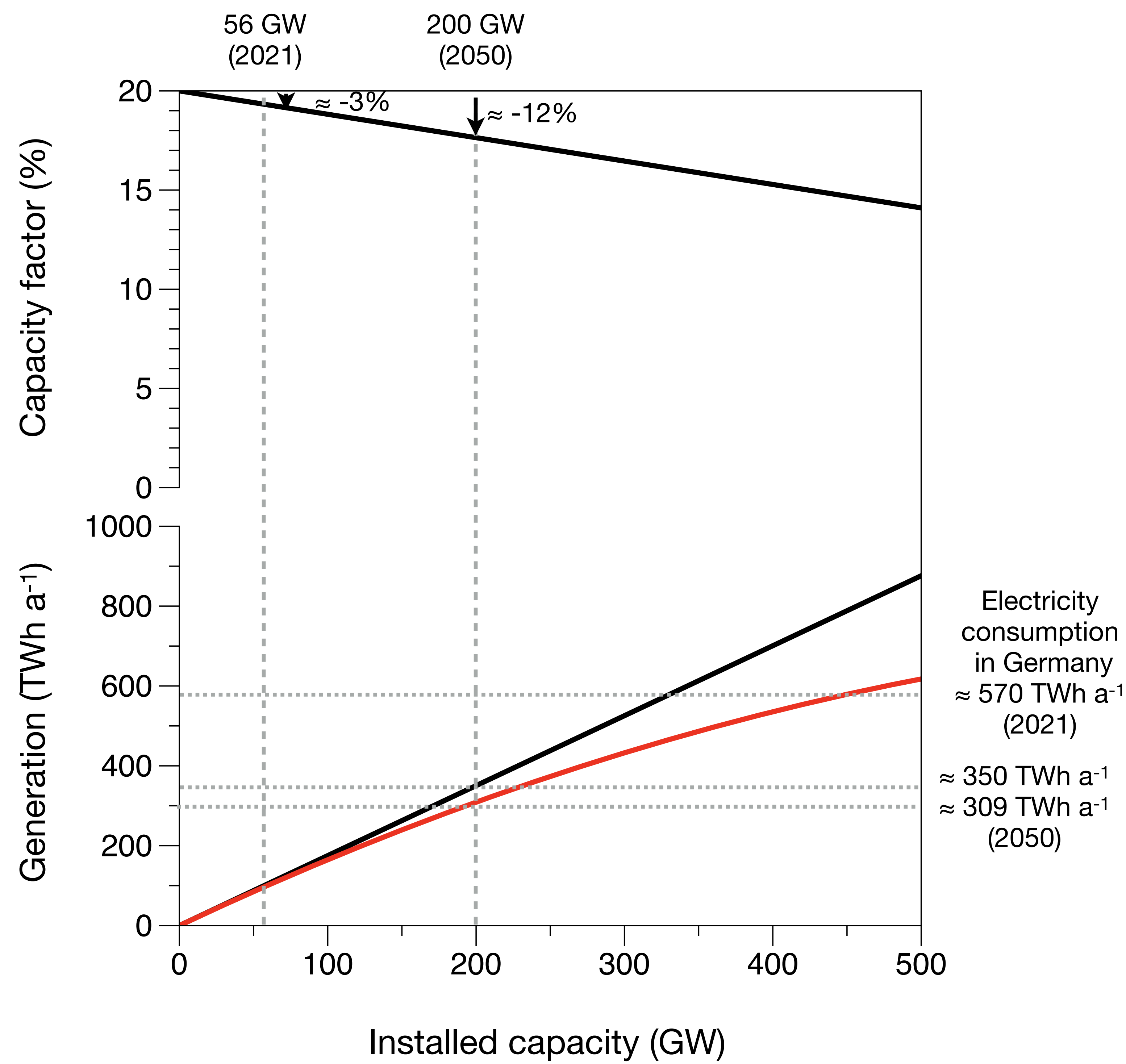
$Y_{ic} = 200$ GW

$$Y \approx f_{cap,max} \cdot \left(1 - \frac{1}{\sqrt{3}} \cdot \frac{Y_0}{Y_{max}}\right) \cdot Y_{ic}$$

$Y_{max} \approx 4$ W m^{-2} x 0.5 x 0.38 x 3.6 x 10^5 km^2 $\approx$ 2400 TWh/a

Yield: 350 TWh a^{-1} ➔ 320 TWh a^{-1}

≈ -10%



Impacts on the atmosphere

Frictional losses:

4 W m^{-2} x 3.6 10^5 km^2 x 8760 h a^{-1}
= 12 500 TWh a^{-1}

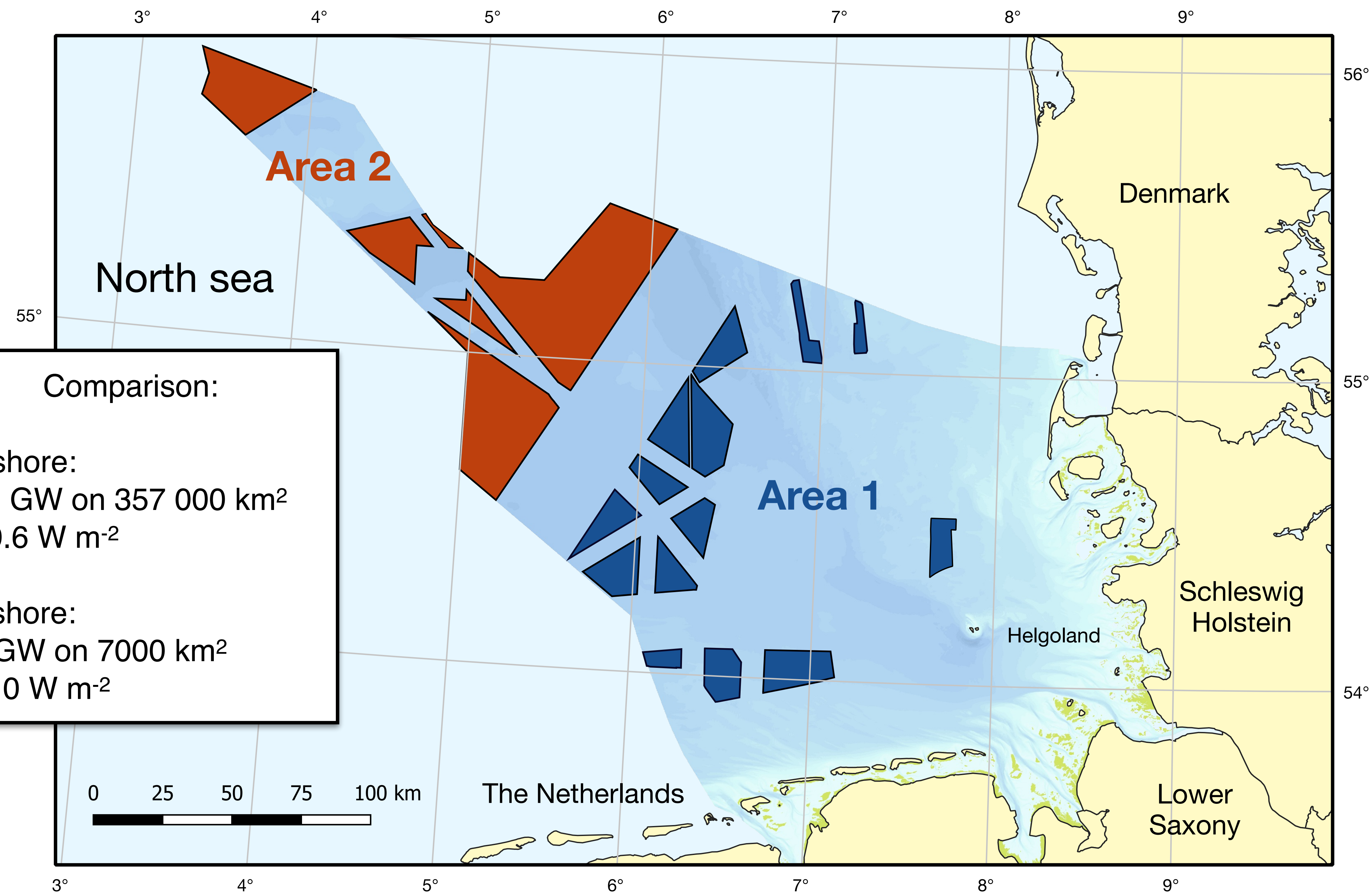
Removal with 200 GW:

309 TWh a^{-1} / 12500 TWh a^{-1}

= 2.5%

Limits to Offshore Wind Energy

Photo: Global Tech One

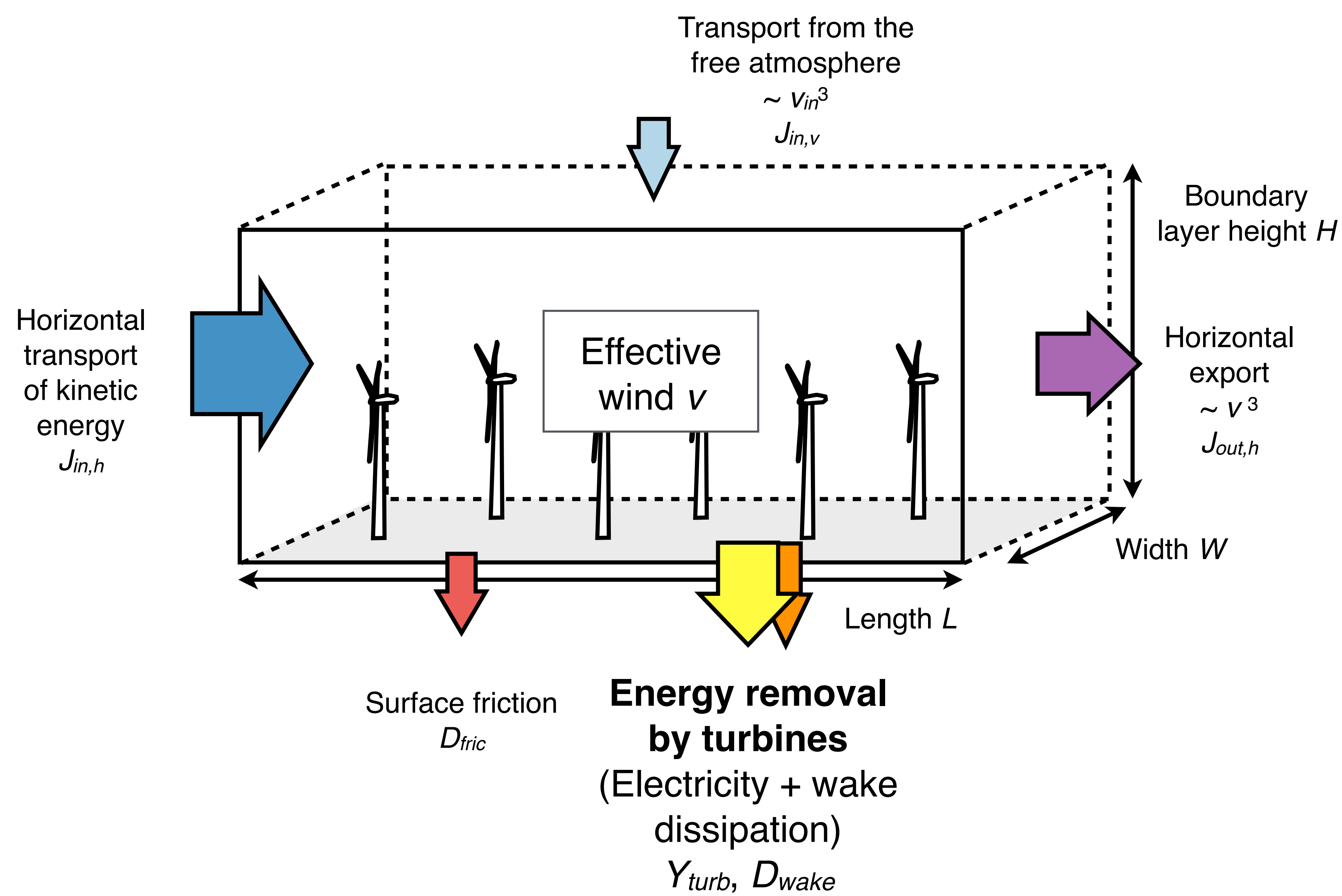


Comparison:

Onshore:
200 GW on 357 000 km^2
➔ 0.6 W m^{-2}

Offshore:
70 GW on 7000 km^2
➔ 10 W m^{-2}

Kinetic Energy Balance of the Atmosphere (KEBA)



"KEBA" Estimate

1. Kinetic energy balance:

$$J_{in,h} + J_{in,v} = J_{out,h} + D_{fric} + Y_{turb} + D_{wake}$$

2. Horizontal influx:

$$J_{in,h} = \frac{\rho}{2} v_{in}^3 \cdot WH$$

3. Vertical influx:

$$J_{in,v} = \rho C_d v_{in}^3 \cdot WL$$

4. Horizontal export:

$$J_{out,h} = \frac{\rho}{2} v^3 \cdot WH$$

5. Frictional loss at the surface:

$$D_{fric} = \rho C_d v^3 \cdot WL$$

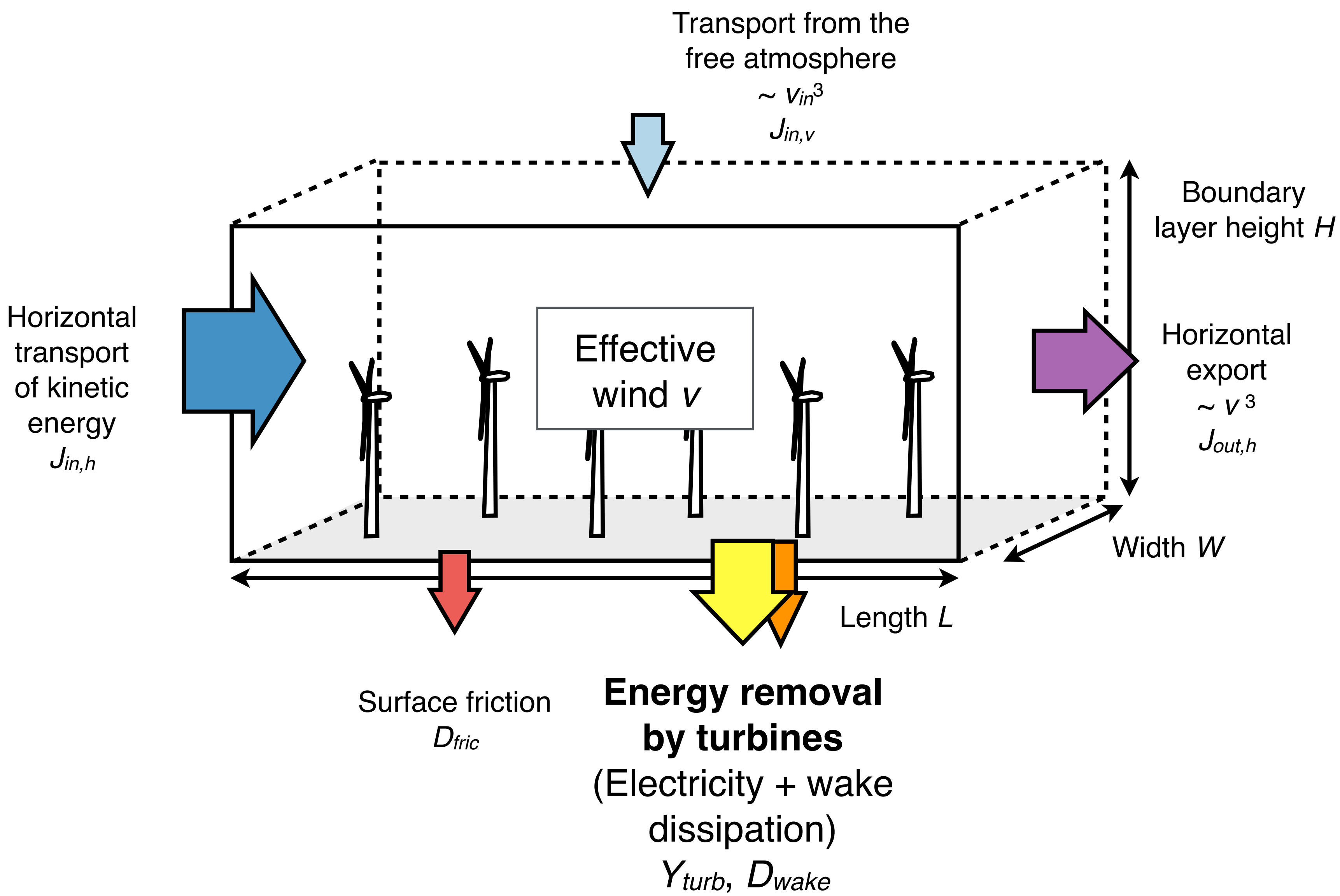
6. Generation by turbines:

$$Y_{turb} = \frac{\rho}{2} v^3 \cdot N\eta A_{rotor}$$

7. Frictional losses in wakes:

$$D_{wake} \approx \frac{1}{2} \cdot Y_{turb}$$

Kinetic Energy Balance of the Atmosphere (KEBA)



"KEBA" Estimate

1. Kinetic energy balance:

$$J_{in,h} + J_{in,v} = J_{out,h} + D_{fric} + Y_{turb} + D_{wake}$$

2. Total influx:

$$J_{in} = \frac{\rho}{2} v_{in}^3 \cdot \left(WH + 2C_d WL\right)$$

3. Removal, losses, exports:

$$J_{out} = \frac{\rho}{2} v^3 \cdot \left(WH + 2C_d WL + 3/2 N \eta A_{rotor}\right)$$

4. Reduction factor:

$$f_{red} = \frac{H + 2C_d L}{H + 2C_d L + (3/2)(N/W) \cdot \eta A_{rotor}}$$

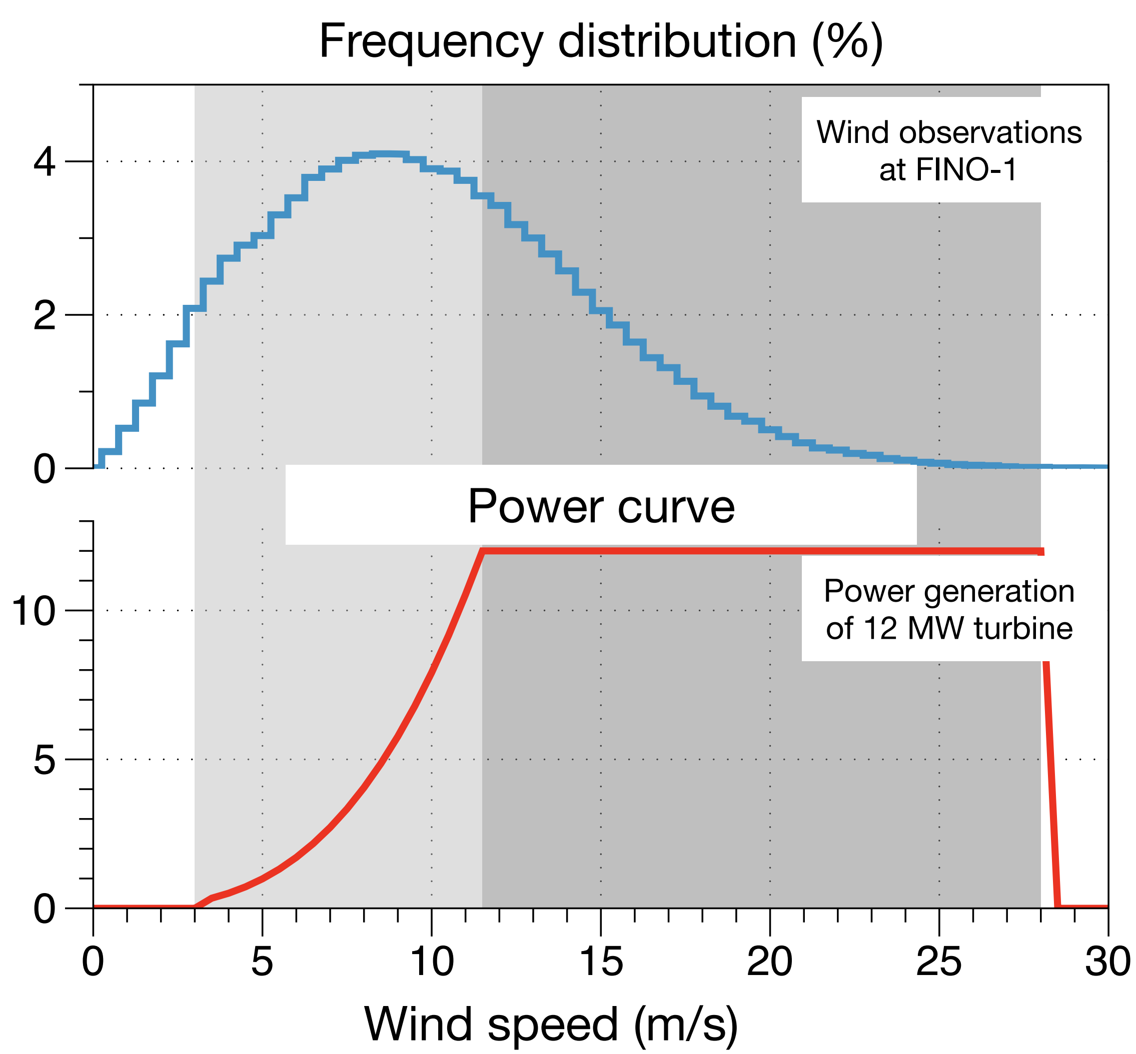
5. Effective velocity:

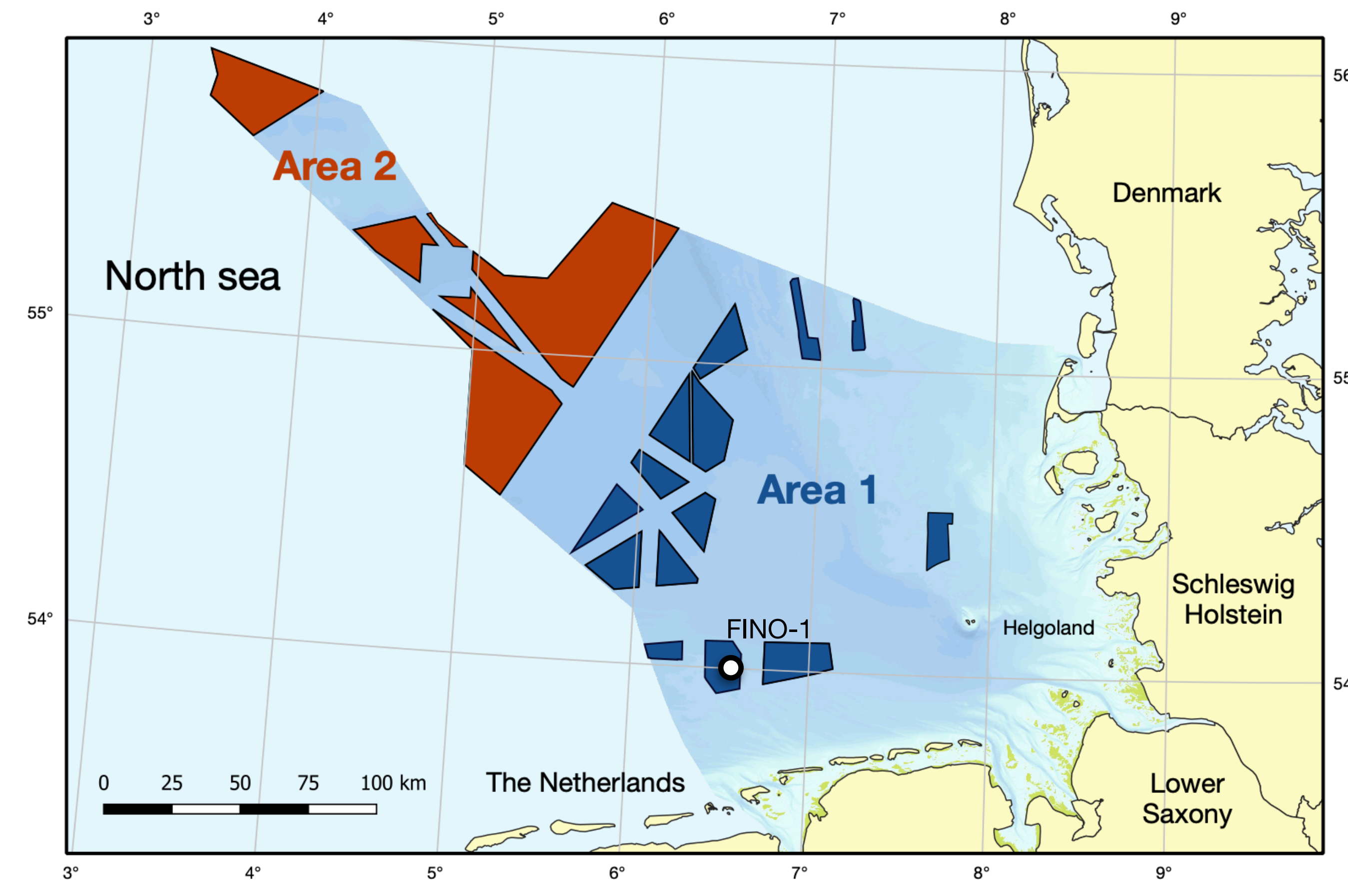
$$v = f_{red}^{1/3} \cdot v_{in}$$

6. Reduced yield:

$$Y_{turb} = f_{red} \cdot Y_{turb,0}$$

KEBA.xls





Wind speeds v_{in}

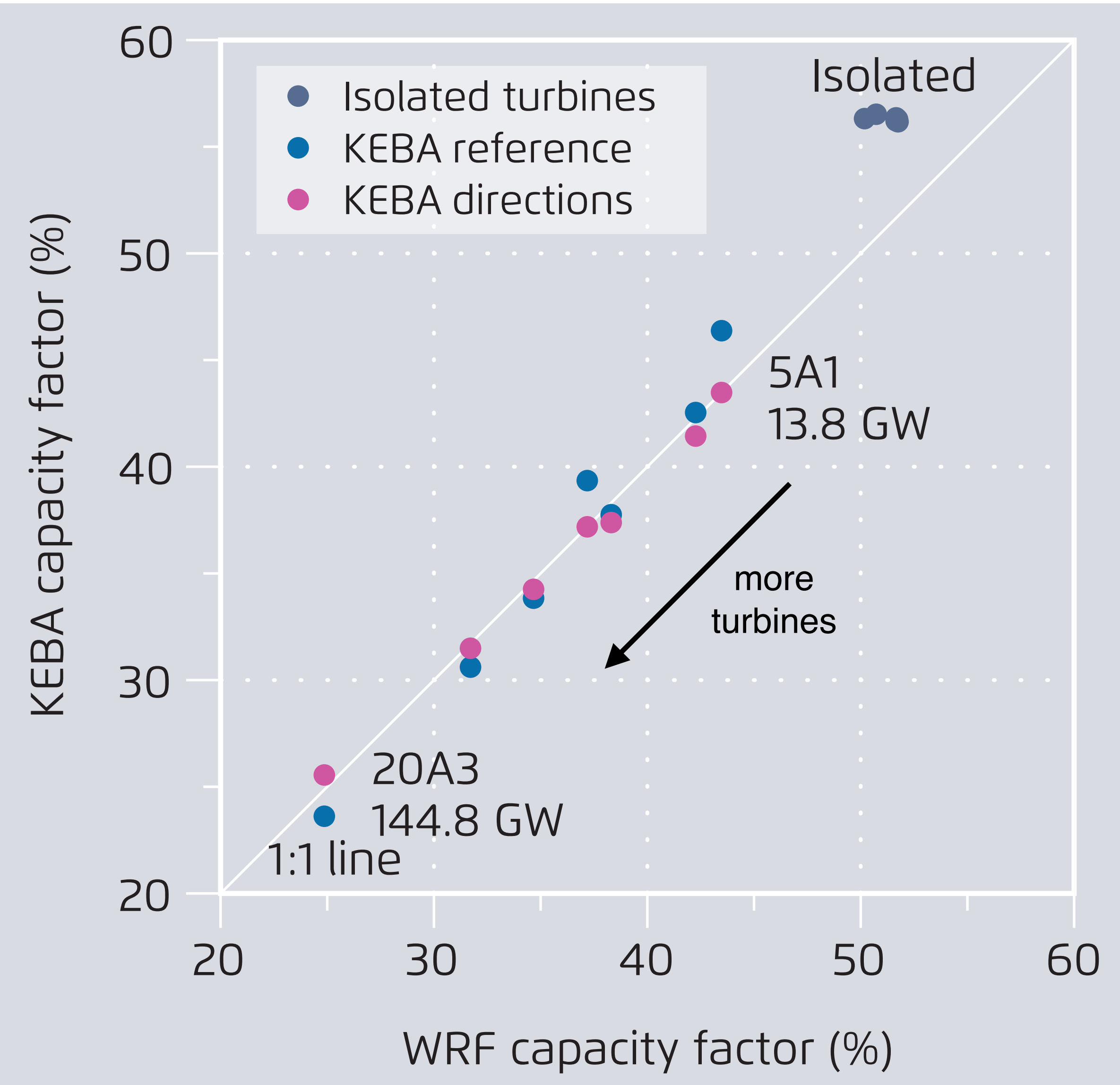
Atmospheric characteristics H, C_d

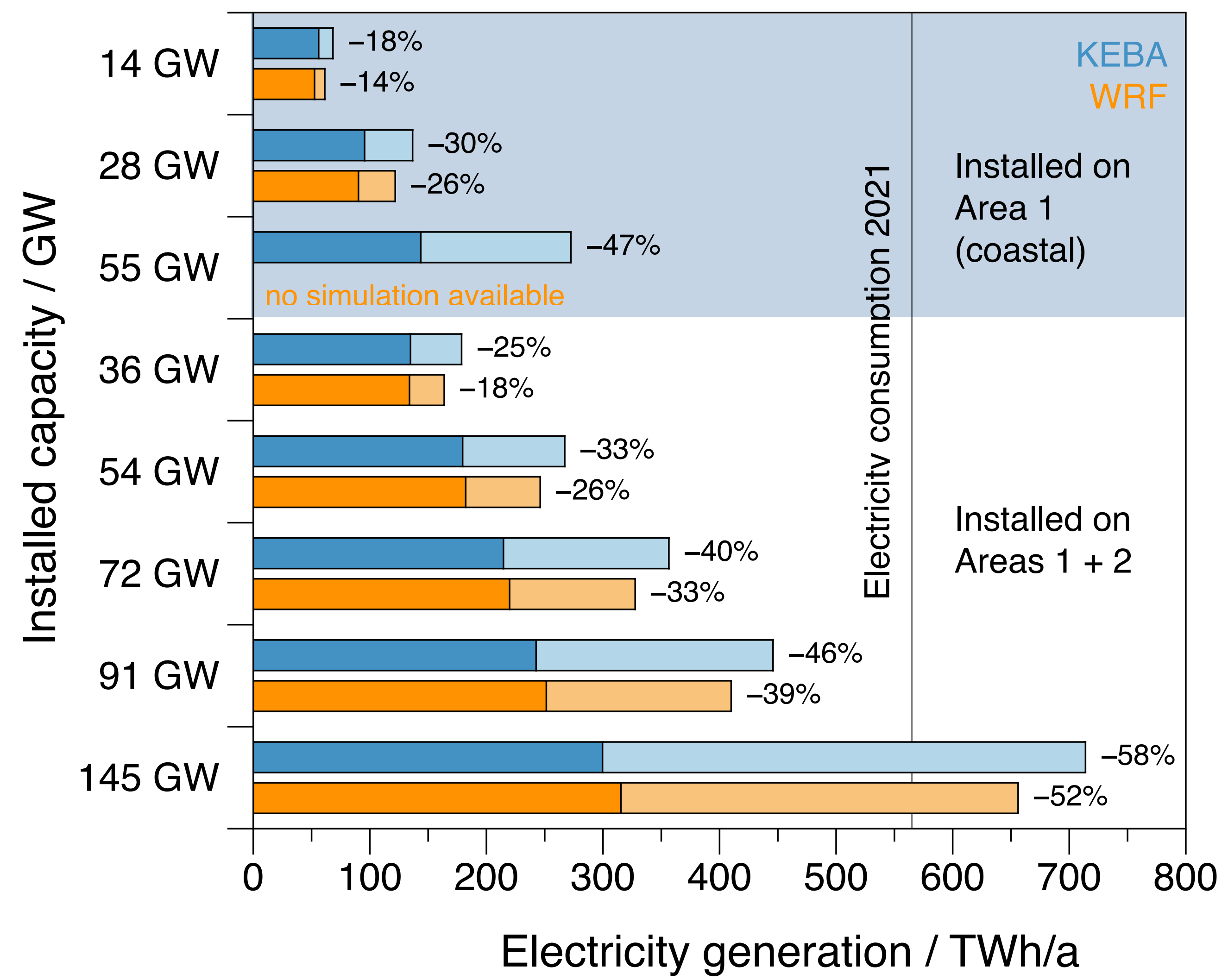
Turbine properties η, A_{rotor}

Spatial dimensions W, L

Number of turbines N

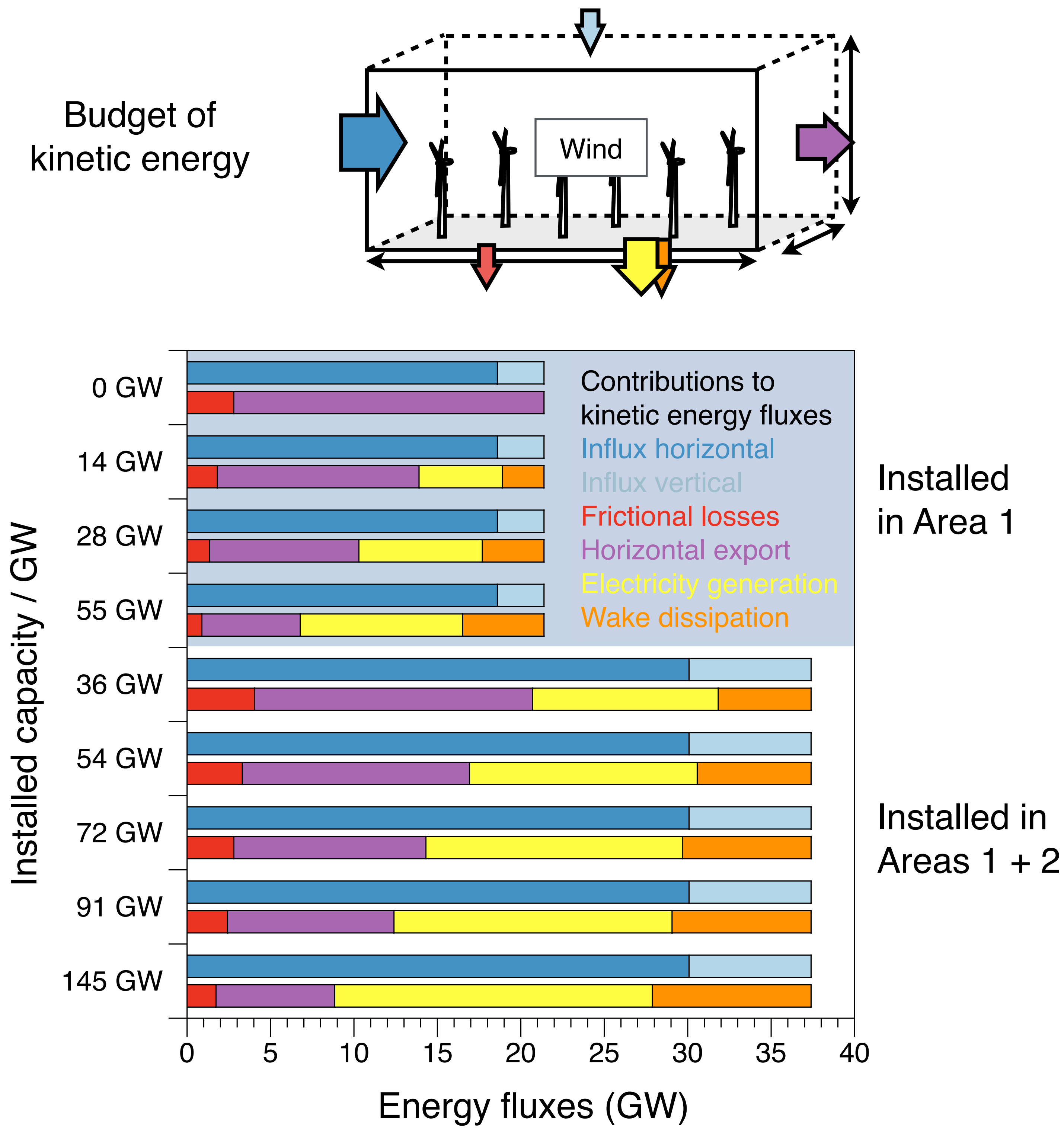
Comparison KEBA vs. numerical simulations (WRF)



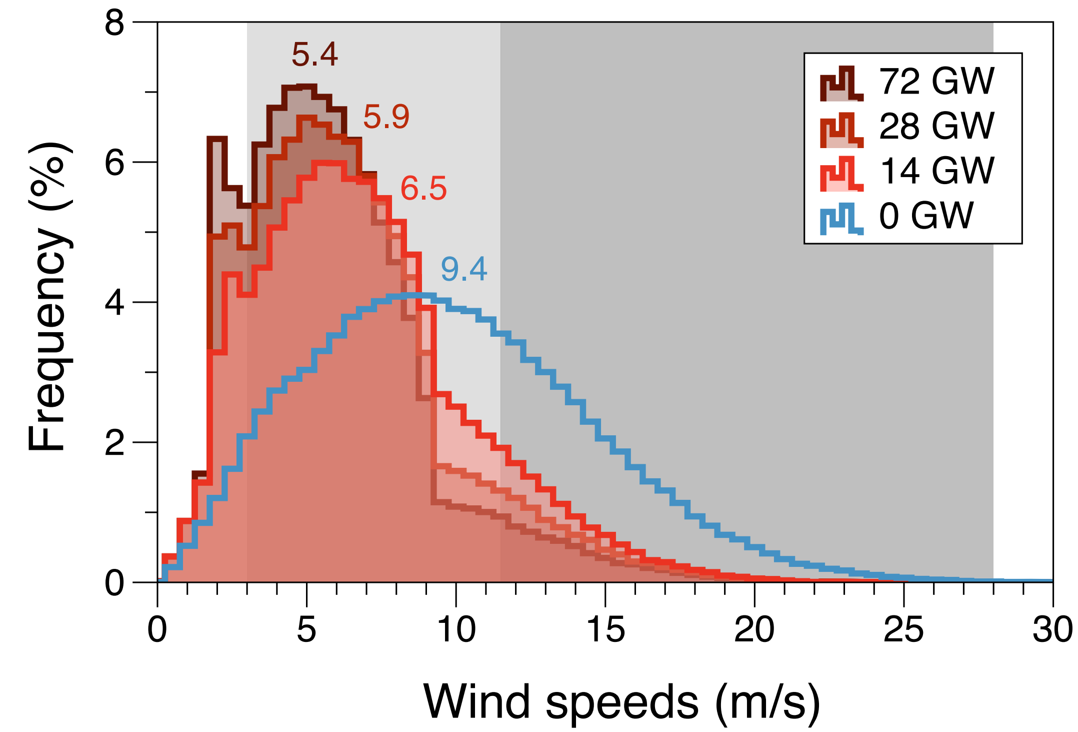


Capacity factor = Yield / capacity of the turbine

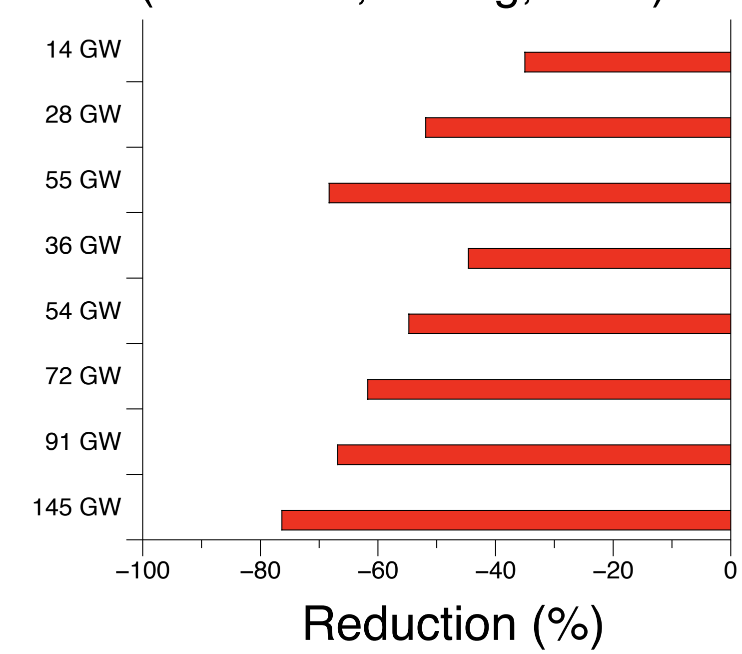
Explanation



Impacts



Frictional loss
(➔ Waves, mixing, biota)



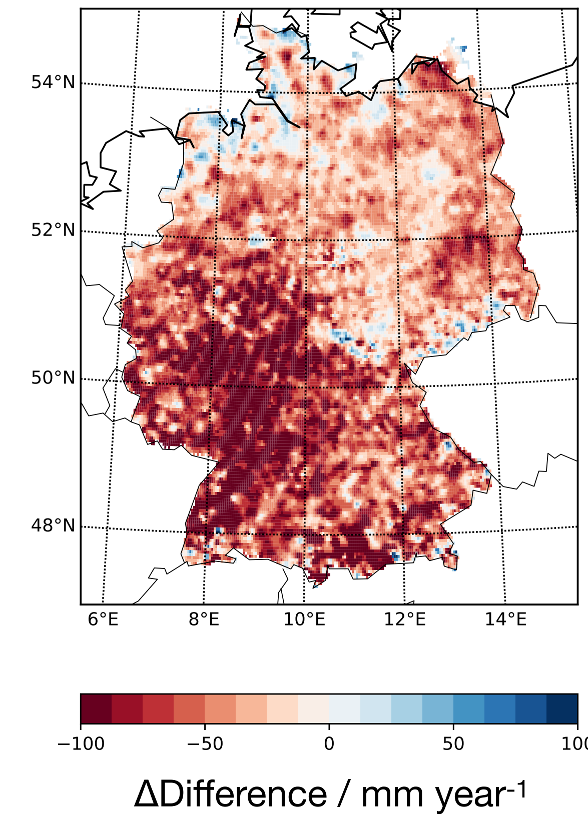
Kleidon (2023) PhysIUZ

Science Denial by Populists

Wrong!

Wrong!

Difference in P - E_{pot}
1991-2020 minus 1961-1990

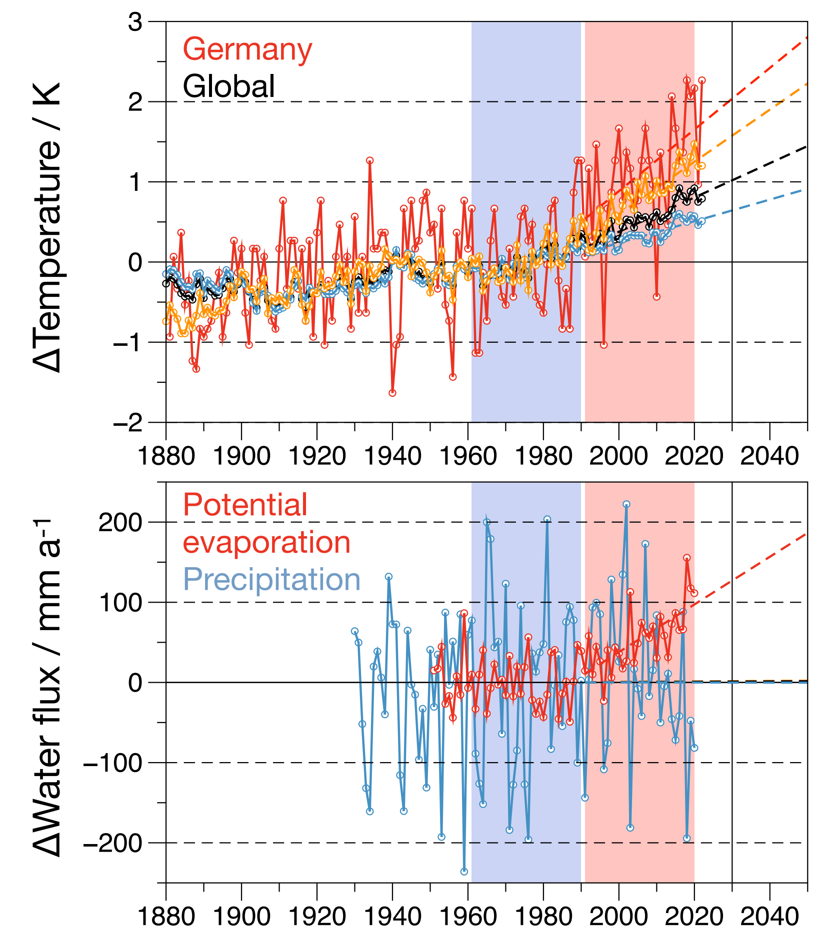


2023: Wind energy contributed 27% to electricity generation in Germany

136.5 TWh a^{-1} Wind energy
508.1 TWh a^{-1} Electricity generation

Even future 200 GW installed capacity only remove < 3% of kinetic energy dissipated over Germany

Drier conditions clearly caused by global warming (and increased solar radiation)



Physical Limits to Wind Energy and its Use:
Theoretical foundations and practical applications

General/Planetary scale:

- Energy generation as in a power plant
- Less conversions ➔ greater potential
- Renewable energy: PV >> wind >> everything else
- Whole system perspective

Germany/Regional scale:

- PV > wind >> everything else
- More wind energy use ➔ less wind, efficiency
- considerable contribution to electricity possible
- Differences in impacts (land/sea)

KISS Principle: Keep It Simple, Stupid! (but physical)

Literature

Meteorol. Z. (Contrib. Atm. Sci.), Vol. 30, No. 3, 203–225 (published online March 9, 2021)
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Review Paper

Physical limits of wind energy within the atmosphere and its use as renewable energy: From the theoretical basis to practical implications

Axel Kleidon*

Max-Planck-Institute for Biogeochemistry, Jena, Germany

Earth Syst. Dynam., 14, 861–896, 2023
https://doi.org/10.5194/esd-14-861-2023
Earth System Dynamics

Working at the limit: a review of thermodynamics and optimality of the Earth system

Axel Kleidon

Max-Planck-Institute for Biogeochemistry, Hans-Knoell-Str. 10, 07745 Jena, Germany

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Geosci. Model Dev., 13, 4993–5005, 2020
https://doi.org/10.5194/gmd-13-4993-2020
Geoscientific Model Development

The Kinetic Energy Budget of the Atmosphere (KEBA) model 1.0: a simple yet physical approach for estimating regional wind energy resource potentials that includes the kinetic energy removal effect by wind turbines

Axel Kleidon[1] and Lee M. Miller[2]

Agora Verkehrswende · Agora Energiewende

Making the Most of Offshore Wind

Re-Evaluating the Potential of Offshore Wind in the German North Sea

STUDY

Max Planck Institute for Biogeochemistry · DTU

Translated version
Originally published in German - Cite as: Kleidon, A. (2023) "Windenergie in der Deutschen Bucht", Physik in unserer Zeit, 54(1), 30-36. https://doi.org/10.1002/piuz.202201654

OFFSHORE-WIND ENERGY | RENEWABLE ENERGY

Wind energy potential of the German Bight

Limits and consequences of large-scale offshore wind energy use

Axel Kleidon

Translated version
Originally published in German - Cite as: Kleidon, A. (2023) "Windenergiepotenzial von Deutschland", Physik in unserer Zeit, 54(3), 142-148. https://www.doi.org/10.1002/piuz.202301670

ONSHORE-WIND ENERGY | RENEWABLE ENERGY

Wind energy potential of Germany

Limits and consequences of large-scale wind energy use

Axel Kleidon

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