

# Physical Limits to Wind Energy and its Use

From the theoretical foundations to practical applications  
of the energy transition

Axel Kleidon

Max-Planck-Institut für Biogeochemie  
[akleidon@bgc-jena.mpg.de](mailto:akleidon@bgc-jena.mpg.de)

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# Science Denial by Populists



Source: <https://facebook.com>

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

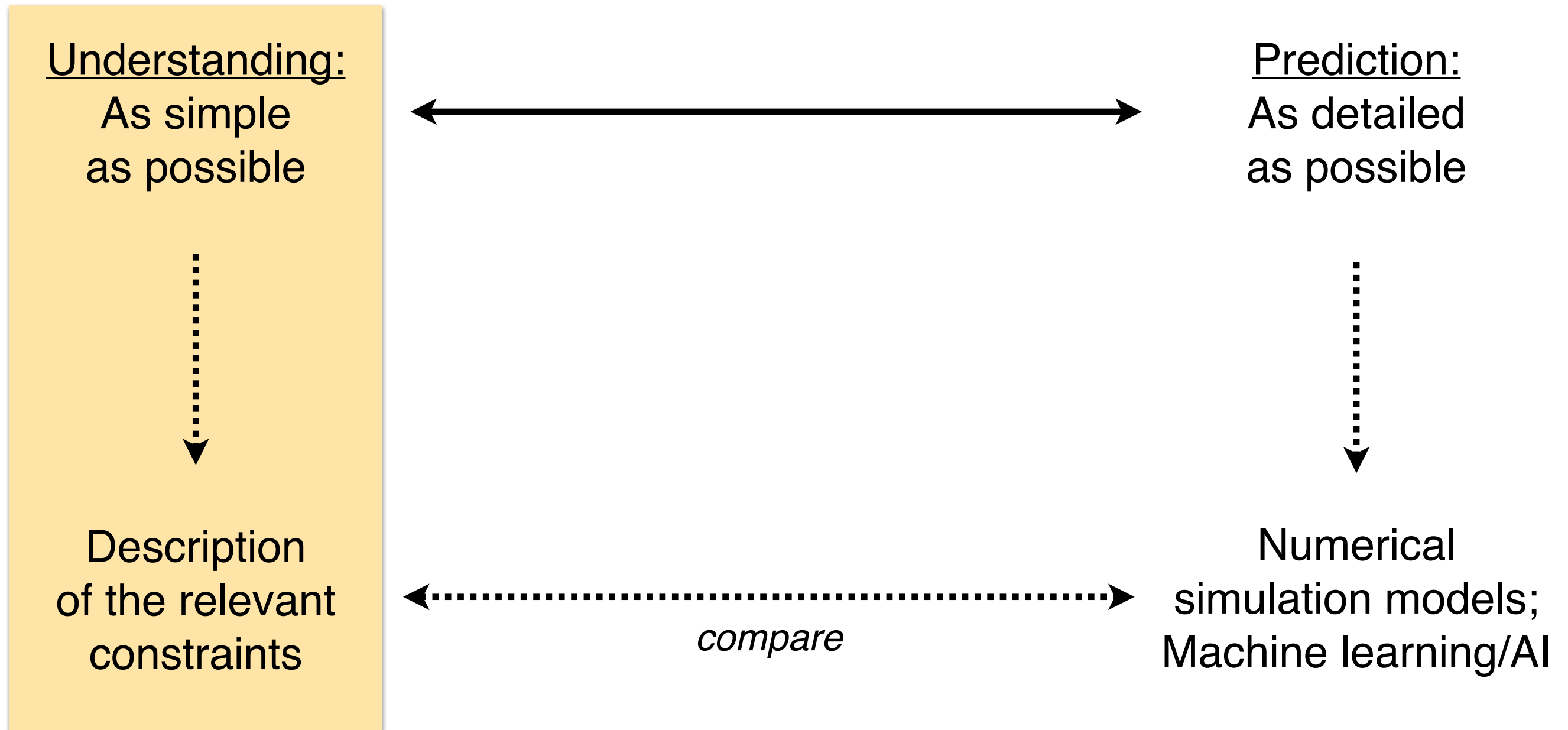


Source: <https://afd.nrw>

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



# Estimating Wind Energy Limits and Impacts





How does Earth generate wind energy?

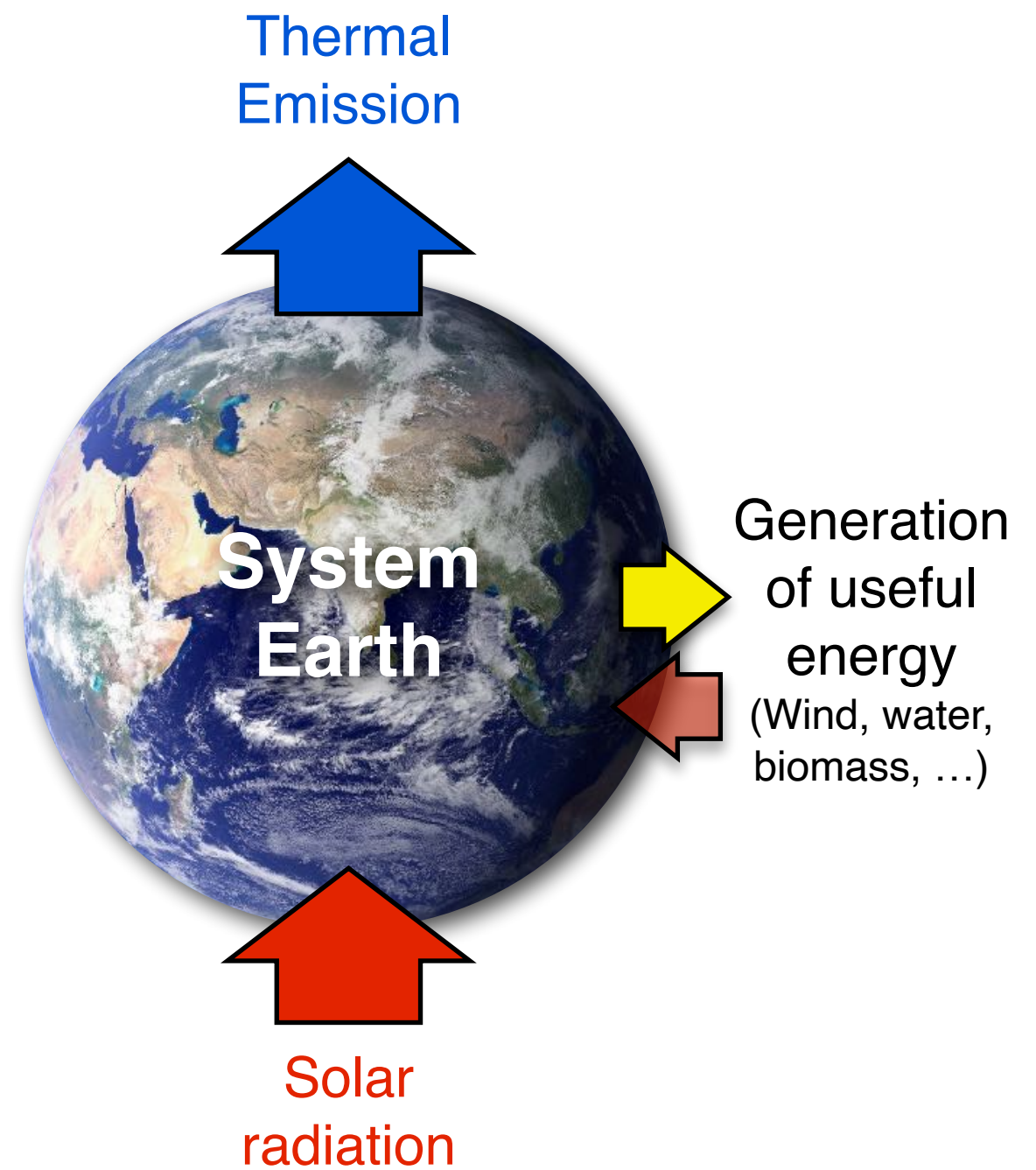
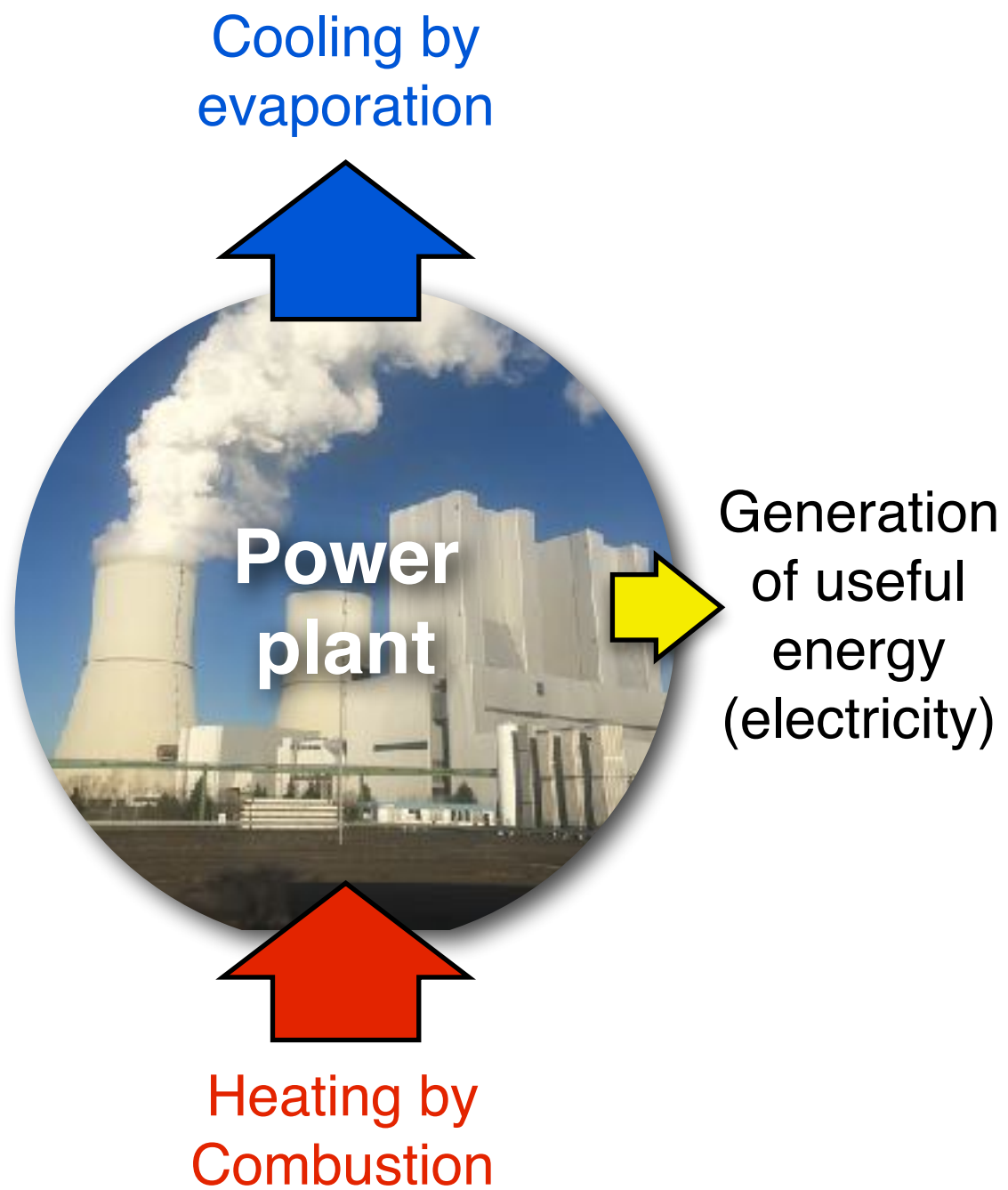
And how much?

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

And for the energy transition?

What are the consequences?





First law of thermodynamics:

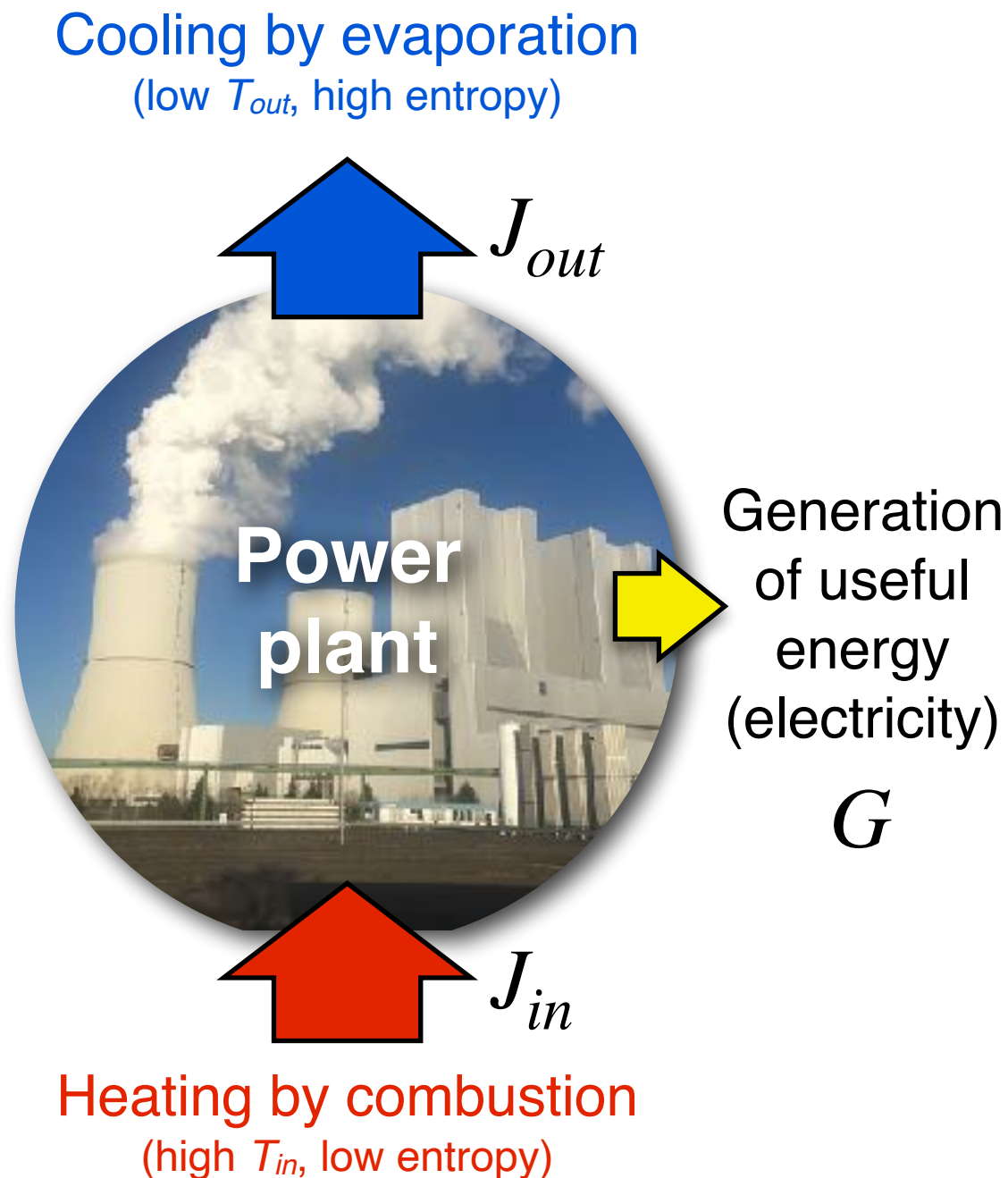
$$J_{in} = J_{out} + G$$

Second law of thermodynamics:

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

Entropy exchange

Entropy production  $\geq 0$



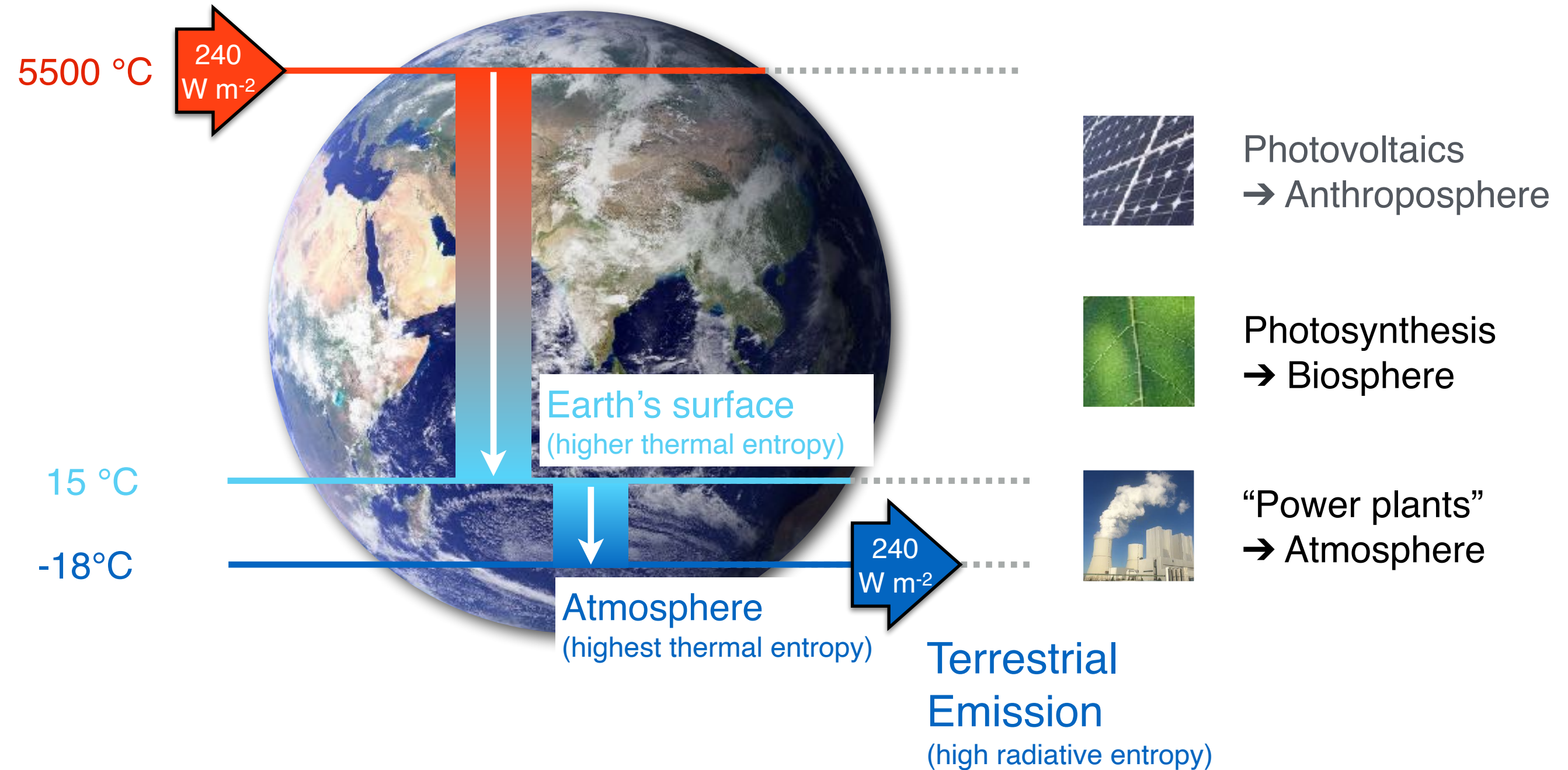
Generation of useful energy  
(no entropy, best case,  $\sigma = 0$ ):

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

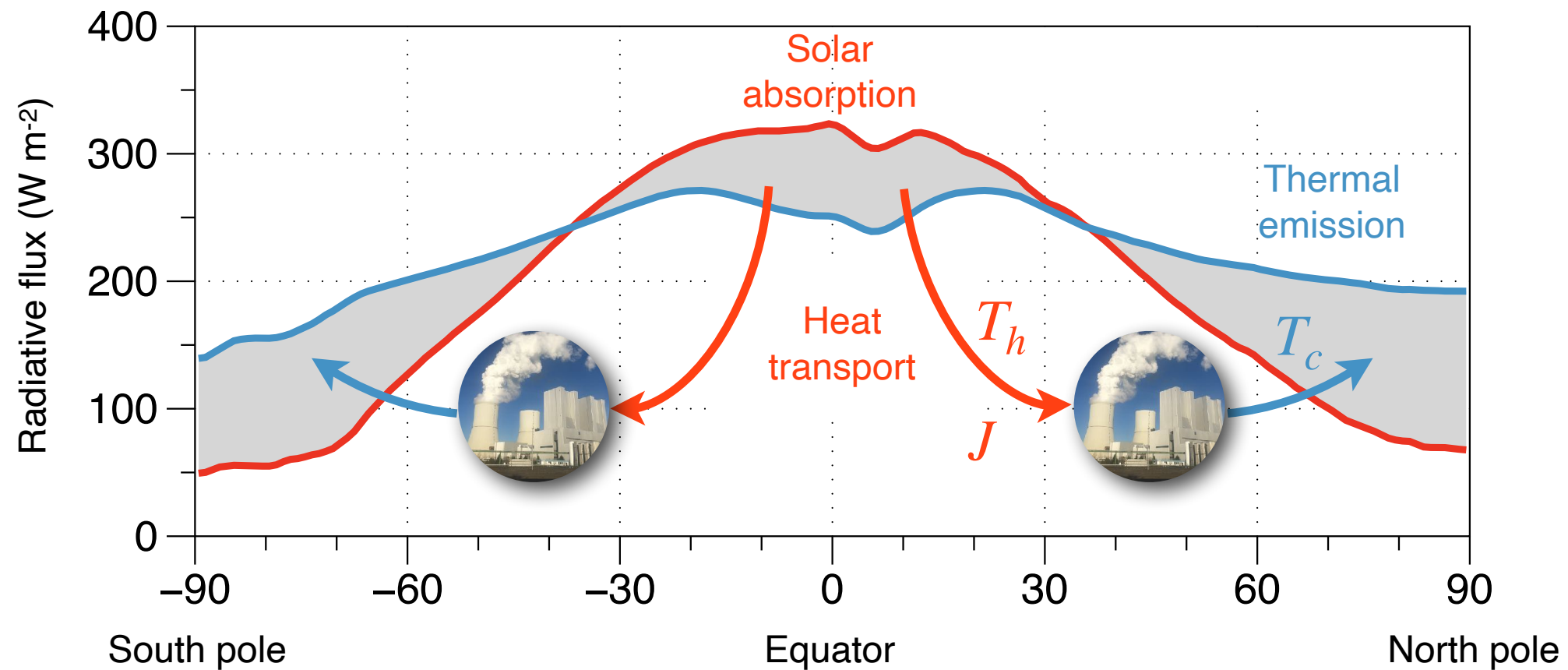


# Generating Power

**Solar  
Radiation**  
(low radiation entropy)



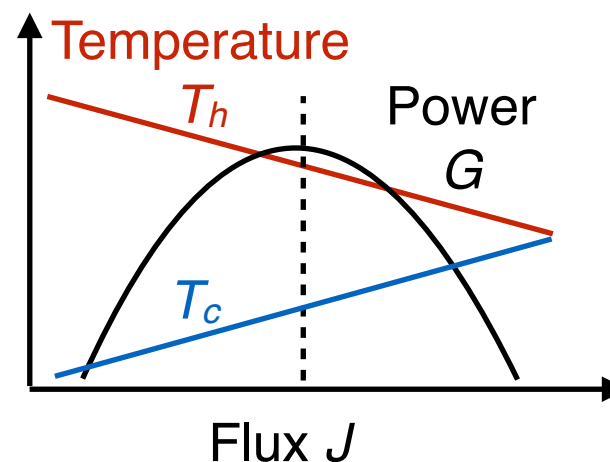
# Generation of Large-scale Wind Energy



Thermodynamic limit:

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

More transport  
→ less efficiency:



Maximum power:

Heat flux:	50 $\text{W m}^{-2}$
$T_h - T_c$ :	$\approx 30 \text{ K}$
Power:	$0.5 \times 50 \times 10\%$
	$\approx 2.5 \text{ W m}^{-2}$
Global:	$\approx 1000 \text{ TW}$
Efficiency:	$\approx 1\%$



Earth system process

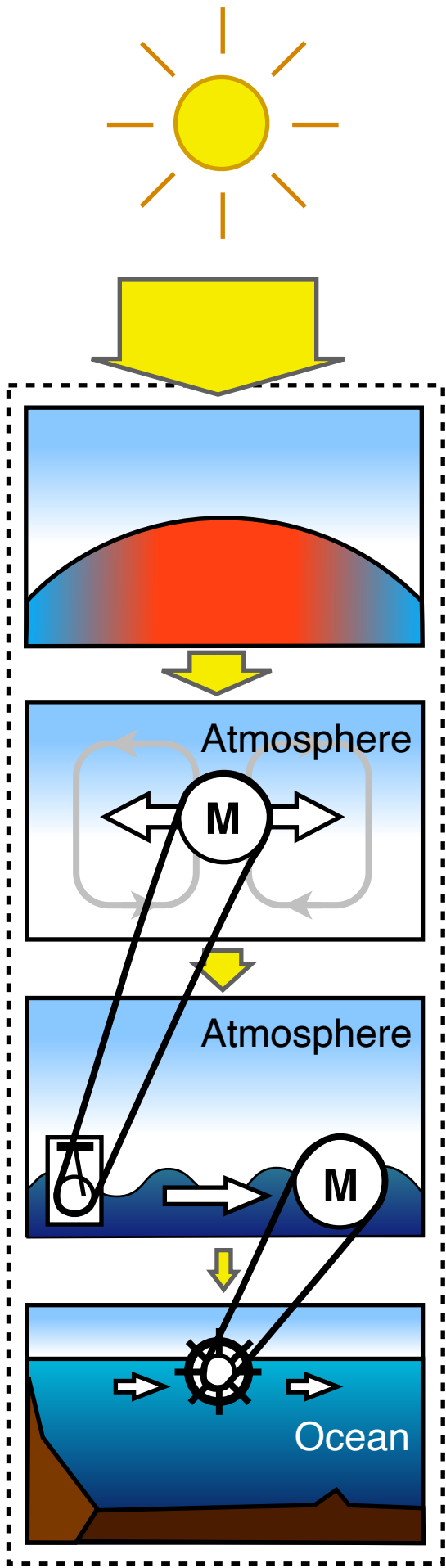
Solar irradiation

Absorption generates heating

Heating differences cause motion

Motion generates waves

Waves generate ocean currents



$\approx 175000$  TW  $\longrightarrow$  Solar power

Absorption 70%  
Differential heating 40%

$\approx 49000$  TW

Conversion (maximal)  
2%

$\approx 1000$  TW  $\longrightarrow$  Wind energy

Conversion (observed)  
6%

$\approx 60$  TW  $\longrightarrow$  Wave energy

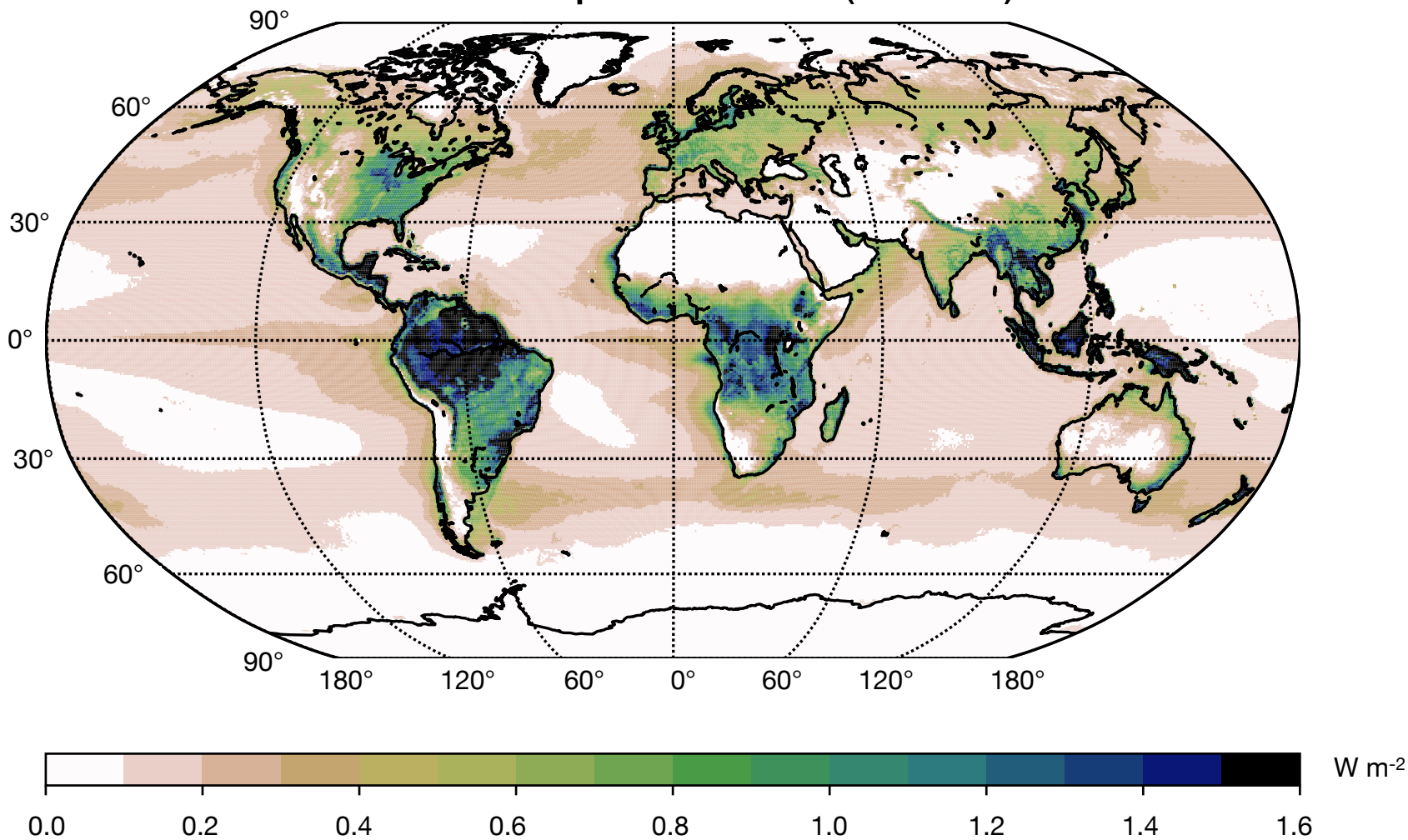
Conversion (observed)  
8%

$\approx 5$  TW  $\longrightarrow$  Energy from ocean currents

$\approx 20$  TW Human societies

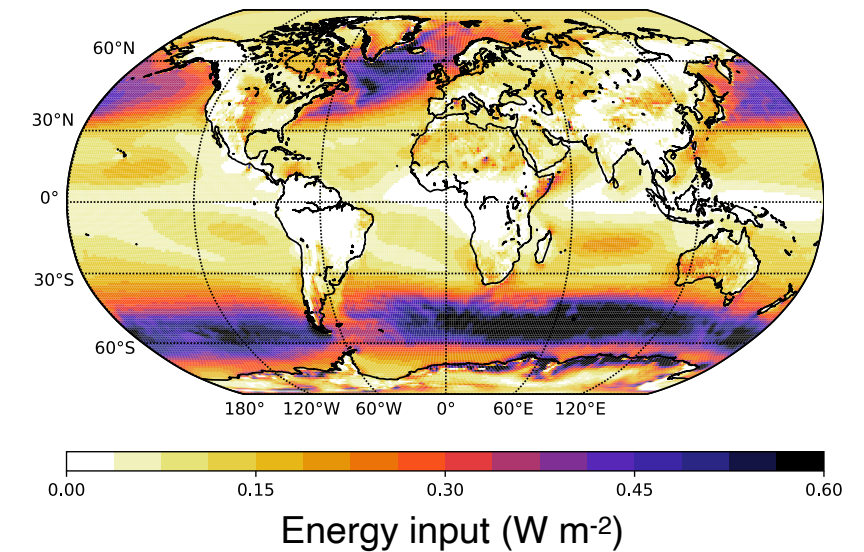
# Power from Photosynthesis

Biomass production ("NPP")

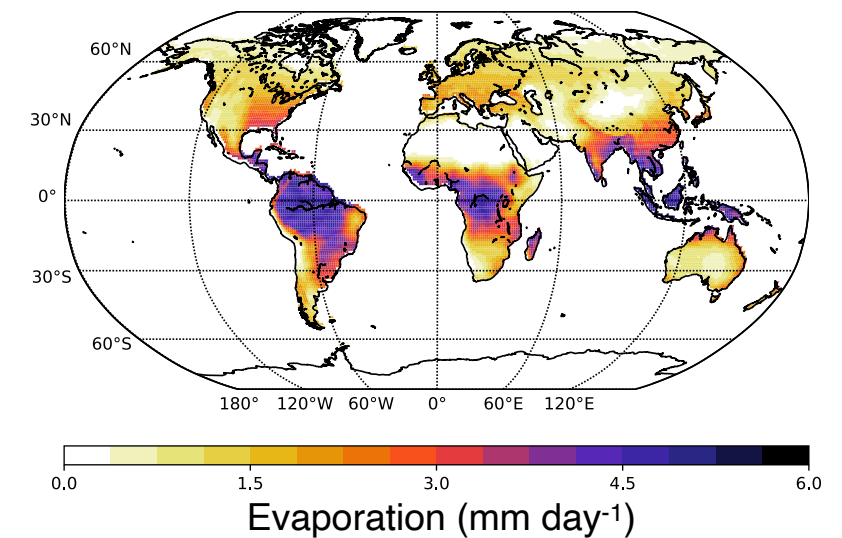


Land: 152 TW ( $\approx 1\%$ )

Ocean: mixing



Land: gas exchange





## Wind energy



Efficiency:  $< 1\%$   
Power: 1 000 TW

## Photosynthesis



Efficiency:  $< 1\%$   
Power: 152 TW

## Photovoltaics



Efficiency:  $\approx 20\%$   
Power: 35 000 TW

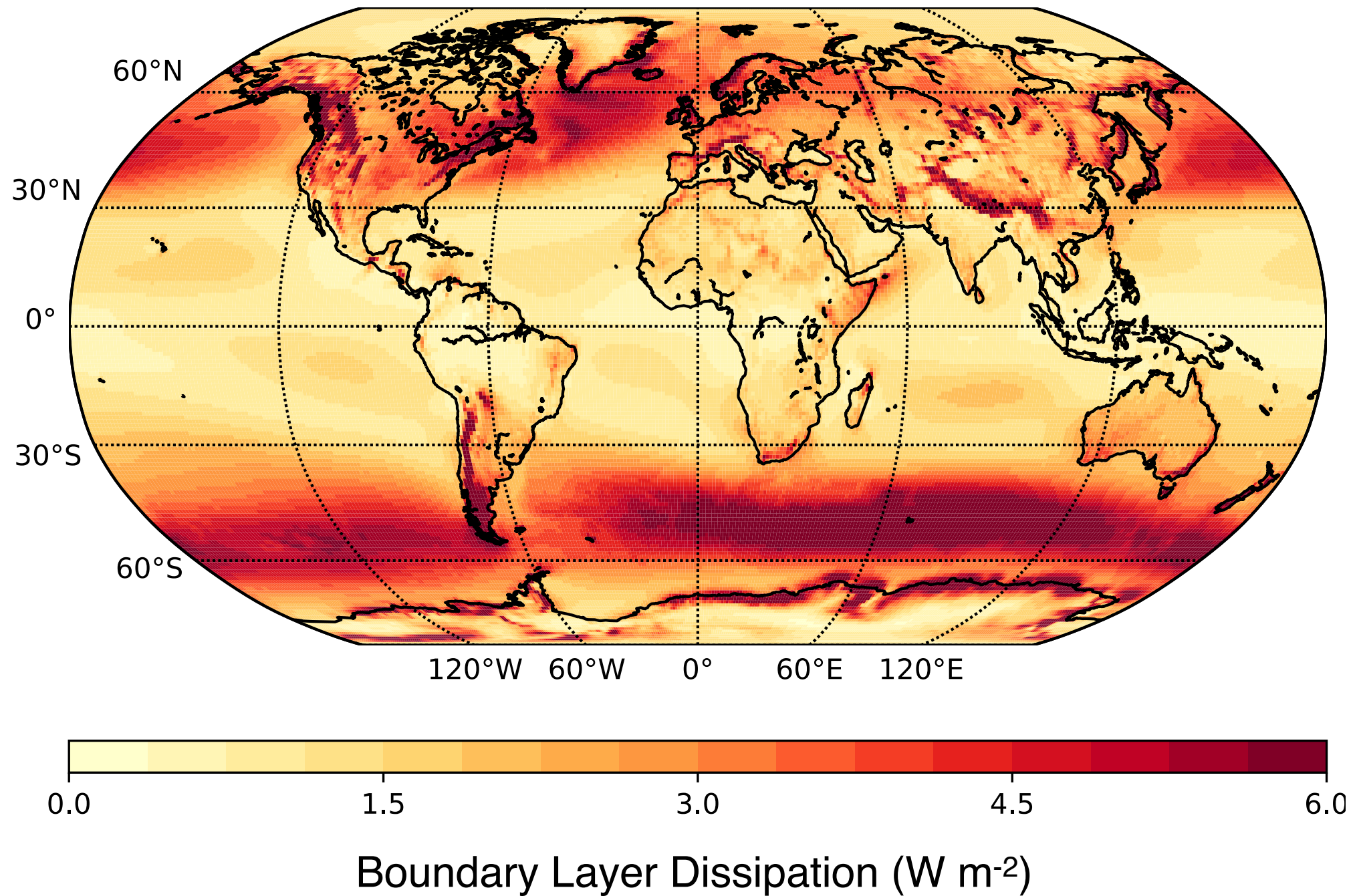
# Limits to Using Wind Energy

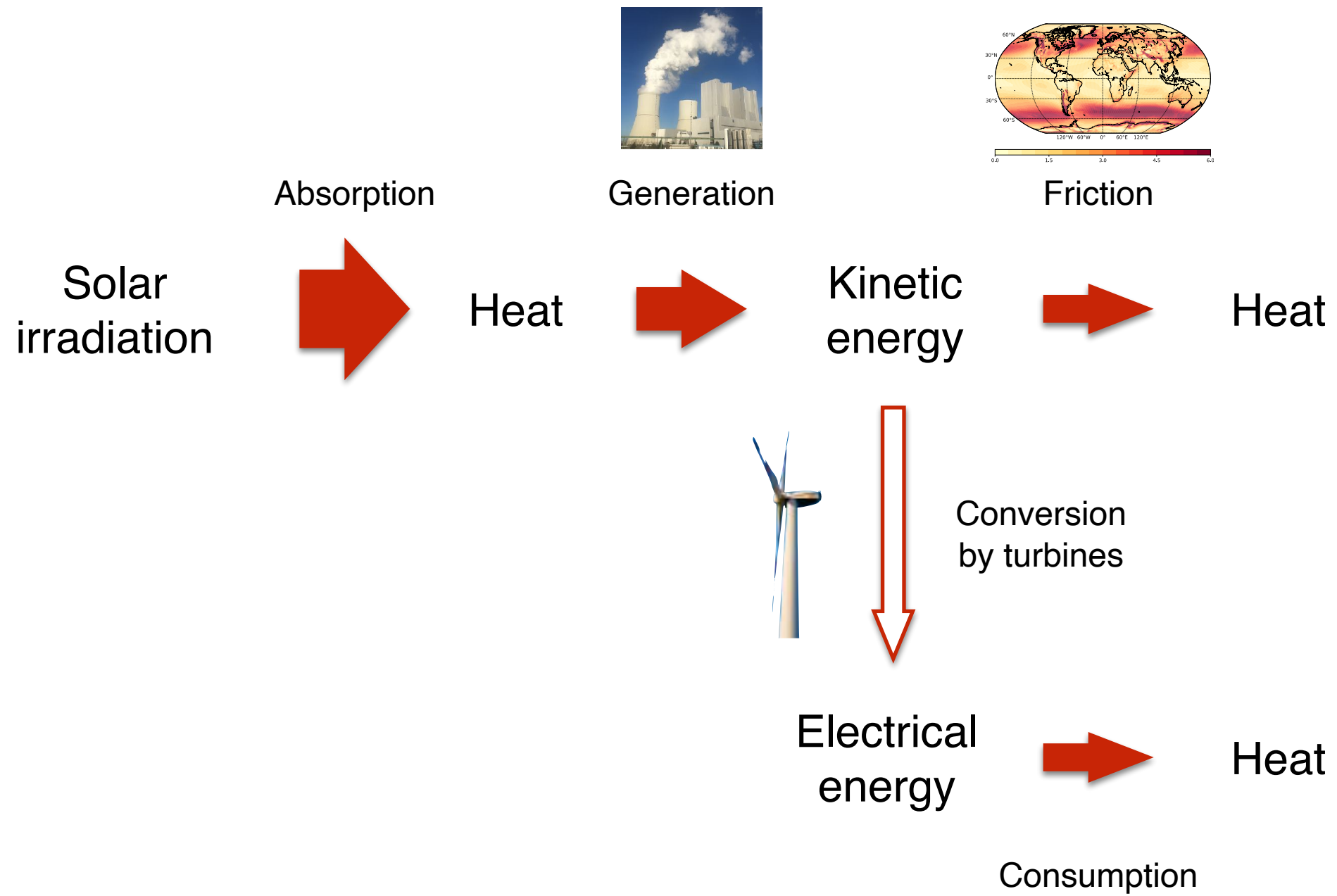


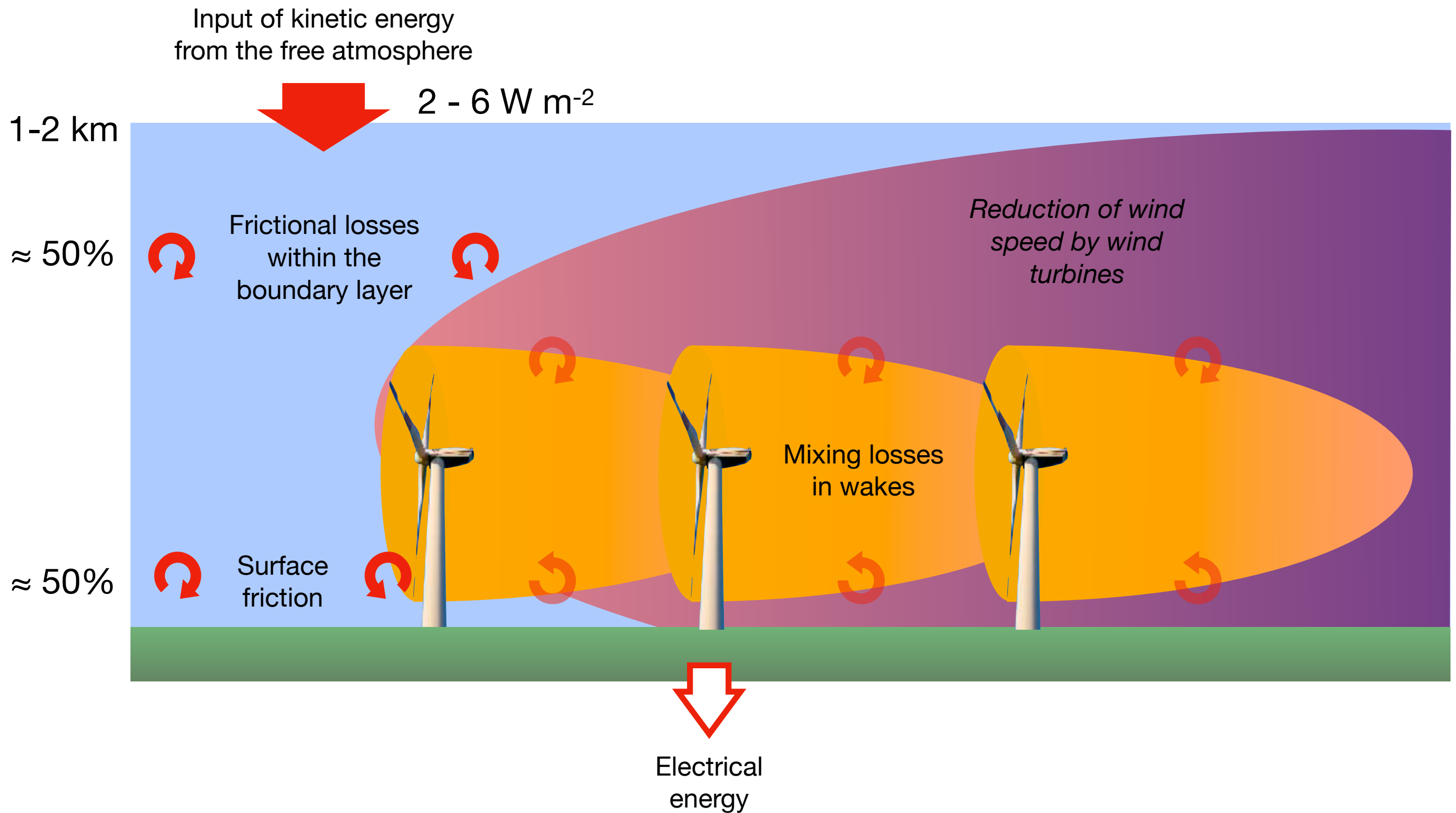


# Frictional Losses by the Atmosphere

Conversion of kinetic energy → heat

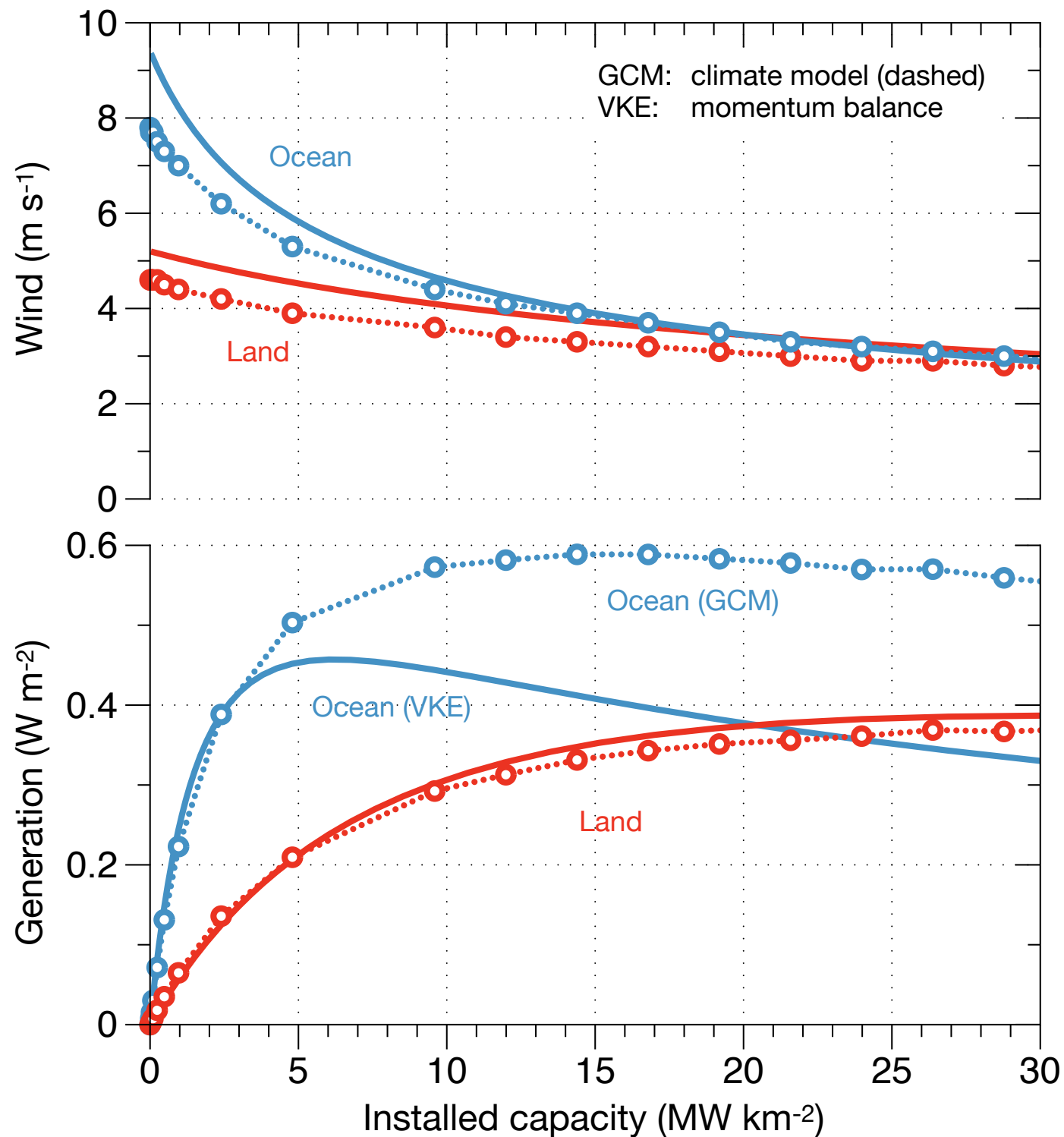








# Global climate models



## “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:

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

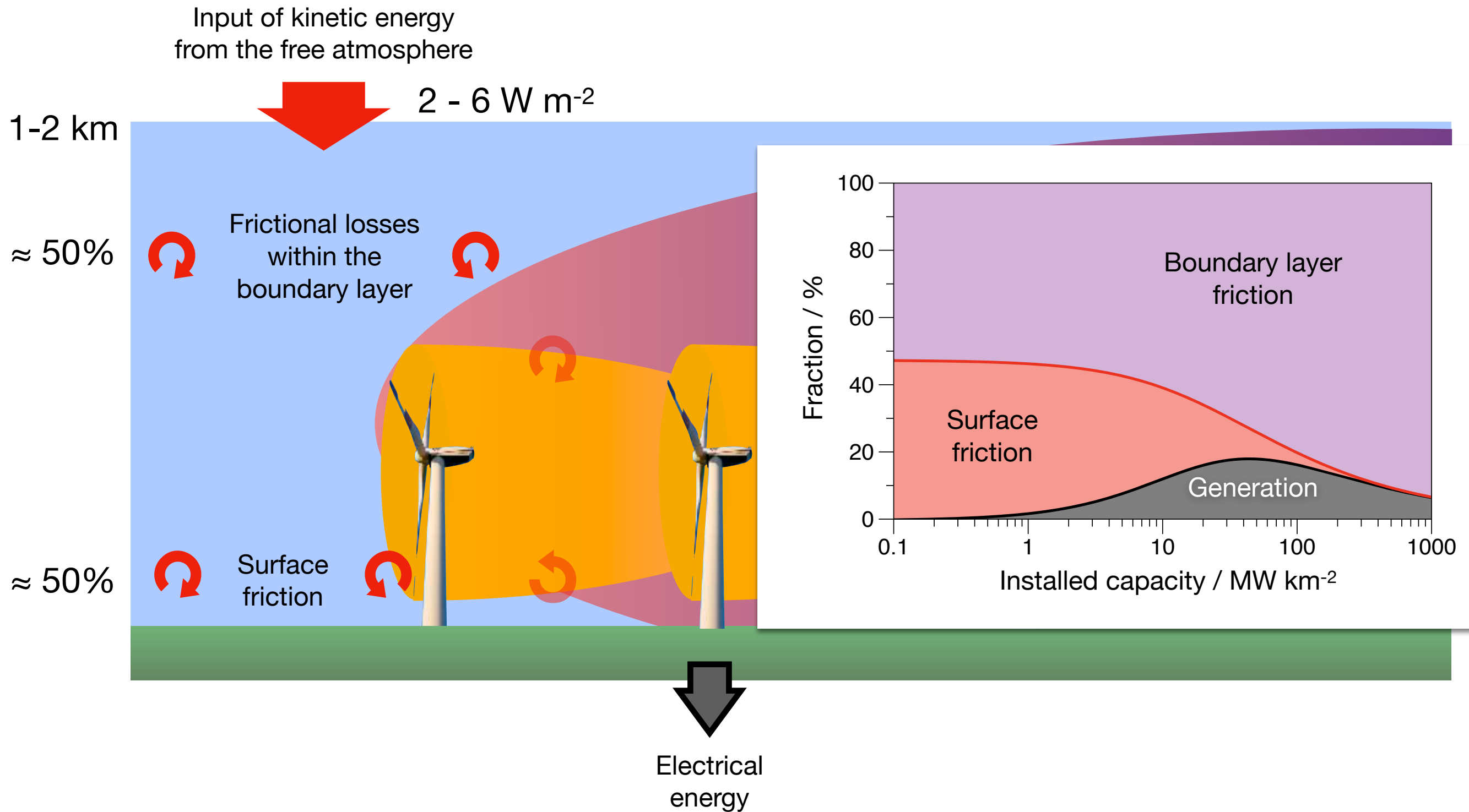
5. Generation by turbines:

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

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

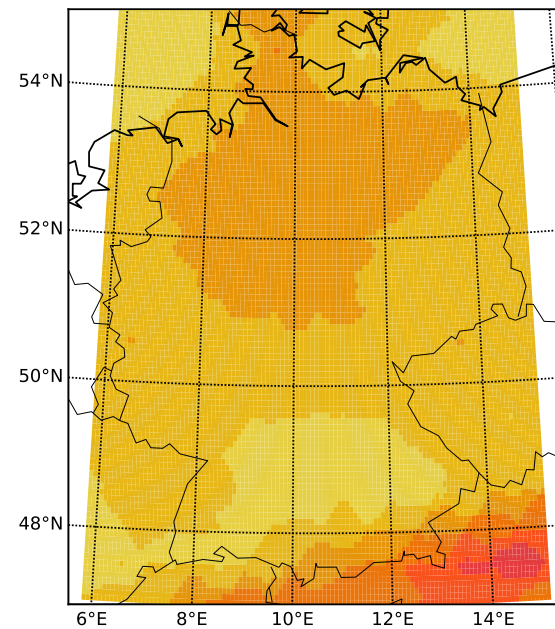
$$v_{opt} = \frac{1}{\sqrt{3}} \cdot v_0$$

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

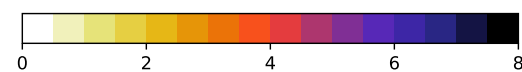
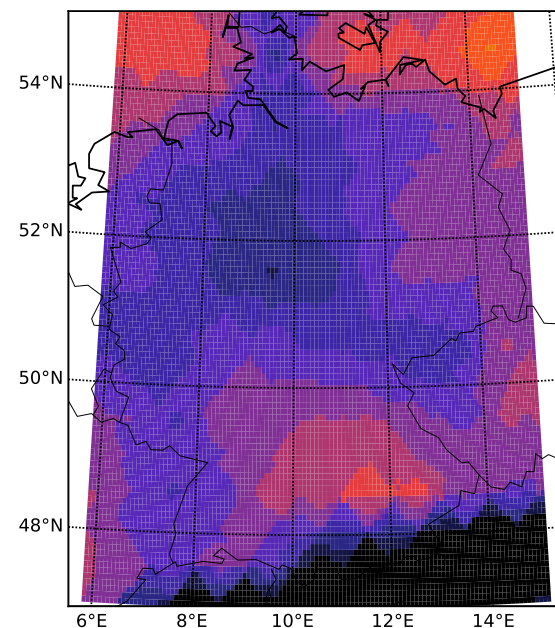


# Application to 200 GW in Germany

Summer

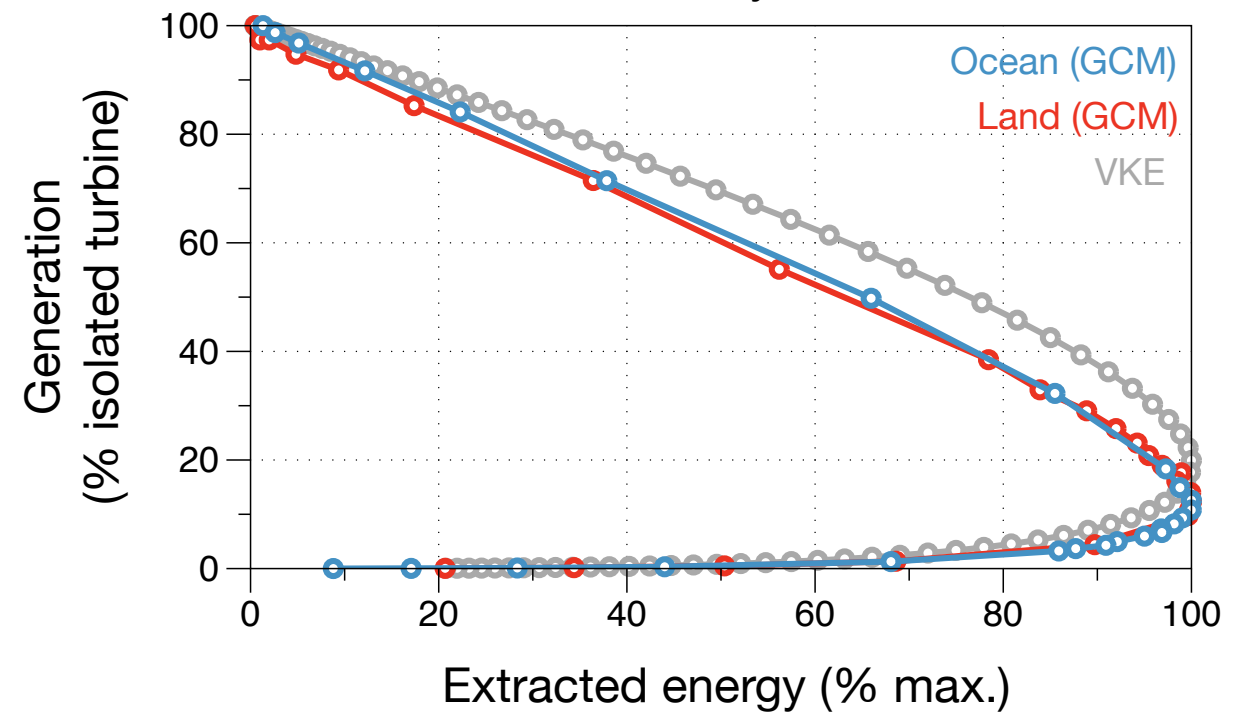


Winter



Dissipation (W m<sup>-2</sup>)

Mean efficiency of turbines



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

Comparison:  
Absorption of solar radiation  
120 W m<sup>-2</sup>



# Estimating yield reductions

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

$f_{cap,max} \approx 20\%$   
 $Y_0 \approx 0.2 \times 200 \text{ GW} \approx 350 \text{ TWh/a}$   
 $Y_{ic} = 200 \text{ GW}$   
 $Y_{max} \approx 4 \text{ W m}^{-2} \times 0.5 \times 0.38 \times 3.6 \times 10^5 \text{ km}^2 \approx 2400 \text{ TWh/a}$

Yield:  $350 \text{ TWh a}^{-1} \rightarrow 320 \text{ TWh a}^{-1}$

$\approx -10\%$

## Impacts on the atmosphere

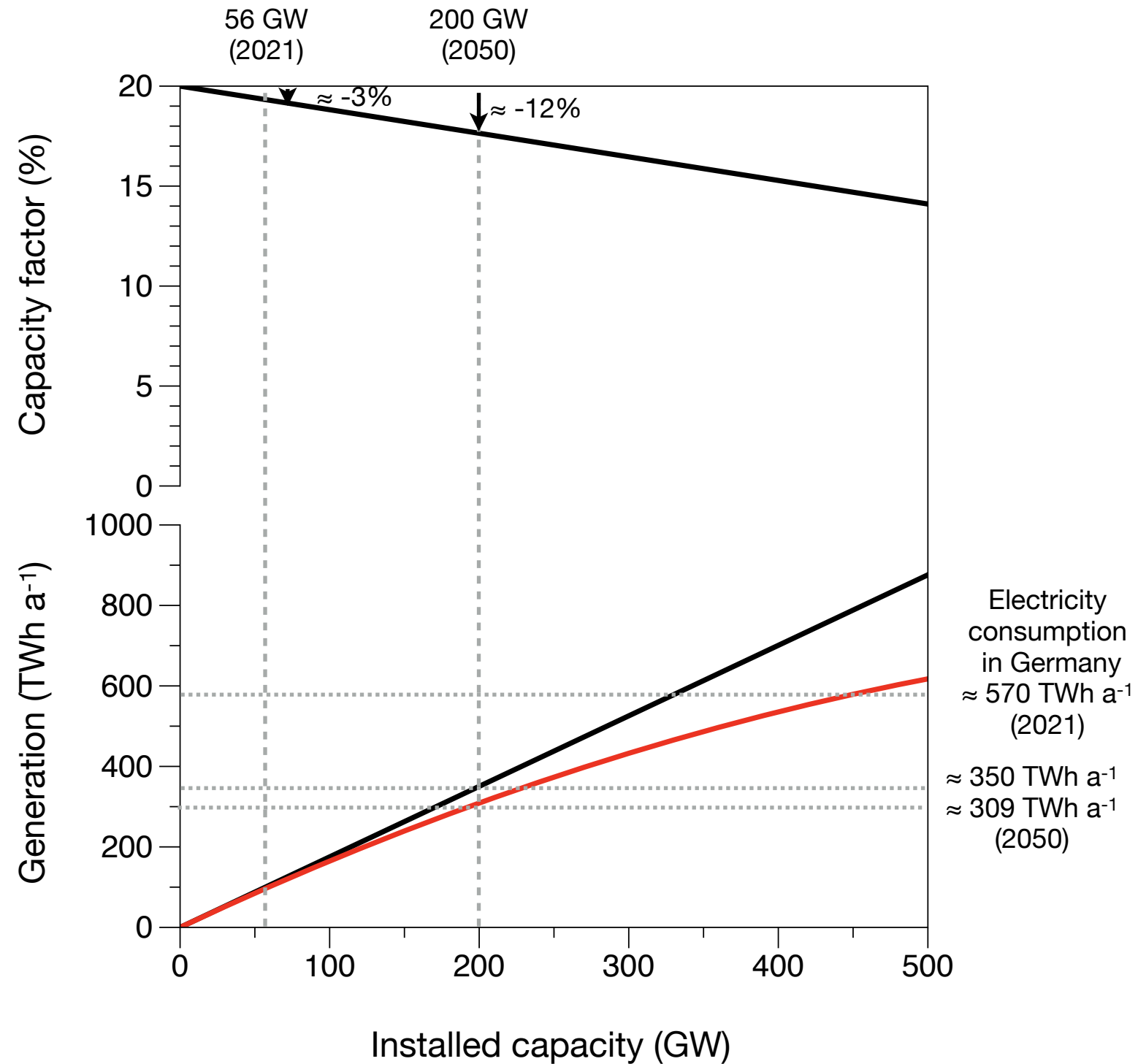
Frictional losses:

$$4 \text{ W m}^{-2} \times 3.6 \times 10^5 \text{ km}^2 \times 8760 \text{ h a}^{-1} = 12\,500 \text{ TWh a}^{-1}$$

Removal with 200 GW:

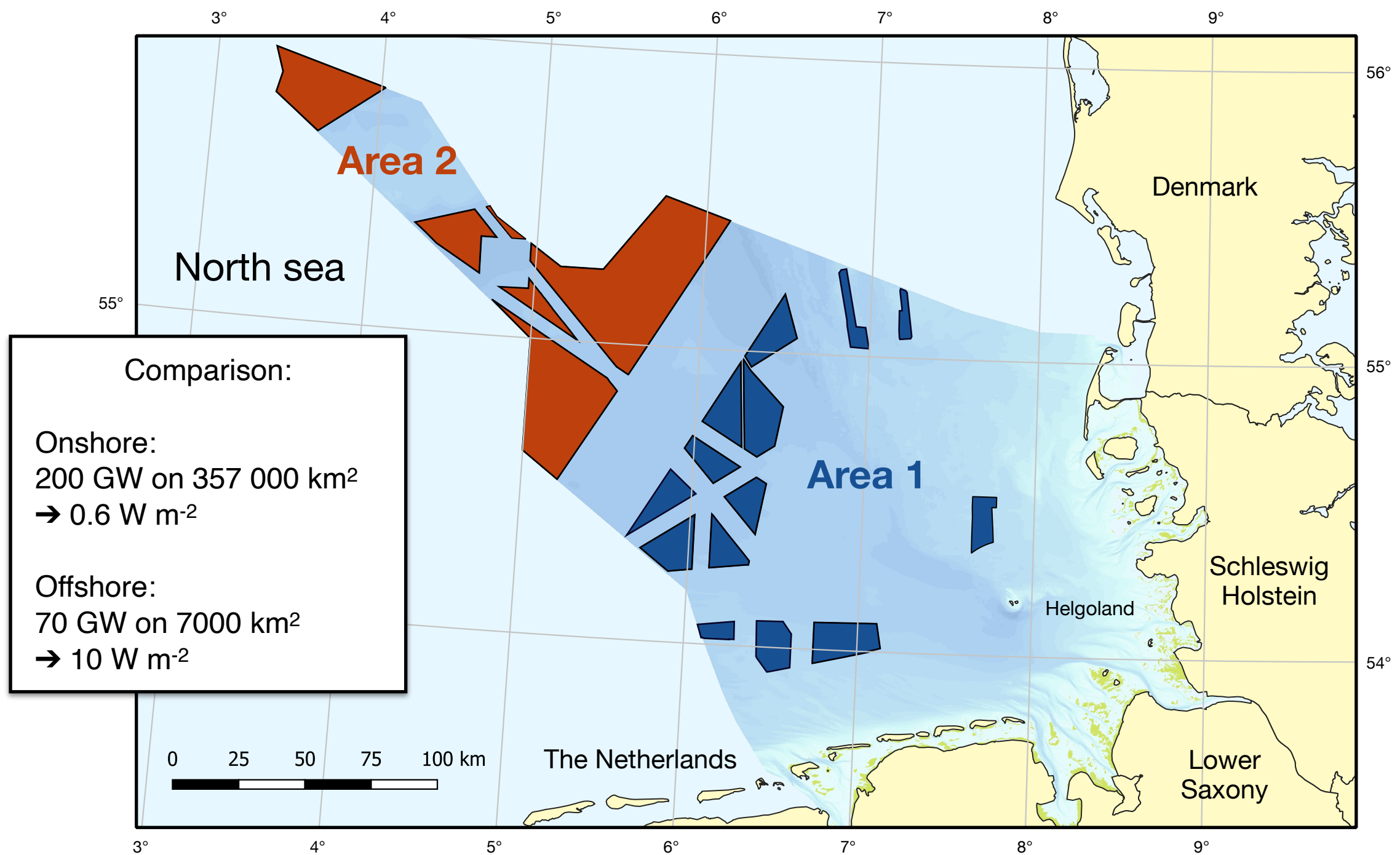
$$309 \text{ TWh a}^{-1} / 12\,500 \text{ TWh a}^{-1}$$

$= 2.5\%$



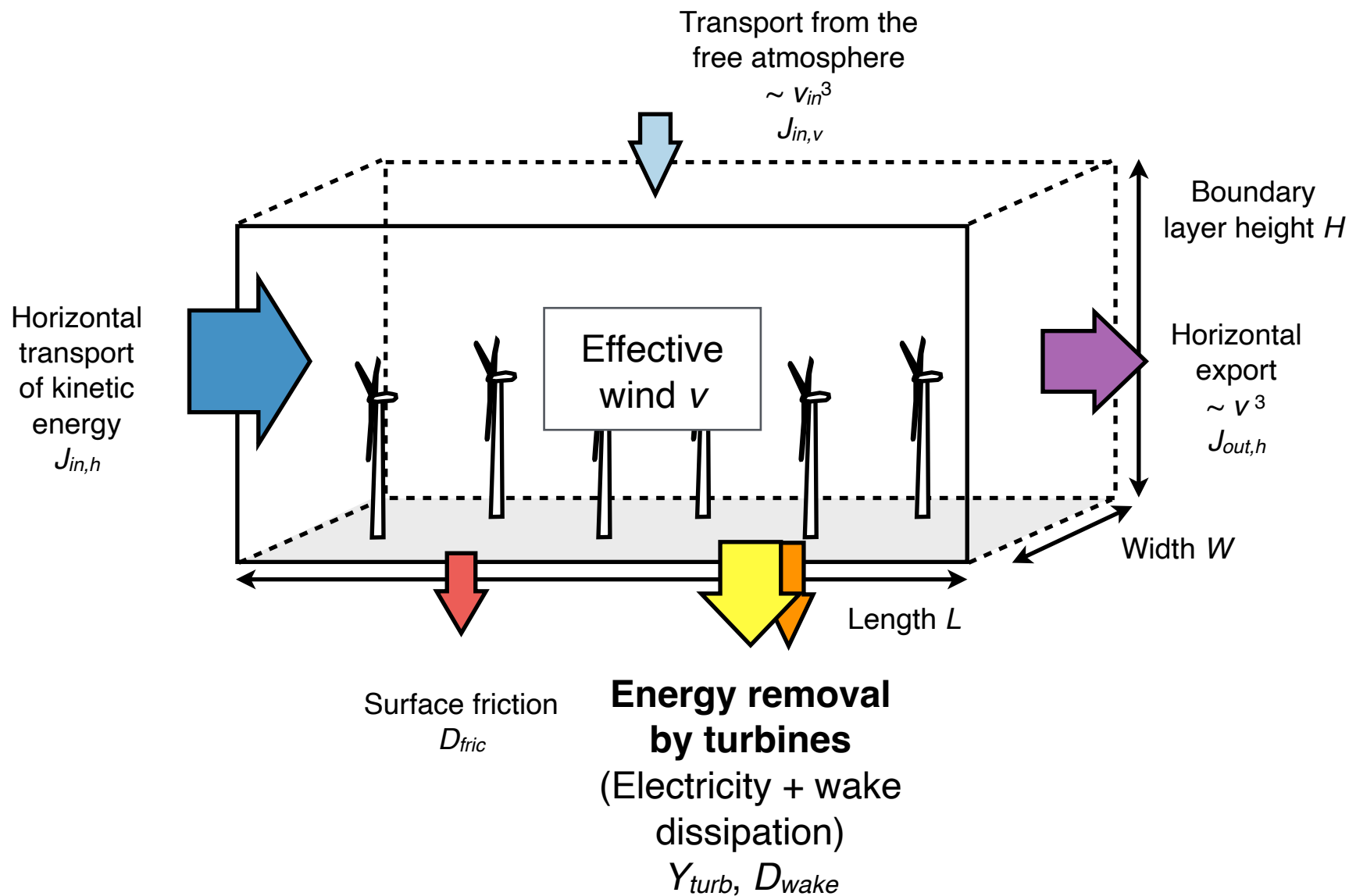
# Limits to Offshore Wind Energy







# 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:

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

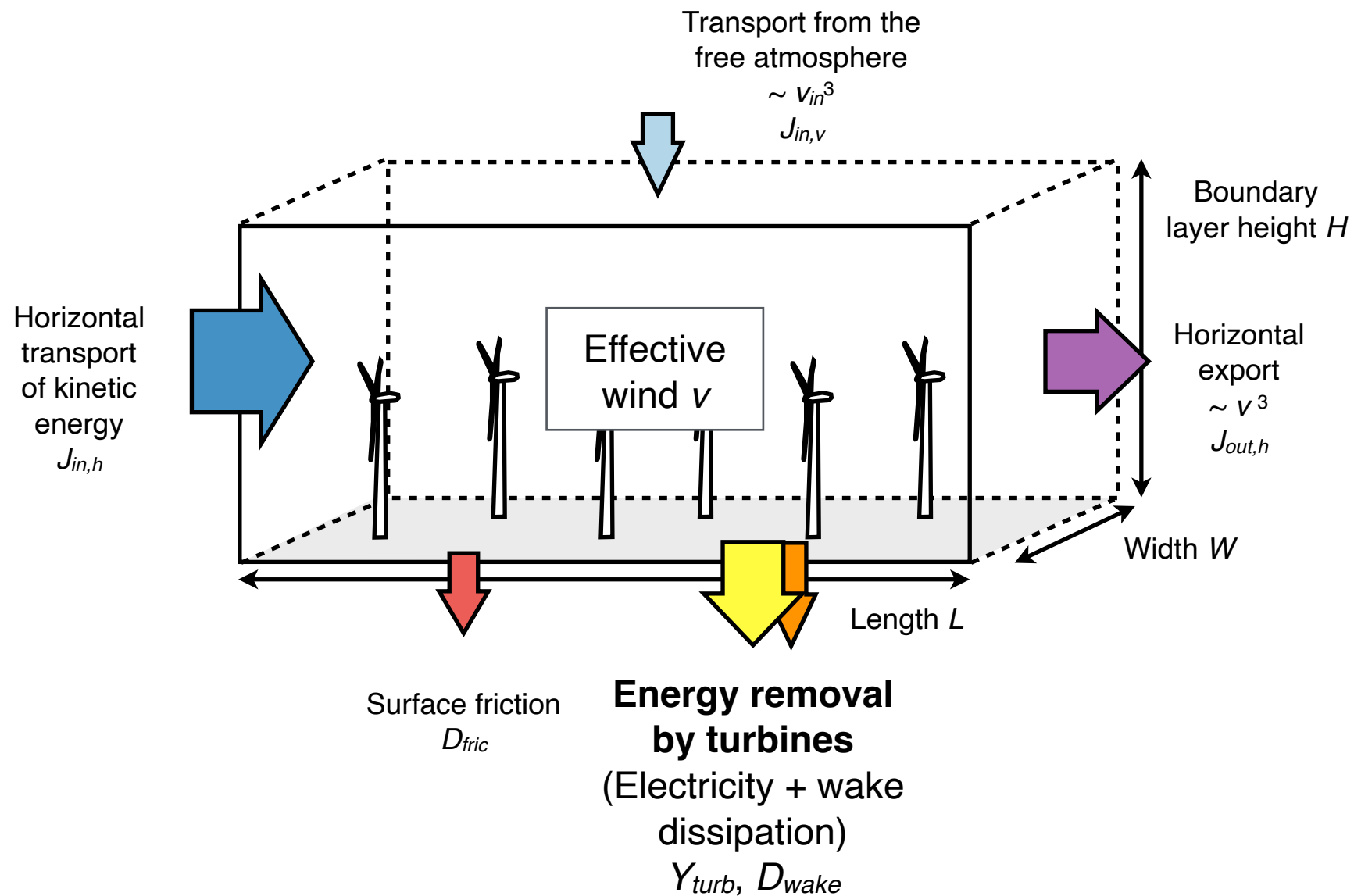
6. Generation by turbines:

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

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:

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

3. Removal, losses, exports:

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

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:

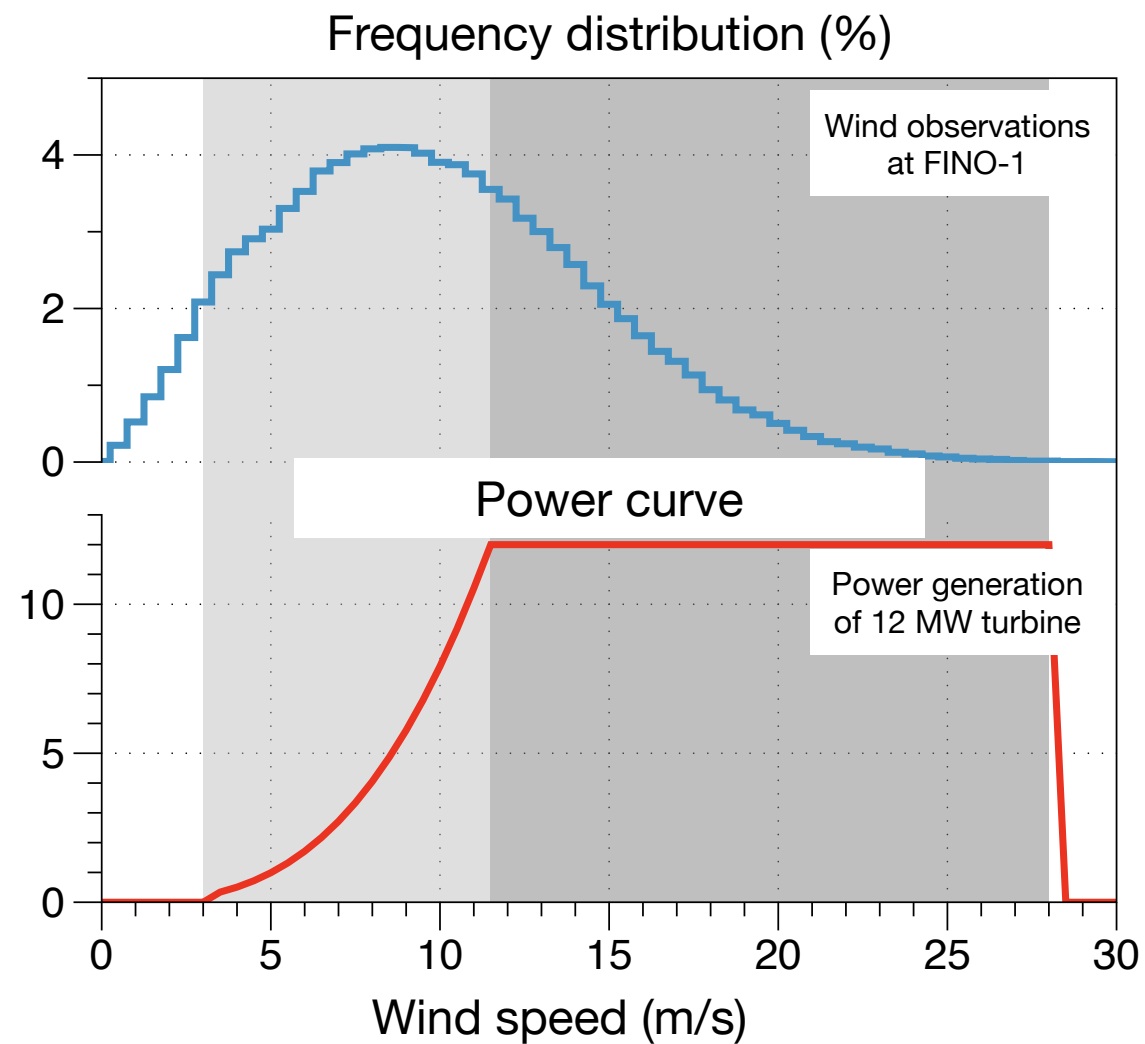
$$v = f_{red}^{1/3} \cdot v_{in}$$

6. Reduced yield:

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



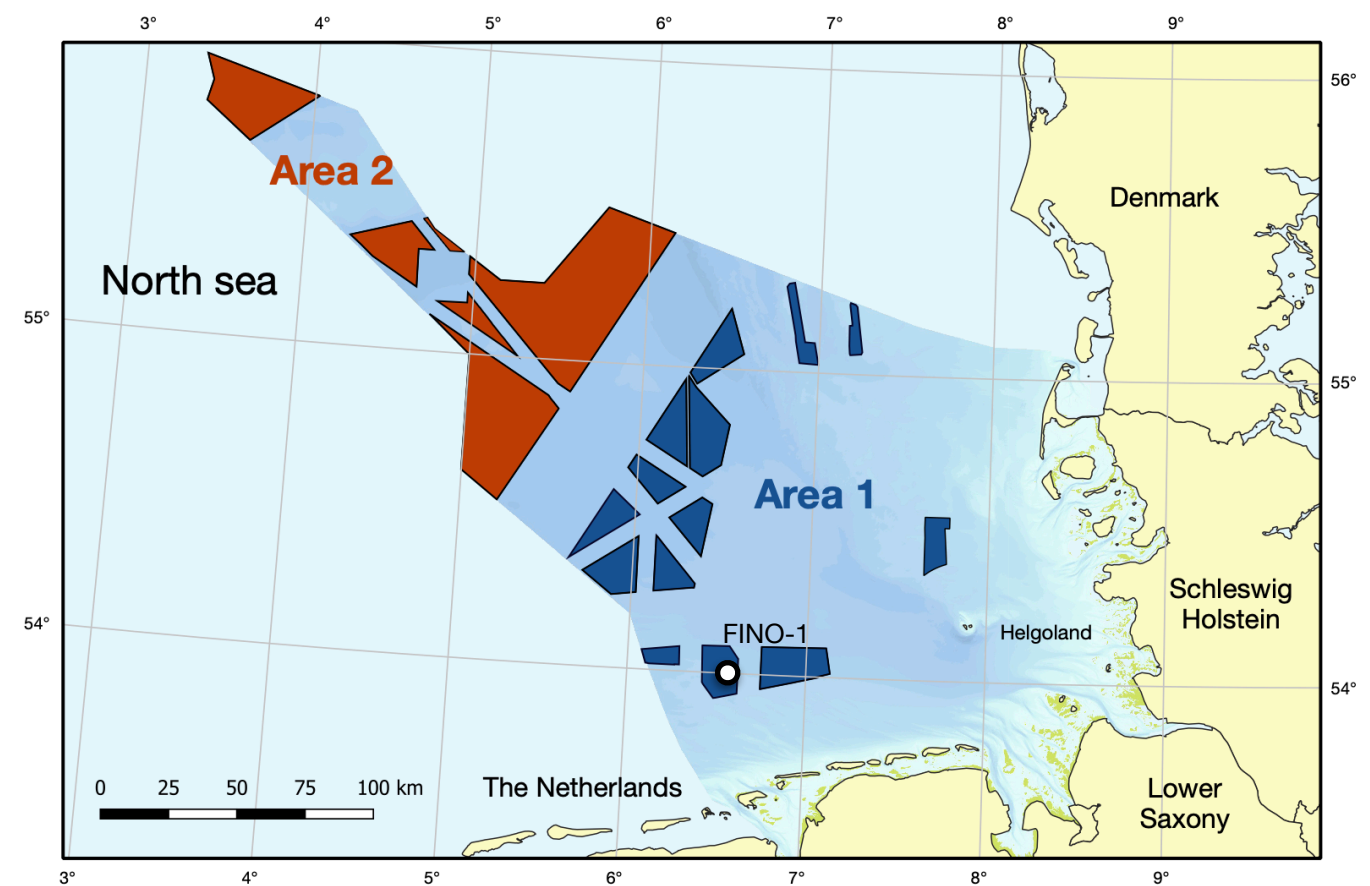
KEBA.xls



Wind speeds  $v_{in}$

Atmospheric characteristics  $H, C_d$

Turbine properties  $\eta, A_{rotor}$

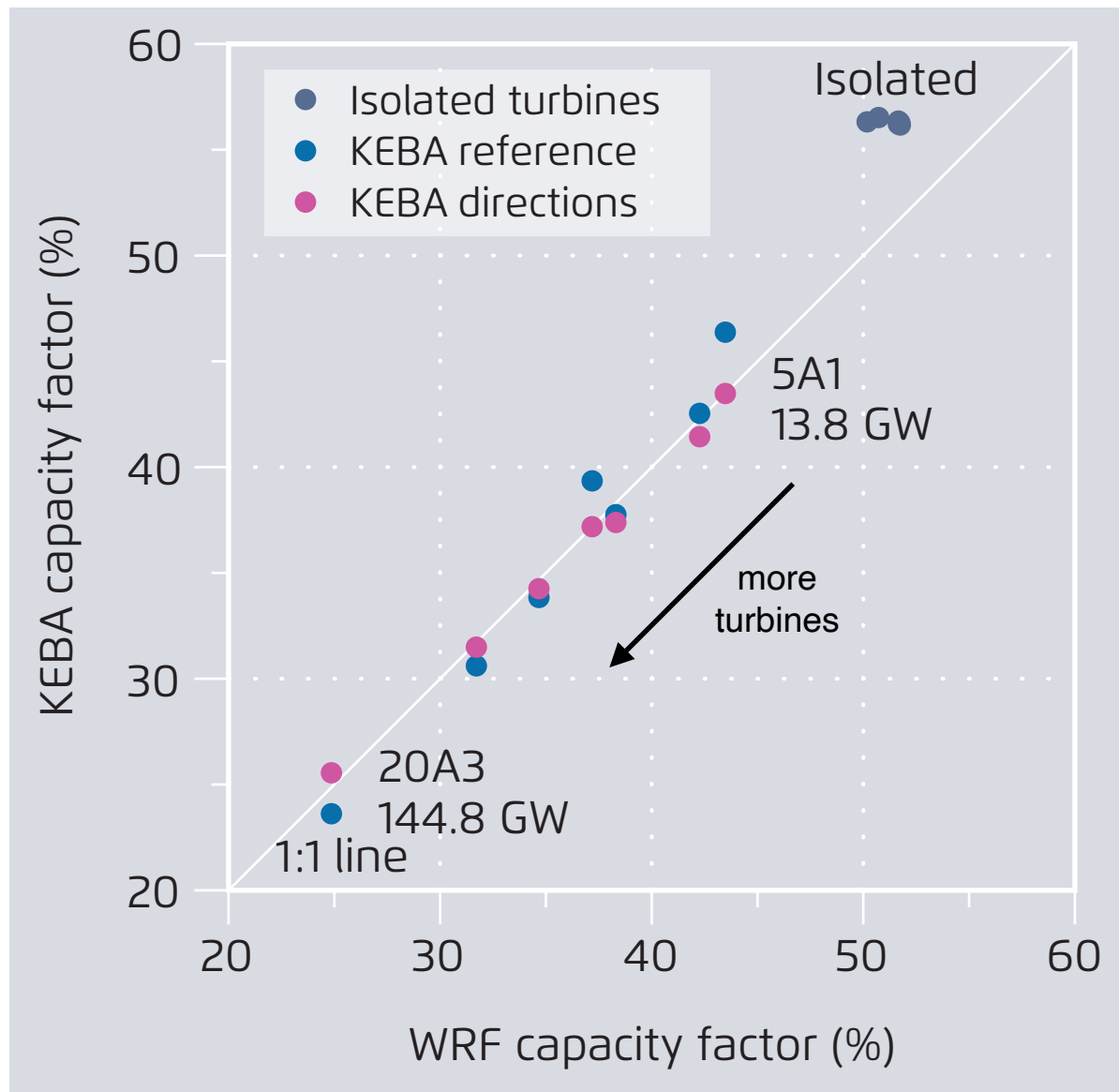


Spatial dimensions  $W, L$

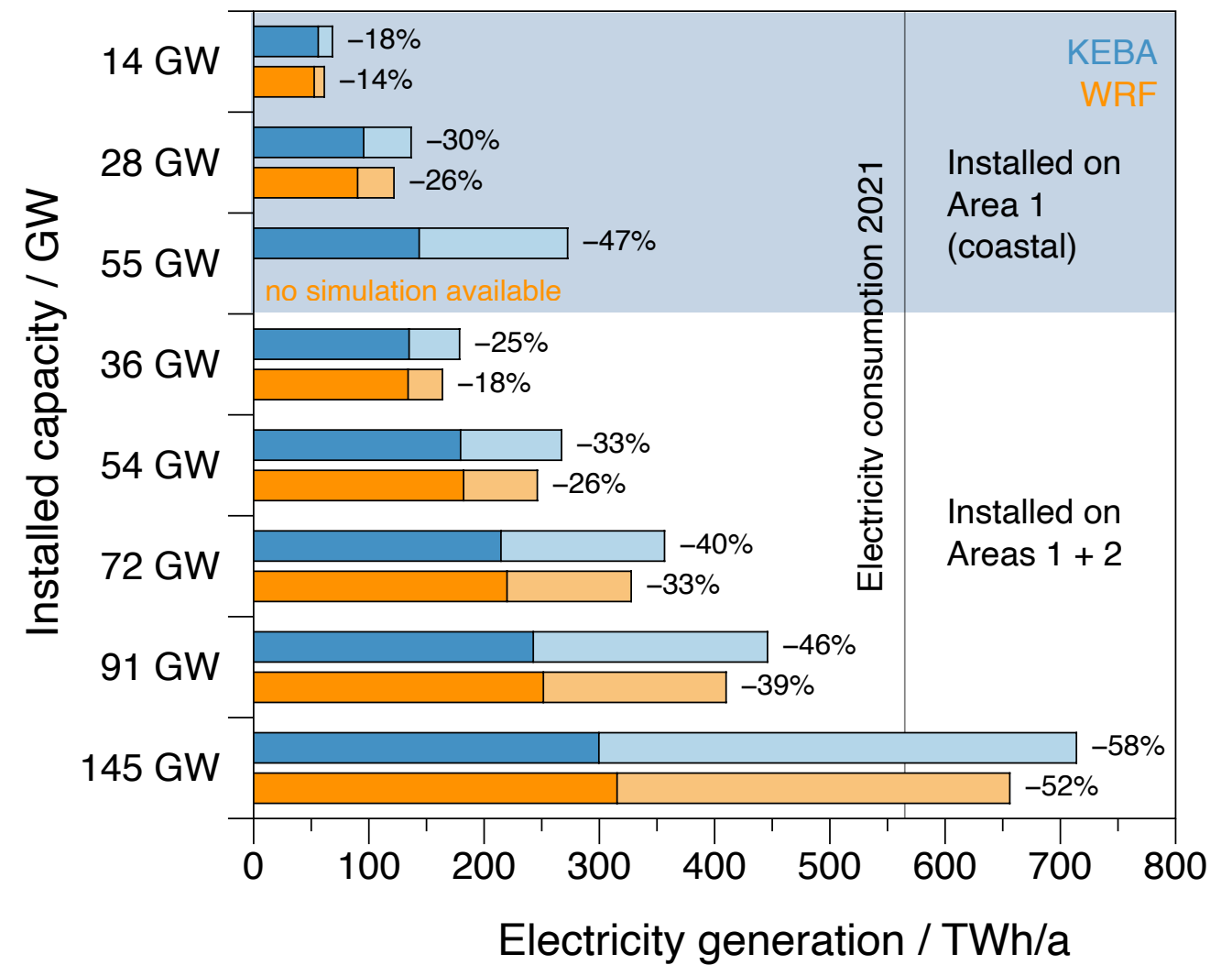
Number of turbines  $N$



# Comparison KEBA vs. numerical simulations (WRF)

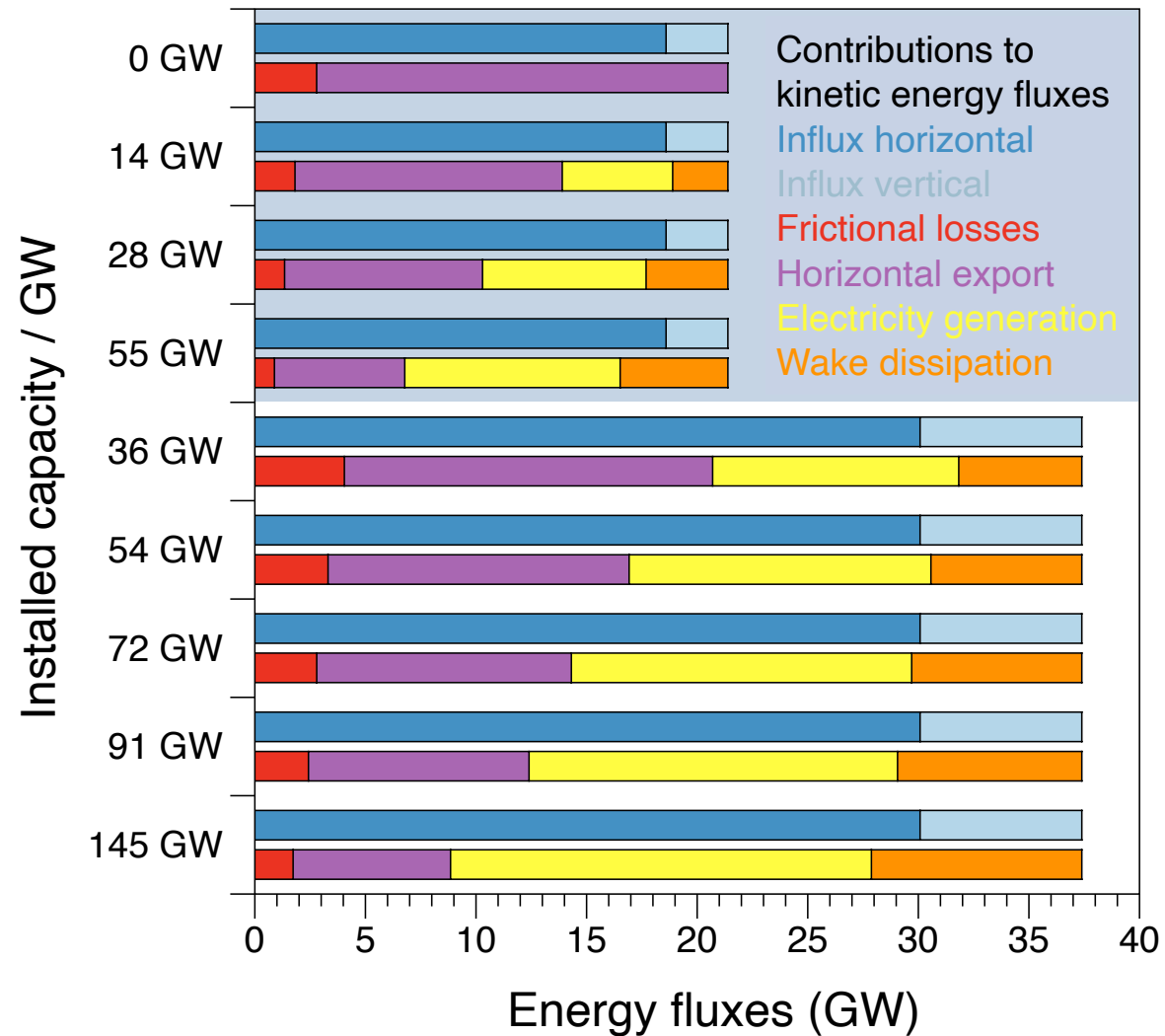
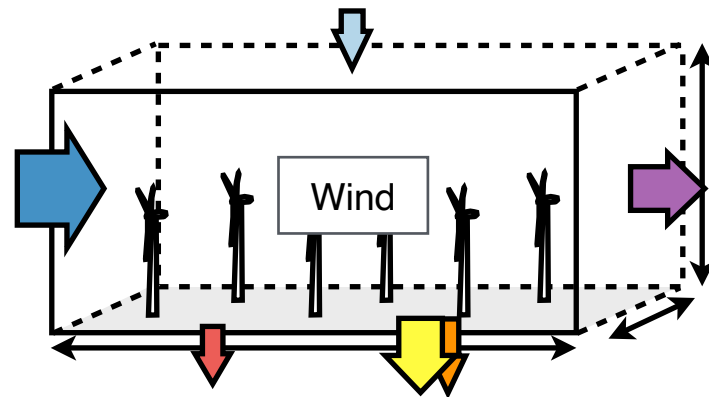


Capacity factor = Yield / capacity of the turbine



## Explanation

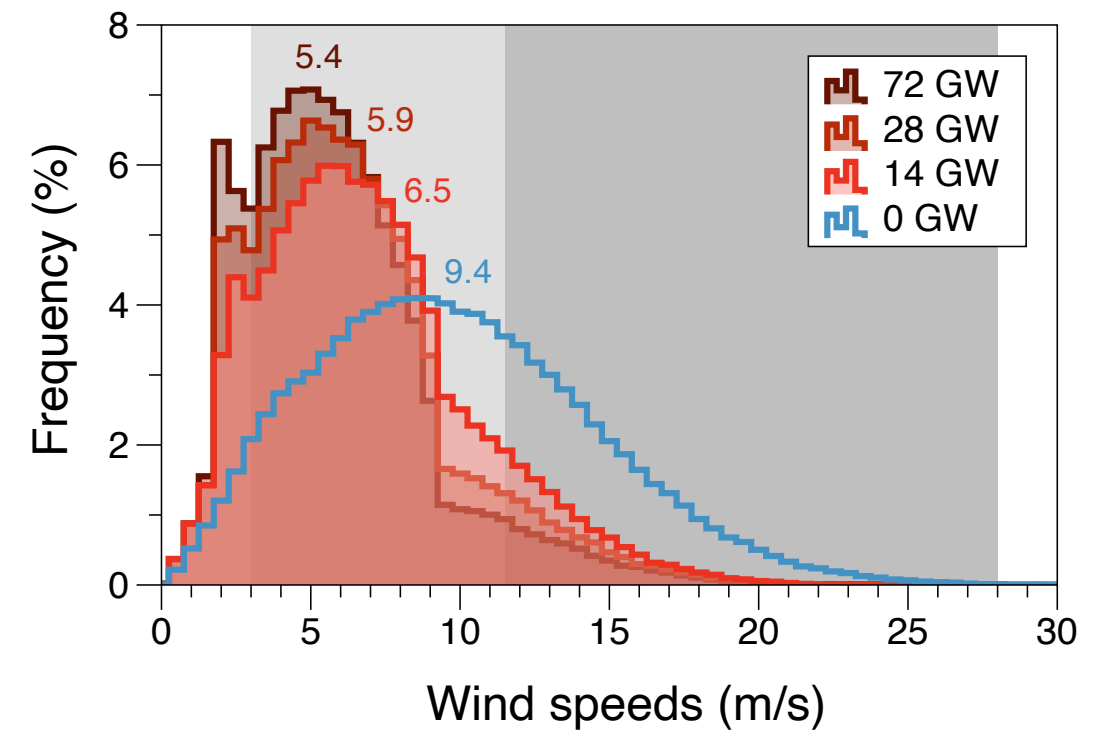
Budget of kinetic energy



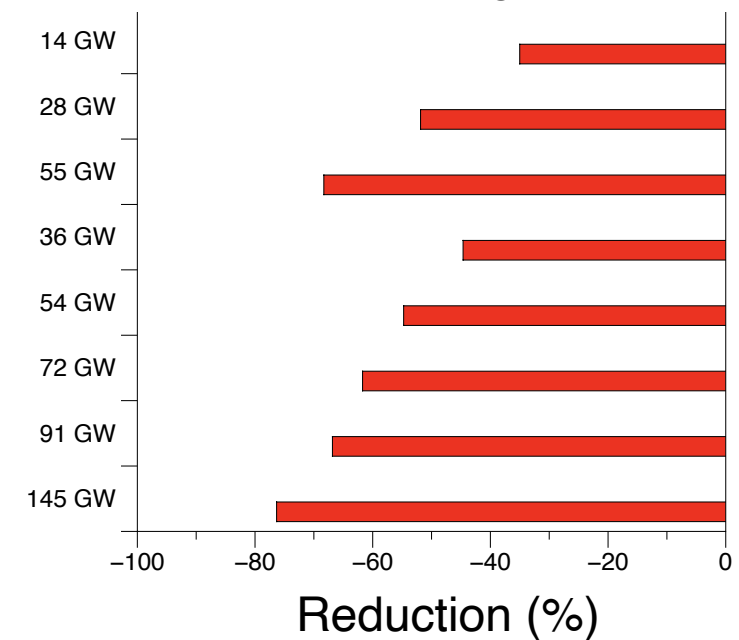
Installed in Area 1

Installed in Areas 1 + 2

## Impacts



Frictional loss  
(→ Waves, mixing, biota)



# Science Denial by Populists



**Wrong!**

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

136.5 TWh a<sup>-1</sup> Wind energy

508.1 TWh a<sup>-1</sup> Electricity generation

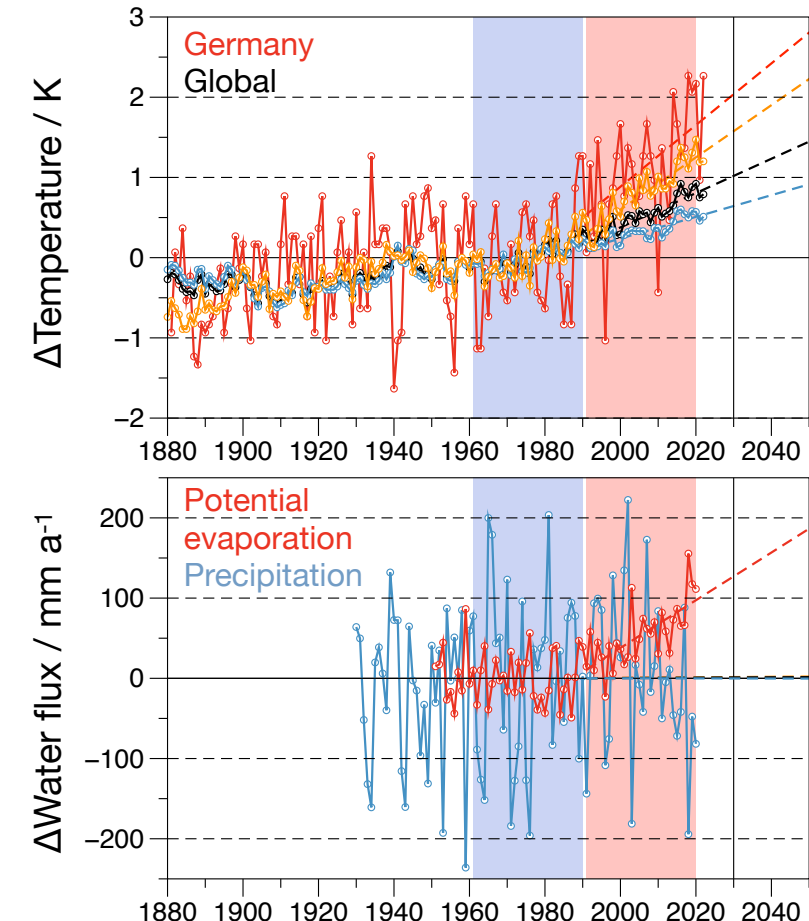
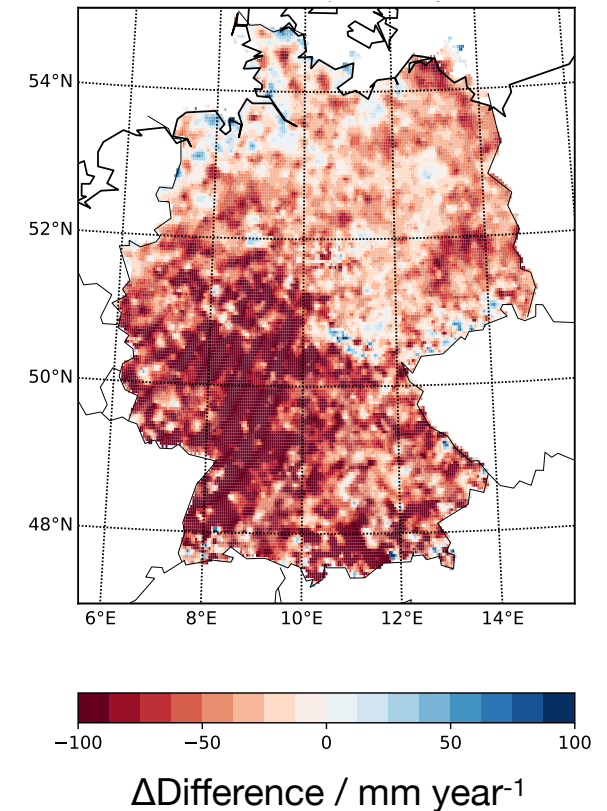


**Wrong!**

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)

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





# 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

Mateowl, Z. (Contrib. Atmos. Sci.), Vol. 30, No. 3, 203–225 (published online March 9, 2021)  
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## 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

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### Abstract

How much wind energy does the atmosphere generate, and how much of it can at best be used as renewable energy? This review aims to give physically-based answers to both questions, providing first-order estimates and sensitivities that are consistent with those obtained from numerical simulation models. The first part describes how thermodynamics determines how much wind energy the atmosphere is physically capable of generating at large scales from the solar radiative forcing. The work done to generate and maintain large-scale atmospheric motion can be seen as the consequence of an atmospheric heat engine, which is driven by the difference in solar radiative heating between the tropics and the poles. The resulting motion transports heat, which depletes this differential solar heating and the associated, large-scale temperature difference, which drives this energy conversion in the first place. This interaction between the thermodynamic driver (temperature difference) and the resulting dynamics (heat transport) is critical for determining the maximum power that can be generated. It leads to a maximum in the global mean generation rate of kinetic energy of about  $1.7 \text{ W m}^{-2}$  and matches rates inferred from observations of about  $2.1\text{--}2.5 \text{ W m}^{-2}$  very well. This represents less than 1 % of the total absorbed solar radiation that is converted into kinetic energy. Although it would seem that the atmosphere is extremely inefficient in generating motion, thermodynamics shows that the atmosphere works as hard as it can to generate the energy contained in the winds. The second part focuses on the limits of converting the kinetic energy of the atmosphere into renewable energy. Considering the momentum balance of the lower atmosphere shows that at large-scales, only a fraction of about 26 % of the kinetic energy can at most be converted to renewable energy, consistent with insights from climate model simulations. This yields a typical resource potential in the order of  $0.5 \text{ W m}^{-2}$  per surface area in the global mean. The apparent discrepancy with much higher yields of single wind turbines and small wind farms can be explained by the spatial scale of about 100 km at which kinetic energy near the surface is being dissipated and replenished. I close with a discussion of how these insights are compatible to established meteorological concepts, inform practical applications for wind resource estimations, and, more generally, how such physical concepts, particularly limits regarding energy conversion, can set the basis for doing climate science in a simple, analytical, and transparent way.

**Keywords:** Thermodynamics, Carnot limit, Maximum Entropy Production, maximum power limit, Lorenz energy cycle, Betz limit, wind energy, resource potential

### 1 Introduction

In the current transition to a sustainable energy system, renewable forms of energy, such as solar, wind energy, hydropower, and biofuels, play a central role. Wind energy, the use of the kinetic energy associated with atmospheric motion by wind turbines, is one of the more common forms of renewable energy that is used today. It has seen a rapid expansion in the recent two decades. In Europe, for instance, the installed capacity of wind turbines has more than doubled over the last decade from 77 GW at the end of 2009 to 205 GW at the end of 2019 (WindEurope, 2020). Some scenarios expect wind energy to continue to grow, considering 450 GW of installed capacity in offshore areas of Europe alone

in 2050, with about half to be installed in the North Sea (WindEurope, 2019). In Germany, wind energy on land has roughly doubled during the last decade, with an increase in installed capacity from 25.7 GW at the end of 2009 to 53.3 GW at the end of 2019, contributing more than 40 % of the renewably generated electricity in Germany (BMWi, 2020). Scenarios for 2050 envision the installed capacity of onshore wind energy in Germany to increase to 102–178 GW, with additional 51 GW–60 GW installed offshore (BDL, 2019; WWF, 2019).

Such an anticipated increased use of wind energy in the future raises questions about the limits to wind energy use. How much can wind energy, at most, contribute to human energy needs? Can wind energy meet the entire energy needs of industrialized countries? Is wind energy so abundant that it can continuously power all human civilization, as some scientists have argued

\*Corresponding author: Axel Kleidon, Max-Planck-Institute for Biogeochemistry, Hans-Knoell-Str. 10, 07745 Jena, Germany, akleidon@bgc-jena.mpg.de



## Making the Most of Offshore Wind

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

### STUDY



Max Planck Institute  
for Biogeochemistry



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Earth System  
Dynamics



Review

## 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

**Correspondence:** Axel Kleidon (akleidon@bgc-jena.mpg.de)

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**Abstract.** Optimality concepts related to energy and entropy have long been proposed to govern Earth system processes, for instance in the form of propositions that certain processes maximize or minimize entropy production. These concepts, however, remain quite obscure, seem contradictory to each other, and have so far been mostly disregarded. This review aims to clarify the role of thermodynamics and optimality in Earth system science by showing that they play a central role in how, and how much, work can be derived from solar forcing and that this imposes a major constraint on the dynamics of dissipative structures of the Earth system. This is, however, not as simple as it may sound. It requires a consistent formulation of Earth system processes in thermodynamic terms, including their linkages and interactions. Thermodynamics then constrains the ability of the Earth system to derive work and generate free energy from solar radiative forcing, which limits the ability to maintain motion, mass transport, geochemical cycling, and biotic activity. It thus limits directly the generation of atmospheric motion and other processes indirectly through their need for transport. I demonstrate the application of this thermodynamic Earth system view by deriving first-order estimates associated with atmospheric motion, hydrologic cycling, and terrestrial productivity that agree very well with observations. This supports the notion that the emergent simplicity and predictability inherent in observed climatological variations can be attributed to these processes working as hard as they can, reflecting thermodynamic limits directly or indirectly. I discuss how this thermodynamic interpretation is consistent with established theoretical concepts in the respective disciplines, interpret other optimality concepts in light of this thermodynamic Earth system view, and describe its utility for Earth system science.

### 1 Introduction

The Earth system is an incredibly complex system, with many processes interacting with each other, from the small and local scale up to the planetary scale. With human activity playing an increasing role, it appears that the system becomes even more complicated. This may seem to make the Earth a highly unpredictable and chaotic system, with arbitrary evolutionary directions and outcomes. It would seem that the only contribution from physics to constrain the dynamics of this complex system comes from the basic conservation laws, as these provide the accounting basis for energy, mass, and momentum as well as other conserved quantities. Yet, on the other hand, we observe various forms of relatively simple emergent patterns in the Earth system that re-

flect highly predictable outcomes. Such emergent simplicity is, for instance, reflected in highly predictable seasonal and geographic variations of temperature and precipitation that have led to climate classifications (e.g. Köppen, 1900), in typical surface energy balance partitioning and associated hydrologic classification schemes, such as the aridity index of Budko (1974) that can be used to describe clear and predictable changes in partitioning with increasing aridity, and in the well-documented variation of terrestrial biomes along gradients in climate (e.g. von Humboldt, 1845; Holdridge, 1947; Whittaker, 1962; Prentice et al., 1992). How does this simplicity emerge from the dynamics of such a complex system? It would seem that there are further constraints at play when it comes to such predictable aspects of the Earth sys-

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### OFFSHORE-WIND ENERGY | RENEWABLE ENERGY

#### Wind energy potential of the German Bight

Limits and consequences of large-scale offshore wind energy use

Axel Kleidon

*The wind blows stronger and more reliably over the sea than over land. Thus, offshore wind energy is expected to make a major contribution to the energy transition in Germany, especially in the German Bight. But what happens when a growing number of wind farms extract more and more wind energy from the atmosphere?*

The challenges of the energy transition for the next decades in Germany are enormous. It is true that 15.9 % of primary energy demand was already covered by renewable energy in 2021 [1], and a lower energy demand is expected in the future due to more modern technologies such as heat pumps and electromobility. However, the transition to a complete, sustainable energy system that is free of fossil fuels is still a long way off.

Many energy transition scenarios focus on the expansion of a combination of solar and wind energy. These two types of renewable energy have the greatest potential in Germany [2] and complement each other very well over the course of the year: while the Sun can supply a particularly large amount of renewable energy in summer, it fails in winter. This can be compensated for by wind energy, as the dark winter months are usually stormier than the summer.

Wind power generation at sea plays a special role in these scenarios. Wind blows stronger and more continuously at sea than on land, so it can generate electricity more efficiently and reliably. In Germany, expansion is planned mainly in the German Bight of the North Sea, where the exclusive economic zone - i.e. the part of the sea that is administered by Germany beyond the territorial sea - offers considerably more surface area than the Baltic Sea. For example, wind farms with 6.7 GW of installed capacity are currently located in the North Sea, compared to only 1.1 GW in the Baltic Sea (as of 2021, [3]). In 2021, these wind farms contributed about 24 TWh/a or 4.9 % to the German electricity demand of 491 TWh/a, which means that the turbines were utilized to an average of 35 % - the so-called capacity factor [3]. Wind turbines at sea were thus almost twice as productive as on land, where the capacity factor was only 18 %.

By 2050, it is assumed that the use of offshore wind energy will increase significantly more than on land, i.e. onshore. In its coalition agreement, the German government has targeted the expansion of offshore wind energy to 70 GW, i.e. roughly a tenfold increase in currently installed capacity. Onshore, there is already 56 GW of turbine capacity, and an expansion to around 200 GW is expected here, distributed over 2 % of the country's surface area. However, with 357,000 km<sup>2</sup> there is considerably more space than in the exclusive economic zone of the North Sea, which is only 28,600 km<sup>2</sup> in size. So the plans envisage a much more intensive use of wind energy at sea than on land. And because each wind turbine draws energy from the atmosphere and thus weakens the winds, the question arises whether, with such a strong expansion, the turbines could take the wind away from each other and thus endanger the high yields.

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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<sup>1</sup> and Lee M. Miller<sup>2</sup>

<sup>1</sup>Biospheric Theory and Modelling Group, Max-Planck-Institut für Biogeochemie, Jena, Germany

<sup>2</sup>Atmospheric and Environmental Research, Lexington, MA, USA

**Correspondence:** Axel Kleidon (akleidon@bgc-jena.mpg.de)

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**Abstract.** With the current expansion of wind power as a renewable energy source, wind turbines increasingly extract kinetic energy from the atmosphere, thus impacting its energy resource. Here, we present a simple, physics-based model (the Kinetic Energy Budget of the Atmosphere; KEBA) to estimate wind energy resource potentials that explicitly account for this removal effect. The model is based on the regional kinetic energy budget of the atmospheric boundary layer that encloses the wind farms of a region. This budget is shaped by horizontal and vertical influx of kinetic energy from upwind regions and the free atmosphere above, as well as the energy removal by the turbines, dissipative losses due to surface friction and wakes, and downwind outflow. These terms can be formulated in a simple yet physical way, yielding analytic expressions for how wind speeds and energy yields are reduced with increasing deployment of wind turbines within a region. We show that KEBA estimates compare very well to the modelling results of a previously published study in which wind farms of different sizes and in different regions were simulated interactively with the Weather Research and Forecasting (WRF) atmospheric model. Compared to a reference case without the effect of reduced wind speeds, yields can drop by more than 50 % at scales greater than 100 km, depending on turbine spacing and the wind conditions of the region. KEBA is able to reproduce these reductions in energy yield compared to the simulated climatological means in WRF ( $n = 36$  simulations;  $r^2 = 0.82$ ). The kinetic energy flux diagnostics of KEBA show that this reduction occurs because the total yield of the simulated wind farms approaches a similar magnitude to the influx of kinetic energy. Additionally, KEBA estimates the slowing of the region's wind speeds, the associated reduction in electricity yields, and how both are due to the depletion of the horizontal influx of kinetic energy by the wind farms. This limits typical large-scale wind energy resource potentials to less than  $1 \text{ W m}^{-2}$  of surface area for wind farms with downwind lengths of more than 100 km, although this limit may be higher in windy regions. This reduction with downwind length makes these yields consistent with climate-model-based idealized simulations of large-scale wind energy resource potentials. We conclude that KEBA is a transparent and informative modelling approach to advance the scientific understanding of wind energy limits and can be used to estimate regional wind energy resource potentials that account for the depletion of wind speeds.

### 1 Introduction

The use of wind energy as a renewable energy resource has substantially increased over the last decades in the attempt to decarbonize the energy system. Particularly wind over the sea is seen as a tremendous yet under-utilized energy resource. In Europe alone, the current installed capacity of 22 GW in offshore wind power has increased by 3.5 GW in 2019 (WindEurope, 2019a). It is expected to expand further to 450 GW and more by 2050 (WindEurope, 2019b), playing

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### ONSHORE-WIND ENERGY | RENEWABLE ENERGY

#### Wind energy potential of Germany

Limits and consequences of large-scale wind energy use

Axel Kleidon

*The transition of our energy system to renewable energies is necessary in order not to heat up the climate any further and to achieve climate neutrality. The use of wind energy plays an important role in this transition in Germany. But how much wind energy can be used and what are the possible consequences for the atmosphere if more and more wind energy is used?*

The German government wants to achieve the goal of a climate-neutral energy system by 2050. This goal envisages a strong expansion of wind energy, and 2 % of Germany's surface area is to be made available for this purpose. Scenarios from various institutions translate this into about 150 - 200 gigawatts of installed capacity, contributing 330 - 770 TWh per year to electricity generation. As an example, we refer to the studies by Agora Energiewende and the German Wind Energy Association [1, 2]. Currently, only 56 GW of capacity is installed, distributed across 28230 wind turbines located in Germany at the end of 2021 [3]. These wind turbines generated 90.3 TWh/year of electricity, contributing just under 16 % to the current electricity generation of 570 TWh per year (as of 2021, [4]). This means that we need a strong increase in wind turbine installations in the coming decades to achieve the goal of climate neutrality.

But how much wind energy is there in Germany, and how much of it can be used? What are the effects on the atmosphere if more and more kinetic energy is extracted from it by the wind turbines? While such energy scenarios often focus on what is technically possible, here we want to look at the physics of the atmosphere and derive simple estimates that can provide answers to these questions.

#### How wind energy comes to Germany

In order to estimate how much wind energy can be used in Germany, we first look at where wind energy comes from and how much of it comes to Germany. Wind turbines in Germany mainly use large-scale winds associated with the high and low pressure systems in the mid-latitudes. These are directly linked to the large-scale atmospheric circulation. This circulation is driven by planetary differences in solar radiation: tropical areas absorb more solar radiation than mid-latitudes and polar areas, thus the tropics are warmer and the poles colder. Temperature differences lead to different air densities, these cause air pressure to drop less with altitude in warm areas, which generates potential energy. This in turn is associated with differences in air pressure in the middle atmosphere, where most of the weather activity takes place. Air is accelerated, mass is moved and rearranged, thus potential energy is dissipated, heat is transported and the differences in solar heating are depleted. Kinetic energy plays a central role in this process, as it is directly linked to motion and heat transport. It is embedded as a form of energy in the conversion chain from incident solar energy to heating differences, which leads to potential energy from which kinetic energy is extracted, which is ultimately converted back into heat by friction and radiated from the Earth into space in the form of longwave radiation.

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