The Kinetic Energy Budget of the Atmosphere (KEBA) approach: Estimating wind power potentials that account for the kinetic energy removal by wind turbines

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Atmospheric model simulations show that turbine yields decline as wind energy use expands in scale because of wind speed reductions.

How can these yield reductions due to interactions with the atmosphere be accounted for?
Budgeting the kinetic energy of the lower atmosphere yields analytic expressions to predict wind speed and yield reductions.

Downward influx of kinetic energy:
\[ J_{in,v} = \rho C_d v_{in}^3 \]

Horizontal influx of kinetic energy:
\[ J_{in,h} = \rho/2 v_{in}^3 \]

Turbulent dissipation:
\[ D_{fric} = \rho C_d v^3 \]

Energy extraction by wind turbines:
\[ v = f_{red}^{1/3} \cdot v_{in} \]
\[ P_{el,tot} = f_{red} \cdot N \cdot P_{el,iso} \]

Effective velocity:
\[ v = f_{red}^{1/3} \cdot v_{in} \]

KEBA equations yields a reduction factor \( f_{red} \), reducing the yield compared to an isolated turbine.
The KEBA Model

The KEBA equations are implemented in an Excel spreadsheet, including:
- wind forcing
- atmospheric characteristics
- turbine characteristics
- scenario specifications
- yield estimates (yellow)
Testing KEBA

Wind forcing from 3 Regions:
- Central US
- North sea
- Strait of Magellan

Input: Wind climate, atmospheric characteristics, power curve, scenarios

Scenarios:
- 3 spacings (W, I, N)
- 4 sizes (S, M, L, XL), ranging from \( L = 5-340 \) km

Output:
- Electricity yields
- Wind speed reduction
- Energy fluxes

KEBA implemented as Excel spreadsheet

\[
\text{KEBA model}
\]

Energy extraction by wind turbines (electricity yield \( P_{\text{el,tot}} \) + wake dissipation \( D_{\text{wake}} \))

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\begin{align*}
\text{Downward influx of kinetic energy} & \quad J_{\text{in,v}} = \rho C_d v_{\text{in}}^3 \\
\text{Horizontal influx of kinetic energy} & \quad J_{\text{in,h}} = \rho C_d v_{\text{in}}^3 \\
\text{Turbulent dissipation} & \quad D_{\text{fric}} = \rho C_d v_{\text{in}}^3 \\
\text{Horizontal outflux of kinetic energy} & \quad J_{\text{out,h}} = \rho C_d v_{\text{in}}^3 \\
\text{Effective velocity} & \quad v_{\text{eff}} = \sqrt{v^2 - D_{\text{fric}}} \\
\end{align*}
\]

WRF simulations from: Volker et al (2017), ERL
KEBA estimates compare very well to WRF-based estimates of Volker et al. (2017) across a set of sensitivities.
Interpreting KE Budgets

Diagnosed kinetic energy (KE) fluxes show that yields (yellow) of large wind farms (> 100 km) get close to how much wind energy enters the box (blue).

Hence, wind speeds and yields per turbine are reduced.

Energy fluxes (left) have the same color as arrows in the KEBA diagram (below).
When downwind length of wind farms increases, the horizontal inflow of kinetic energy becomes less important, while the vertical mixing becomes more important.

Hence, at larger scales, the wind energy yields converge from initially large (> 1 W m\(^{-2}\)) to a low limit of < 1 W m\(^{-2}\) per surface area.
Summary

The Kinetic Energy Budget of the Atmosphere (KEBA):
A physics-based method to account for wind speed and yield reductions in large wind farms
Works very well compared to WRF simulations
Provides explanations why wind energy potentials decline to < 1 W m⁻² at large, downwind scales \( L > 100 \text{ km} \)

More Information:
Application to German Offshore wind energy potentials
https://www.agora-energiewende.de/projekte/offshore-wind-potenzial/

KEBA Spreadsheet available on MPG Data Repository
https://edmond.mpdl.mpg.de/imeji/collection/ctvrVzG7CpKsqBB?q=

Manuscript has been submitted

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