A Dynamic Function for the **E**nergy **R**eturn **o**n **I**nvestment (EROI) of Wind Energy

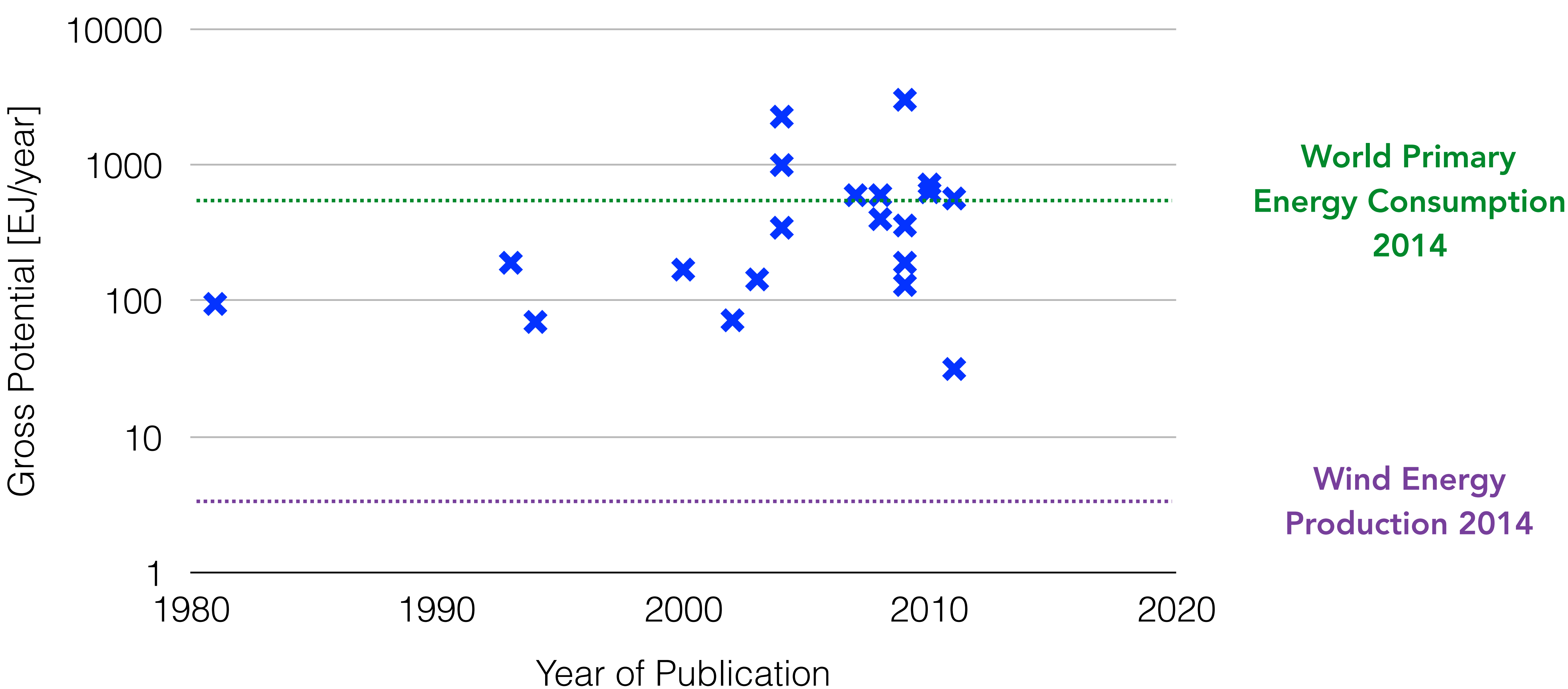
Elise Dupont[1], Rembrandt Koppelaar[2,3] and Hervé Jeanmart[1]

1. iMMC - Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, Belgium
2. Centre for Environmental Policy, Faculty of Natural Science, Imperial College London
3. Institute for Integrated Economic Research, London

Wind Energy Science Conference 2017, Copenhagen

What is the global potential of wind energy ?

Global wind potential estimates:

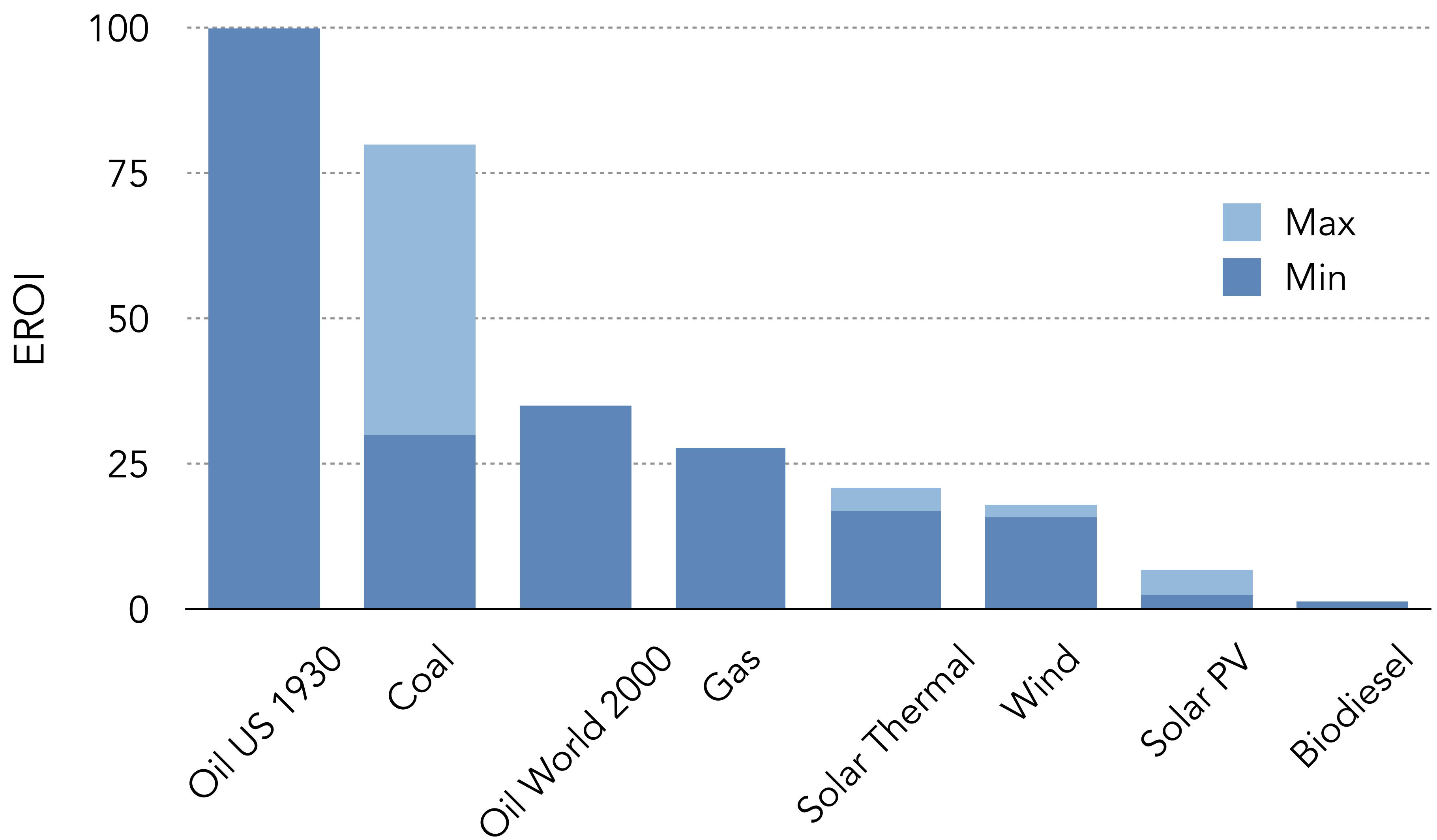


Physical limits are often overlooked !

Net Energy fuels society

Net Energy = Energy Produced - Energy Invested

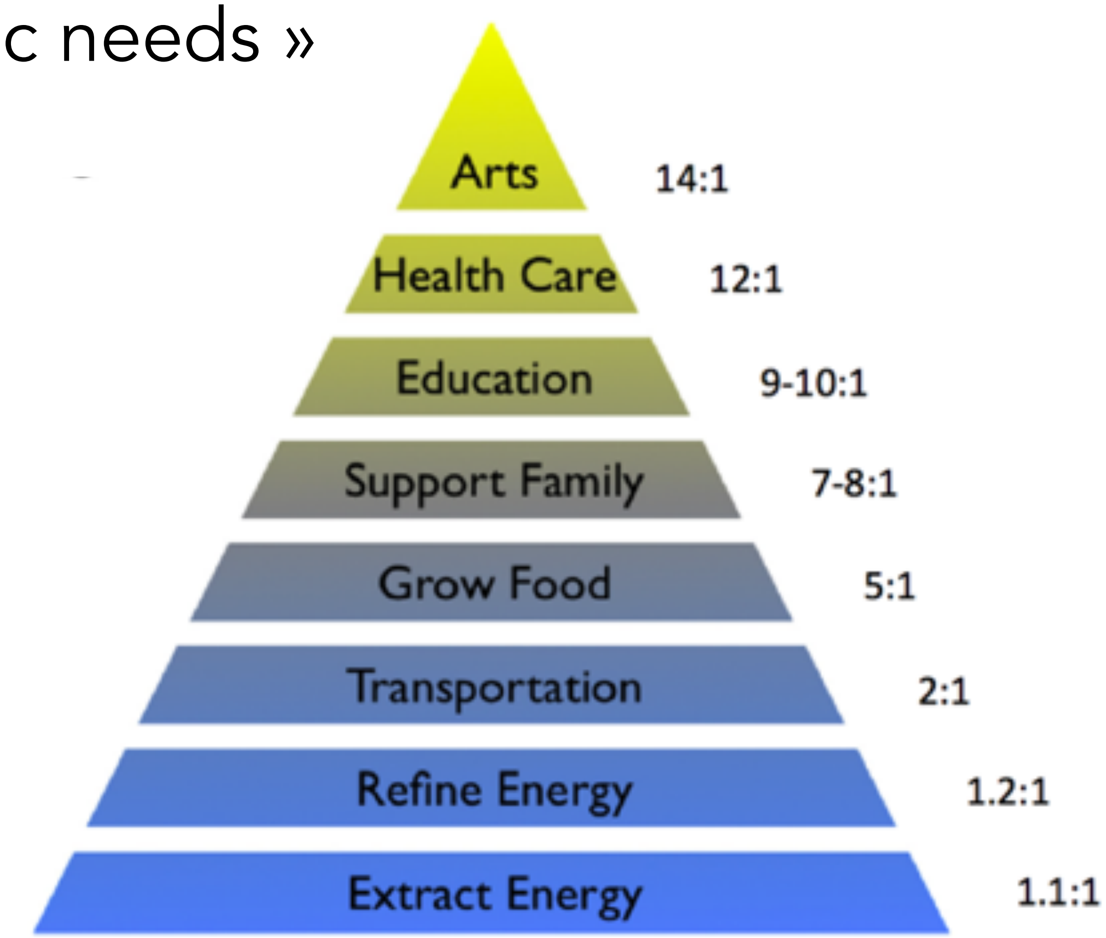
$$\textbf{Energy Return on Investment: EROI} = \frac{\text{Energy Produced}}{\text{Energy Invested}}$$



Data from: Year in review—EROI or energy return on (energy) invested, Murphy D. & Hall C.

Minimum EROI to sustain living standards

Society’s Hierarchy
of « energetic needs »



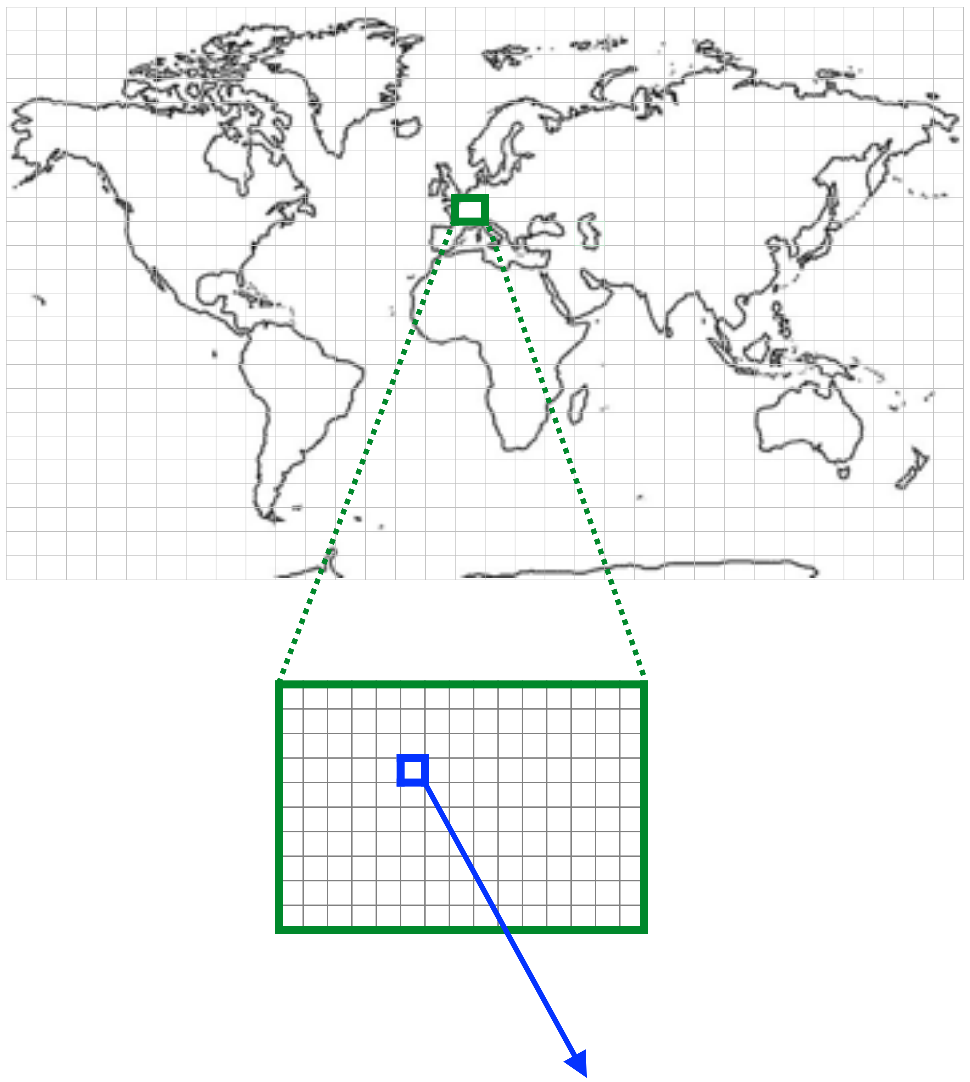
Speculative values

Published Values
for conventional oil

Energy, EROI and quality of life, Lambert et al., 2014

Importance to assess the amount of net energy
and the associated EROI !

What is the EROI of wind energy ..
.. and how will it evolve ?



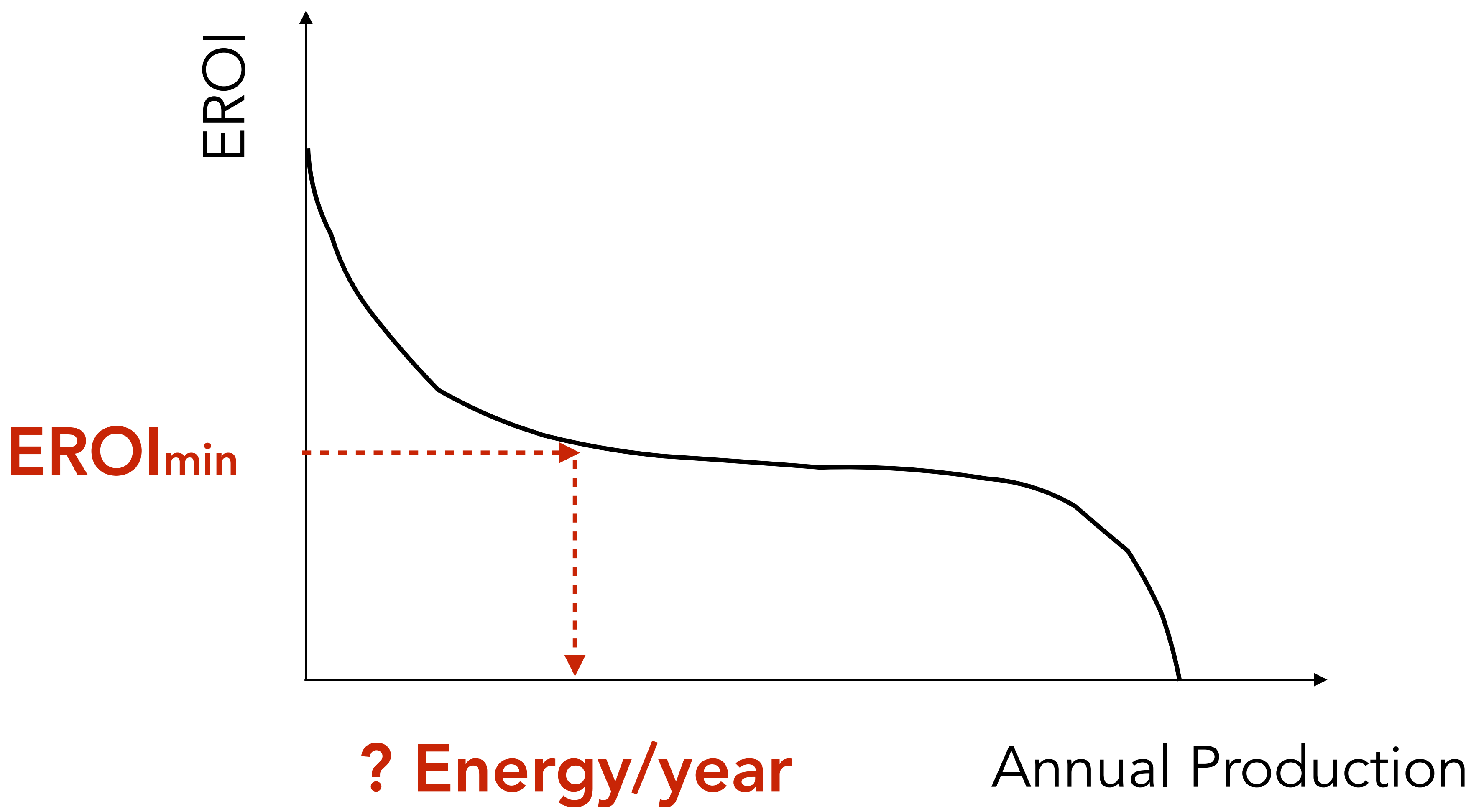
Grid-cell approach

Mesh resolution : 0.75° x 0.75° = 115.200 cells

Average cell size ~ 4.000 km²

- Calculate theoretical net potential and associated EROI in each cell
- Constraint the results with energy conservation in ABL

Dynamic Function: EROI vs Annual Production



Global wind potential calculation: Grid-cell approach

1. Energy Outputs
    - *Land Use Constraints*
    - *Capacity Factor Calculation*
    - *Wind Farm Efficiency*
2. Energy Inputs
    - *Life cycle analysis*
3. Exergy analysis
    - *Energy Conservation in Atmospheric Boundary Layer*
4. Net Energy Maximisation

Land Use Constraints

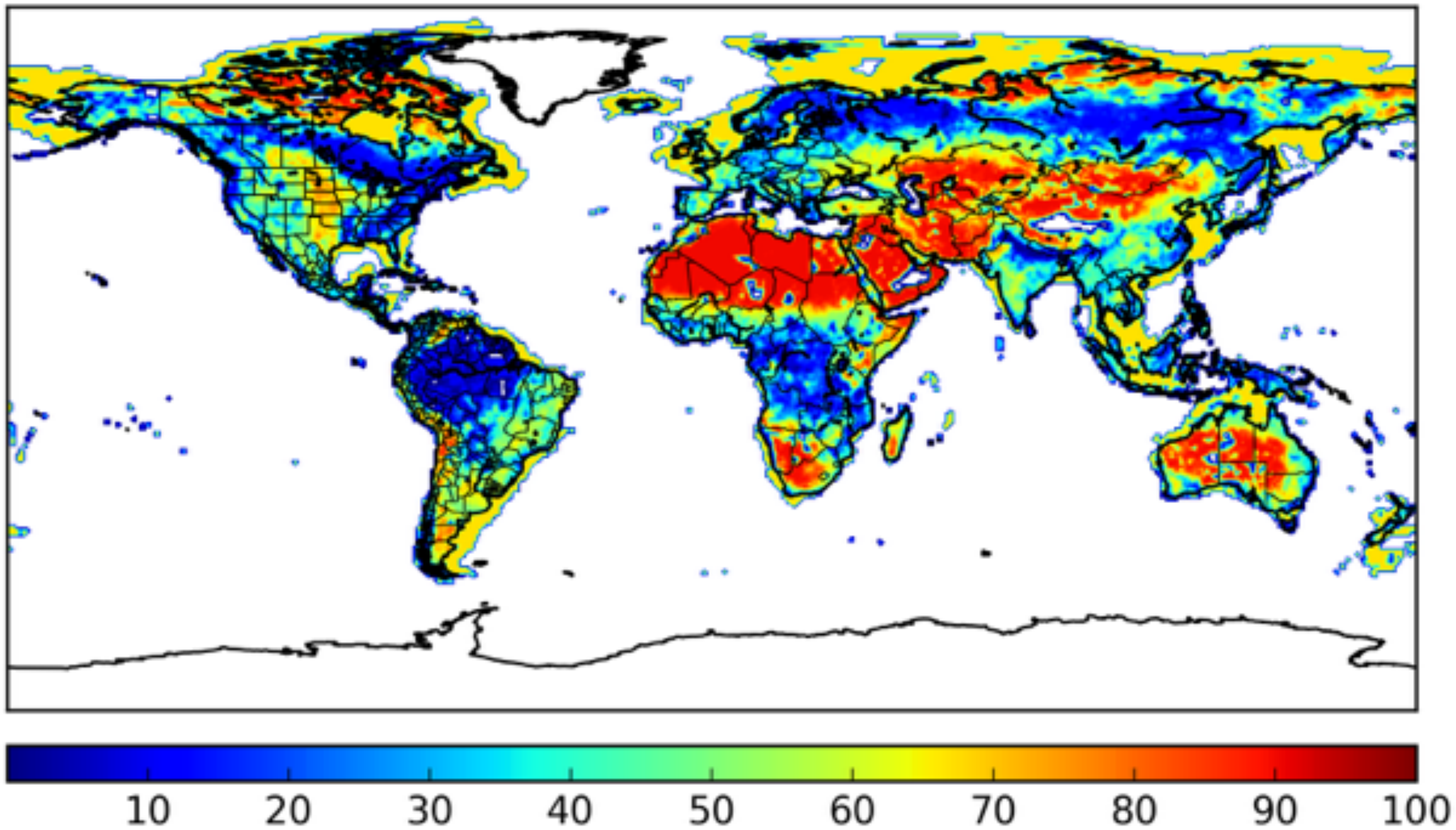
To take into account technical and geographical constraints :
a **suitability factor** is associated to each cell

Land cover repartition (% forests, agricultural lands, etc)

% Protected areas

Water depth, distance to shore

→



Suitability Factor = Proportion of the cell's area available for wind turbine installation

Capacity Factor Calculation

$$C_F = \frac{\bar{P}_{\text{Generated}}}{P_{\text{Rated}}} = \frac{1}{P_R}\int_0^\infty f(v)P(v)dv$$

f(v) ~ Weibull(k,c)

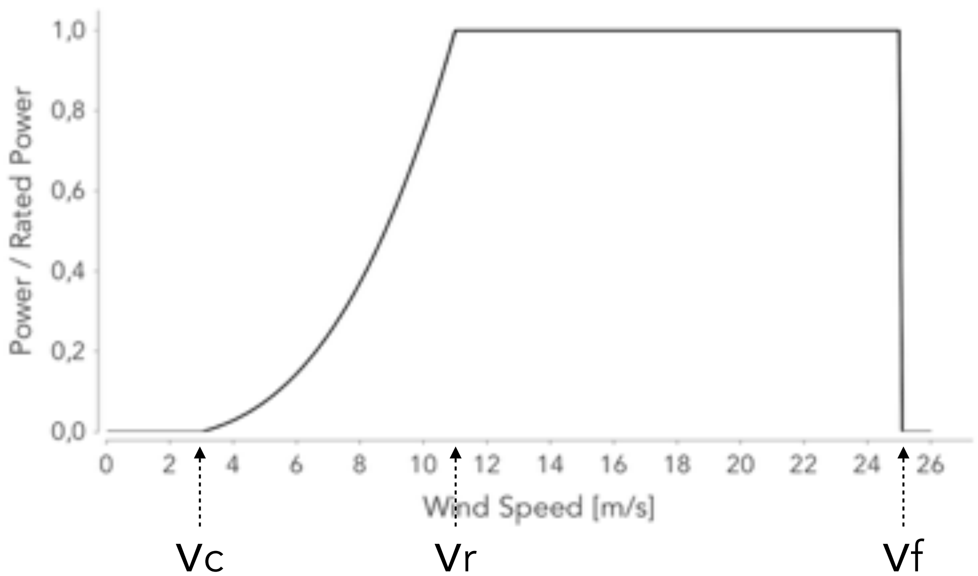
With:

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086}$$

$$c = \frac{\bar{v}}{\Gamma(1 + 1/k)}$$

Mean $\bar{v}$ and standard deviation $\boldsymbol{\sigma}$ of wind speed estimated with 40 years of reanalysis data from ERA-Interim

Wind turbine power curve



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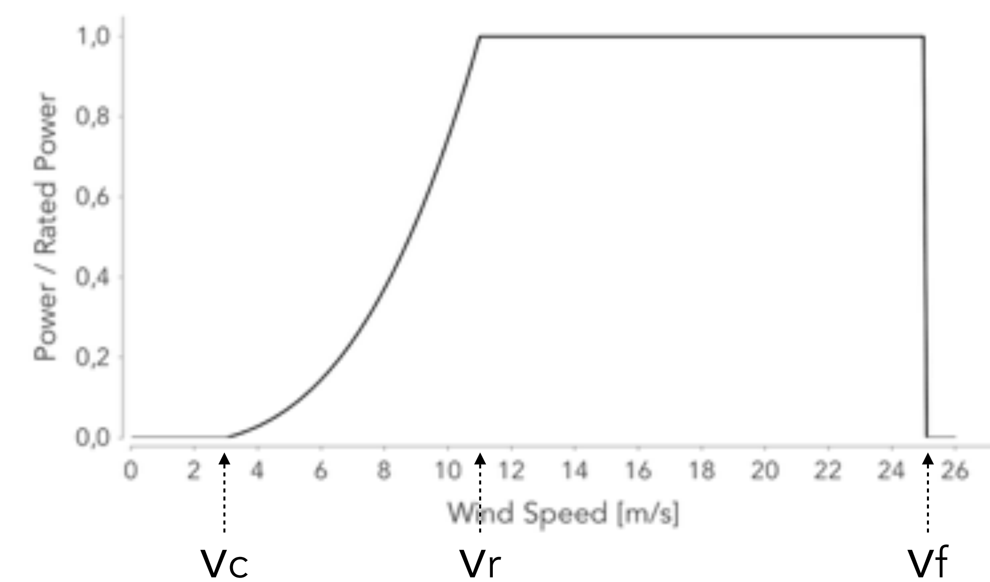
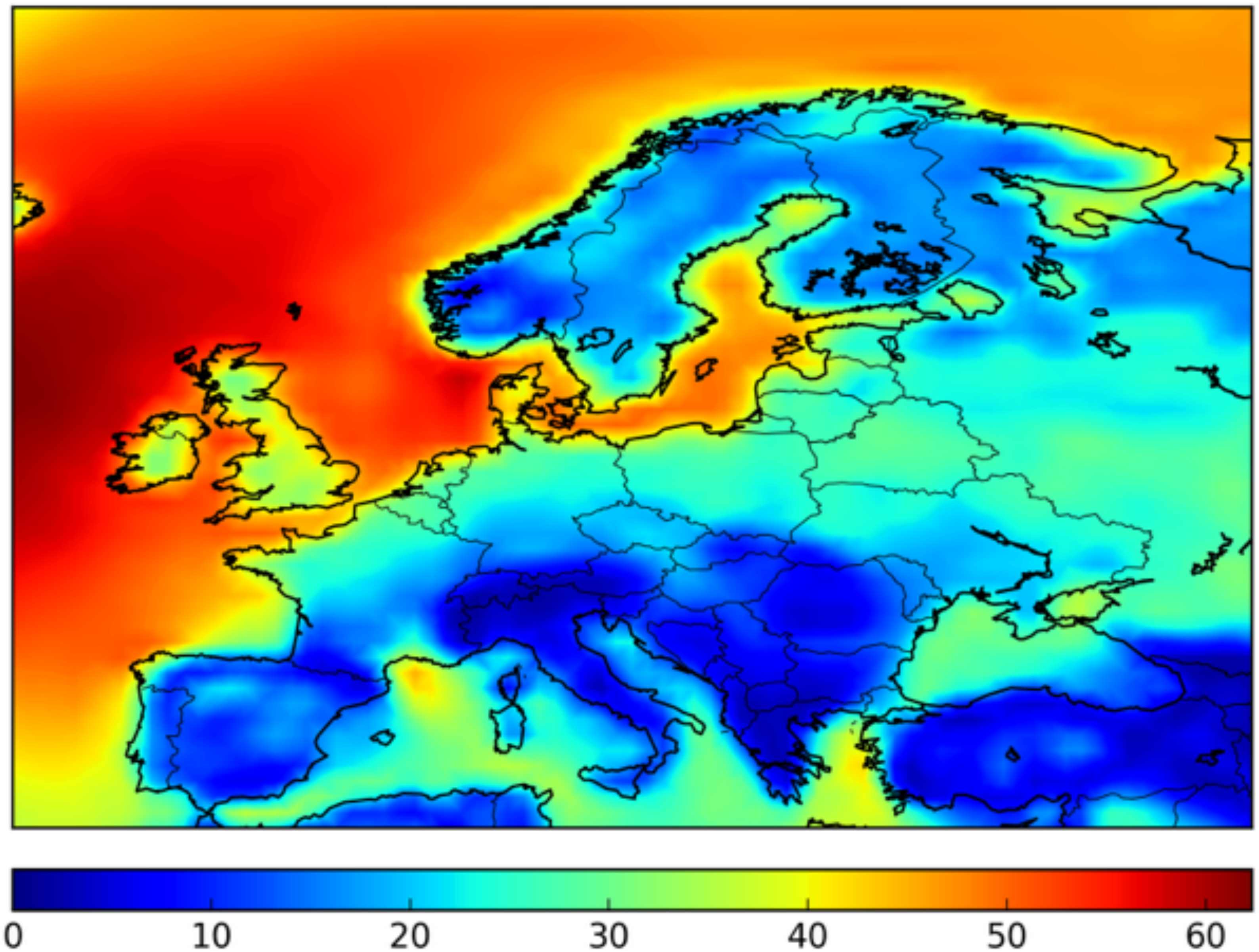


$C_F = f(k, c, v_c, \mathbf{v_r}, v_f)$

May be optimised !

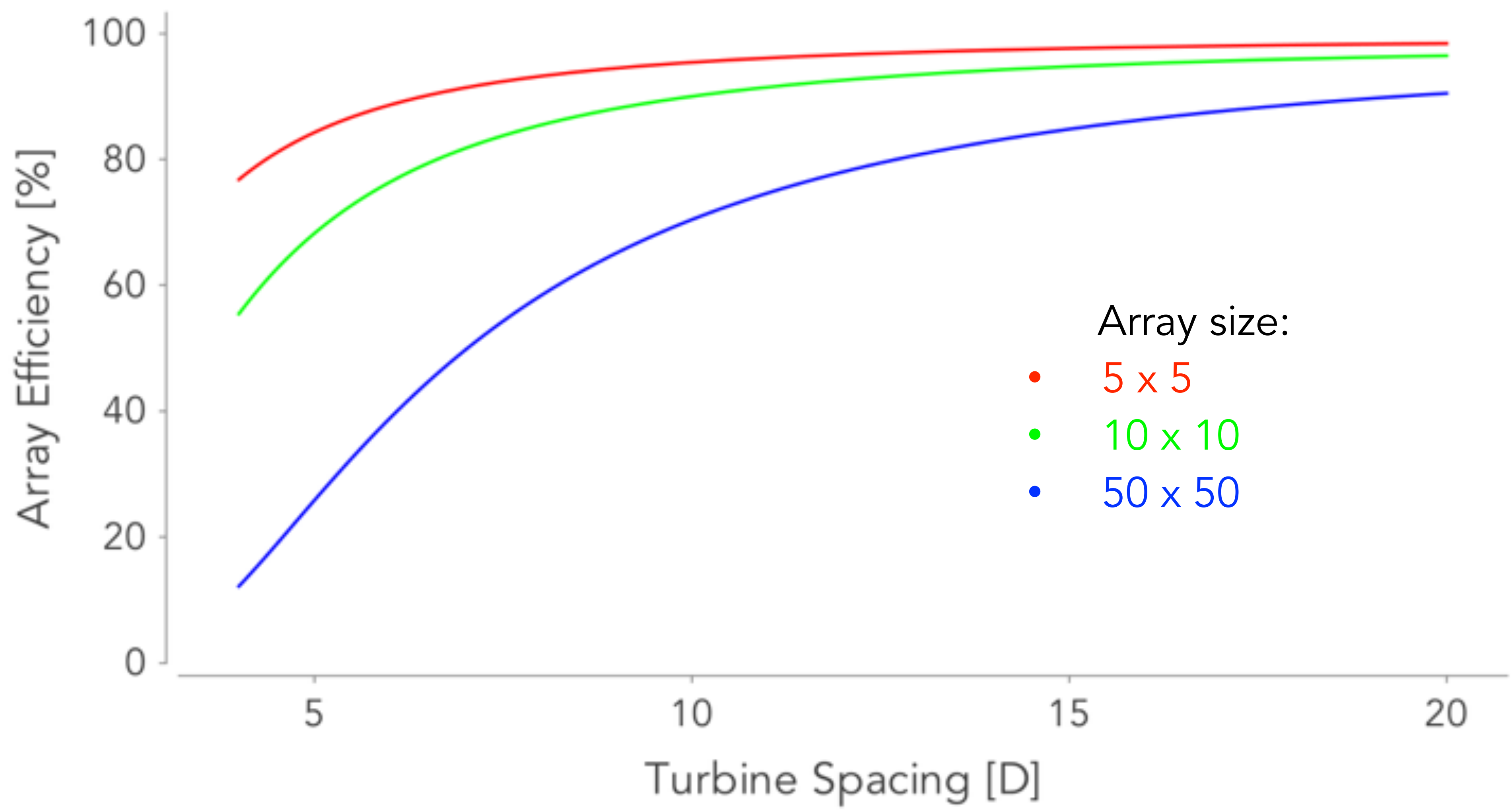
Capacity Factor Calculation



Capacity Factor [%]

Hub height = 125 m, v_c = 3 m/s, v_r = 12 m/s, v_f = 25 m/s

Wind Farm Efficiency



Extrapolation of data from : Limits To Wind Power Density, Gustavson, 1979

Global wind potential calculation: Grid-cell approach

1. **Energy Outputs**
   - ***Land Use Constraints***
   - ***Capacity Factor Calculation*** → **Average power generated for a given installed capacity**
   - ***Wind Farm Efficiency***
2. Energy Inputs
   - *Life cycle analysis*
3. Exergy analysis
   - *Energy Conservation in Atmospheric Boundary Layer*
4. Net Energy Maximisation

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Energy Conservation in ABL

Incoming Solar Radiation
175.000 TW

↓

Wind Kinetic Energy Dissipated
870 TW

↓ → *2/3 dissipated in free atmosphere*

Wind Kinetic Energy Dissipated in ABL
290 TW

From : Quantifying Global Energy Sources, Hermann, 2006

Energy Conservation in ABL

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Wind Kinetic Energy Dissipated in ABL
290 TW

From : Quantifying Global Energy Sources, Hermann, 2006

↓ *Dissipation $\propto v^2$*
Onshore & offshore < 1000 m depth

57 TW

↓ *Suitability Factor*

Wind Kinetic Energy Dissipated over Suitable Areas
~26 TW (World Consumption Today ~ 18 TW)

Global wind potential calculation: Grid-cell approach

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3. **Exergy analysis**
    - ***Energy Conservation in ABL*** → **Limit on Wind Power Density**
4. Net Energy Maximisation

Global wind potential calculation: Grid-cell approach

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    - *Energy Conservation in ABL* → Limit on Wind Power Density
4. **Net Energy Maximisation**

Net Energy Maximisation

In each cell find the optimal installed capacity, i.e. the optimal # of turbines, that satisfies:

Maximise Net Energy

= Energy Outputs - Energy Inputs

Installed Capacity * CF * η

Embodied Energy(Installed Capacity)
+ Operational Energy(Energy Outputs)

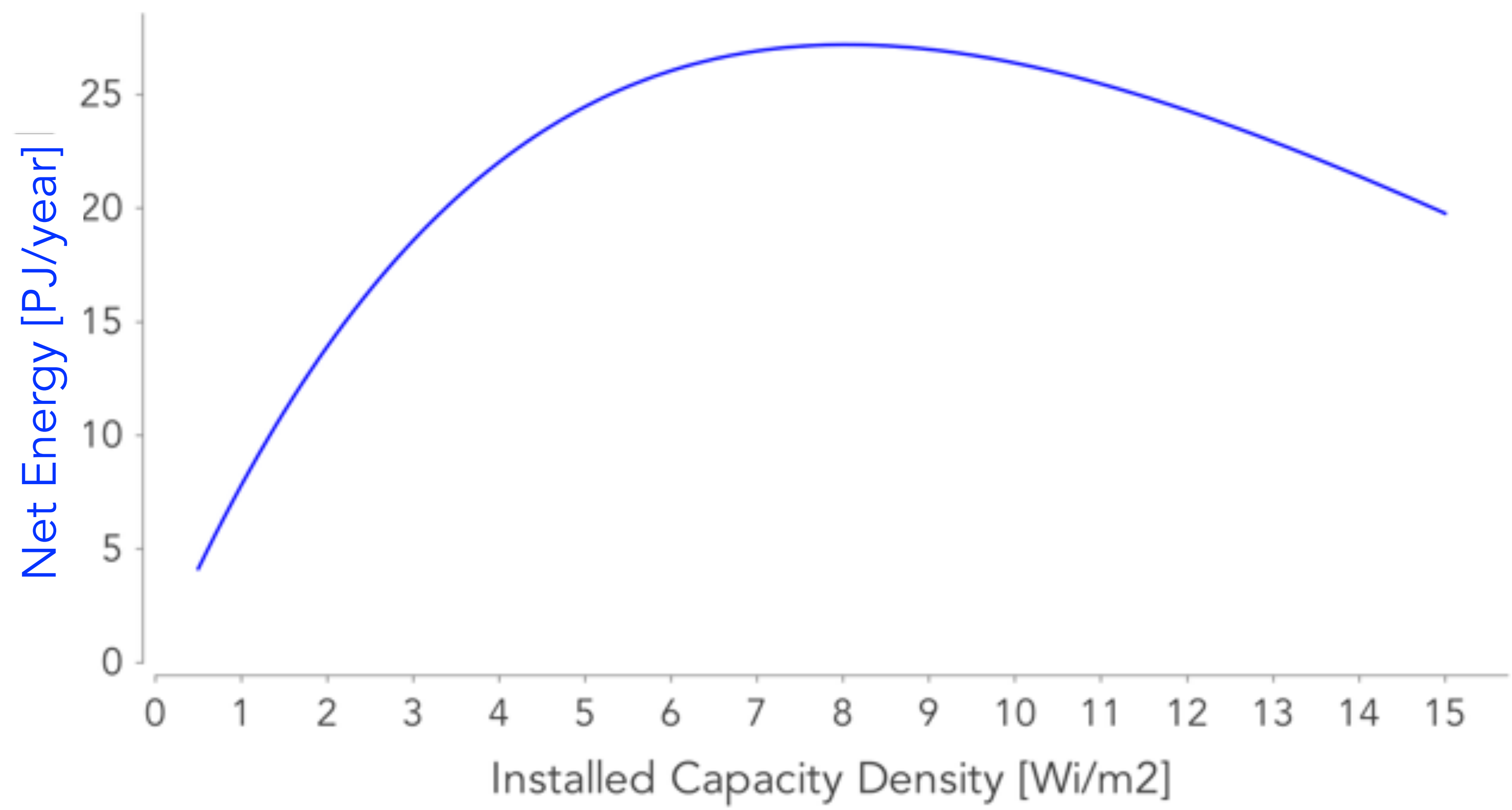
With constraints:

- Energy Outputs ≤ Available Kinetic Energy
- EROI ≥ $EROI_{min}$

Net Energy Maximisation

Example :

- Onshore cell of 1.000 km²
- Capacity factor: 30 %
- Embodied Energy: 14.000 GJ/MW



Net Energy Maximisation

Example :

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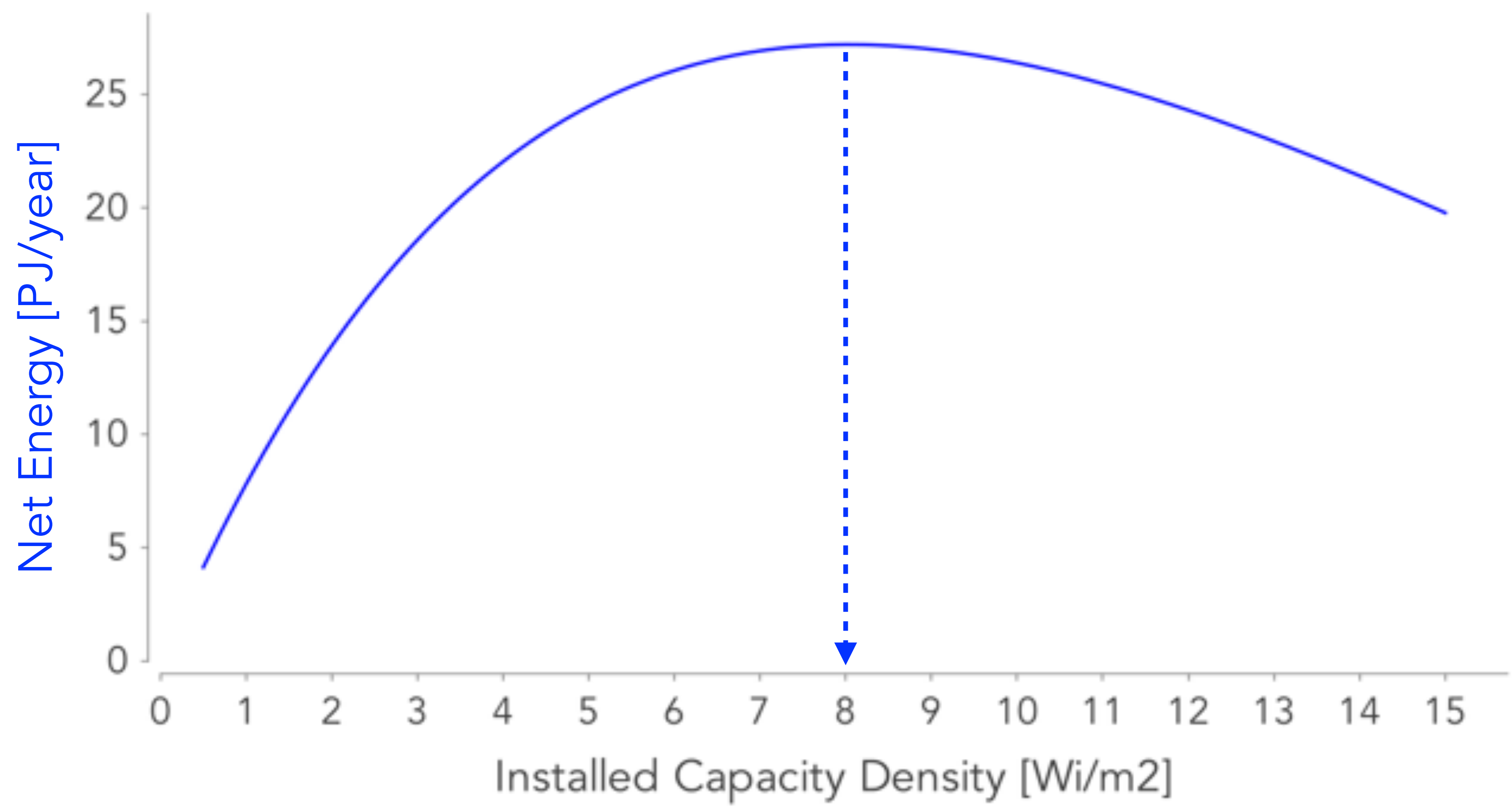
Maximum: 8 Wi/m²



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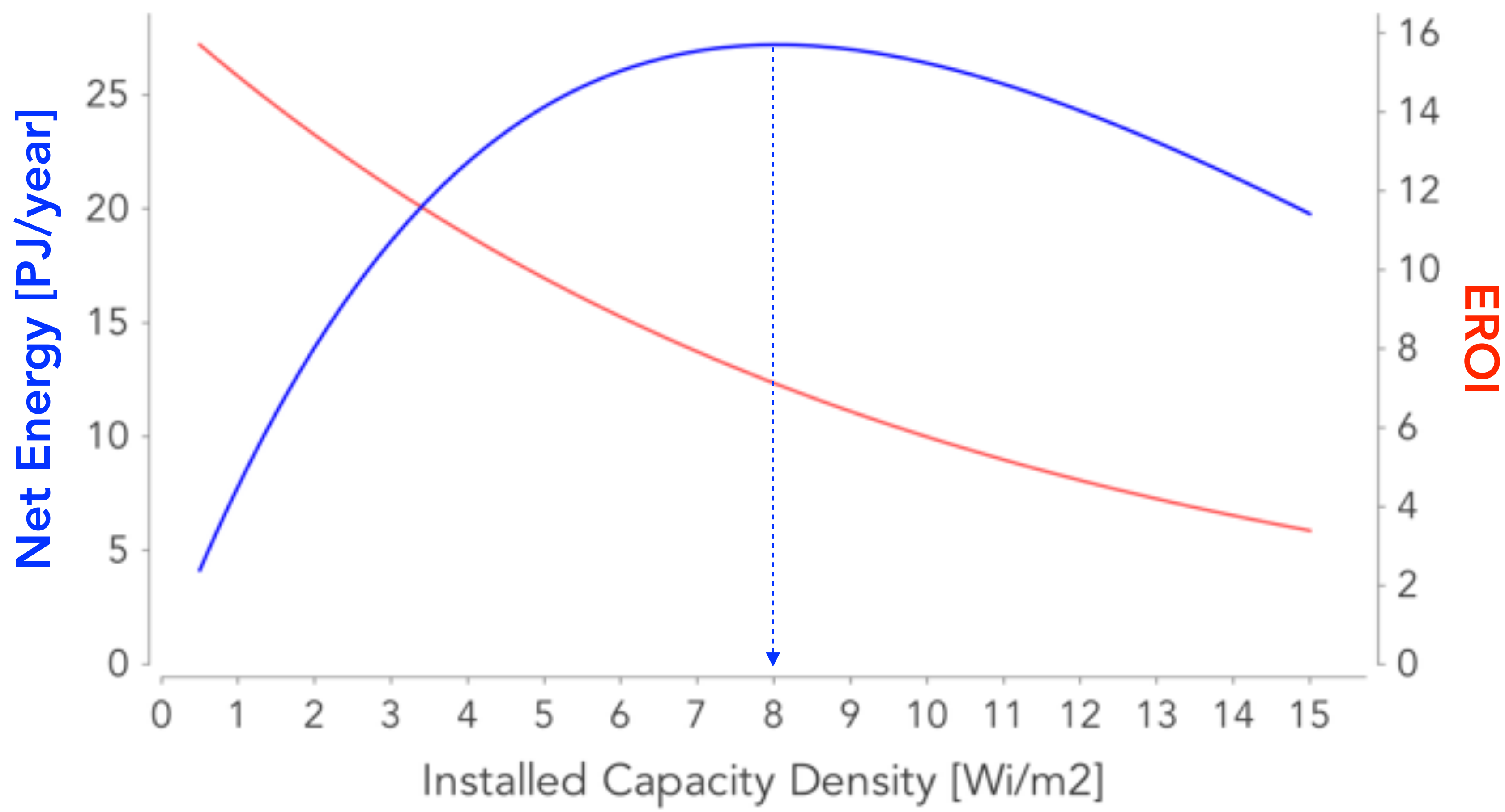

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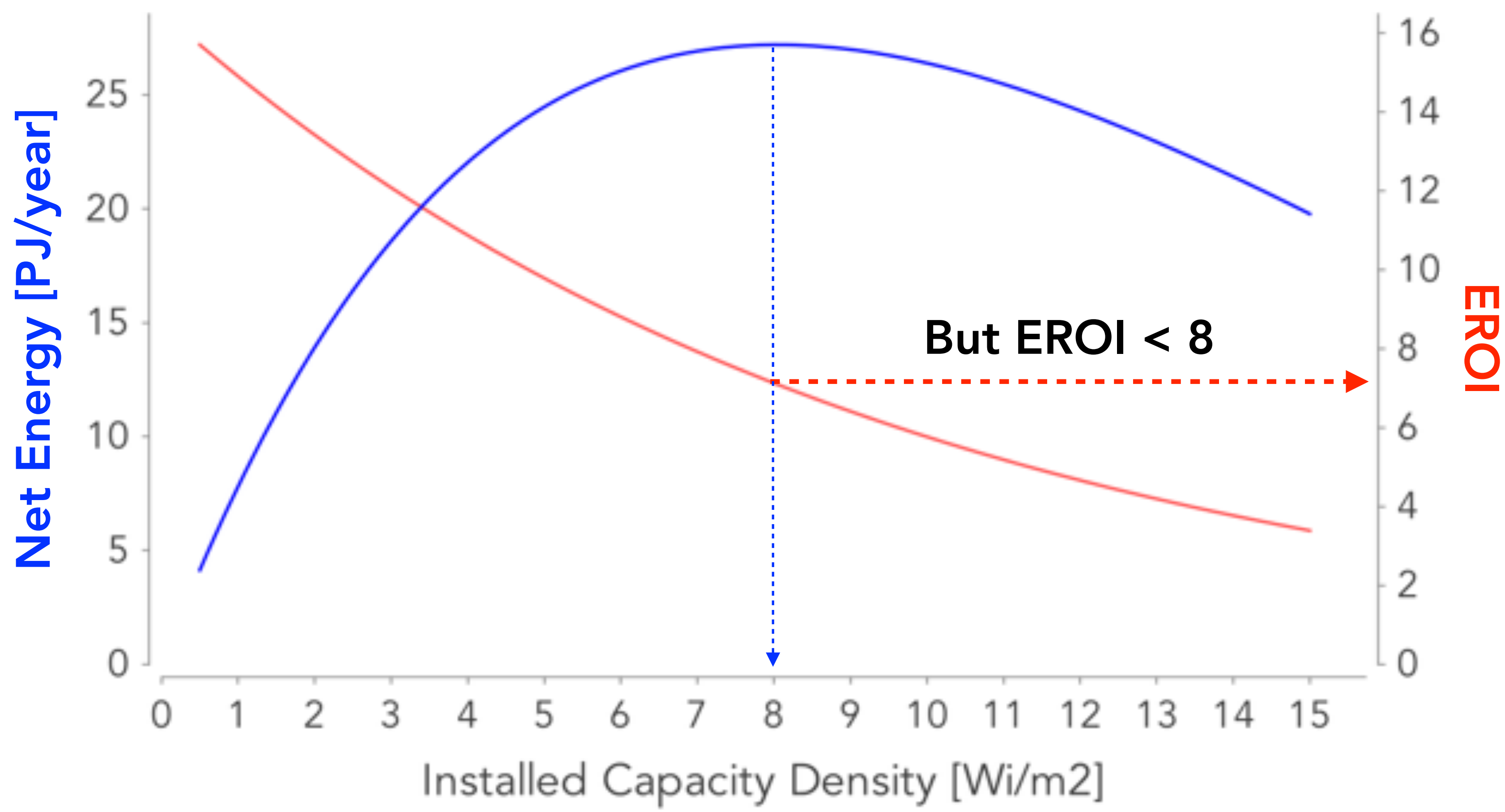

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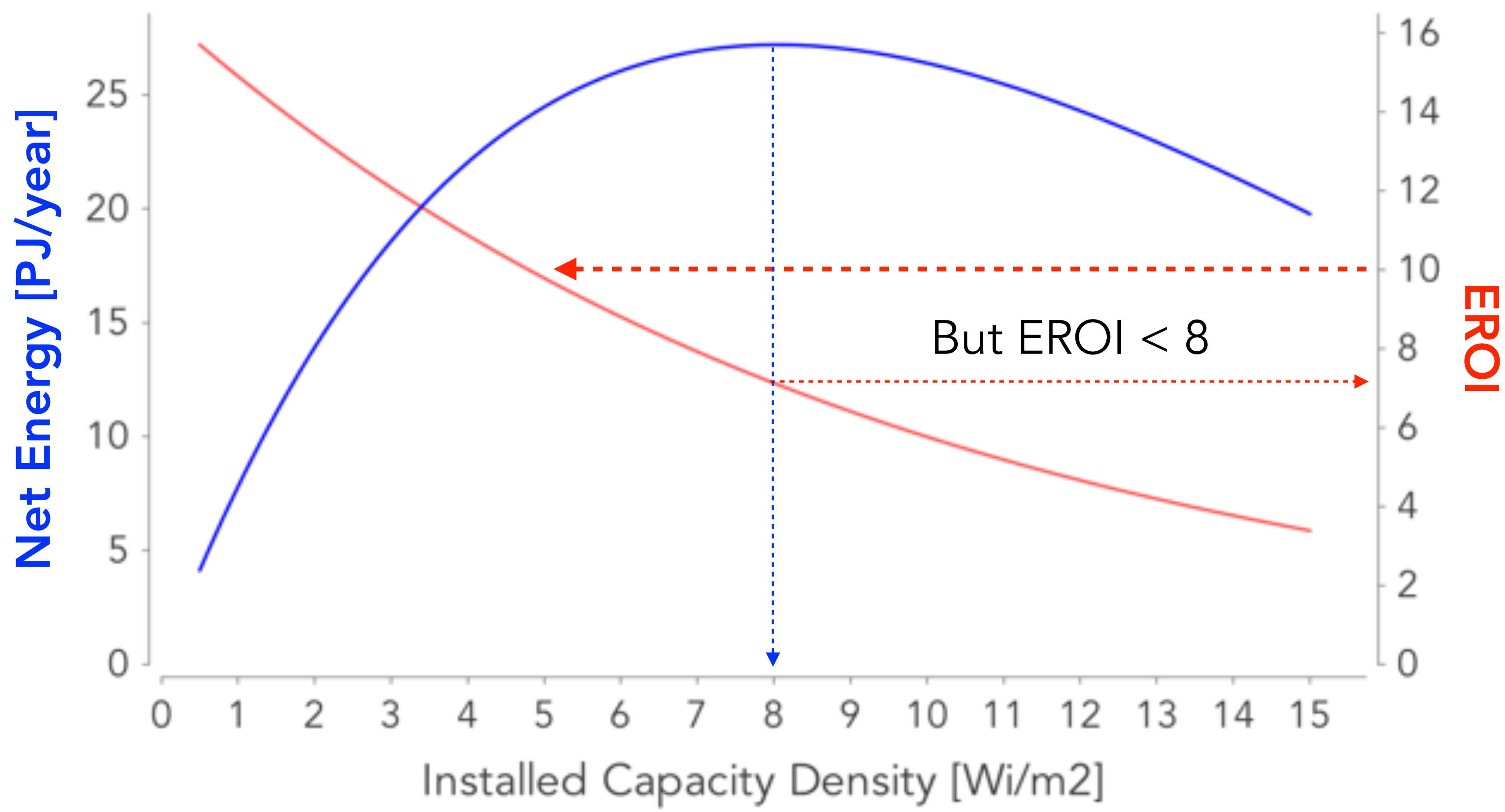

If we want EROI ≥ 10

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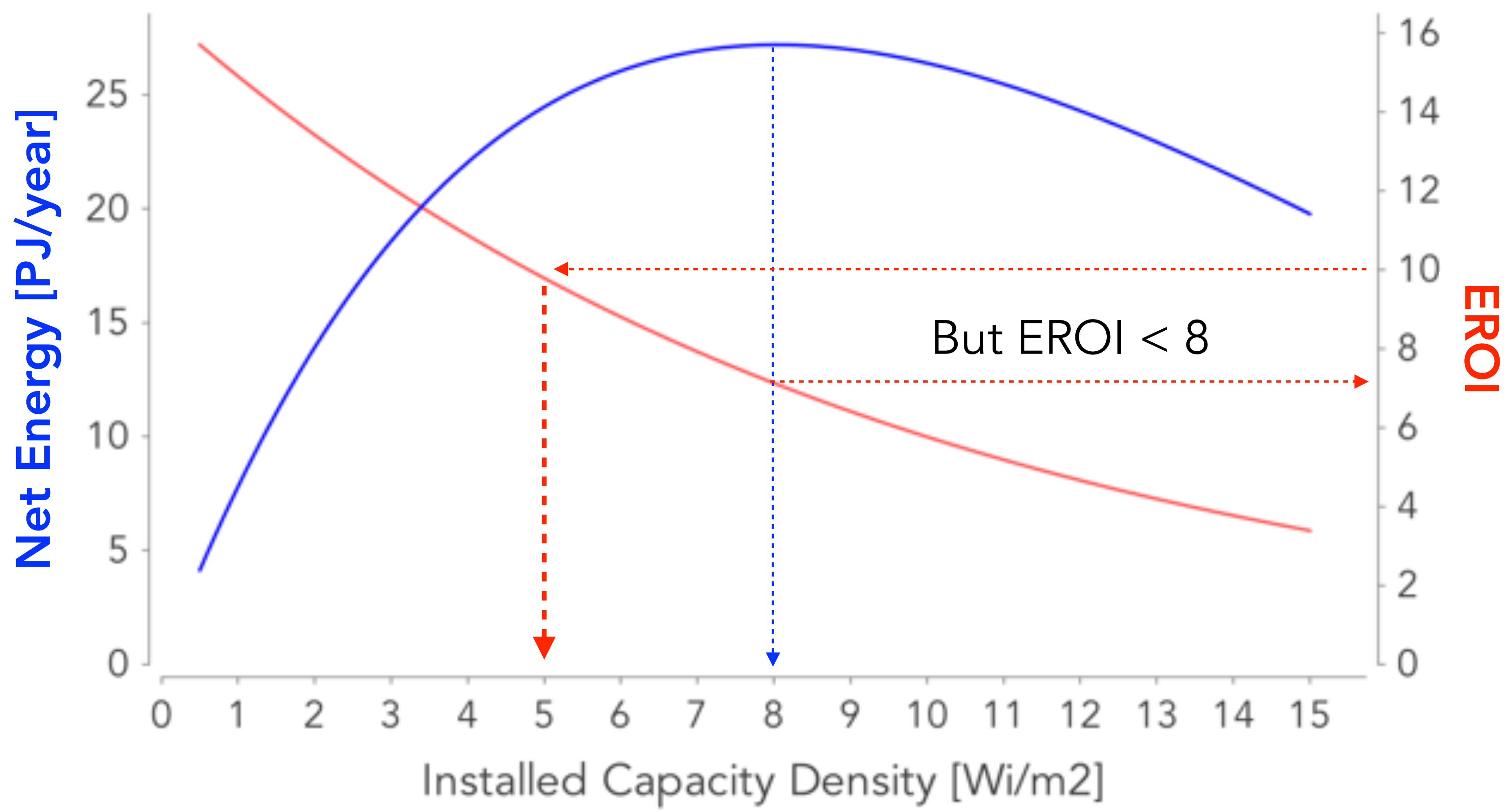
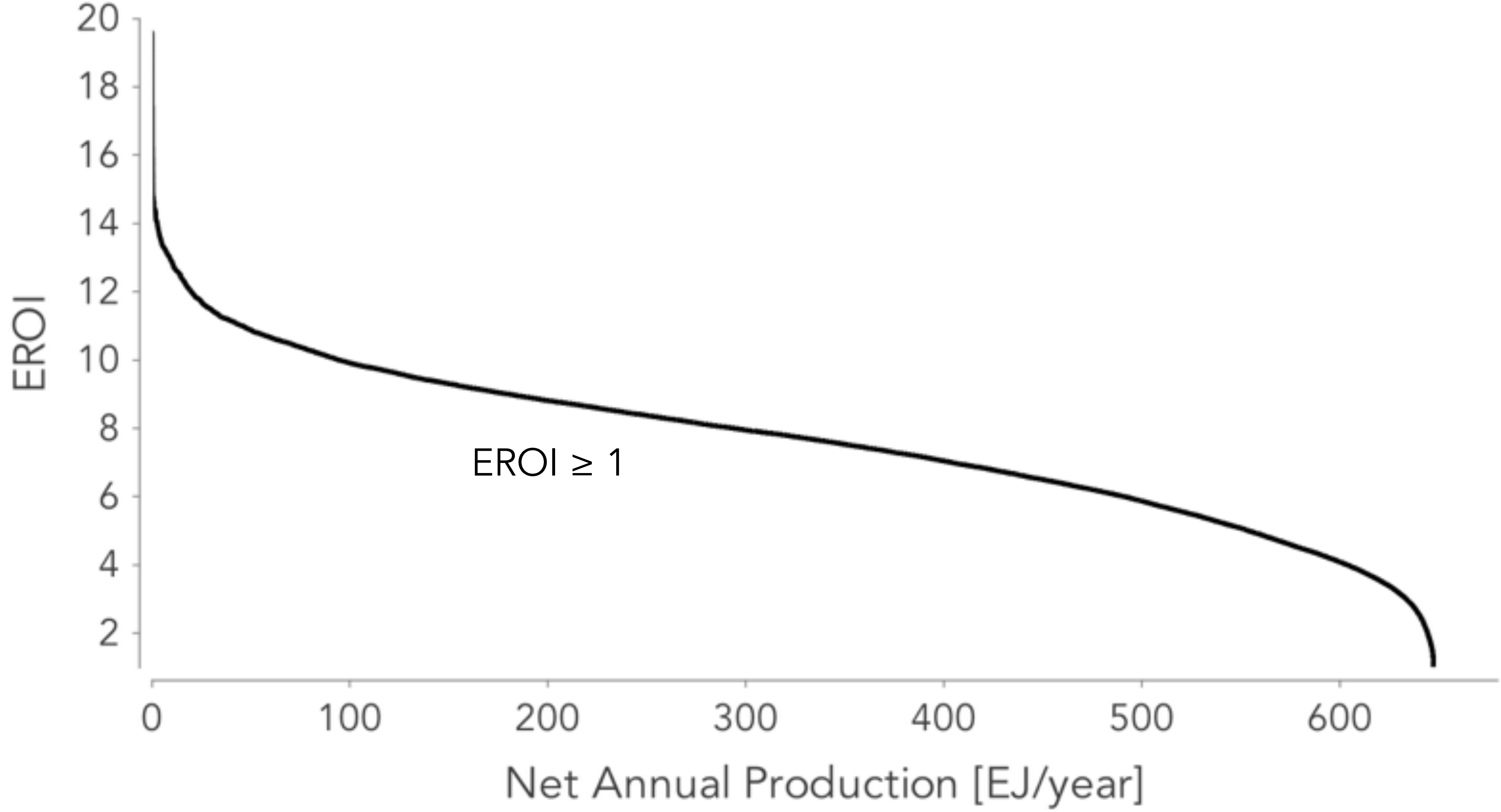


If we want EROI ≥ 10

The optimal installed capacity is 5 Wi/m²

Net Energy Maximisation



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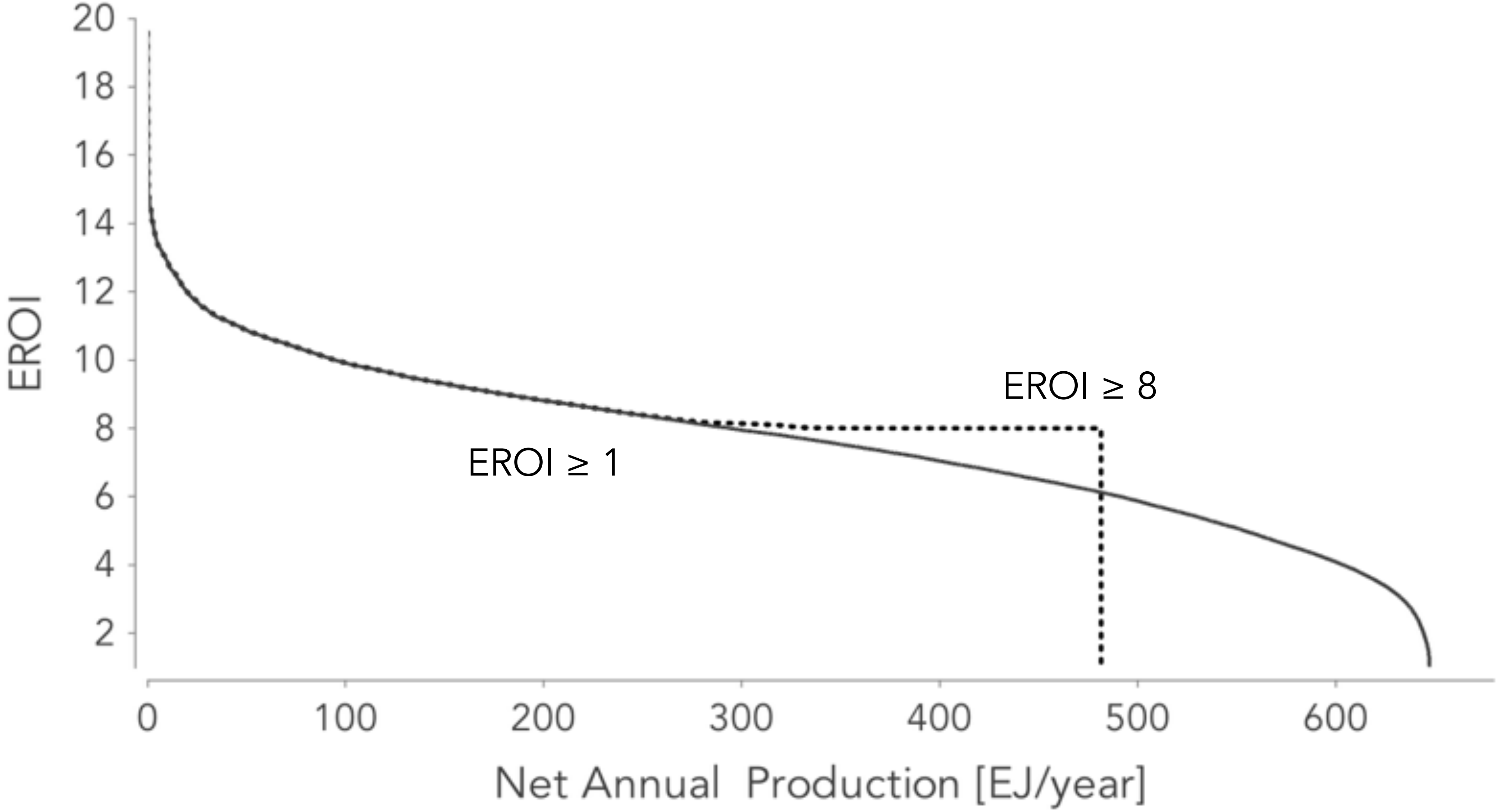

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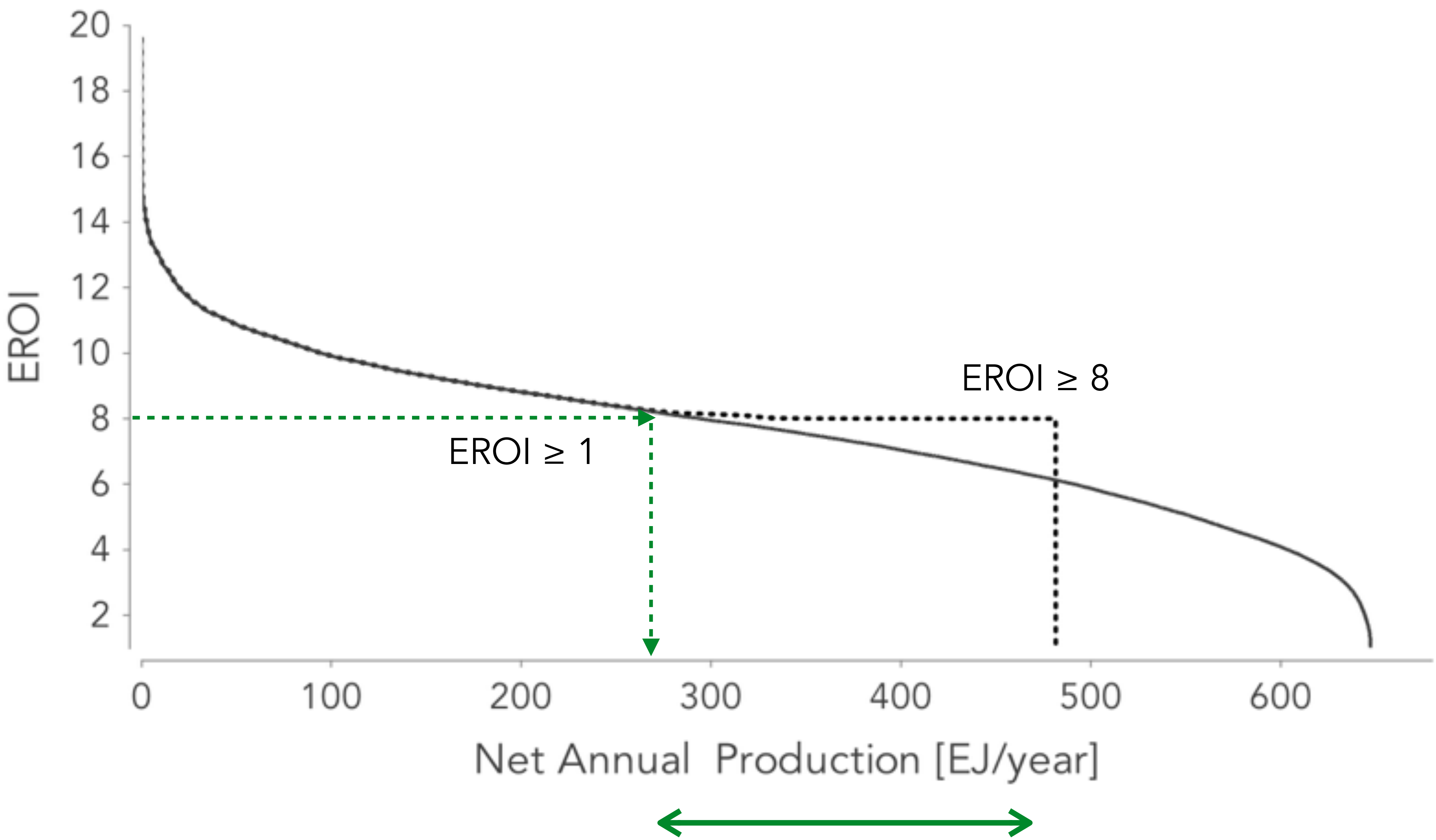
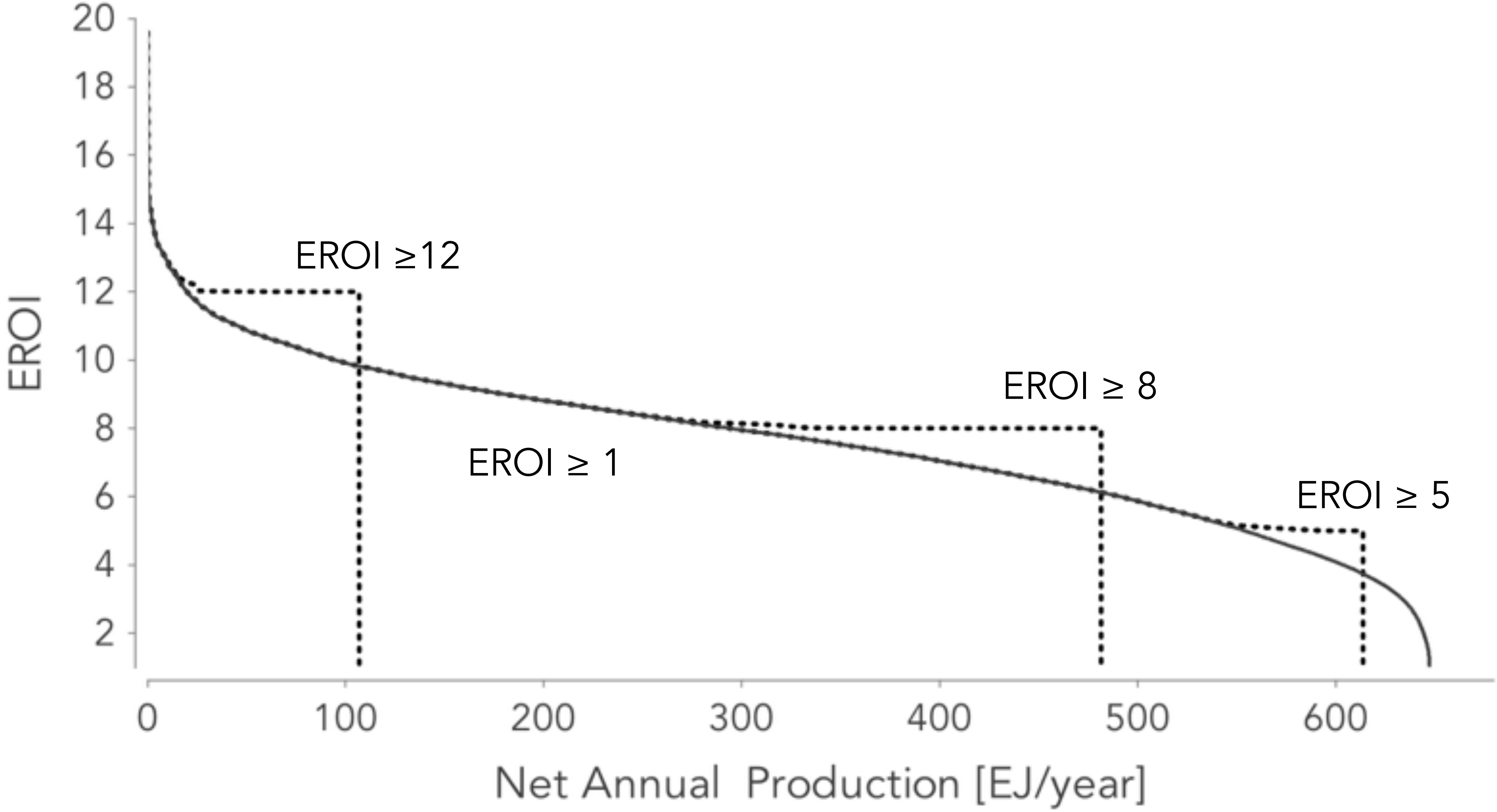


Increase in potential thanks to the constraint on the EROI$_{min}$!

Net Energy Maximisation



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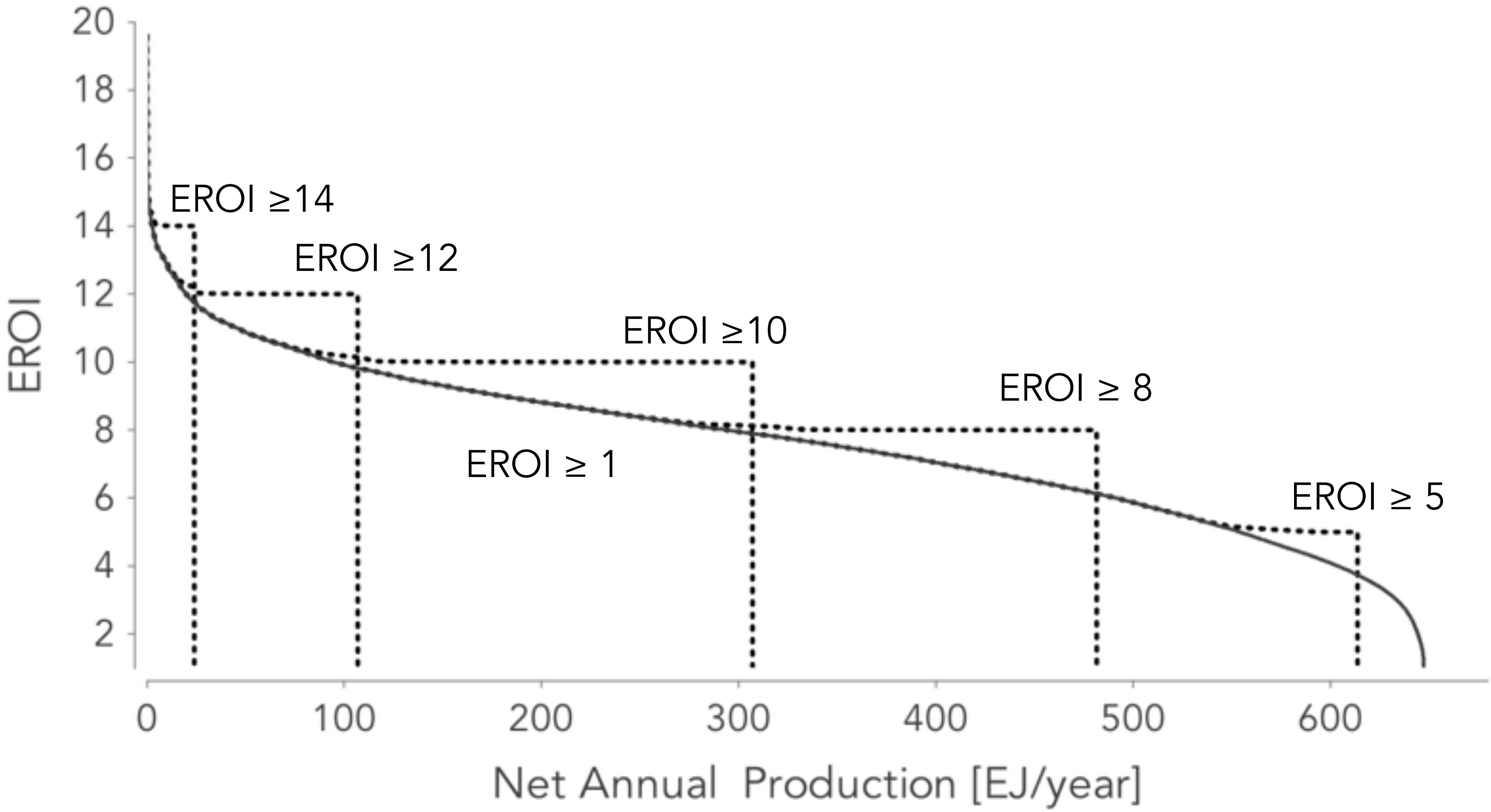
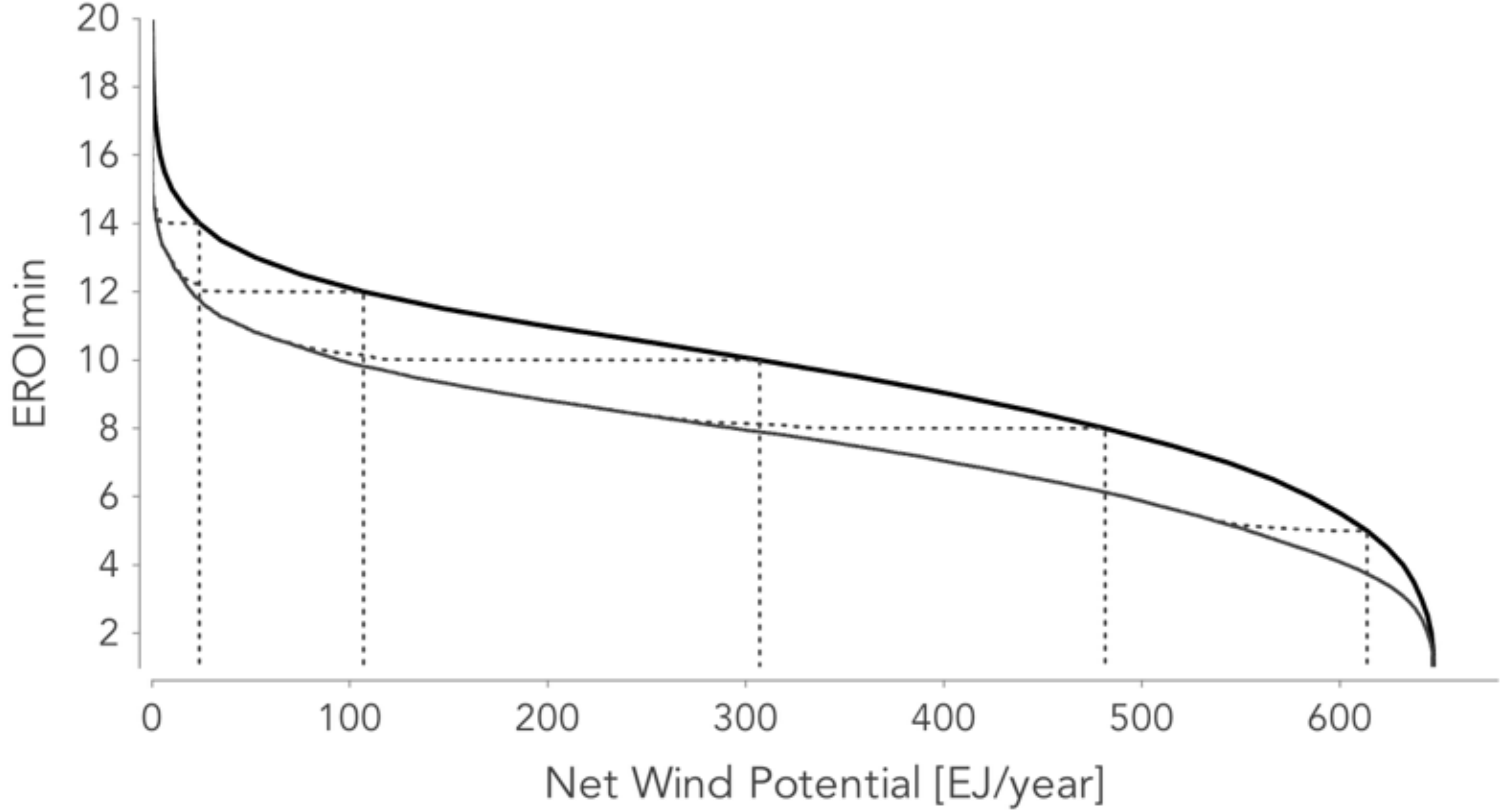
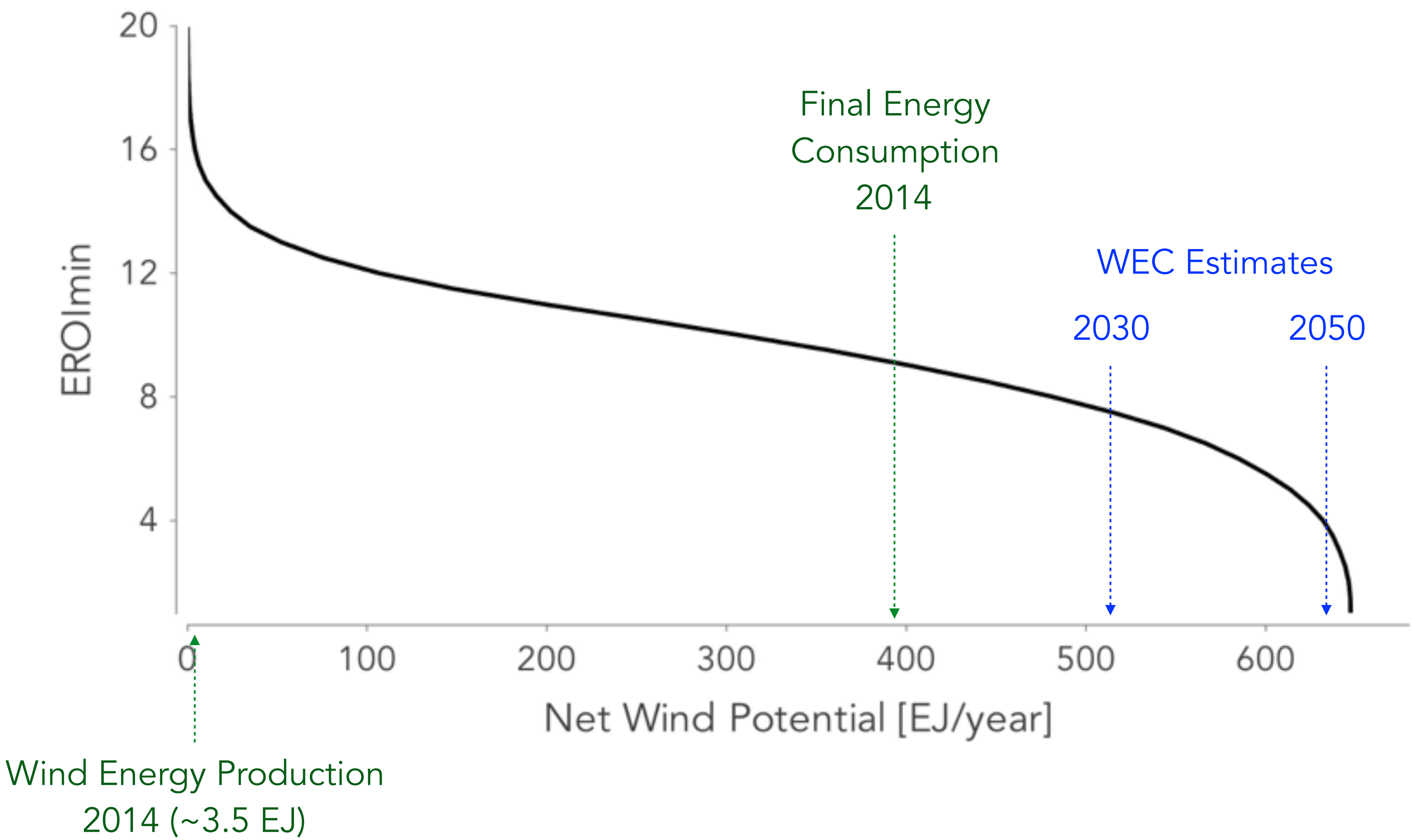


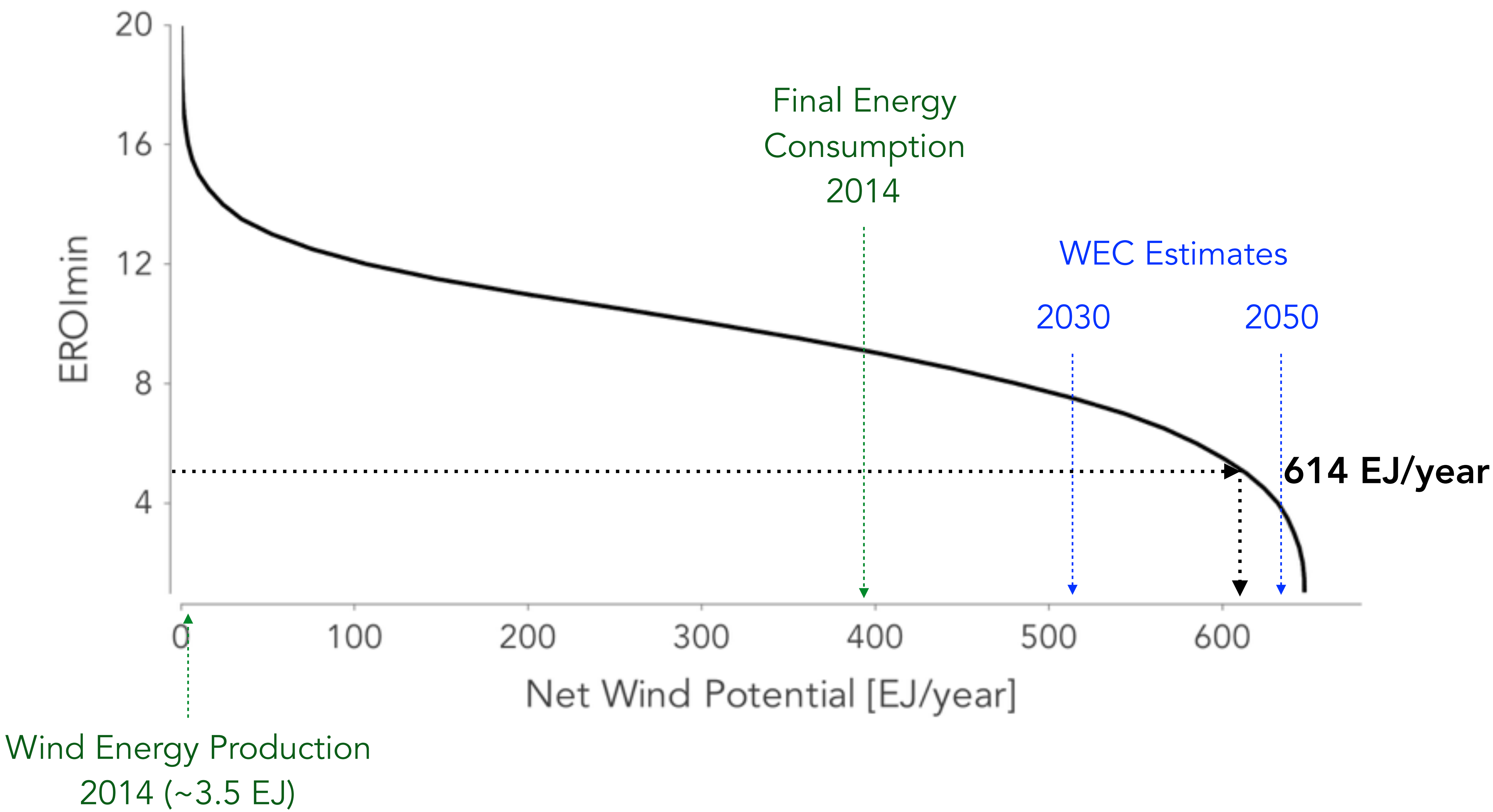
Enveloppe of the Global Wind Potential



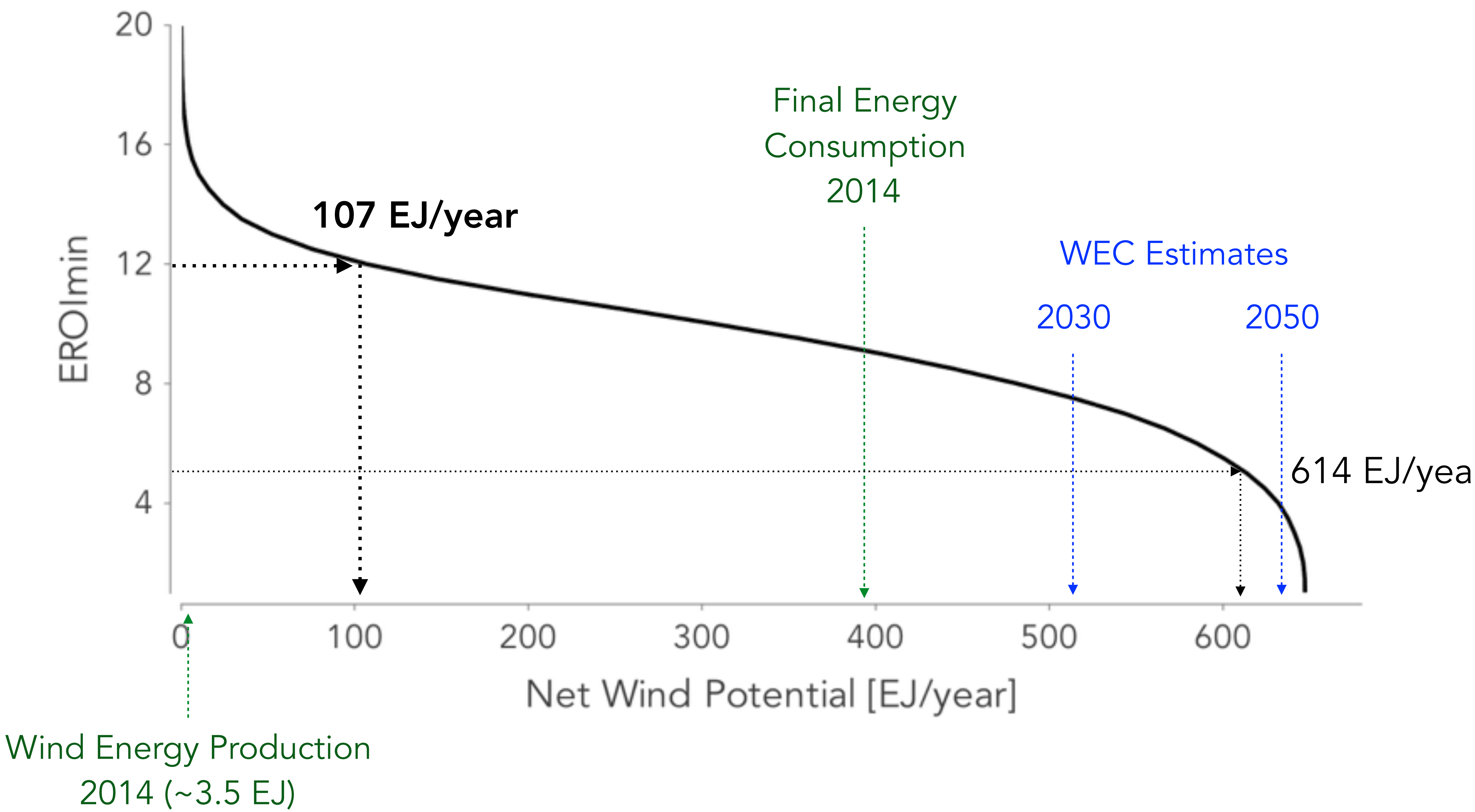
Global Wind Potential



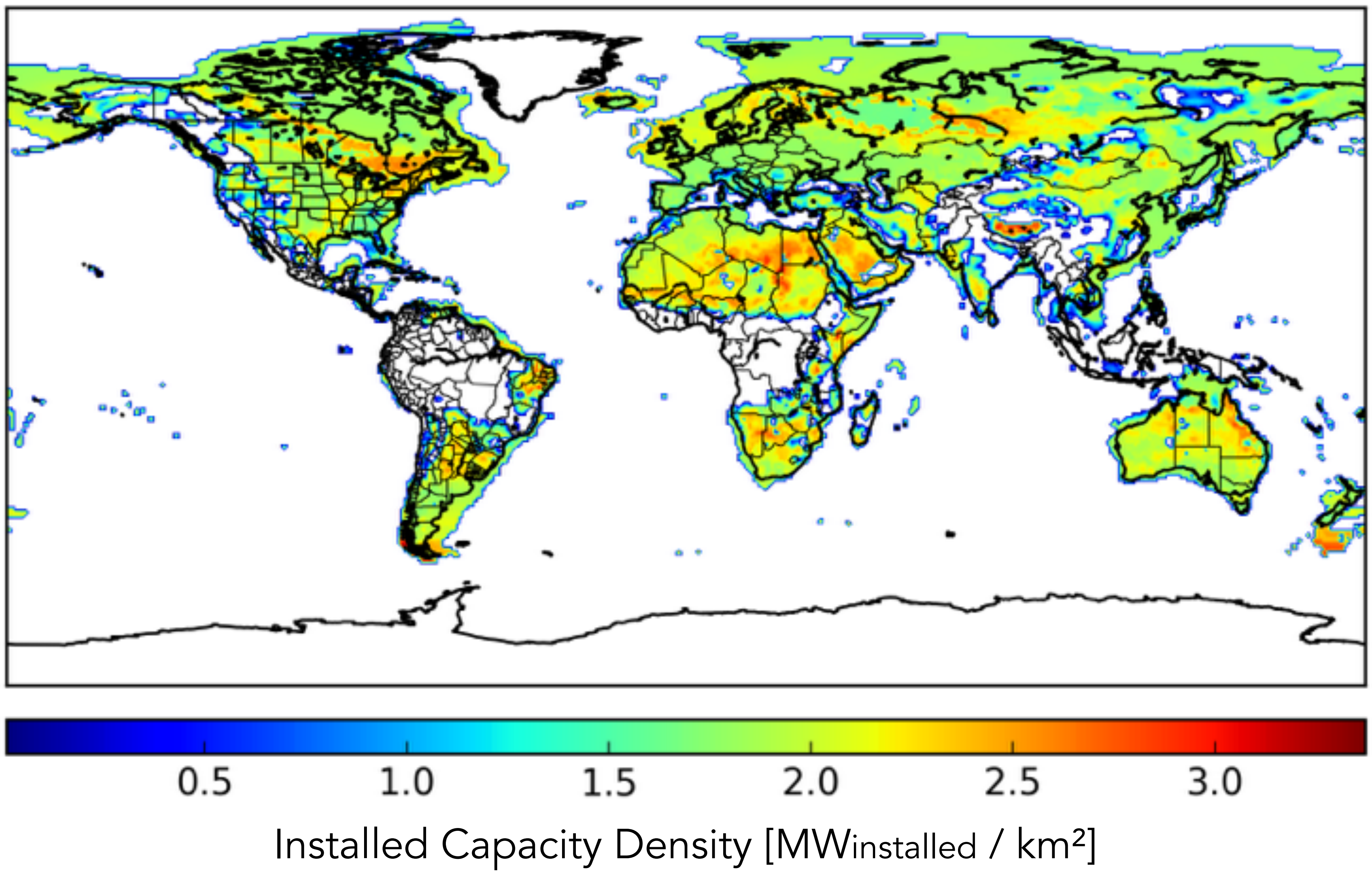
Global Wind Potential



Global Wind Potential

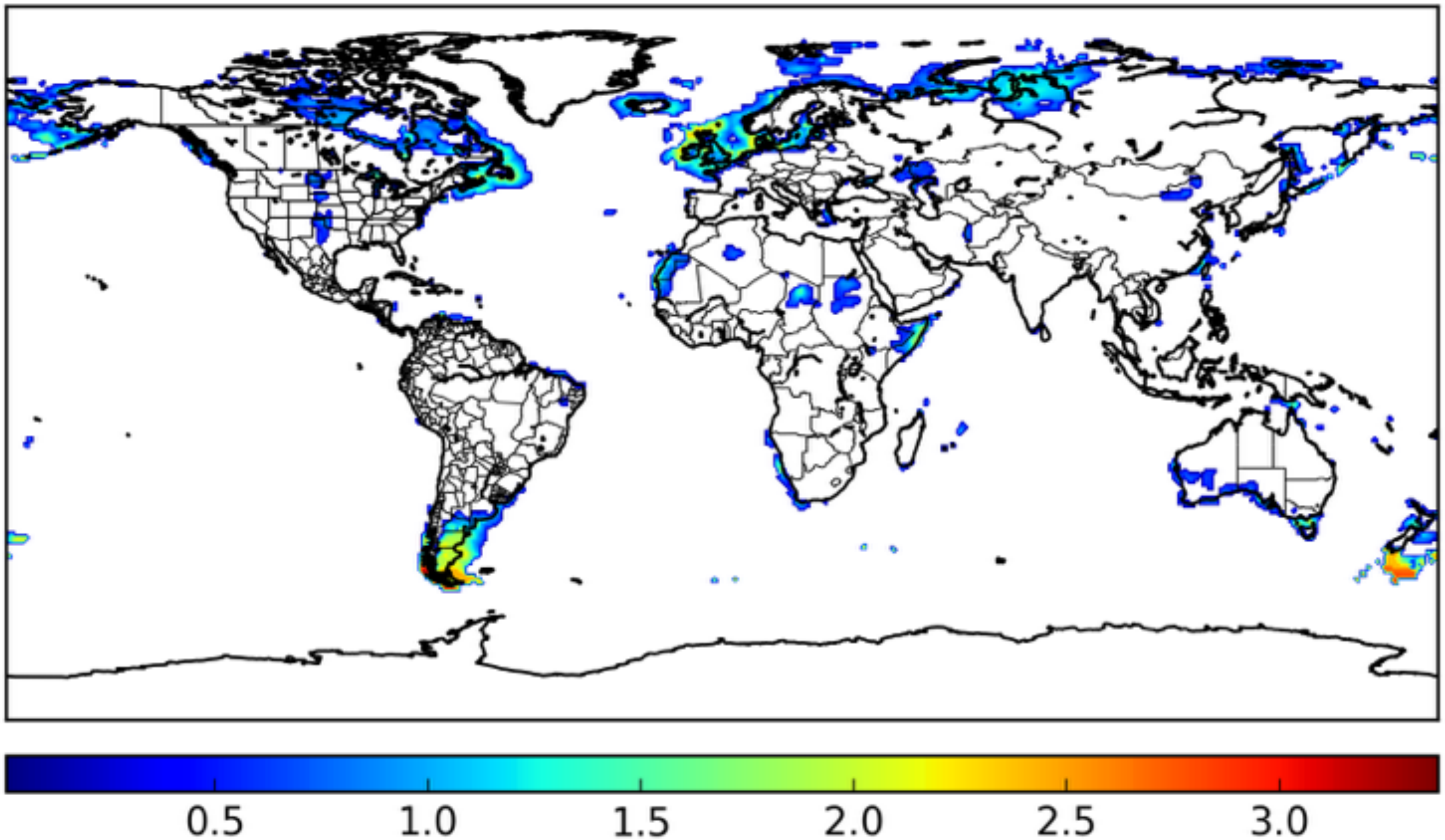


Spatial Distribution



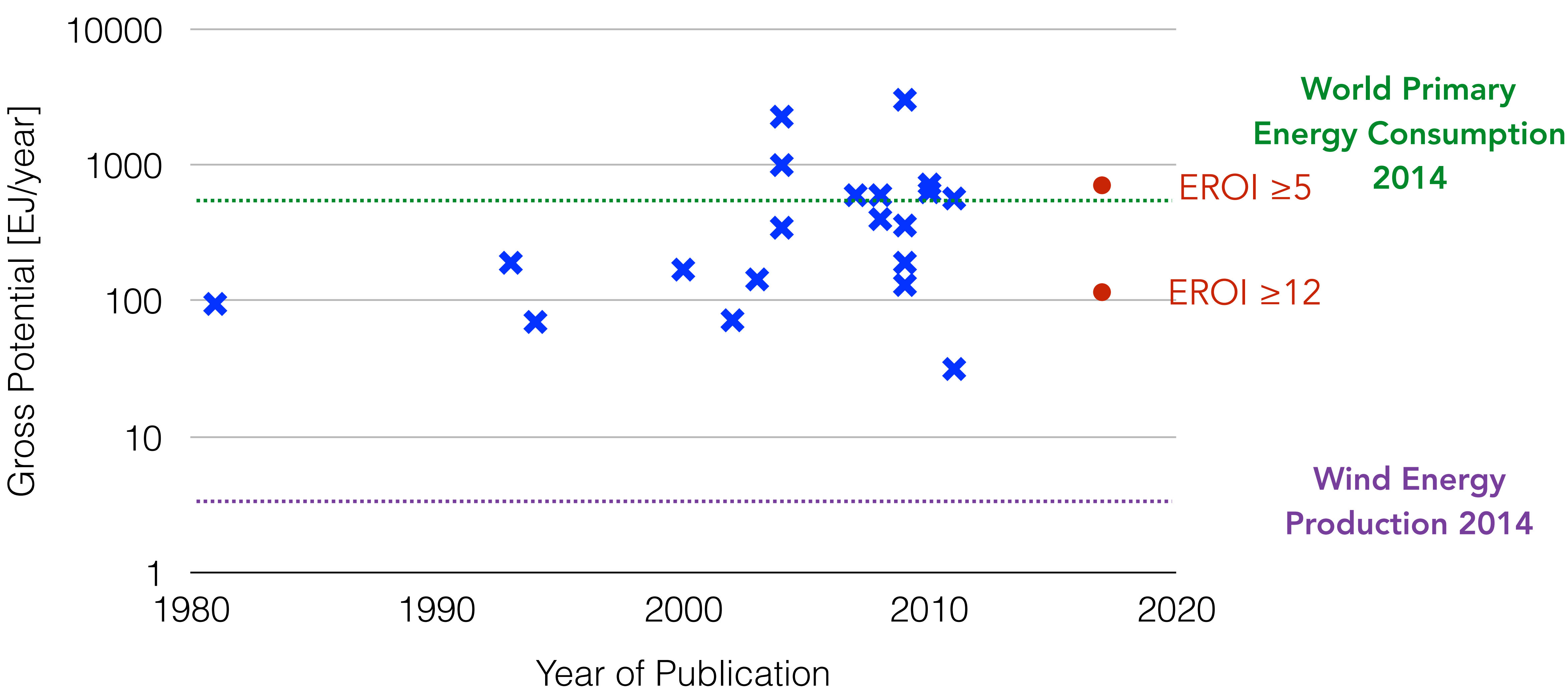
EROI ≥ 5, Net potential = 614 EJ/year

Spatial Distribution



EROI ≥ 12, Net potential = 107 EJ/year

Conclusion


10000
1000
100
10
1
Gross Potential [EJ/year]
1980
1990
2000
2010
2020
Year of Publication
EROI ≥5
EROI ≥12
World Primary
Energy Consumption
2014
Wind Energy
Production 2014

Thank you !

Wind Energy Science Conference 2017, Copenhagen