# Wind Supply and Demand

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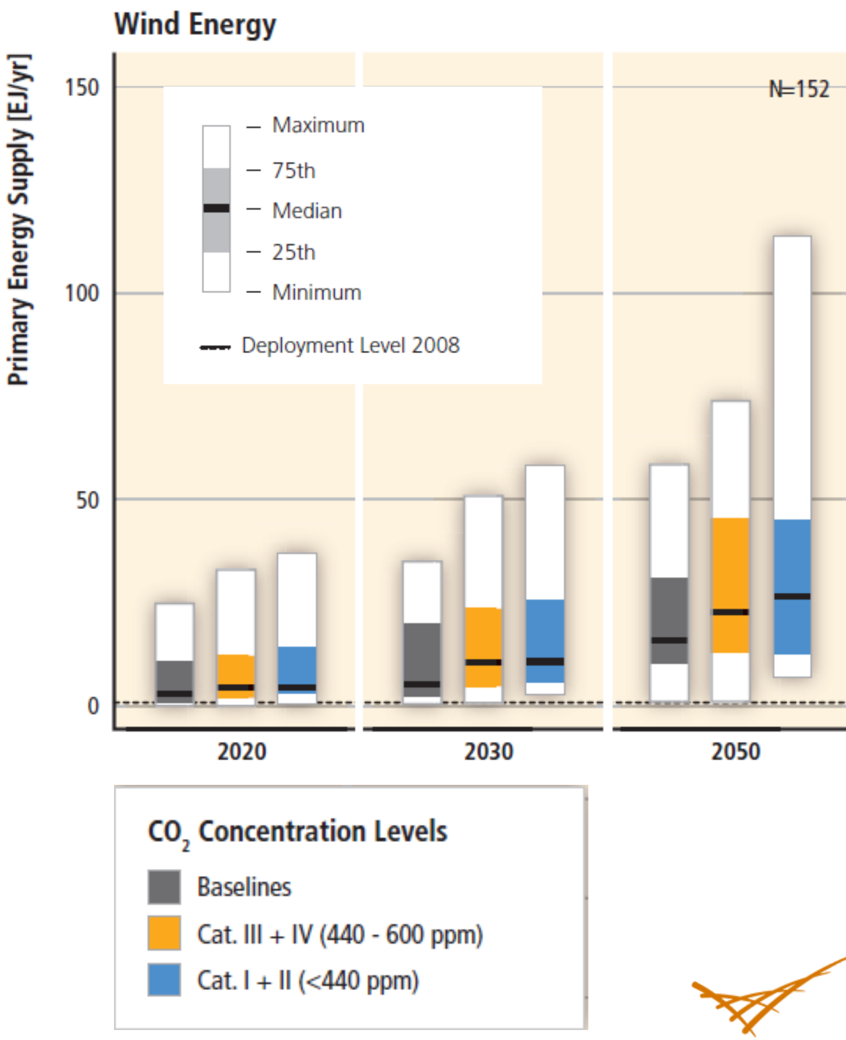
# There is a lot of uncertainty about the deployment of renewable energy in future scenarios.

Differences arise due to differences in a range of factors

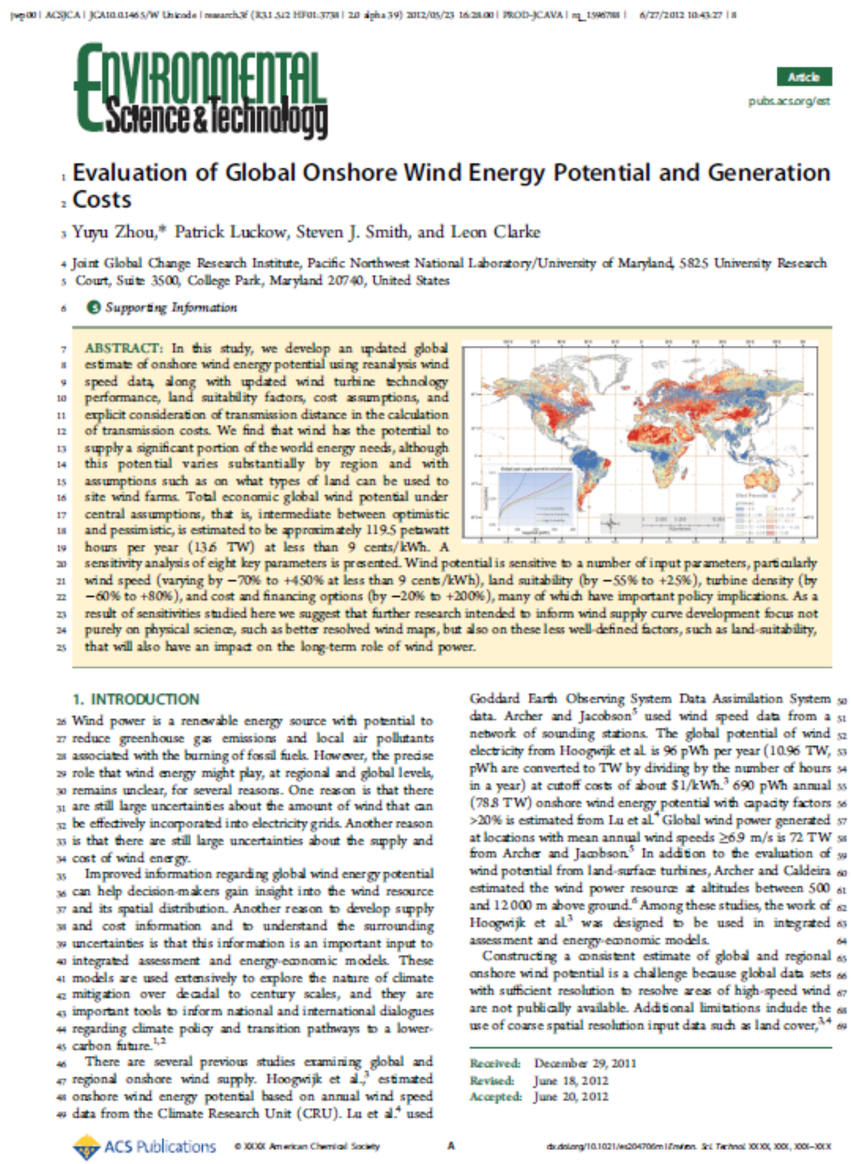
- Assumptions about drivers (GDP, population, etc)
- Assumptions about competing technologies.
- Approaches to integration of intermittent sources.
- Resource assumptions.



# Three Topics

- Developing Onshore Wind Supply Curves
- Exploratory GCAM runs

# Global Onshore Wind Supply Curves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## Evaluation of Global Onshore Wind Energy Potential and Generation Costs

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*Supporting Information*

**ABSTRACT:** In this study, we develop an updated global estimate of onshore wind energy potential using reanalysis wind speed data, along with updated wind turbine technology performance, land suitability factors, cost assumptions, and explicit consideration of transmission distance in the calculation of transmission costs. We find that wind has the potential to supply a significant portion of the world energy needs, although this potential varies substantially by region and with assumptions such as on what types of land can be used to site wind farms. Total economic global wind potential under central assumptions, that is, intermediate between optimistic and pessimistic, is estimated to be approximately 119.5 petawatt hours per year (13.6 TW) at less than 9 cents/kWh. A sensitivity analysis of eight key parameters is presented. Wind potential is sensitive to a number of input parameters, particularly wind speed (varying by −70% to +450% at less than 9 cents/kWh), land suitability (by −55% to +25%), turbine density (by −60% to +80%), and cost and financing options (by −20% to +200%), many of which have important policy implications. As a result of sensitivities studied here we suggest that further research intended to inform wind supply curve development focus not purely on physical science, such as better resolved wind maps, but also on these less well-defined factors, such as land-suitability, that will also have an impact on the long-term role of wind power.

### 1. INTRODUCTION

Wind power is a renewable energy source with potential to reduce greenhouse gas emissions and local air pollutants associated with the burning of fossil fuels. However, the precise role that wind energy might play, at regional and global levels, remains unclear, for several reasons. One reason is that there are still large uncertainties about the amount of wind that can be effectively incorporated into electricity grids. Another reason is that there are still large uncertainties about the supply and cost of wind energy.

Improved information regarding global wind energy potential can help decision-makers gain insight into the wind resource and its spatial distribution. Another reason to develop supply and cost information and to understand the surrounding uncertainties is that this information is an important input to integrated assessment and energy-economic models. These models are used extensively to explore the nature of climate mitigation over decadal to century scales, and they are important tools to inform national and international dialogues regarding climate policy and transition pathways to a lower-carbon future.[1,2]

There are several previous studies examining global and regional onshore wind supply. Hoogwijk et al.,[3] estimated onshore wind energy potential based on annual wind speed data from the Climate Research Unit (CRU). Lu et al.[4] used Goddard Earth Observing System Data Assimilation System data. Archer and Jacobson[5] used wind speed data from a network of sounding stations. The global potential of wind electricity from Hoogwijk et al. is 96 pWh per year (10.96 TW, pWh are converted to TW by dividing by the number of hours in a year) at cutoff costs of about \$1/kWh.[3] 690 pWh annual (78.8 TW) onshore wind energy potential with capacity factors >20% is estimated from Lu et al.[4] Global wind power generated at locations with mean annual wind speeds ≥6.9 m/s is 72 TW from Archer and Jacobson.[5] In addition to the evaluation of wind potential from land-surface turbines, Archer and Caldeira estimated the wind power resource at altitudes between 500 and 12 000 m above ground.[6] Among these studies, the work of Hoogwijk et al.[3] was designed to be used in integrated assessment and energy-economic models.

Constructing a consistent estimate of global and regional onshore wind potential is a challenge because global data sets with sufficient resolution to resolve areas of high-speed wind are not publically available. Additional limitations include the use of coarse spatial resolution input data such as land cover,[3,4]

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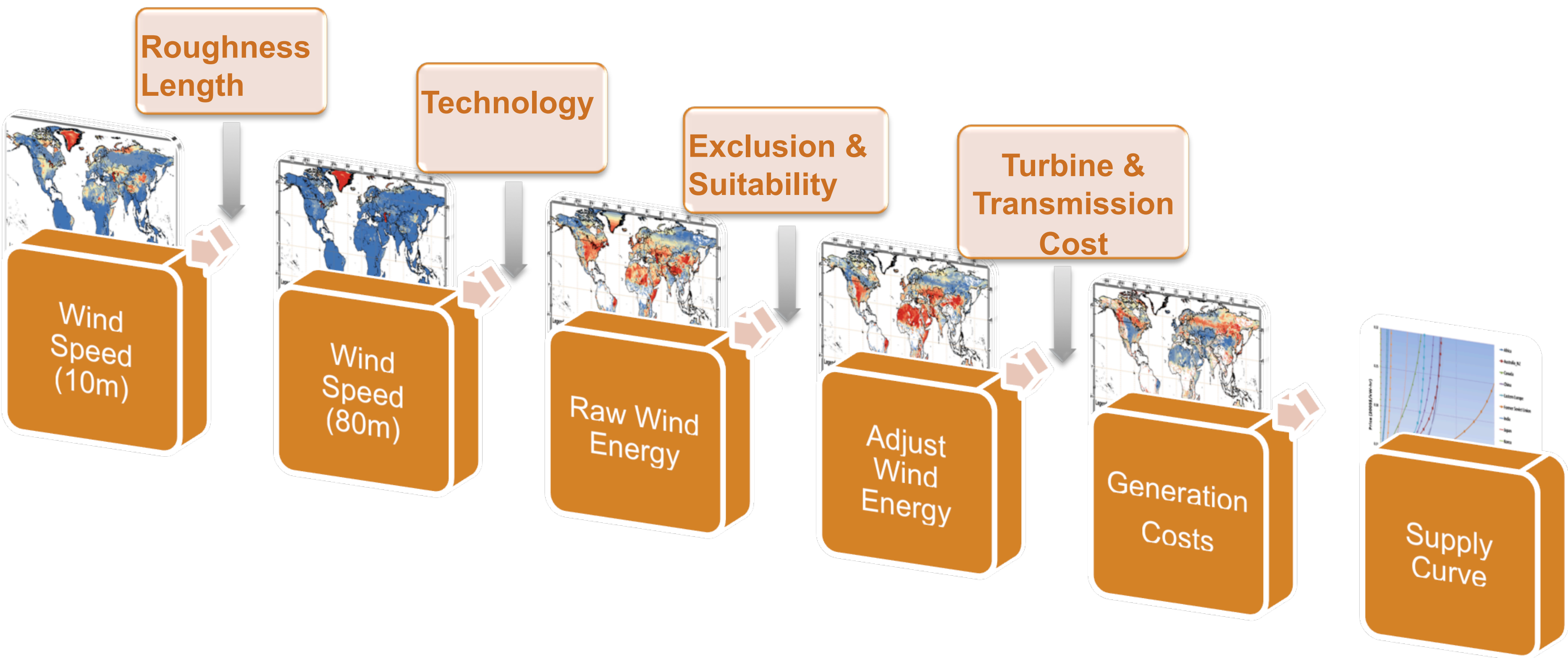
# Overview of Methodology for Wind Supply Curve

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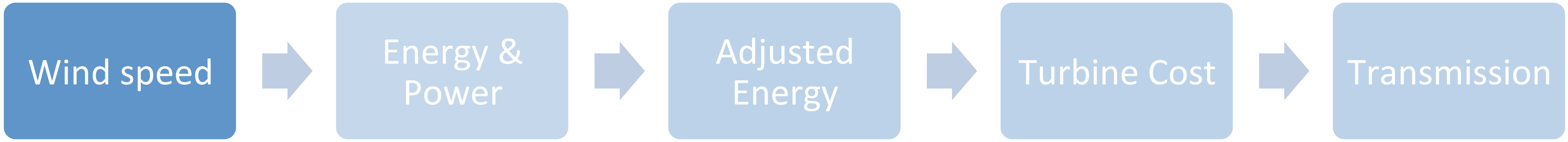
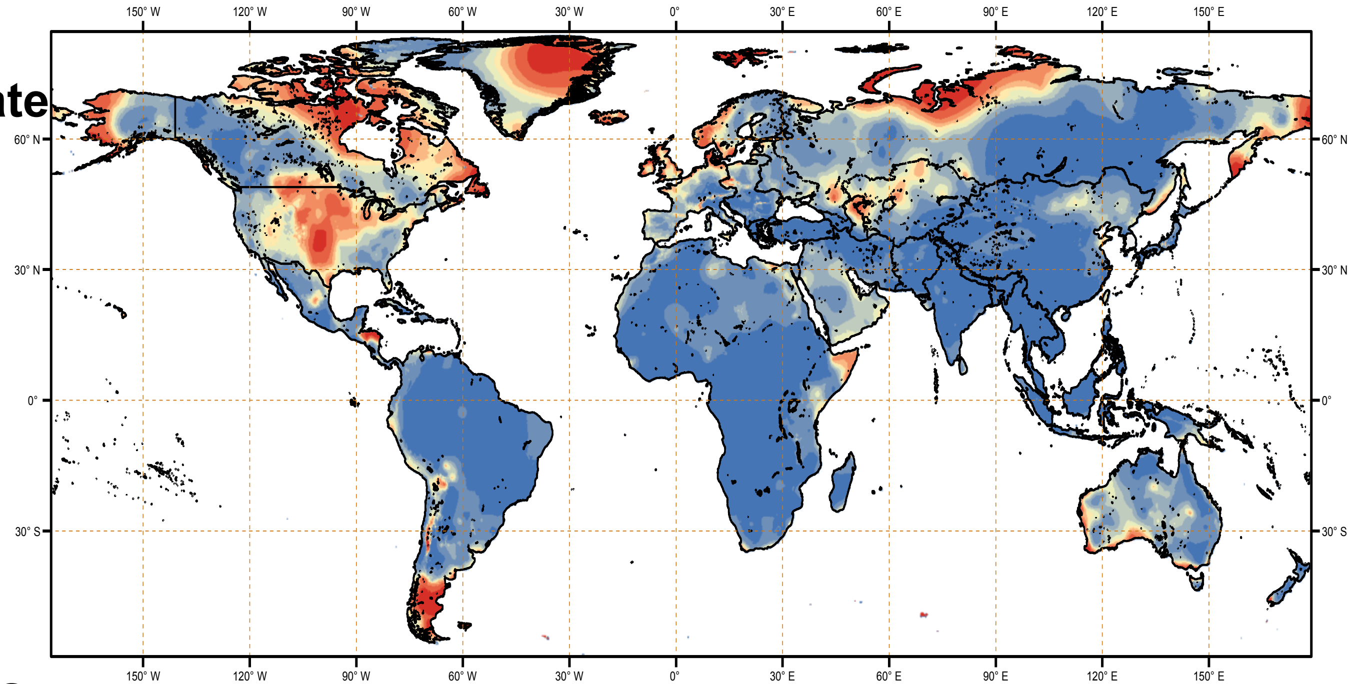
# Step 1: Wind Speed Data



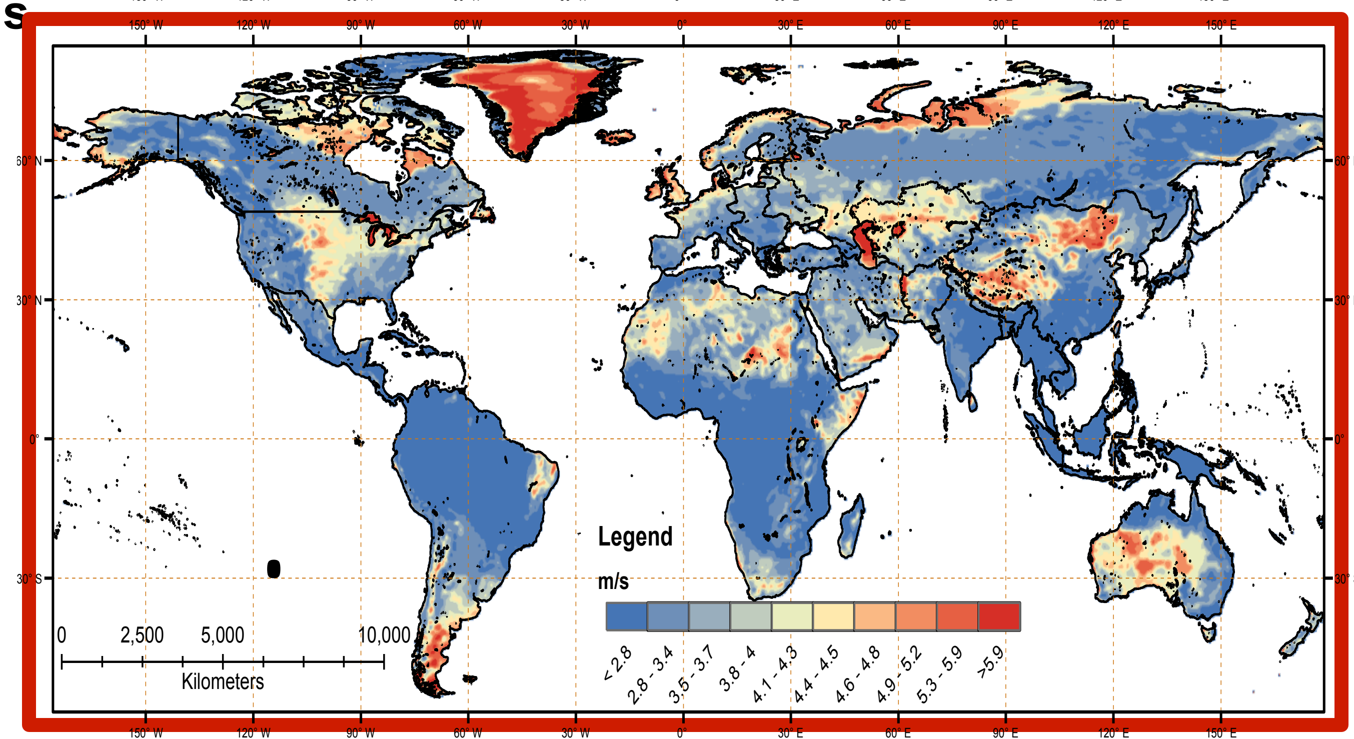
**CRU station interpolate**
**1/6 degree**
**1960-1990 (monthly)**
**Hoogwijk *et al.***



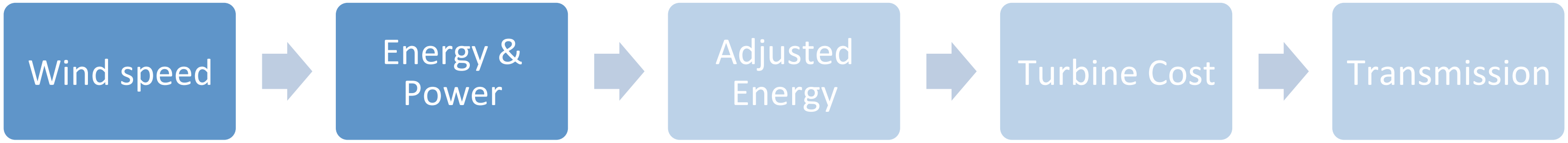

**NCEP/CFSR reanalysis**
**0.3125 degree**
**1979-2009 (hourly)**
***PNNL/JGCRI***

GEOS Assimilation data
0.5 degree (6 hour)
*Lu et al.*

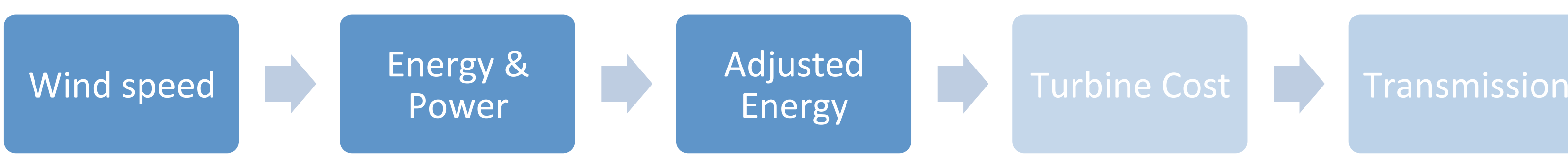
Surface stations
Point (hourly)
*Archer and Jacobson*



# Step 2: Raw wind power (technical potential)



# Step 3: Exclusions and Suitability



# What are the reasons that land might be totally or partially excluded?

- There is land that you might not want to disturb with development.
- There are areas where you don't want to put people at risk (e.g., right next to people).
- Public acceptance and local ordinance: i.e. aesthetics – noise and visual impacts.
- Transmission and access constraints: some terrain is just not amenable to turbines (e.g., steep slopes, hard to access land, forests due to roughness)

# The Approach for Treating Suitability

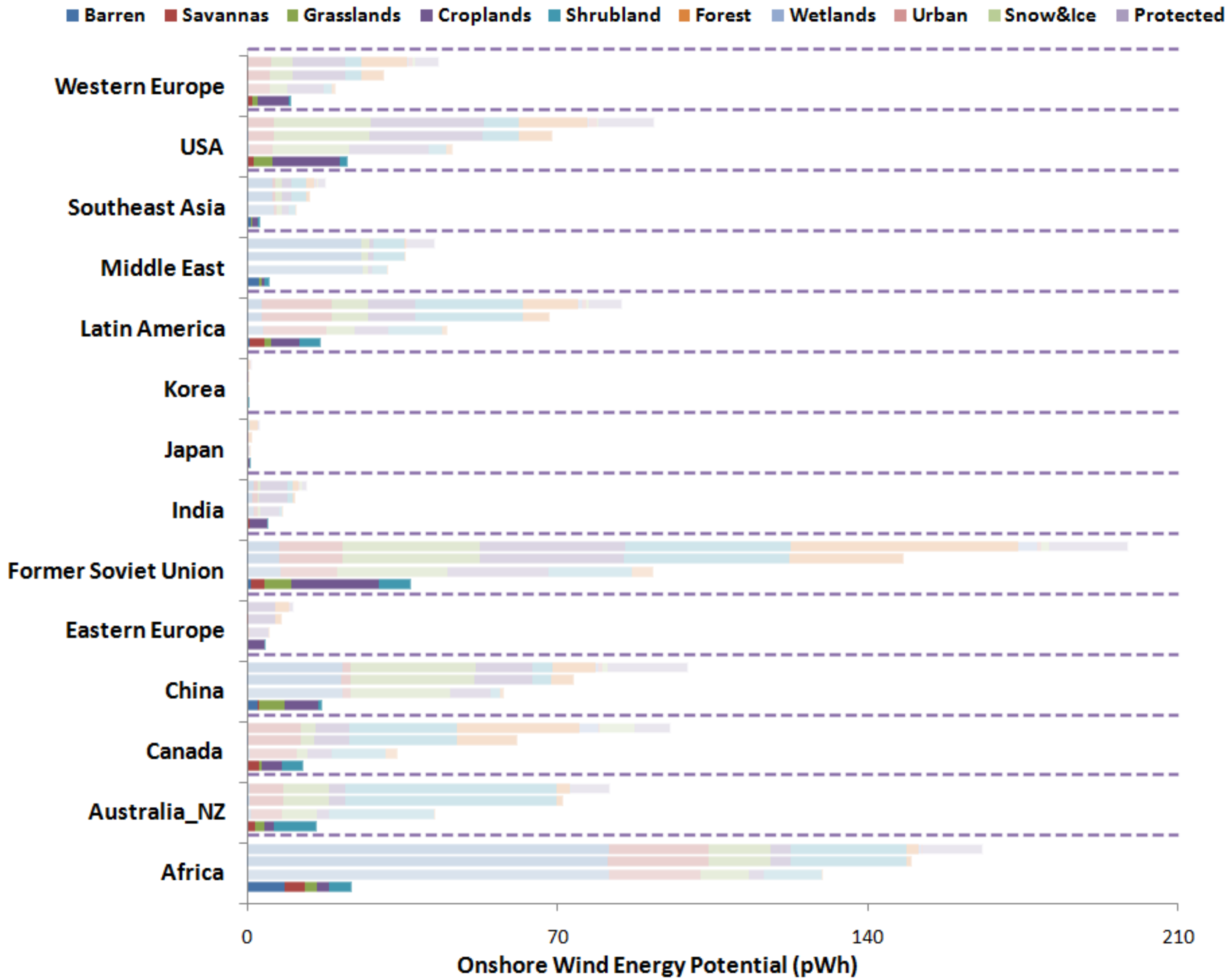
- Step 1: Remove protected lands, like national parks.
- Step 2: Apply suitability factors based on land type

Note that we are calculating suitability and exclusions based on the current situation. We are not considering changes in land use.

# Suitability factors for land cover (summary)

| Land use | Hoogwijk et al. | de Vries et al. | Honnery et al. | Elliott et al. | EIA | NREL | This study (low) | This study (central) | This study (high) |
|---|---|---|---|---|---|---|---|---|---|
| Protected | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Urban | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Water | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wetland | - | | 0-1 | 0 | - | - | 0 | 0 | 0 |
| Agriculture | 0.7 | 0.6 | 0-1 | 0.5 | 1 | 1 | .6 | .7 | 1 |
| Barren | 1 | 0.1 | 1-1 | 0.9 | 1 | 1 | .1 | 1 | 1 |
| Forests | 0.1 | 0 | 0-1 | 0.5 | 0.5 | 0.5 | 0 | .1 | .5 |
| Grassland | 0.8 | 0.2 | 1-1 | - | 1 | 1 | .2 | .8 | 1 |
| Savannah | 0.9 | 0.2 | 1-1 | - | - | - | .2 | .9 | 1 |
| Shrubland | 0.5 | 0.2 | 1-1 | - | 1 | 1 | .2 | .5 | 1 |
| Tundra | 0.8 | 0.1 | 1-1 | - | 1 | 1 | - | - | - |

# Wind energy potential in each land cover

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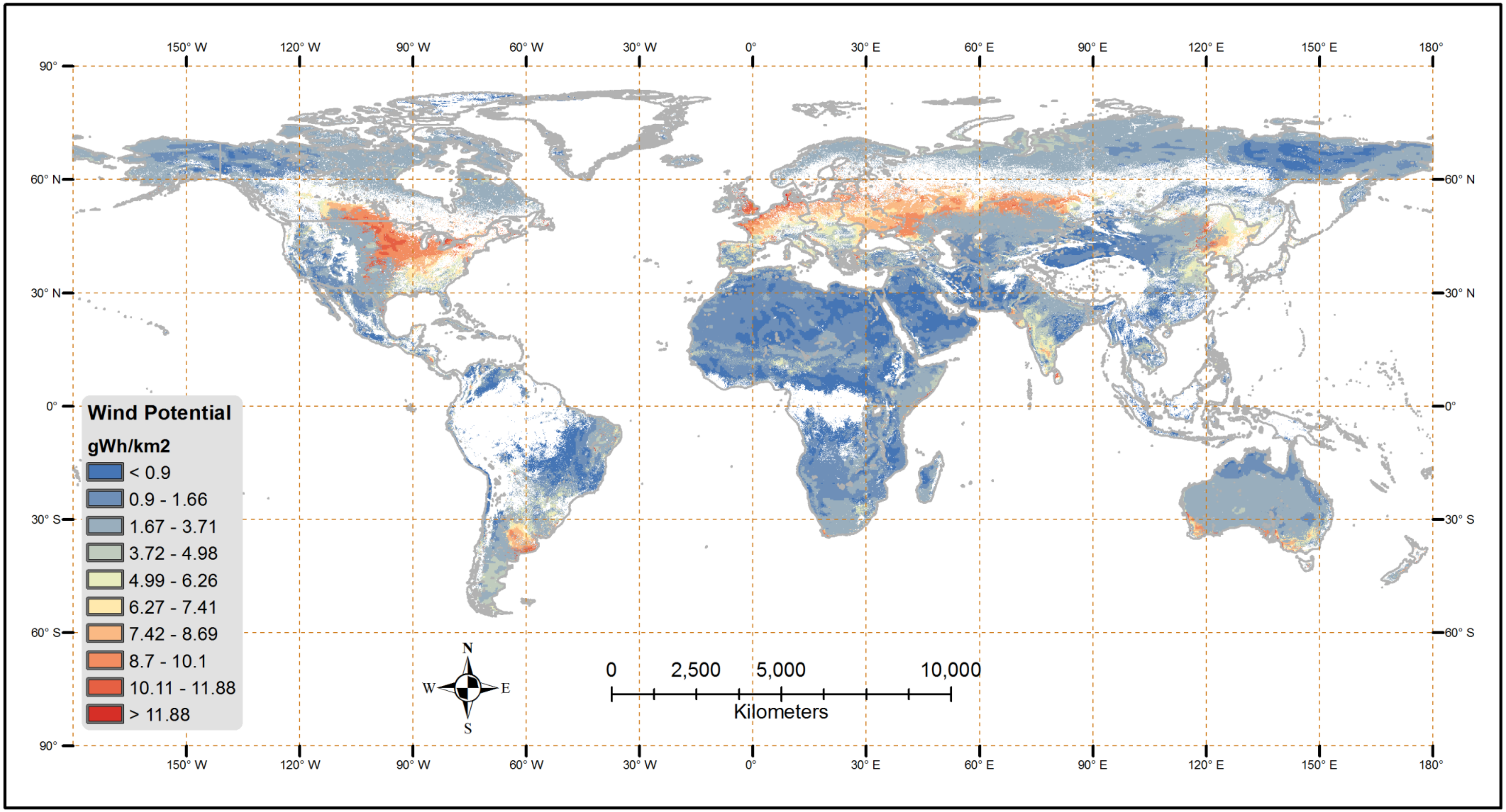
# Practical potential per unit area (low suitability)

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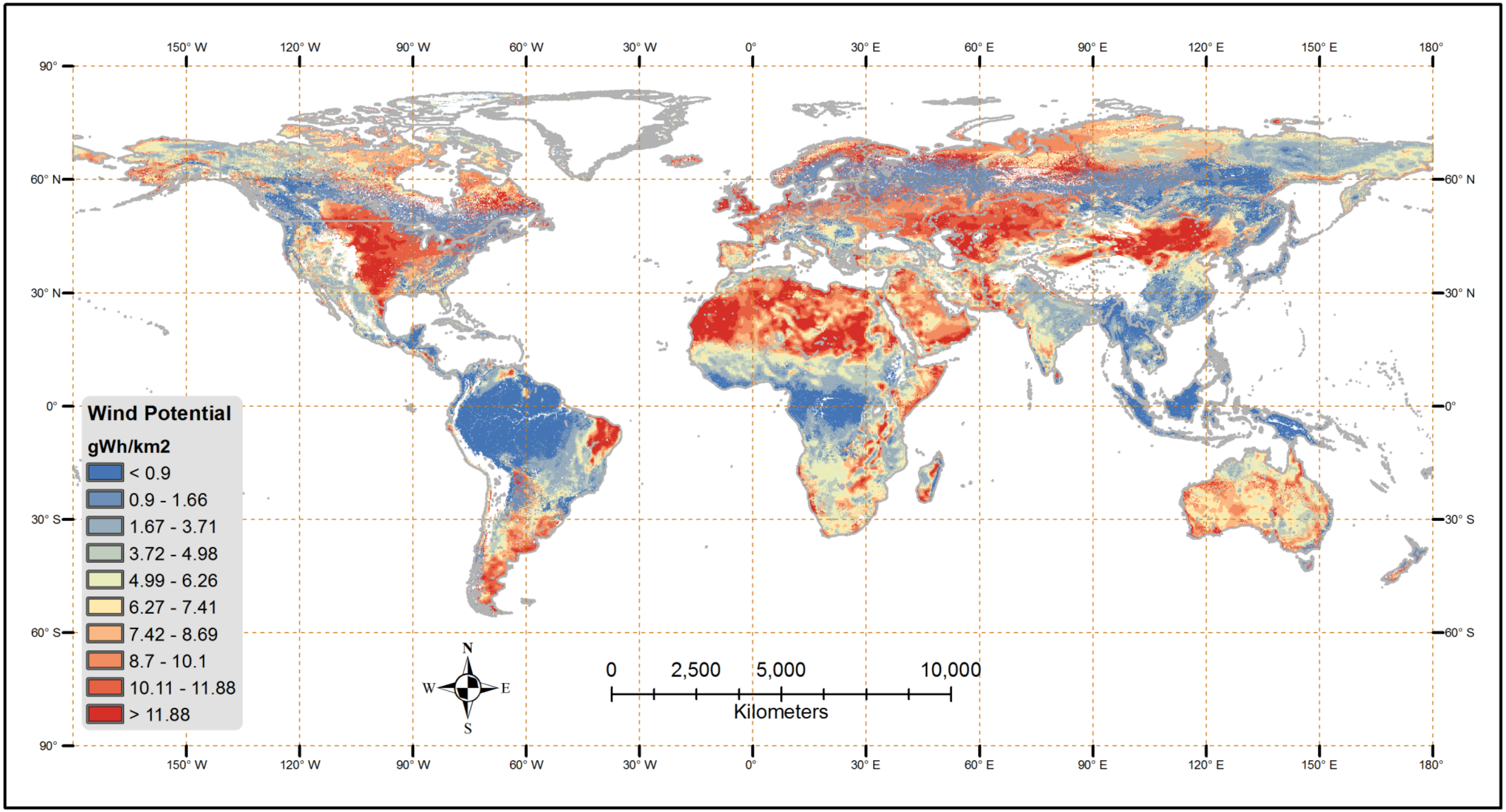
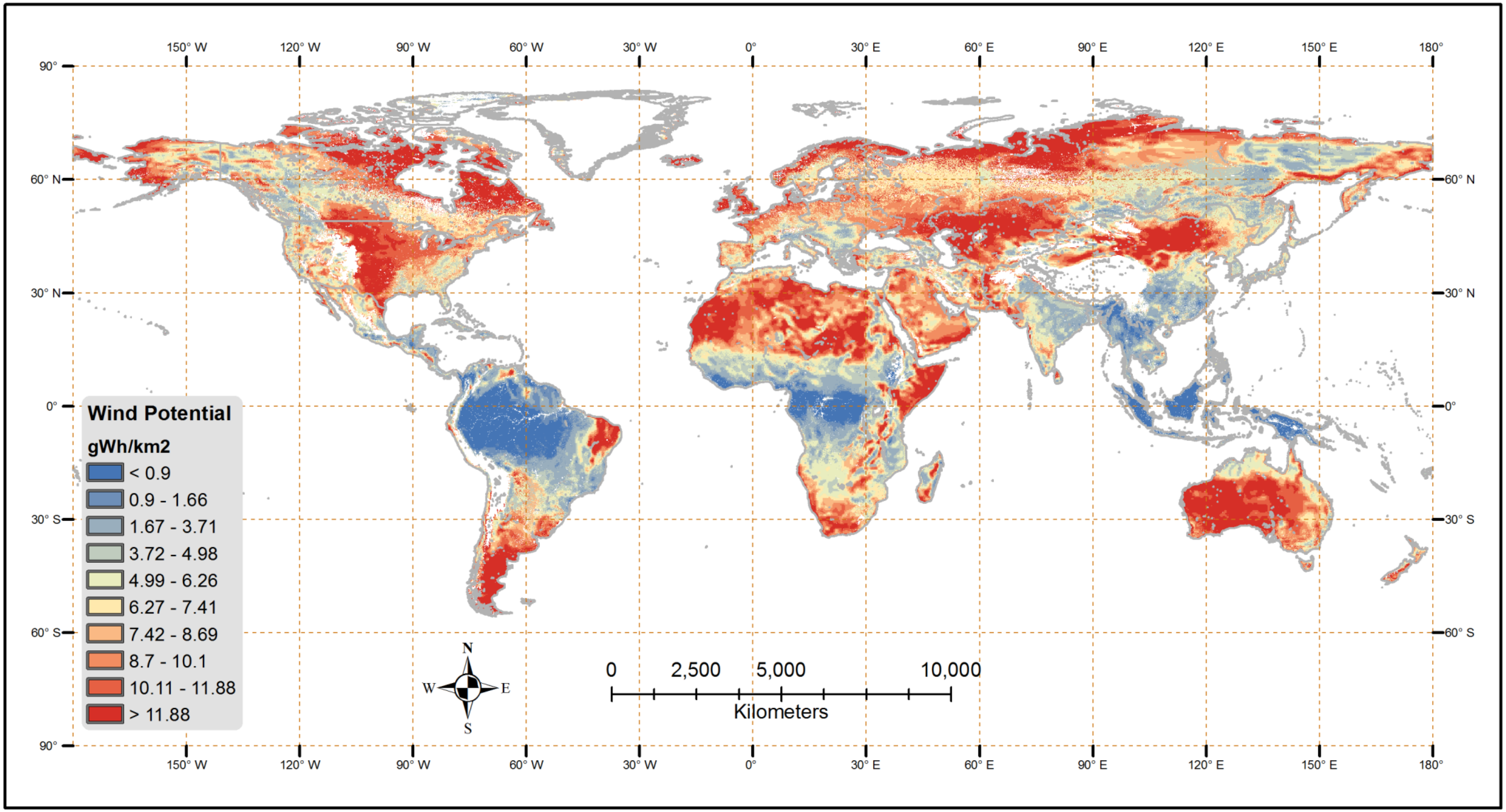
# Practical potential per unit area (central suitability)



# Practical potential per unit area (high suitability)

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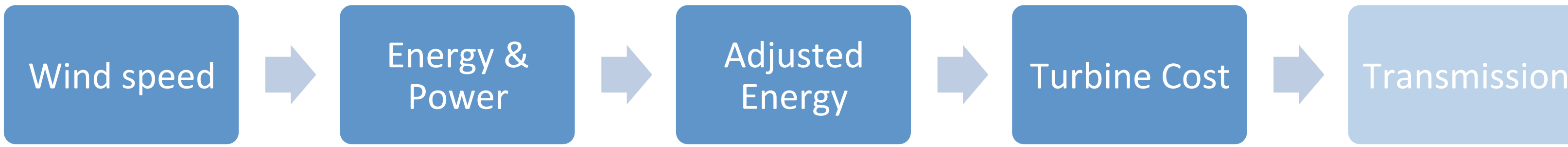
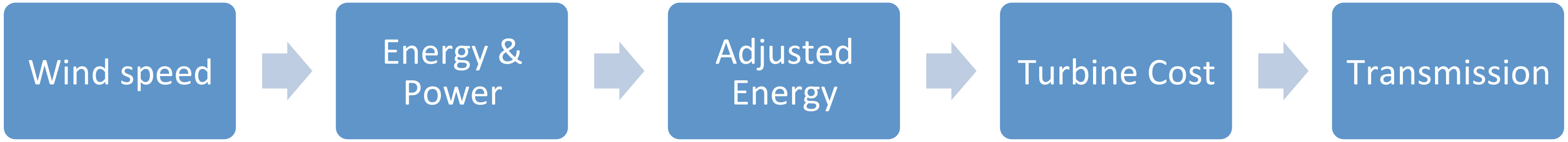
# Step 4: Turbine Cost



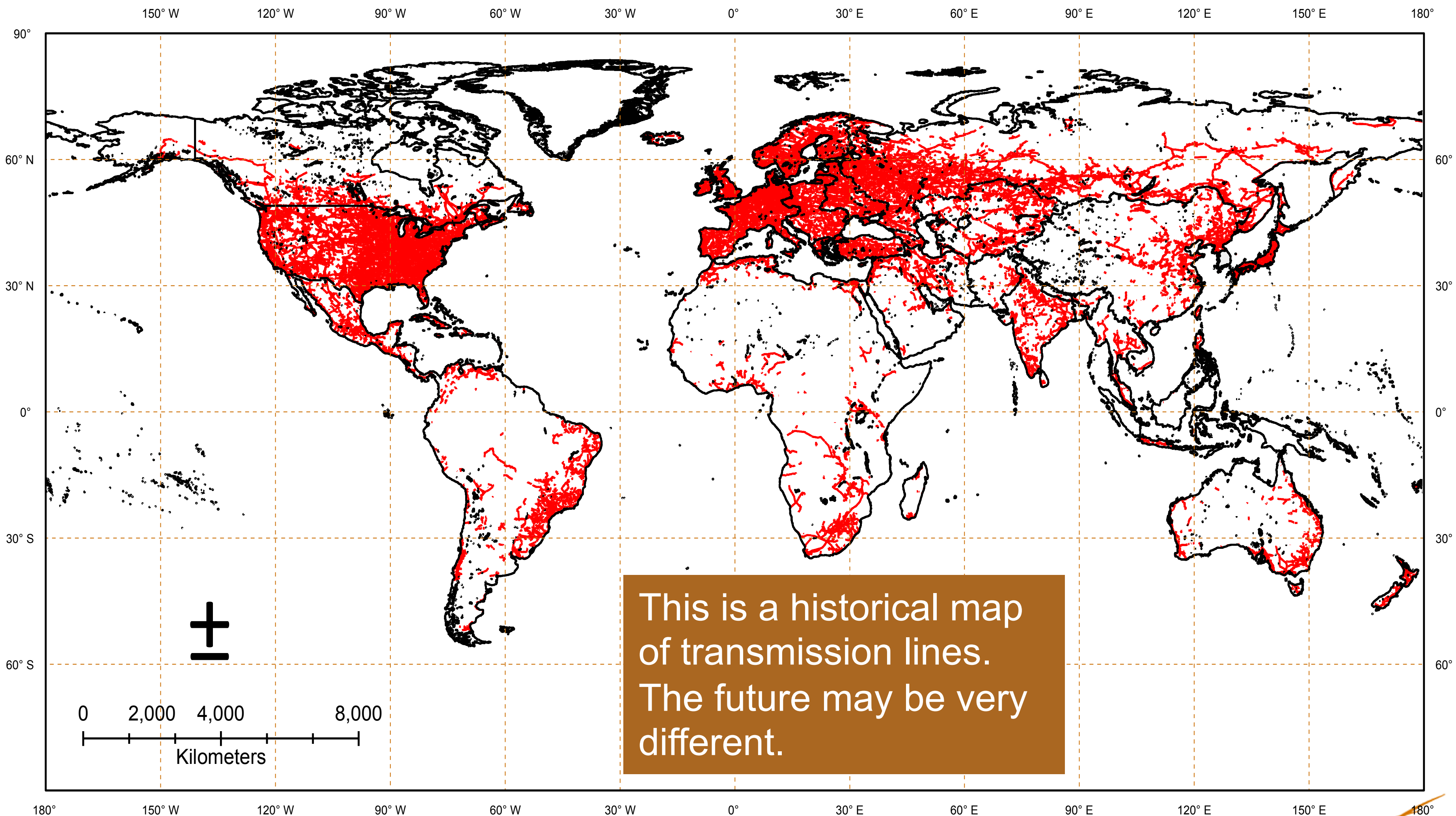
# Step 5: Transmission Cost



# What are the issues that we need to consider for transmission costs?

- Wind is highly dispersed; and often far from population centers.
- So connection “to the grid” is an important part of the wind cost.
- What is the cost of transmission?
  - Increased cost per mile method used by NREL
  - Central case at $745/MW·km

# Powerline Map from Digital Chart of World




This is a historical map of transmission lines. The future may be very different.

– Power Line

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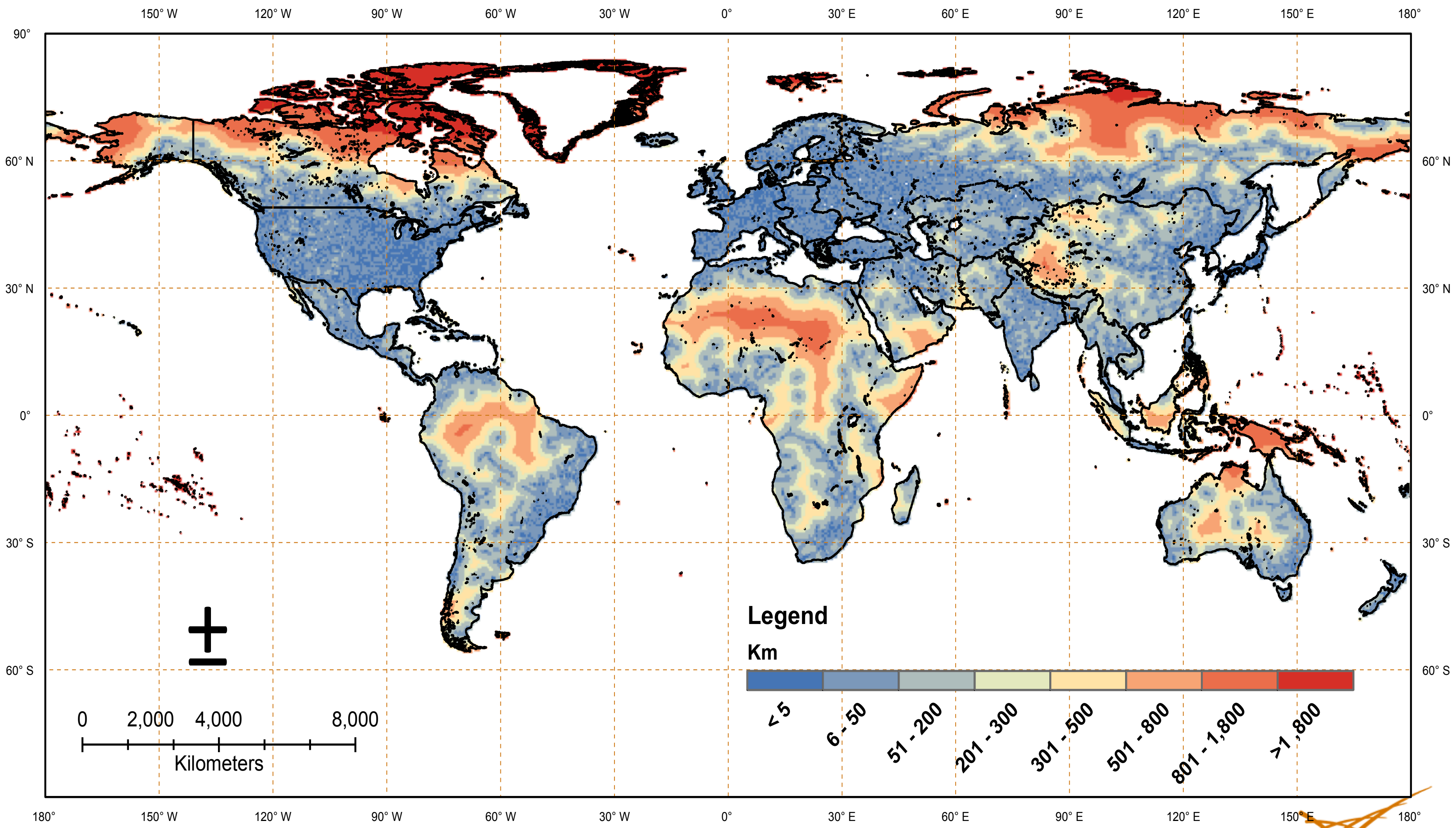
# Distance to Transmission Line

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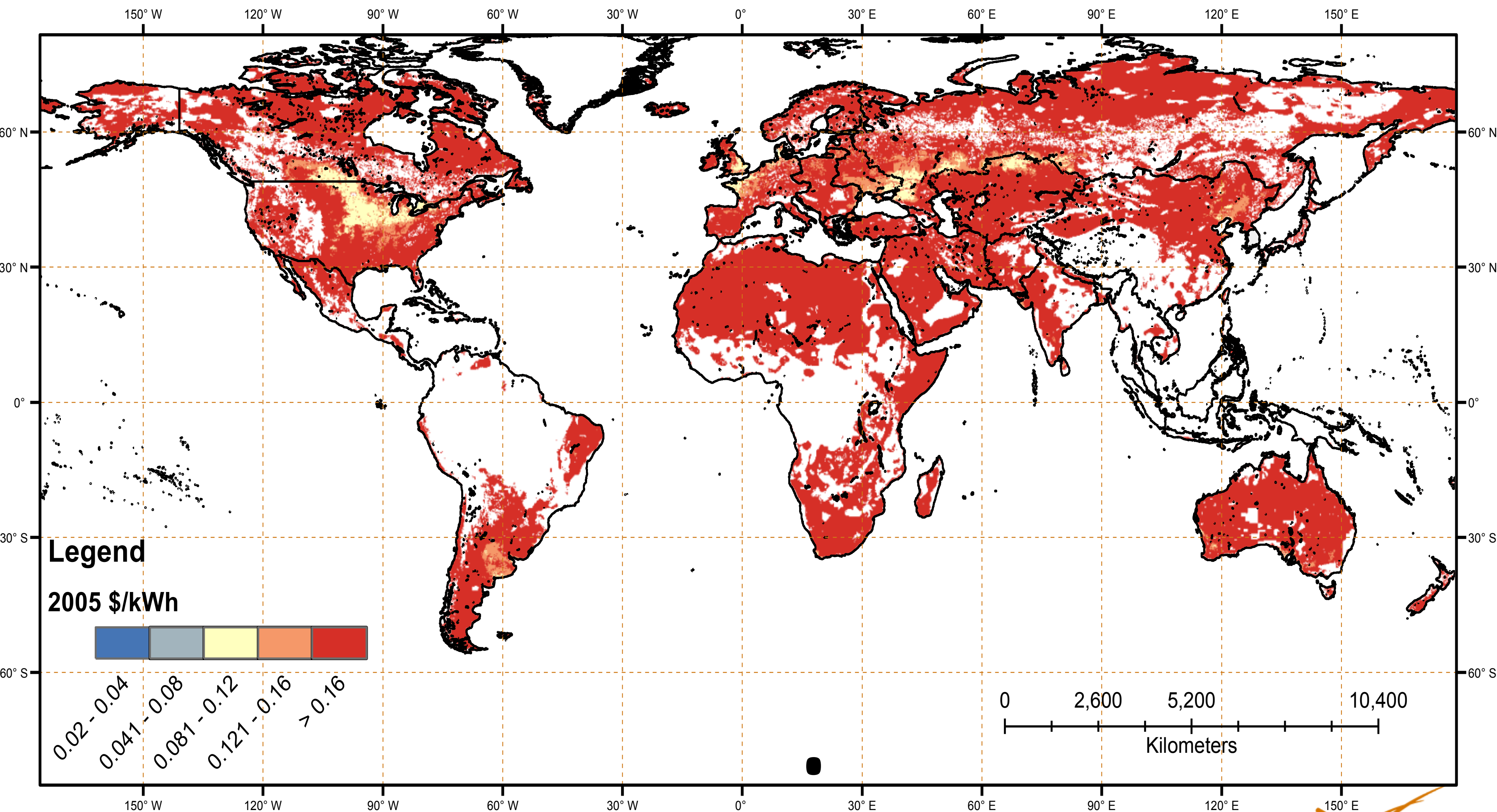
# Result 1: Generation Cost

# Wind Cost Map (Pessimistic Case)




Results expressed as 2005 $ per kW-hr

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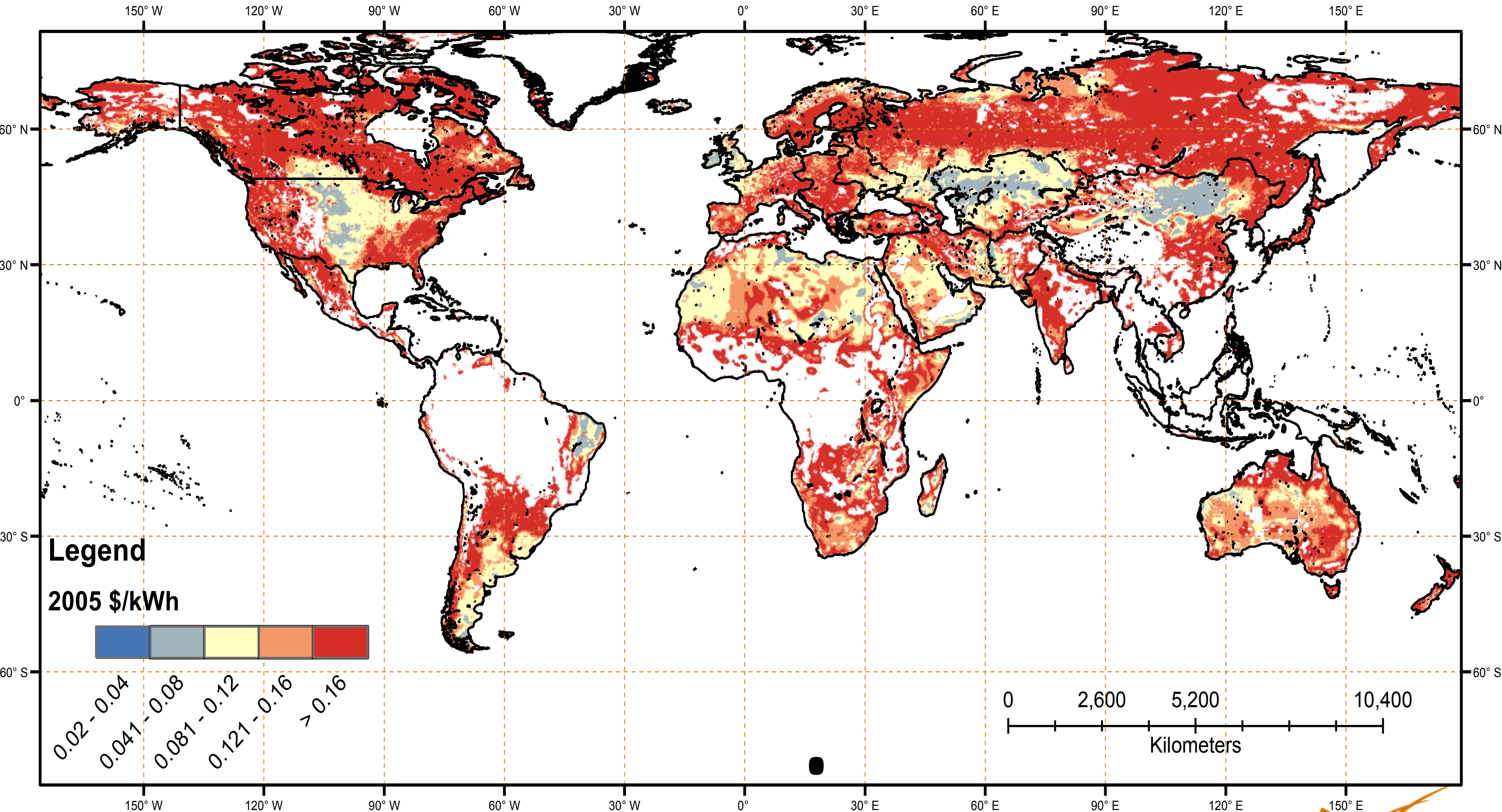
# Wind Cost Map (Central Case)




Results expressed as 2005 $ per kW-hr

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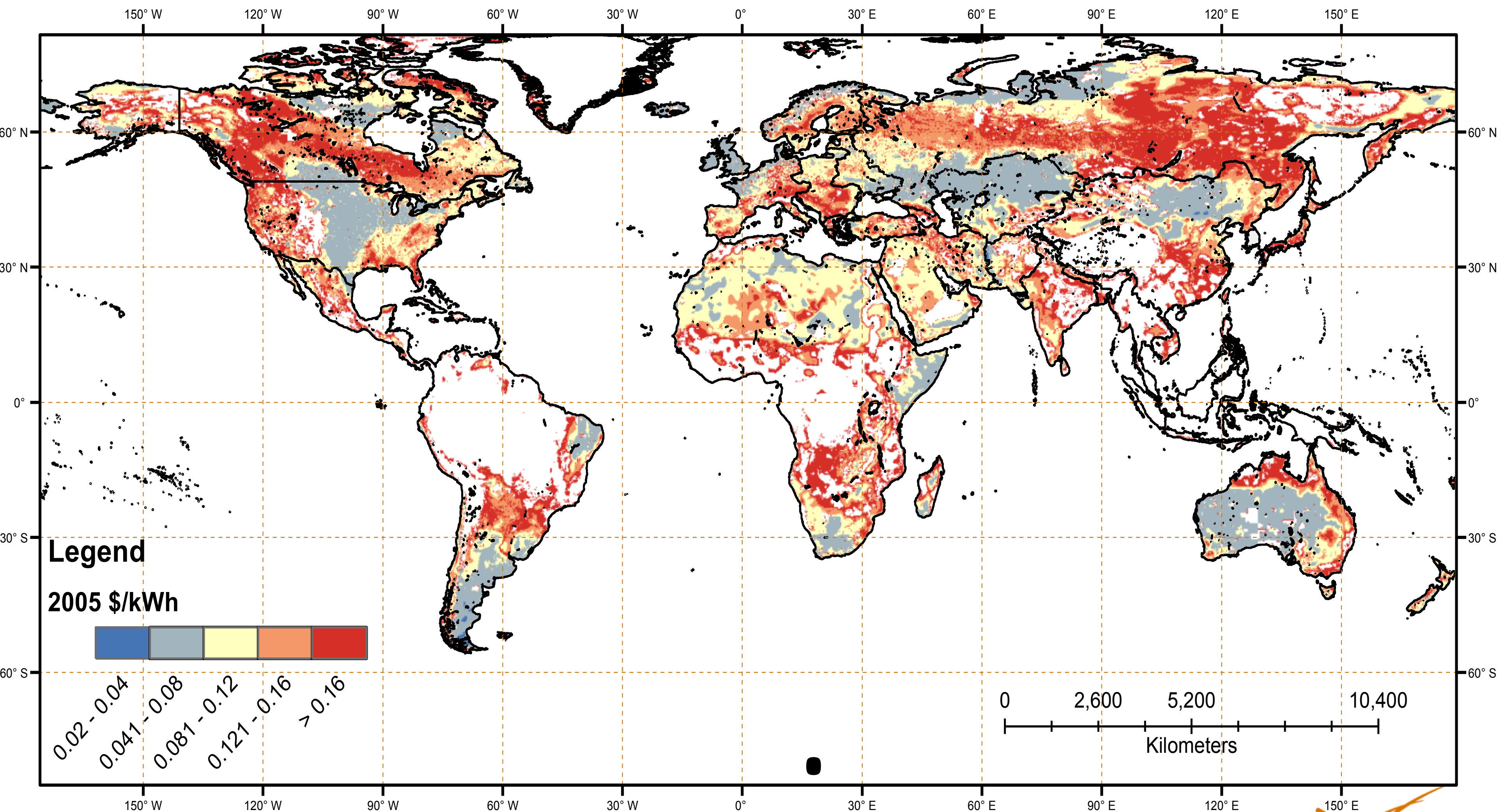
# Wind Cost Map (Optimistic Case)




Results expressed as 2005 $ per kW-hr

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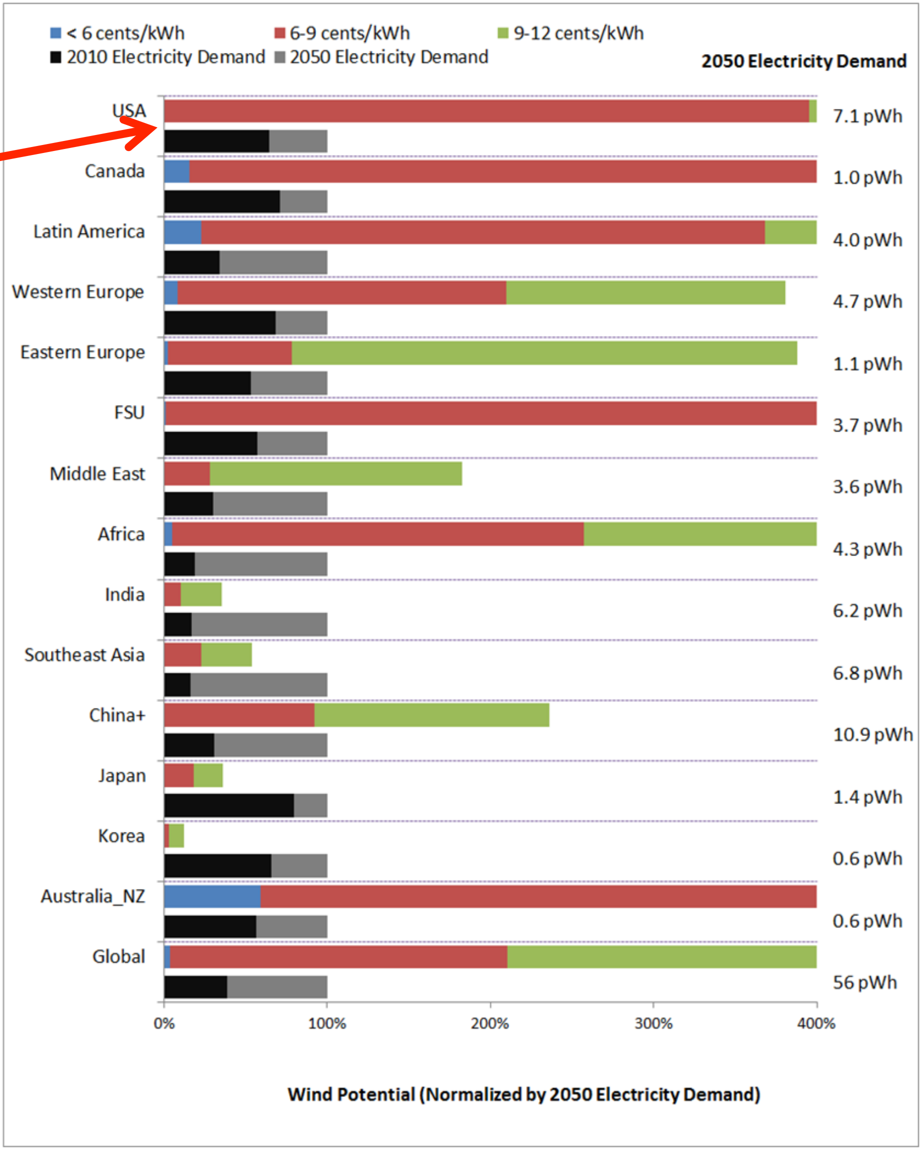
# Wind Energy Potential in the Central Case

The bias against high wind speeds in the reanalysis dataset limits the estimates of the cheapest wind.

In three of the four comparison regions examined in this study, the CFSR data set used here missed 90% of the area with winds power class 5 and above.




Wind energy supplies at less than 9 cents/kWh are quite large in many regions relative to projected electricity demand. In other regions, wind supplies are more constrained.

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# Parameters in Sensitivity

| Parameter | Units | Pessimistic | Central | Optimistic |
|---|---|---|---|---|
| Wind Speed | $ms^{-1}$ | 0.9 * central case | NCEP/CFSR | 1.3 * central case |
| Suitability | / | Low | Central | High |
| Roughness Length | meter | 0.5 * central case | NCEP/CFSR | 2 * central case |
| Density | WM $km^{-2}$ | 2 | 5 | 9 |
| Turbine Cost | $/kWh | 2400 | 1800 | 1200 |
| Unit Transmission Cost | $/MW·km | 1491 | 745 | 373 |
| Turbine Height | meter | 60 | 80 | 100 |
| Fixed Charge Rate | / | 0.156 | 0.13 | 0.104 |

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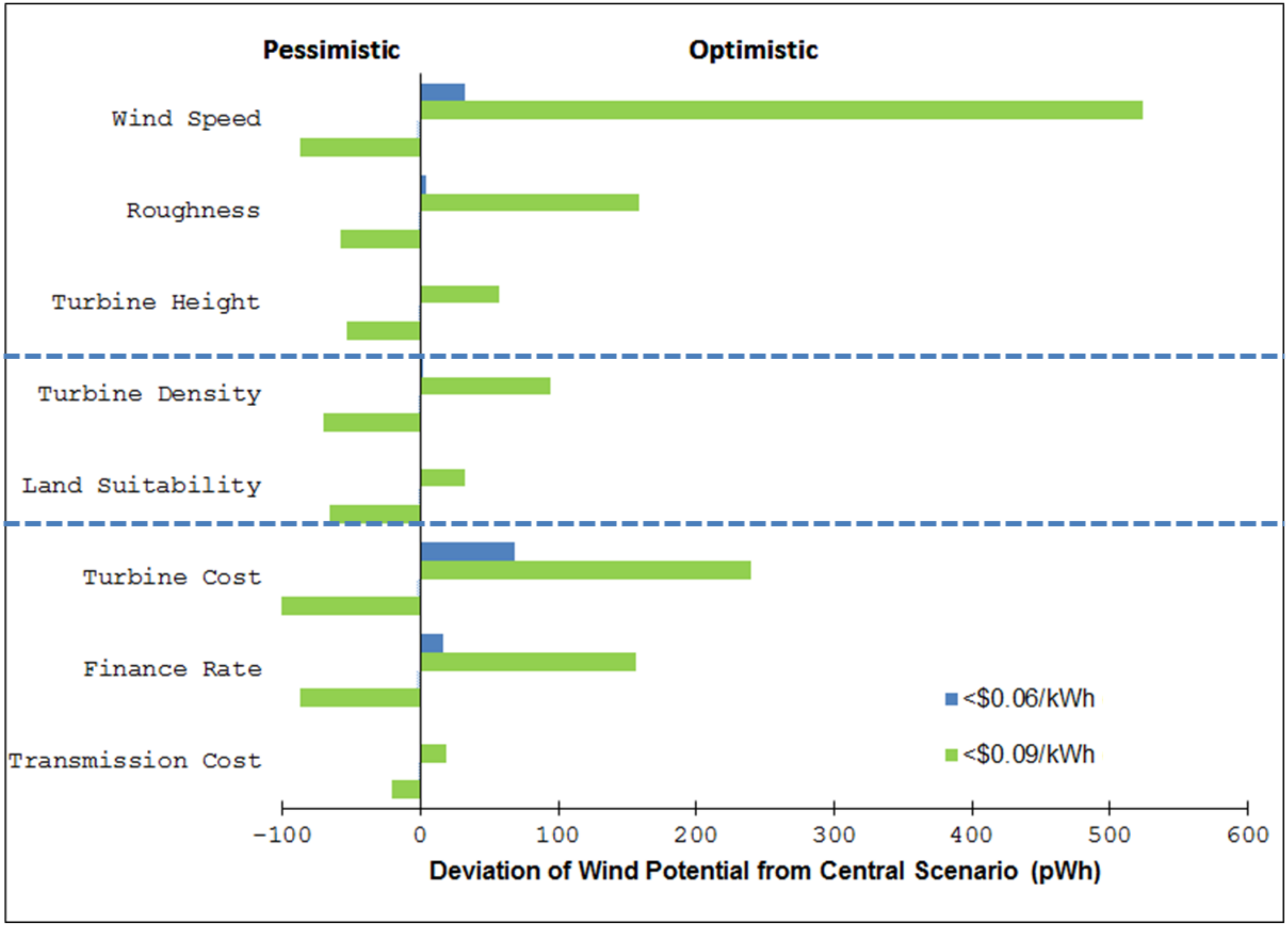
# Sensitivity of wind energy potential

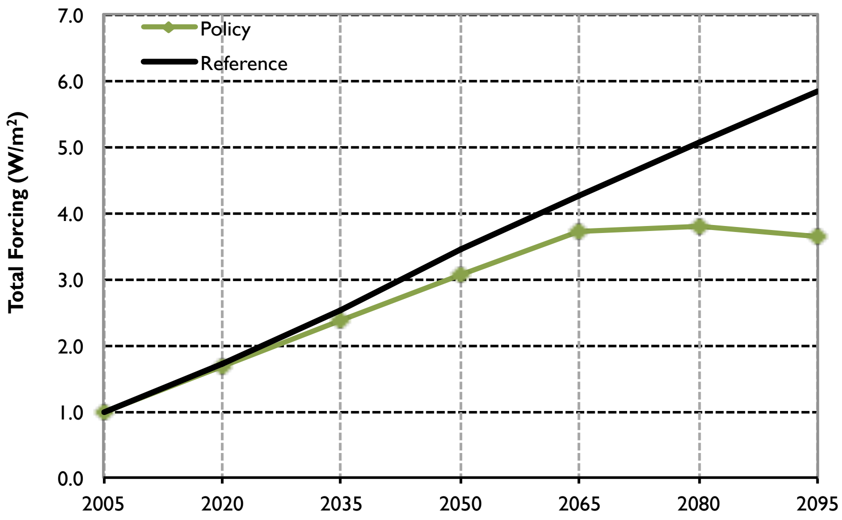


# Wind Exploration with GCAM

# The Cases We'll Explore

- With and without a 3.7 $W/m^2$ global climate policy.
- Three levels assumptions about the requirements for backup power on the grid.
- Two assumptions about wind resource.
- Two assumptions about wind turbine costs.
- One case where all generating technologies are available and one in which nuclear and CCS are not available.

3.7 $W/m^2$ or 550 ppmv CO2-e

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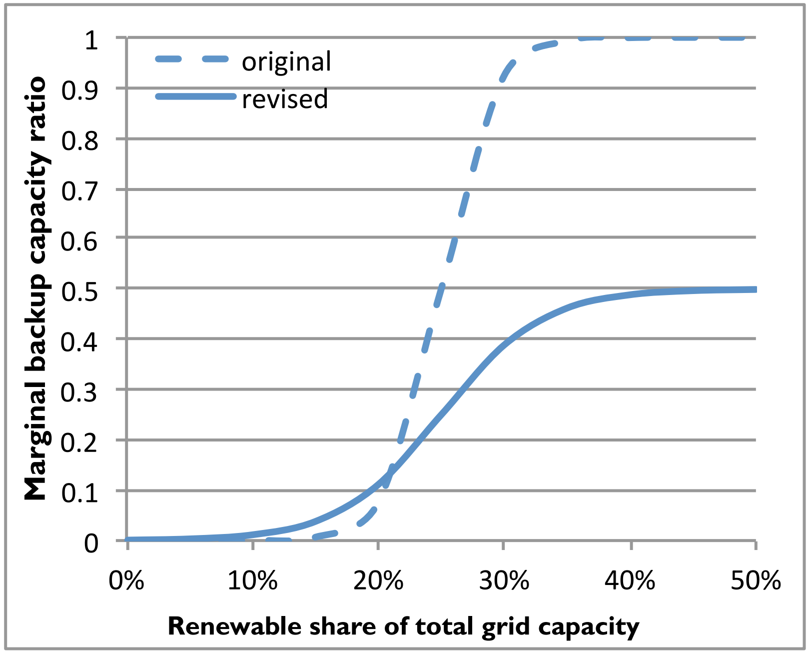
# Backup Requirements

- Increasing wind penetration means you need more backup generation in case wind doesn't blow
  - We assume gas turbine backup, with increasing backup requirements with increasing renewables (not just wind)
  - Default capacitylimit is 25%. Try increasing to 30% and 40%




$$BackupRatio = \frac{1}{1 + e^{b*(capacityLimit - elecShare)}}$$

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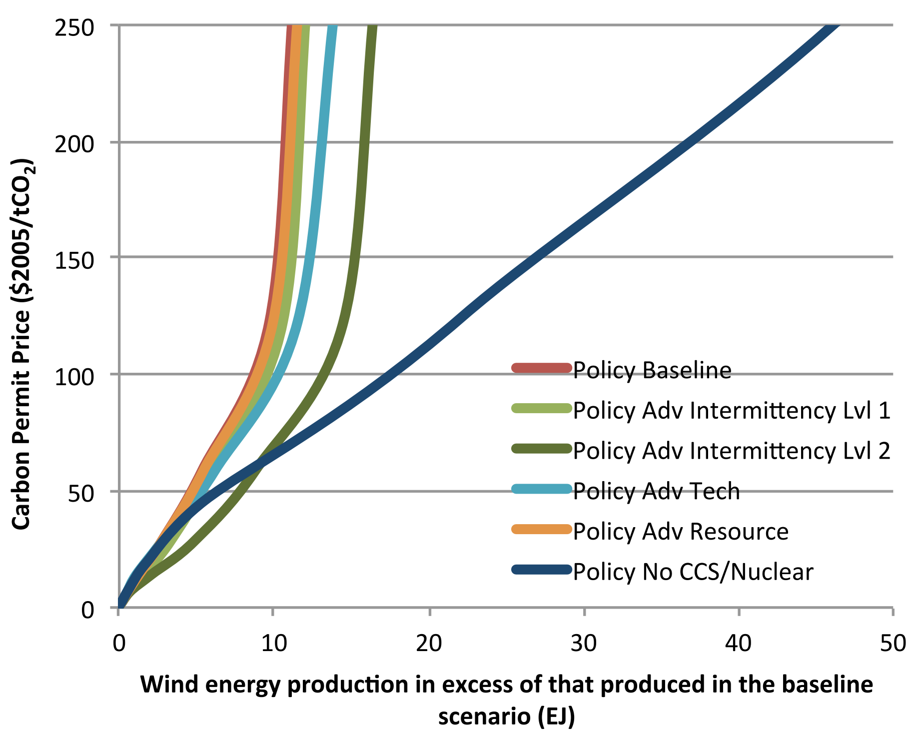
# How does wind deployment change with the carbon price?

- Wind production increases with time in the reference case
- For many policy cases, the increase in wind deployment tends to approximately max out, potentially indicating limitations from the integration costs.
- But if you need it enough, you will use it.

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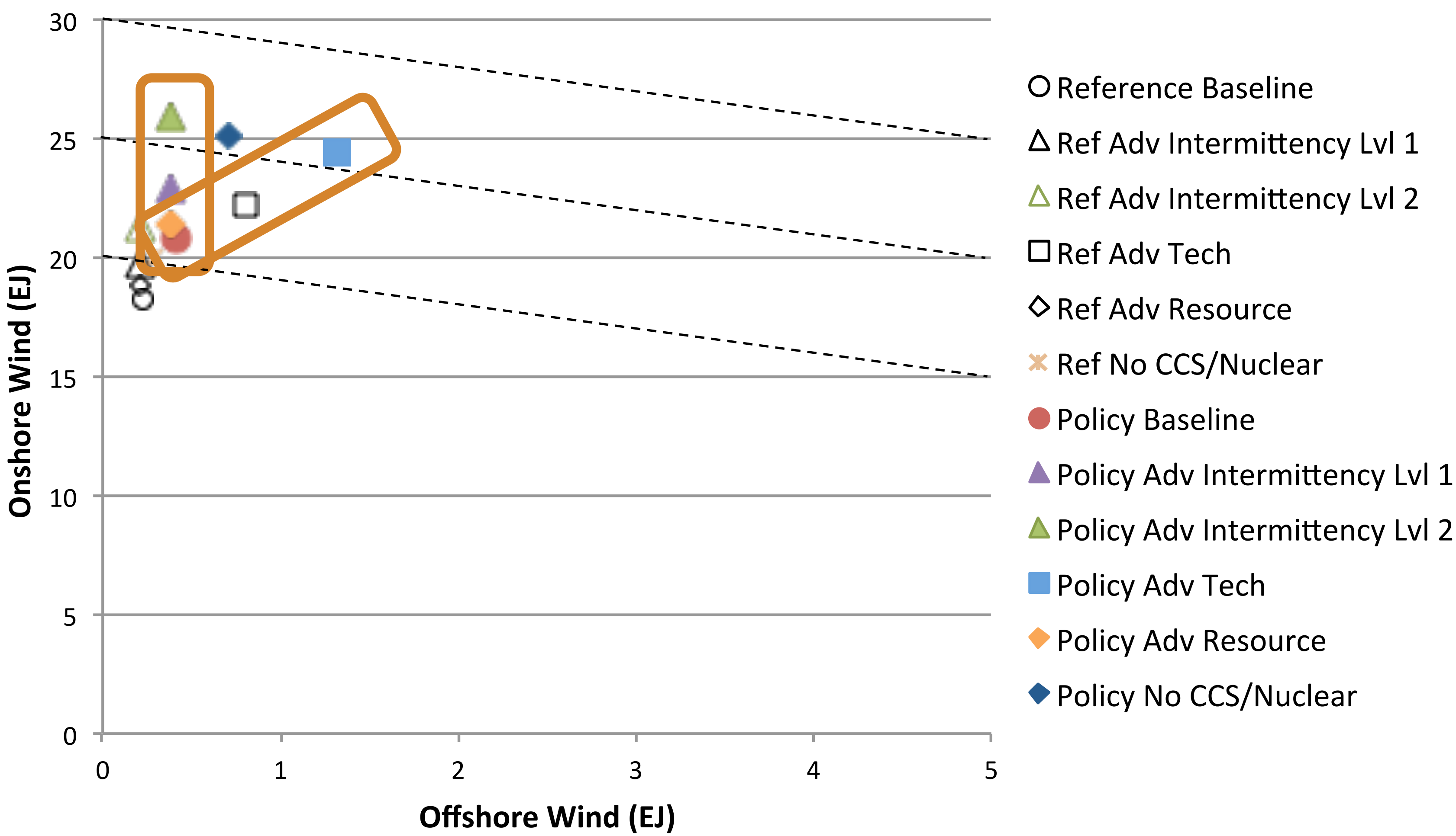
# Global Wind Production in *2050*

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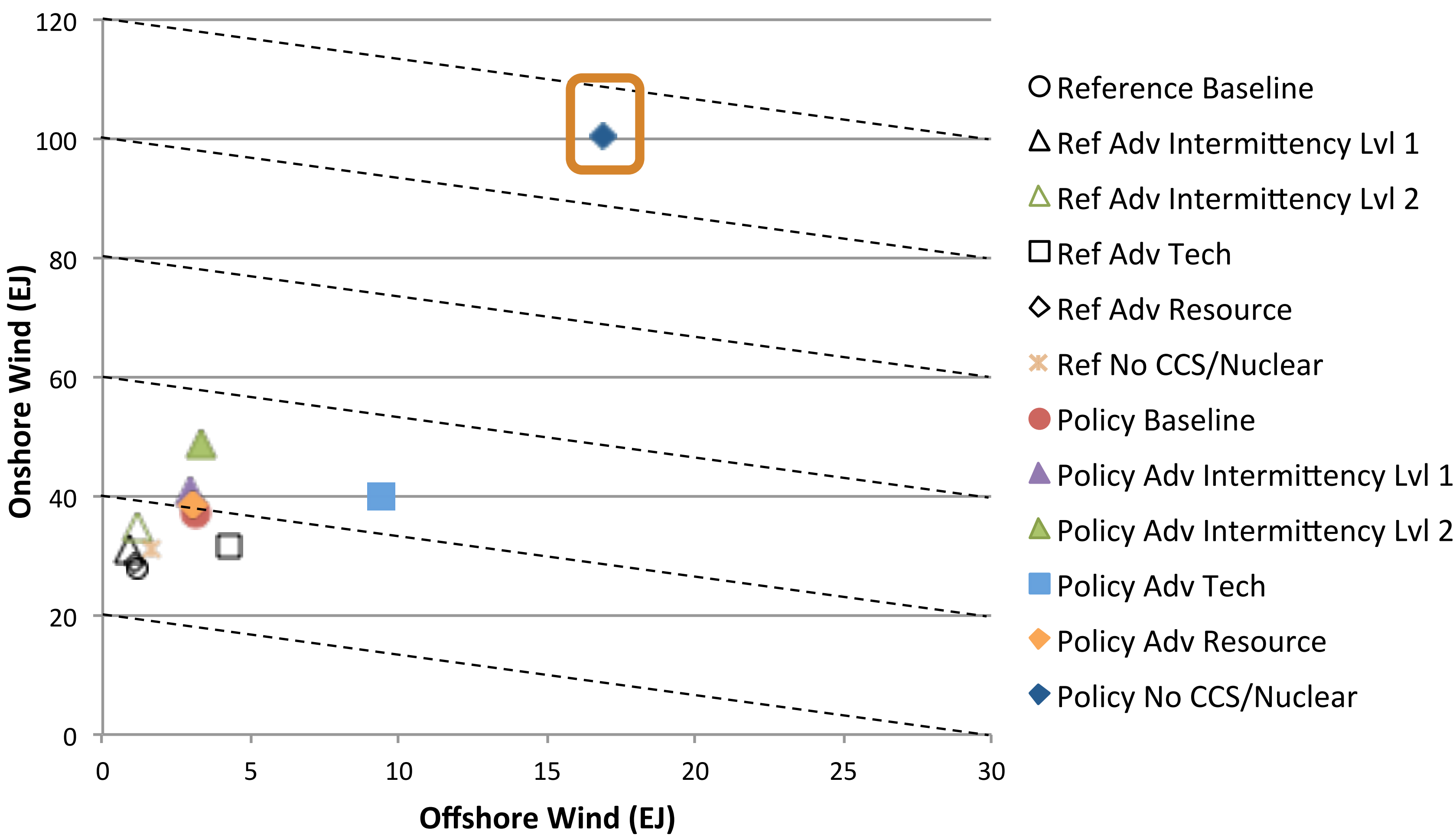
# Global Wind Production in *2095*

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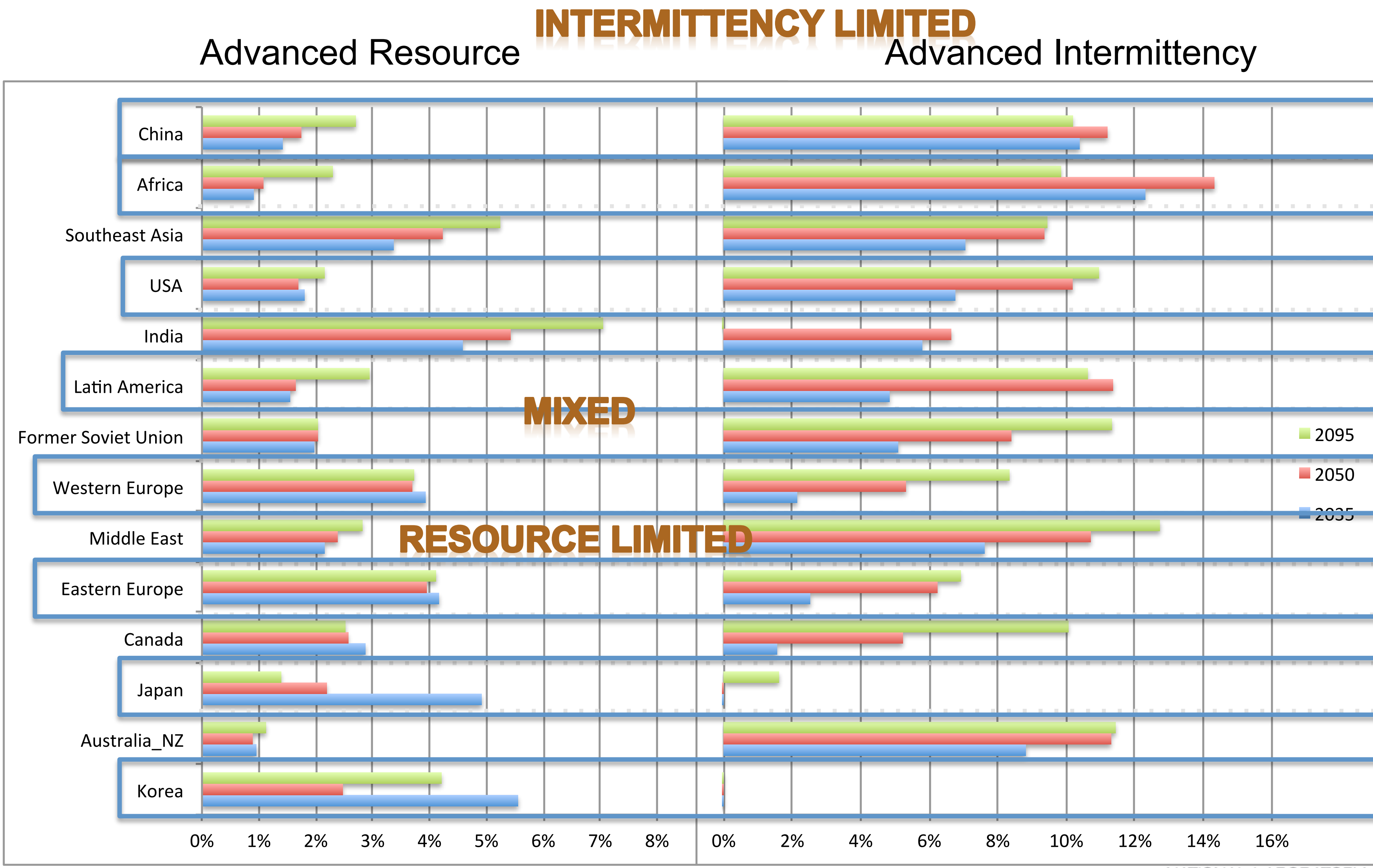
# Regional Change in Wind Production

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# Thank You!