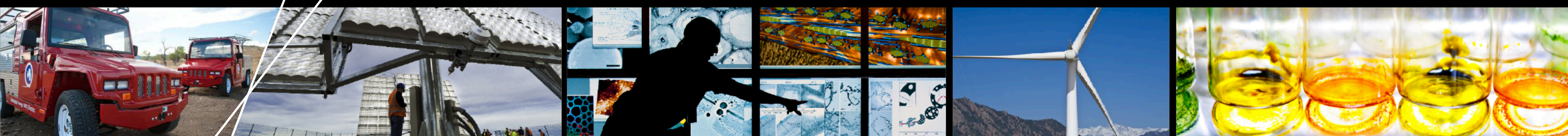
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL/CFDDA Global Wind Supply Curves



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Patrick Sullivan

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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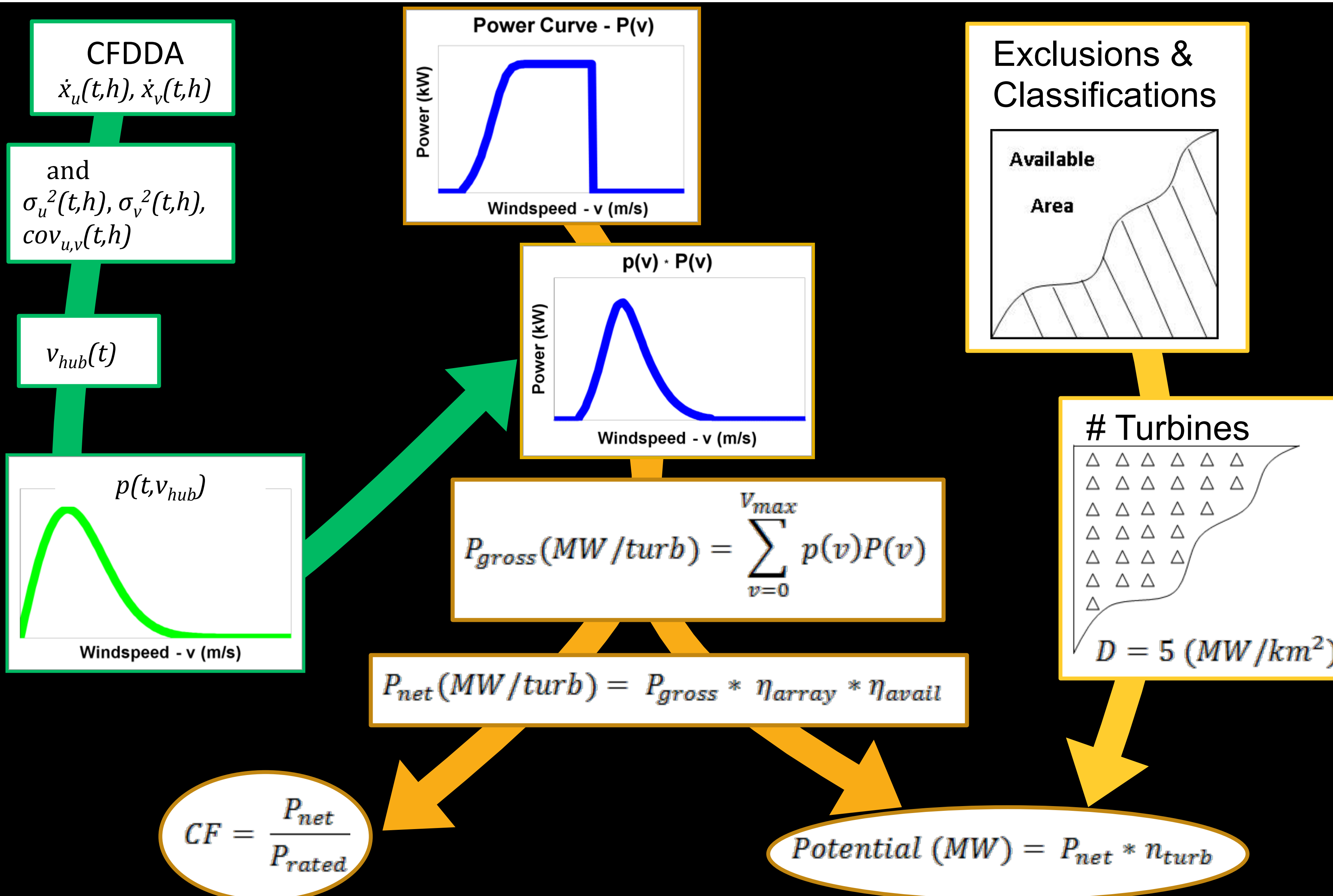


CFDDA 40km Wind Speed Data Description

Source: NCAR's CFDDA global reanalysis product

- Hourly wind speed vectors (u and v)
- Multiple hub heights (15.7m, 58m, 115m, 180m, and up)
- 40km grid (land and sea)
- 21 years of measured/modeled data
- (also temperature, pressure, insolation, etc.)

Our starting point

- For each grid cell,
- at each of the four lowest hub heights (up to 180m):
- mean wind velocity vectors by month-hour (e.g., the mean across 21 years of 30 days of July, 9am)
- and variances and u-v covariance for each month-hour

Reconstruct scalar wind speed distributions

Step 1: For each height and month-hour, construct u and v wind velocity distributions using means and variances.

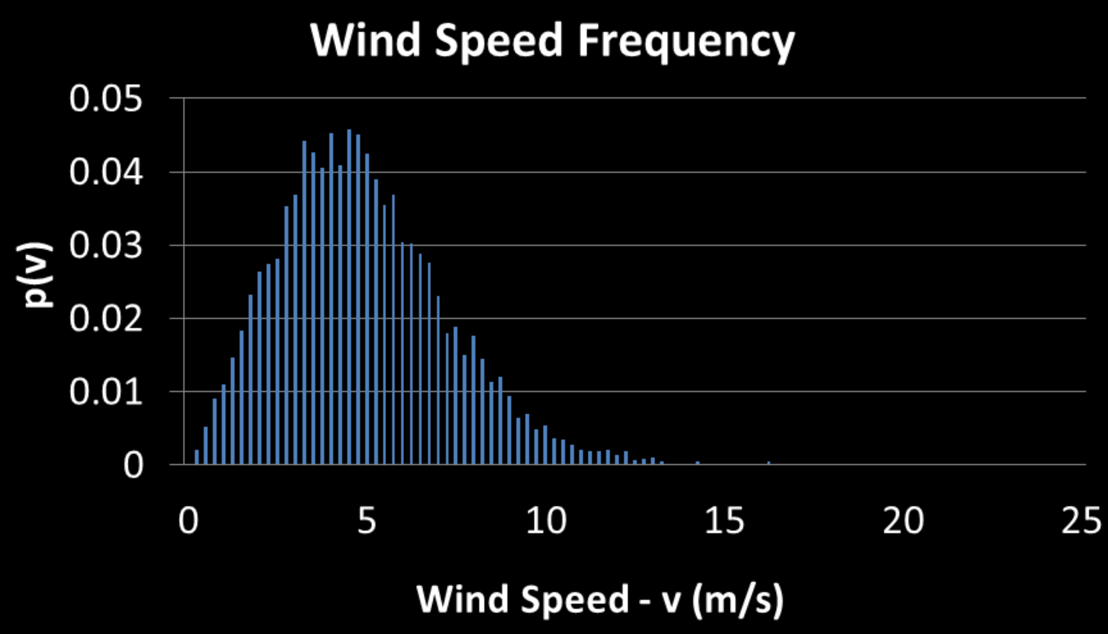
Step 2: Construct random sample vectors of u and v distributions.

Step 3: Reorder v-vector to obtain appropriate covariance with u-vector (Cholesky factorization in this step).

Step 4: Combine ordered u-v pairs to produce vector of scalar wind speeds for the height and month-hour.

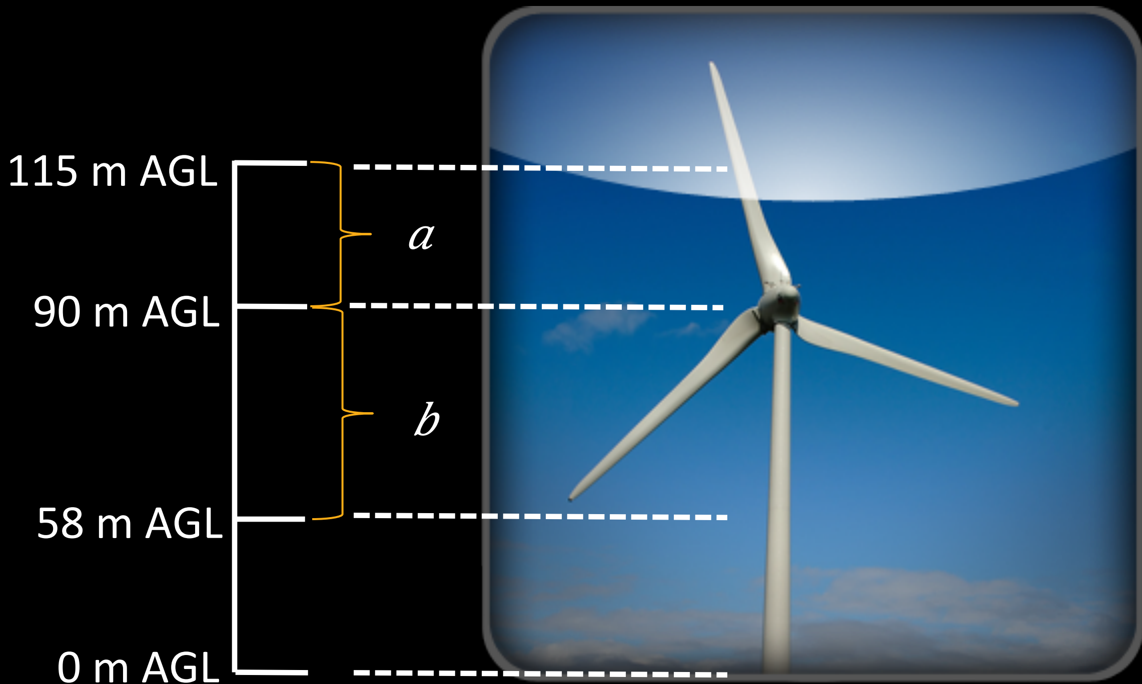
Reconstruct scalar wind speed distributions

Step 5: Construct wind speed distribution



Determine a weighted average wind speed histogram between two heights

Step 6: Calculate the mean wind speed histogram for 90 m AGL hub height by linear interpolation between 58 and 115 m AGL values



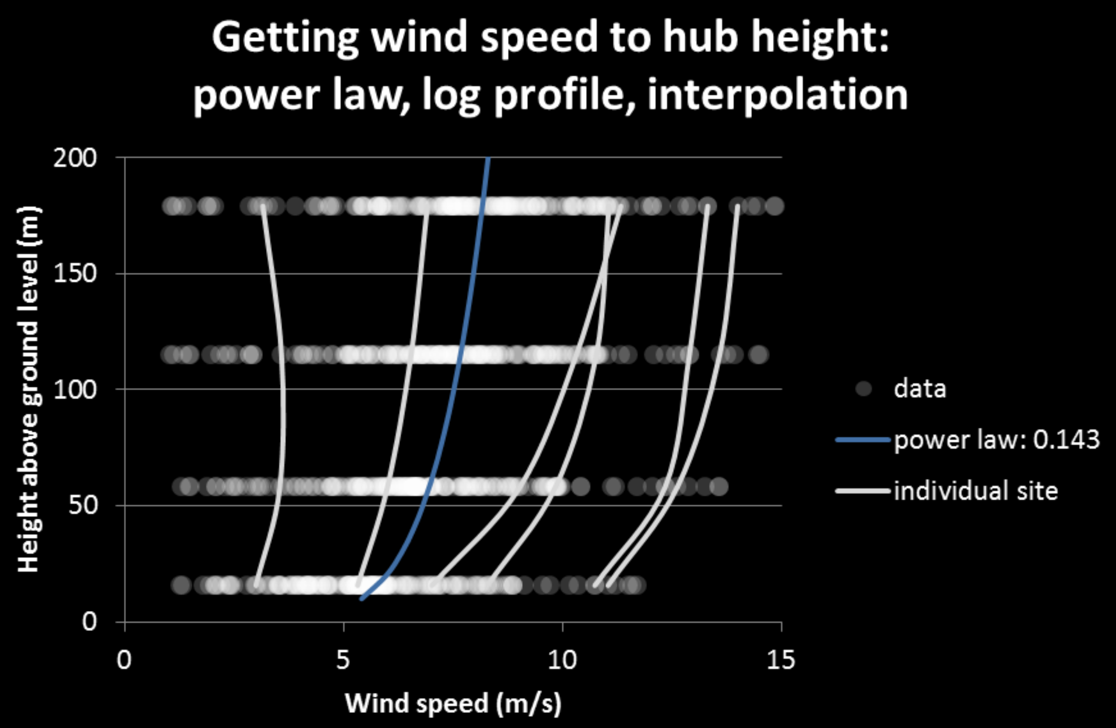
$$f(115)=b/a+b$$

$$f(58)=a/a+b$$

Interpolation vs. power law extrapolation to hub height

On average, interpolation produces a similar wind speed/height relationship to the 0.143 power law assumption used previously.

But on an individual-site basis, interpolation provides more resolution.



Select a power curve base on wind regime

We assume IEC Class I and II composite wind turbine power curve for offshore and onshore, respectively.

> *"The IEC 1 and 2 curves are based on a composite of three commercial turbines (General Electric/GE, Vestas, and Gamesa brands). In consultation with NREL, it was decided to base the IEC 3 curve on just two turbines (GE 1.5xle and Gamesa G90) to avoid an inconsistency in the cut-out speed of the Vestas V100. In addition, the cut-out speed of the GE turbine was changed from 20 to 21 m/s to match that of the Gamesa turbine. The IEC 1 and 2 turbines are assumed to have a hub height of 60 m and the IEC 3 turbine 80 m."*
>
> *~Manobianco et al. (2010)*

In the future we would like to have the algorithm choose a turbine based on the wind regime and IEC61400-1 design parameters:

Table 1 – Basic parameters for wind turbine classes[1]

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

In Table 1, the parameter values apply at hub height and

V_{ref} is the reference wind speed average over 10 min,

A designates the category for higher turbulence characteristics,

B designates the category for medium turbulence characteristics,

C designates the category for lower turbulence characteristics and

I_{ref} is the expected value of the turbulence intensity[2] at 15 m/s.

Manobianco, J.; Alonge, C.; Frank, J.; Brower, M. (2010). Development of Regional Wind Resource and Wind Plant Output Datasets for the Hawaiian Islands. 37 pp.; NREL Report No. SR-550-48680. http://www.nrel.gov/docs/fy10osti/48680.pdf

Adjust the power curve to account for altitude

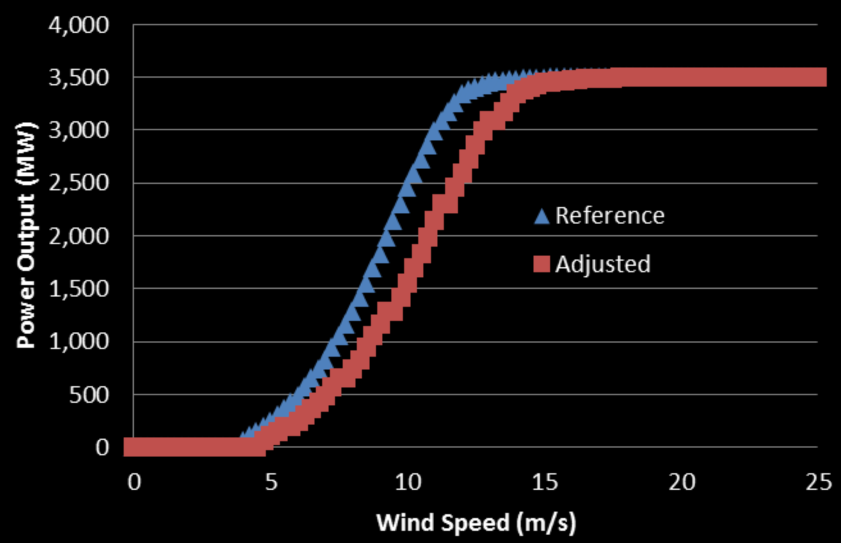
Based on IEC61400-12, a pitch controlled wind turbine will be able to maintain the same peak power output at different altitudes (shift to the left or right).

1. Calculate the wind speed required to maintain the same power output (v_{adj}, P_{ref})
2. Resample the adjusted power curve at the original wind speeds (v_{std}, P_{adj})

$$P_{wind} = ½ \rho * A * v^3$$

$$P_{turbine} = C_p * ½ \rho * A * v^3$$

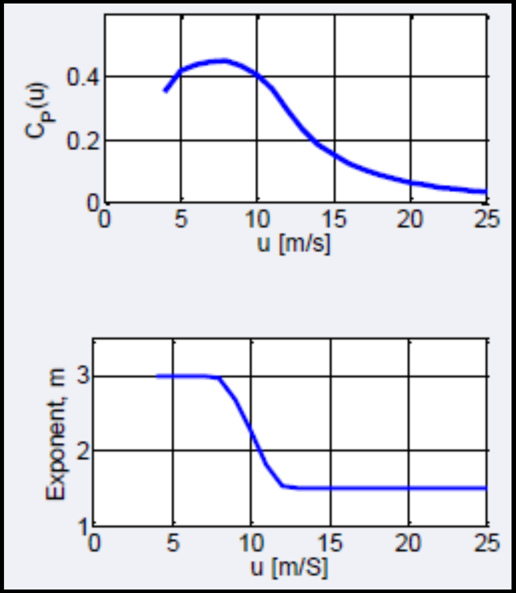
Where C_p is the coefficient of performance, and is often assumed to be constant for all wind speeds.



Adjust the power curve to account for altitude

Assuming that the coefficient of performance (C_p) is constant for all wind speeds introduces errors in adjusting a power curve for air density.

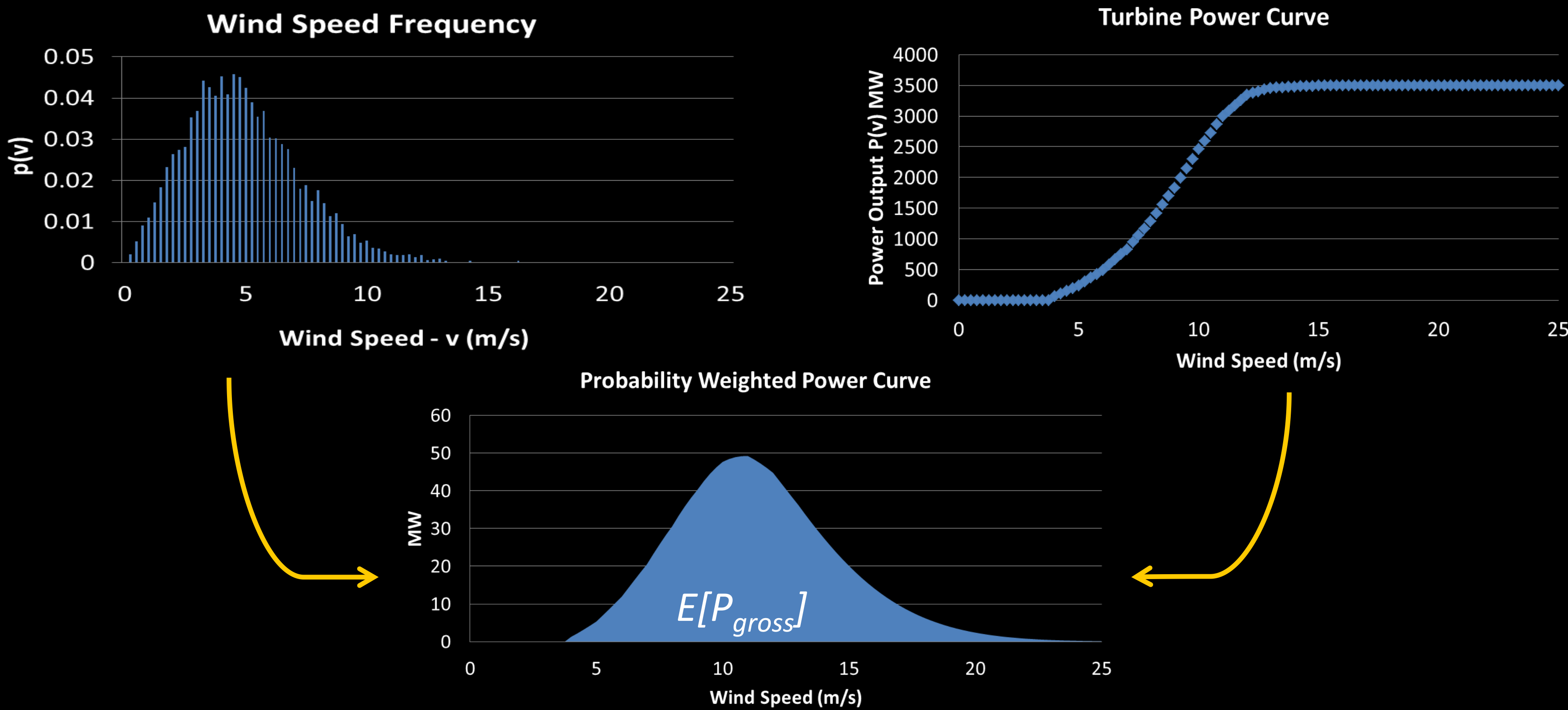
Svenningsen (2010) proposes an improved method whereby replacing the 1/3 exponent of the IEC approach by *1/m.*



Lasse Svenningsen. *Proposal of an Improved Power Curve Correction.* European Wind Energy Conference & Exhibition 2010, April 2010, Warsaw, Poland.

Calculate the expected value of the gross power output

Define a Probability Weighted Power Curve as the product of the histogram and the Composite IEC Class I/II 3.5 MW turbine representative power curve.



Calculate the expected value of the gross power output $E[P_{gross}]$, as the approximate area under the probability weighted power curve.

Calculate the annual average capacity factor

Calculate the expected value of the net power output, by applying the turbine availability and array efficiency to .

$$E[P_{net}](m,h) = E[P_{gross}](m,h)*\eta_{avail}*\eta_{array}$$

Calculate the hourly average capacity factor for hour of month .

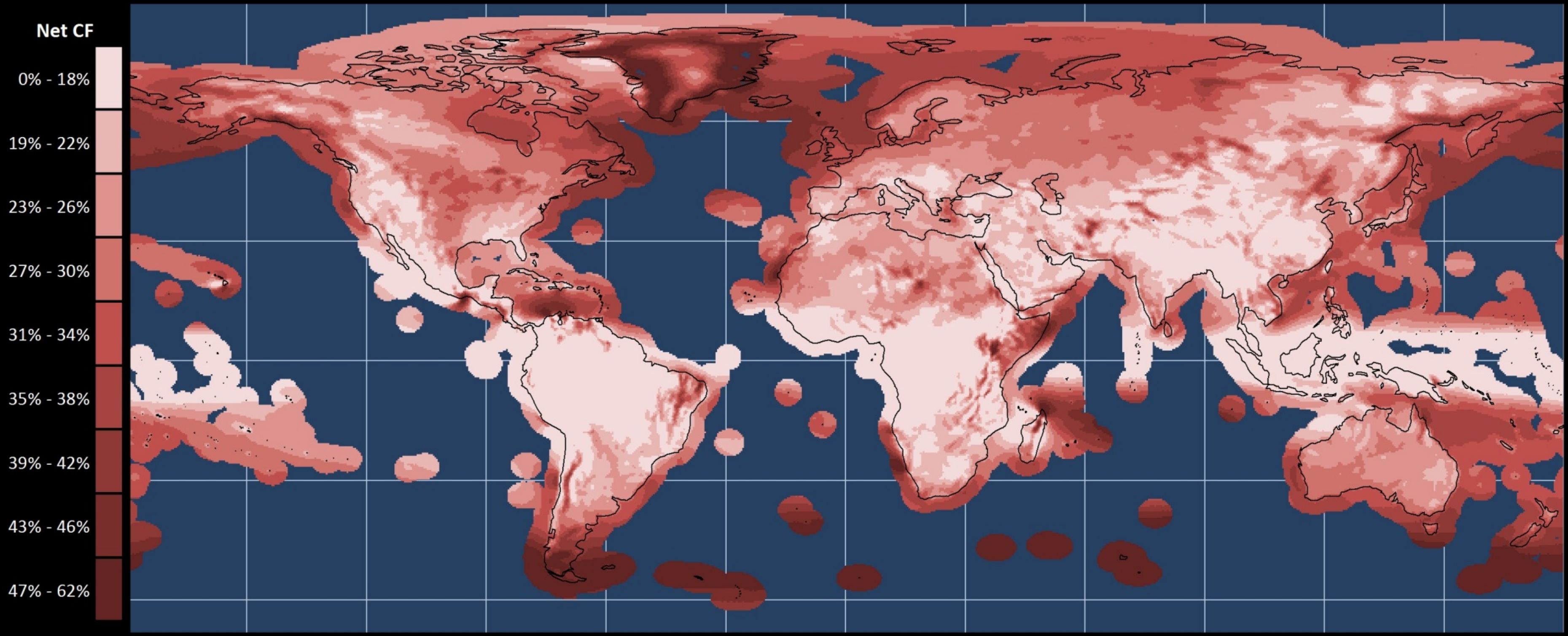
$$CF(m,h) = E[P_{net}](m,h)/P_{rated}$$

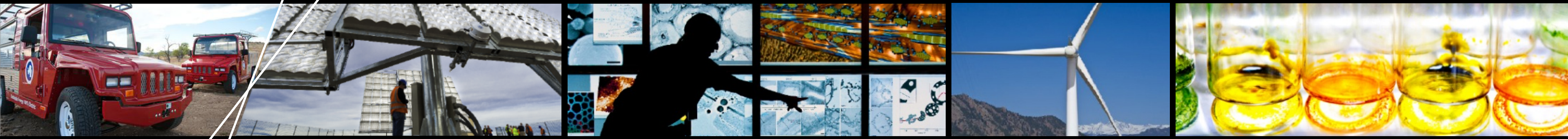
Sum the month-hours to produce annual average capacity factor for each CFDDA 40km grid cell.

$$CF = 1/8760 * \Sigma_{m,h}\, days(m)*CF(m,h)$$

CFDDA Calculated Annual Average Capacity Factors

Gridded annual average capacity factors: 80m hub height, IEC Class I/II turbine, availability and array efficiency applied.





Exclusions and Classification

ONSHORE: Apply exclusions and aggregate resource potential based on 1km grid cell projections

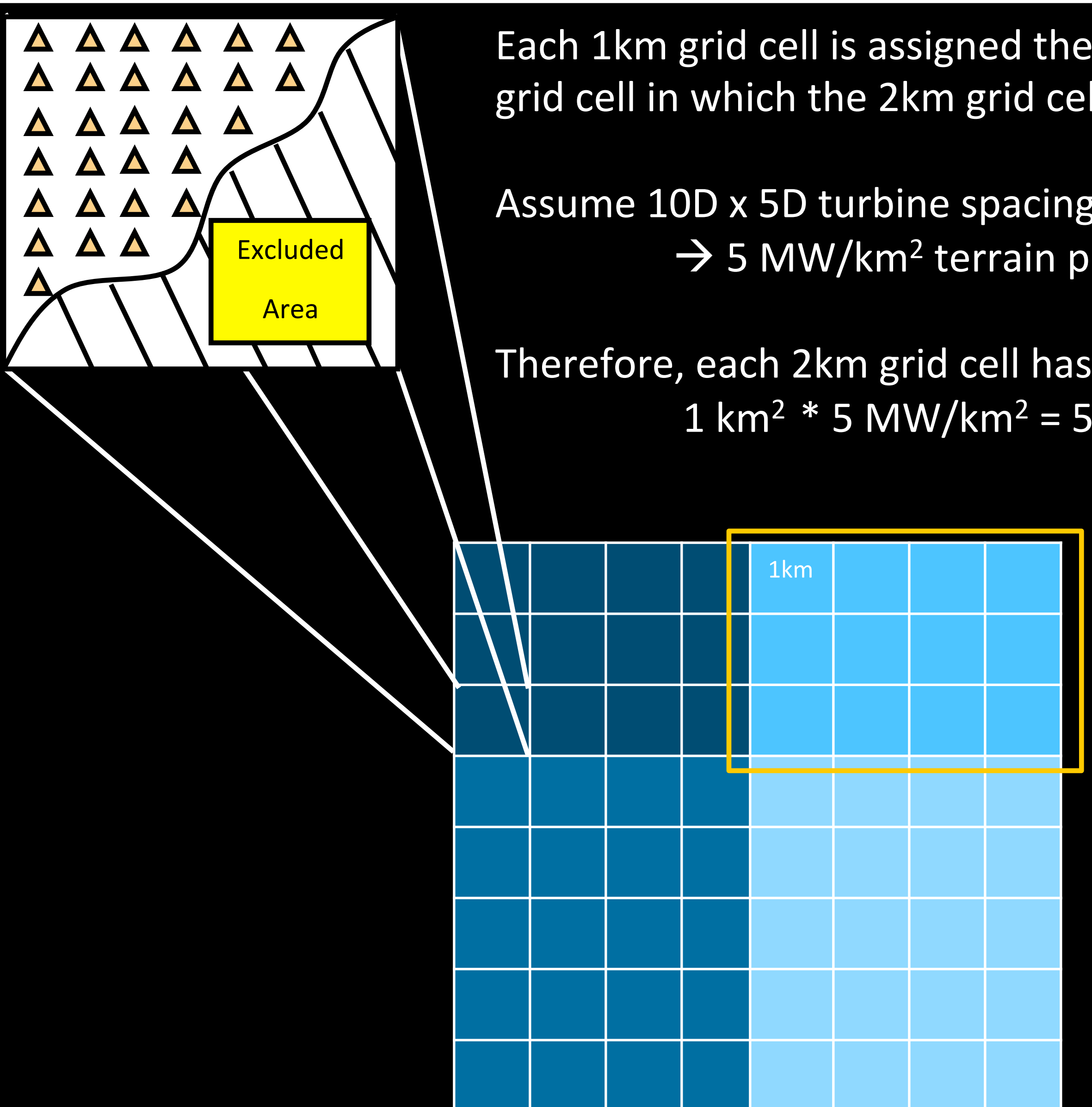
Each 1km grid cell is assigned the annual average CF for the 40km grid cell in which the 2km grid cell exists.

Assume 10D x 5D turbine spacing

→ 5 MW/km² terrain power density

Therefore, each 2km grid cell has a maximum potential of :

$1\ km^2 * 5\ MW/km^2 = 5\ MW$

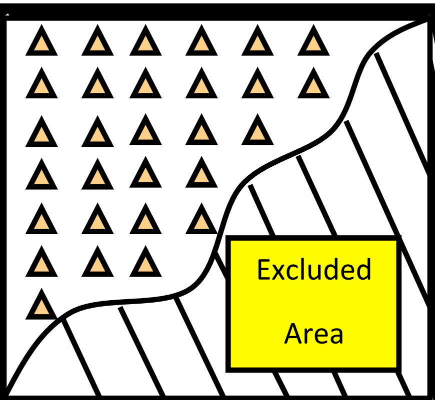


The different shades of blue represent subsets of different 40 km grid cells.

1km grid cell attributes:

- Distance to Grid
- Protected Areas
- Elevation and Slope
- Permafrost
- Land Use/Land Cover

OFFSHORE: Apply exclusions and aggregate resource potential based on 2km grid cell projections



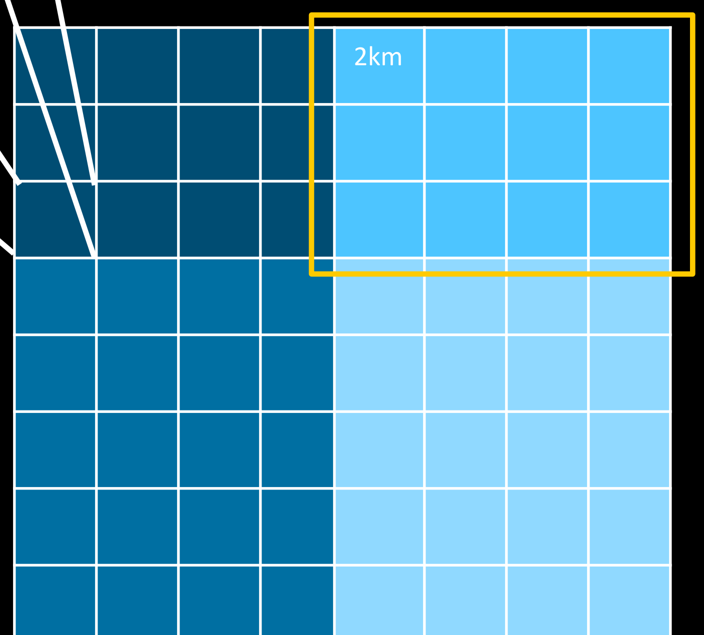
Each 2km grid cell is assigned the annual average CF for the 40km grid cell in which the 2km grid cell exists.

Assume 10D x 5D turbine spacing

→ 5 MW/km^2 terrain power density

Therefore, each 2km grid cell has a maximum potential of :

$$4\ km^2 * 5\ MW/km^2 = 20\ MW$$



The different shades of blue represent subsets of different 40 km grid cells.

2km grid cell attributes:

- Bathymetry
- Distance to Shore
- Protected Marine Areas
- Months of Ice Cover
- Exclusive Economic Zone

Exclusion Criteria: Protected Planet

Onshore and Offshore:

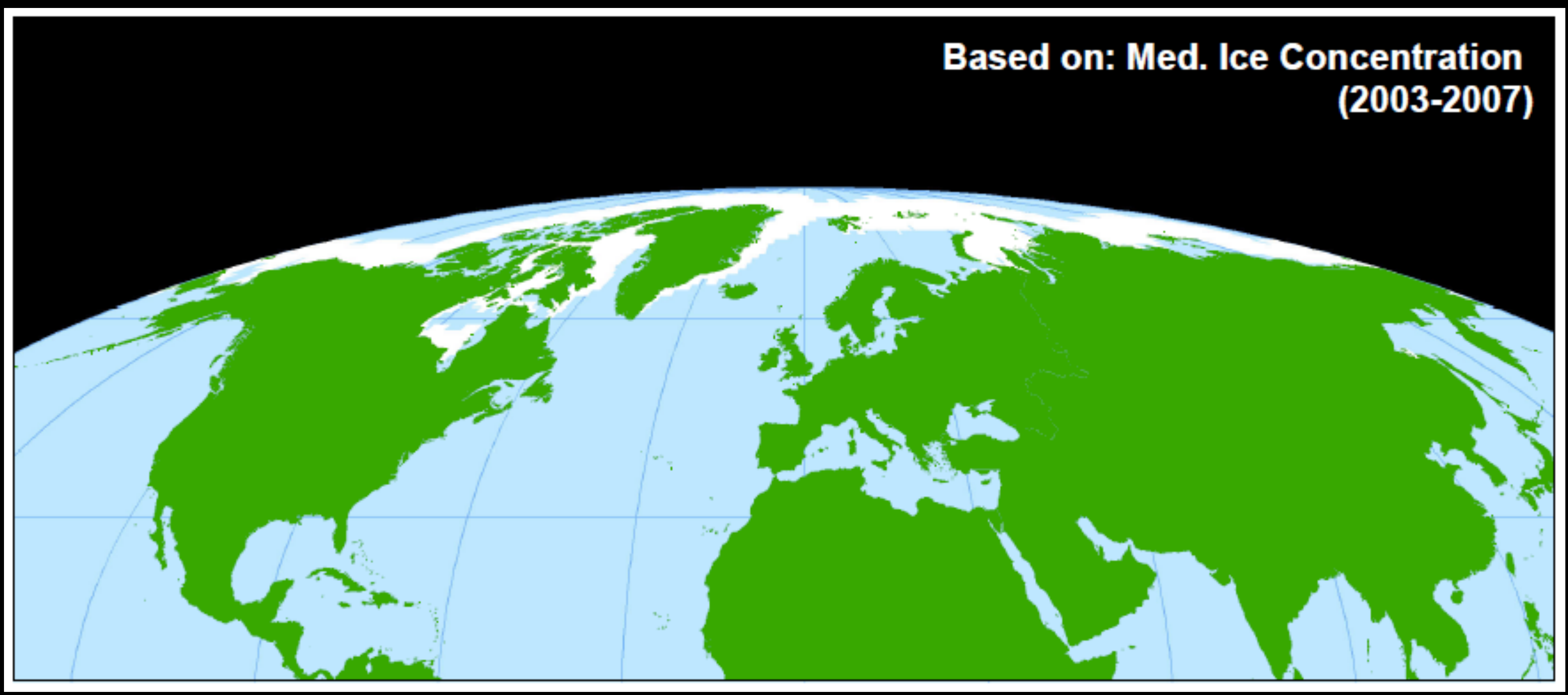
Excluded areas with IUCN (International Union for Conservation of Nature) codes I-III

http://www.protectedplanet.net/

Exclusion Criteria: Ice Cover

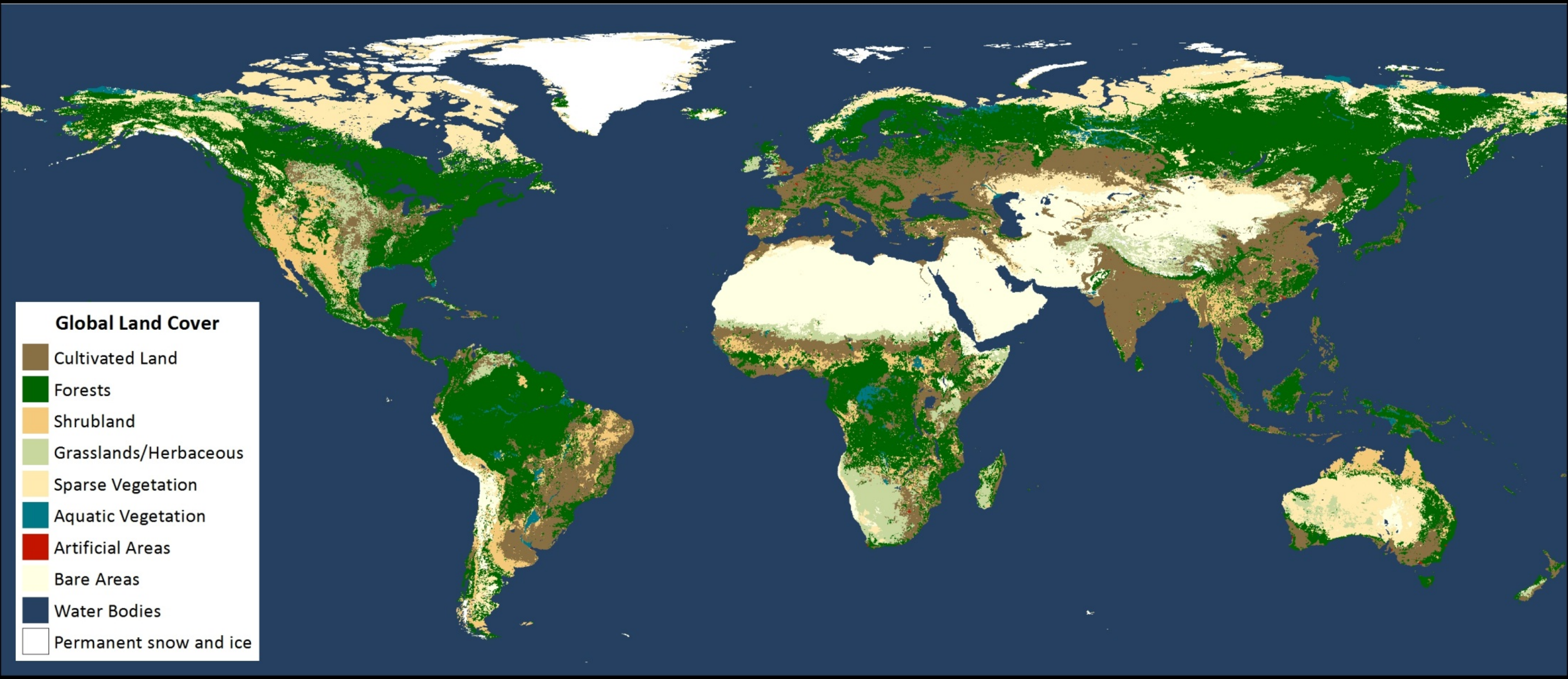
Excluded areas with at least 8 months of ice cover.
Ice coverage defined as monthly median surface concentration >15%.

From "National Ice Center Arctic Sea Ice Charts and Climatologies in Gridded Format," National Snow and Ice Data Center (NSIDC).
http://nsidc.org/data/docs/noaa/g02172_nic_charts_climo_grid/index.html



Exclusion Criteria: Land Use/Land Cover

Global Land Cover Datasets from Globcover, a 1 km^2 grid surface cover database classified from satellite measurements.



Bontemps S., P. Defourny, E. Van Bogaert, "GLOBCOVER 2009 Products Description and Validation Report", European Space Agency, 2009.

Exclusion Criteria: Land Use/Land Cover

GLOBCOVER 2009 Categories

Value	GlobCover global legend	Suitability Factor
11	Post-flooding or irrigated croplands	0
14	Rainfed croplands	0.7
20	Mosaic Cropland (50-70%) / Vegetation (grassland, shrubland, forest) (20-50%)	0.7
30	Mosaic Vegetation (grassland, shrubland, forest) (50-70%) / Cropland (20-50%)	0.7
40	Closed to open (>15%) broadleaved evergreen and/or semi-deciduous forest (>5m)	0.1
50	Closed (>40%) broadleaved deciduous forest (>5m)	0.1
60	Open (15-40%) broadleaved deciduous forest (>5m)	0.1
70	Closed (>40%) needleleaved evergreen forest (>5m)	0.1
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	0.1
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0.1
110	Mosaic Forest/Shrubland (50-70%) / Grassland (20-50%)	0.5
120	Mosaic Grassland (50-70%) / Forest/Shrubland (20-50%)	0.65
130	Closed to open (>15%) shrubland (<5m)	0.5
140	Closed to open (>15%) grassland	0.8
150	Sparse (>15%) vegetation (woody vegetation, shrubs, grassland)	0.9
160	Closed (>40%) broadleaved forest regularly flooded - Fresh water	0
170	Closed (>40%) broadleaved semi-deciduous and/or evergreen forest regularly flooded - Saline water	0
180	Closed to open (>15%) vegetation (grassland, shrubland, woody vegetation) on regularly flooded or waterlogged soil - Fresh, brackish or saline water	0
190	Artificial surfaces and associated areas (urban areas >50%)	0
200	Bare areas	.9
210	Water bodies	0
220	Permanent snow and ice	0

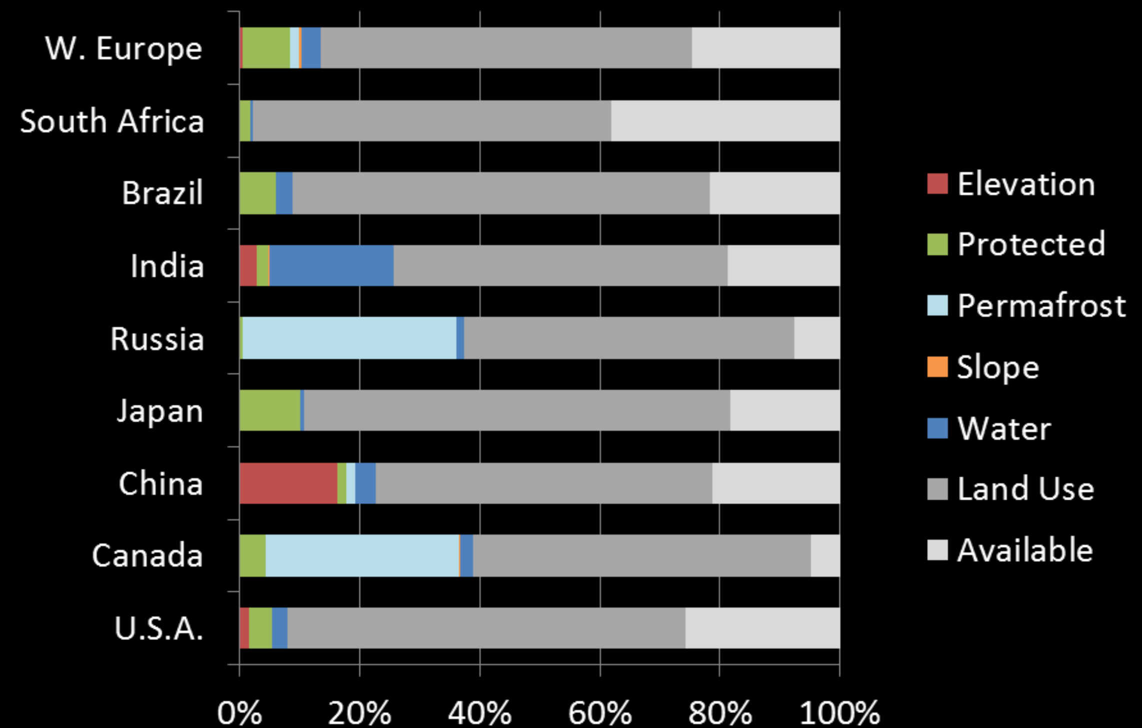
Exclusion Criteria: Land Use/Land Cover

Land Use/suitability tends to be one of the largest factors in removing land from the potential.

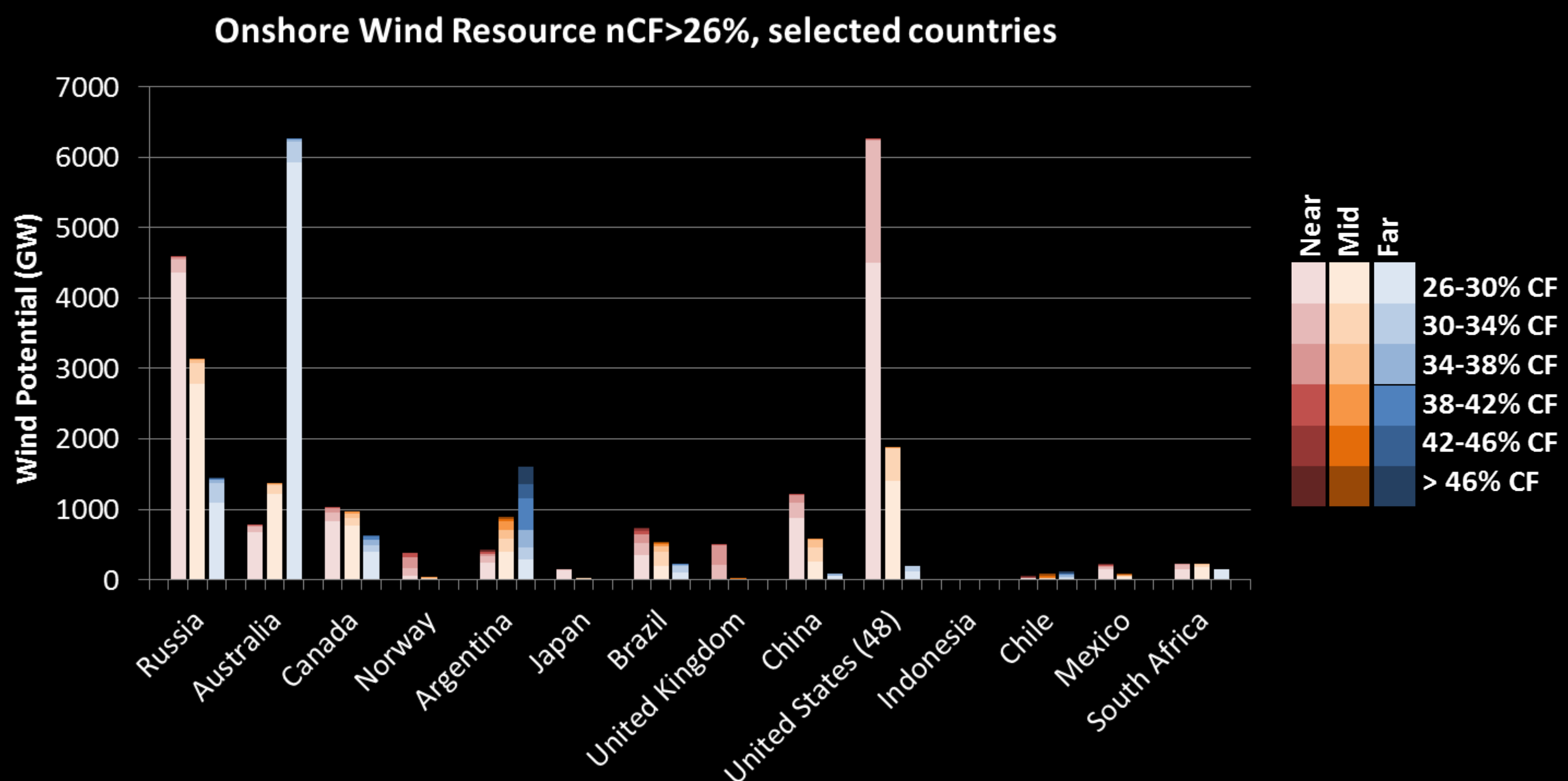
Russia and Canada lose substantial land to permafrost.

India has a lot of marshland; China loses the Tibetan Plateau due to elevation.

Some grid cells are excluded multiple times (e.g., elevation and protection). In the chart, the exclusions are applied in descending order (e.g., if elevation and protection => elevation).



Summary: Global Wind Potential Supply Curves



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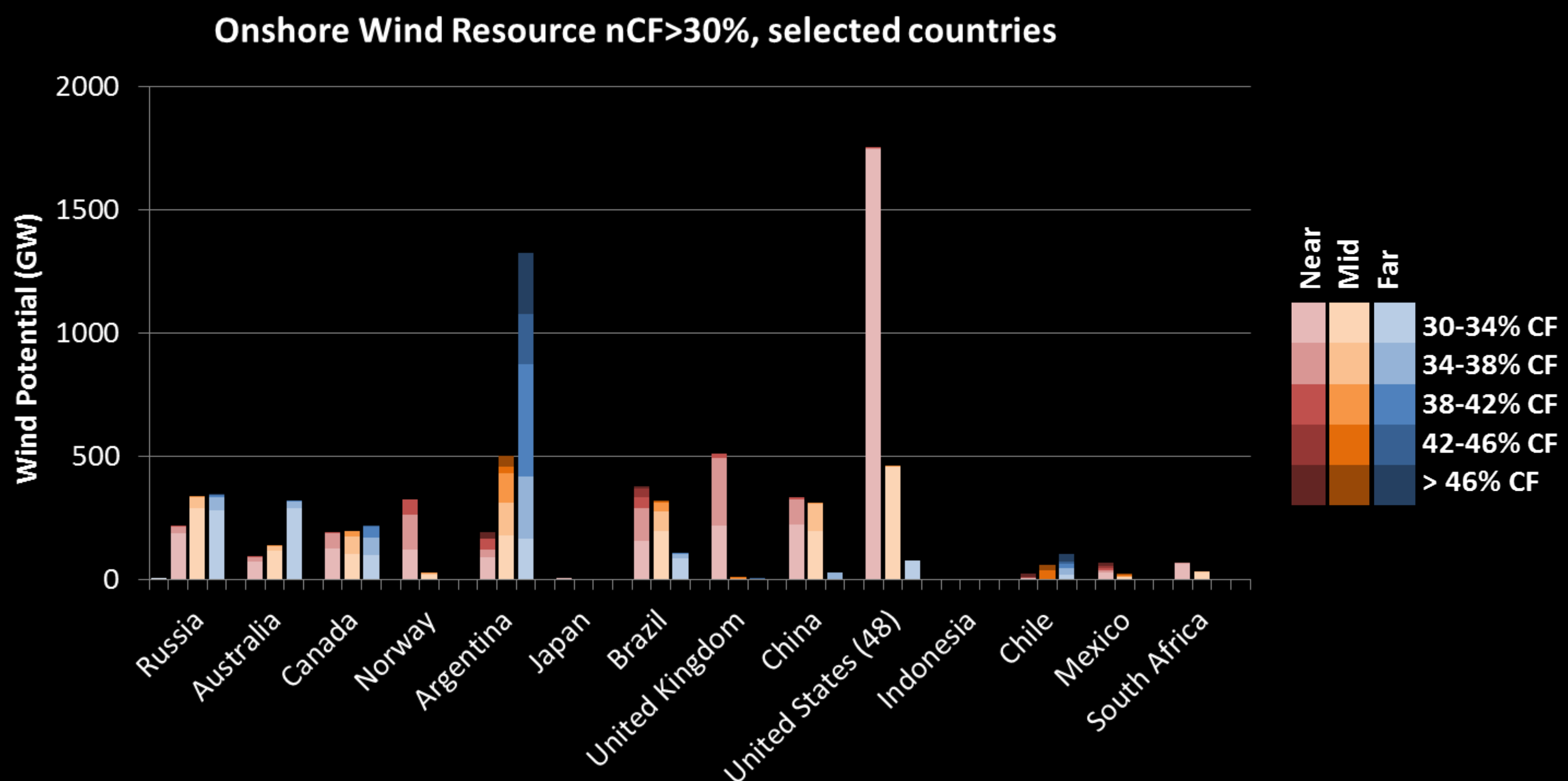

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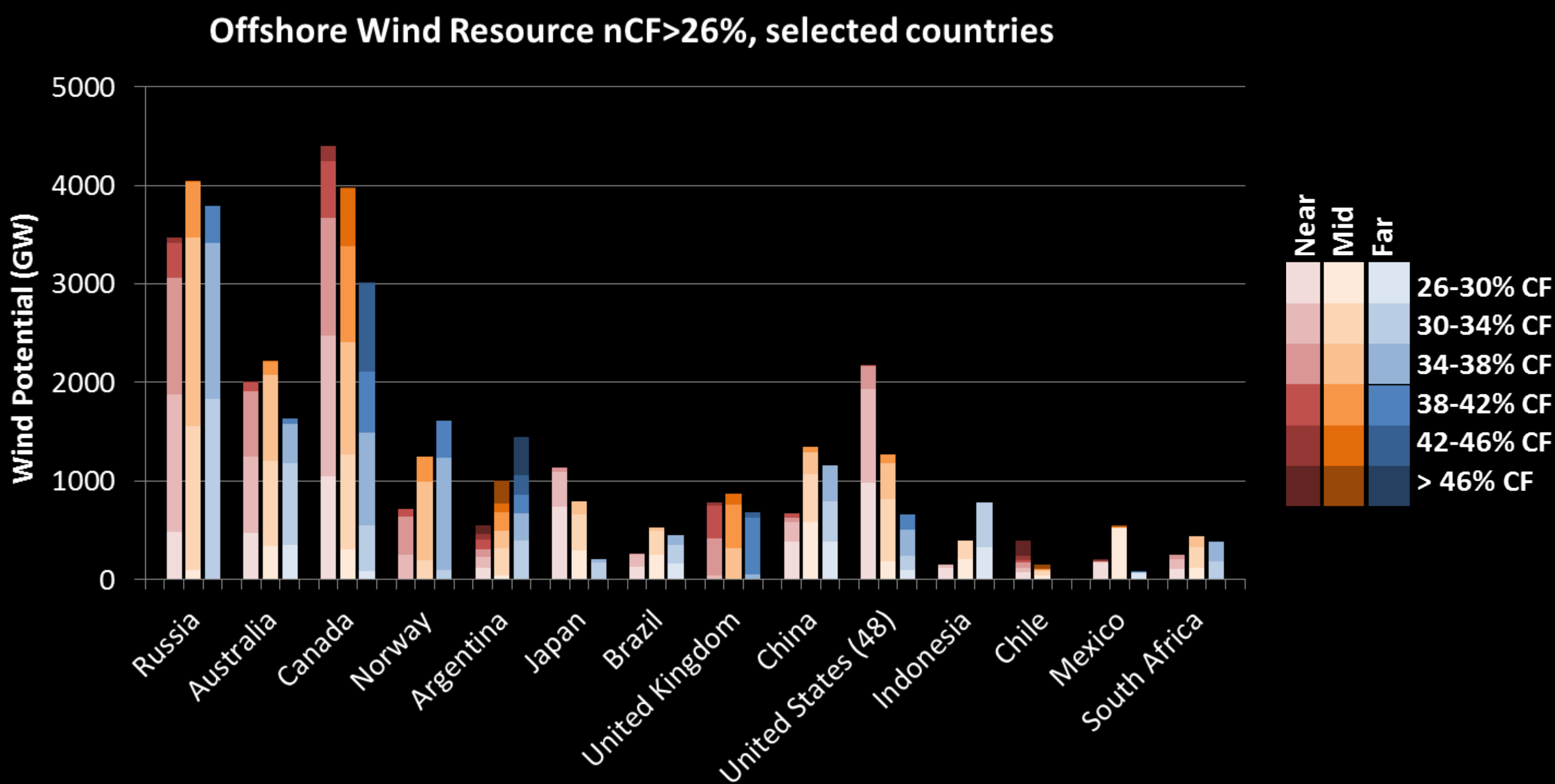

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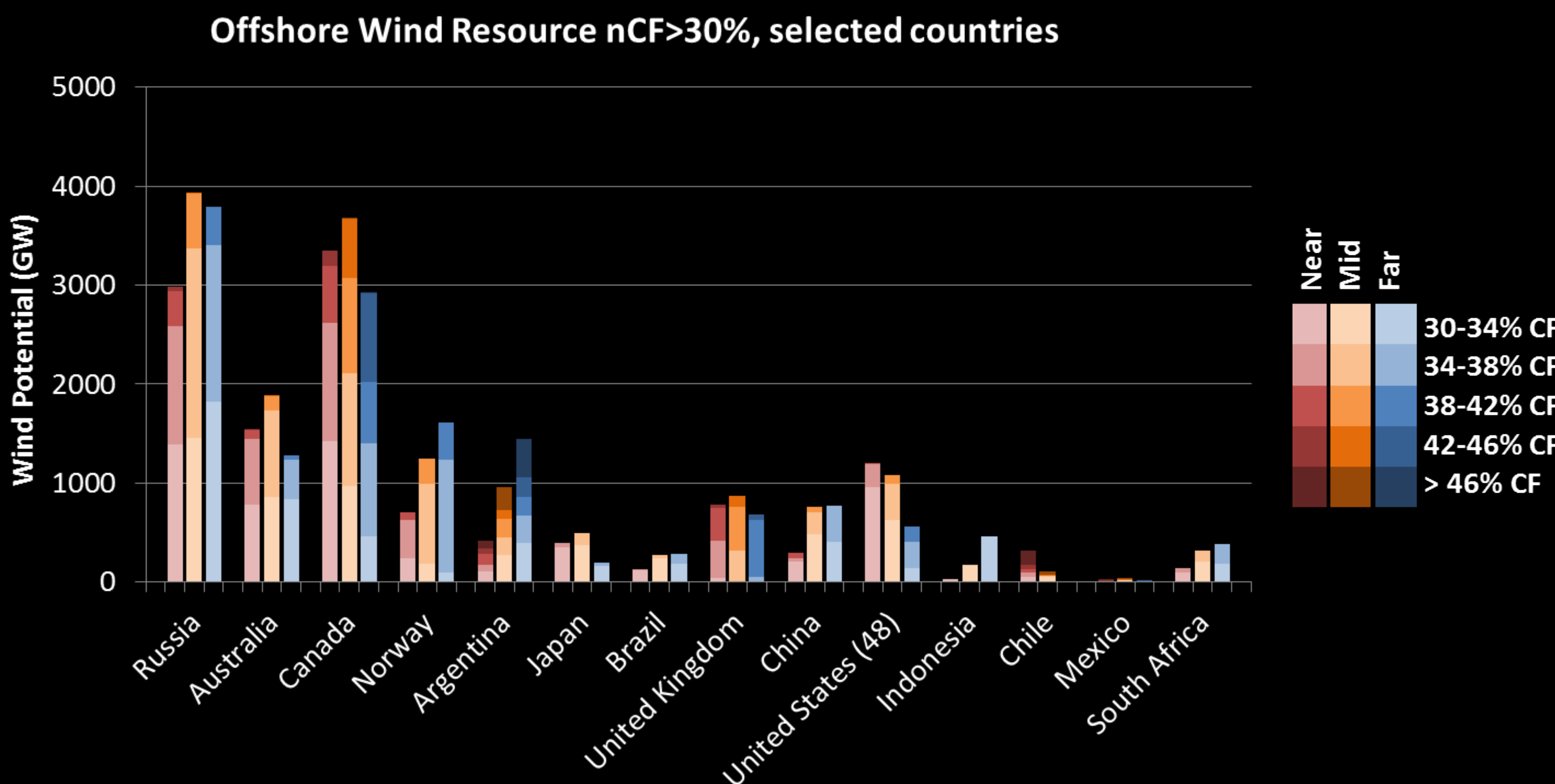


Summary: Global Wind Potential Supply Curves

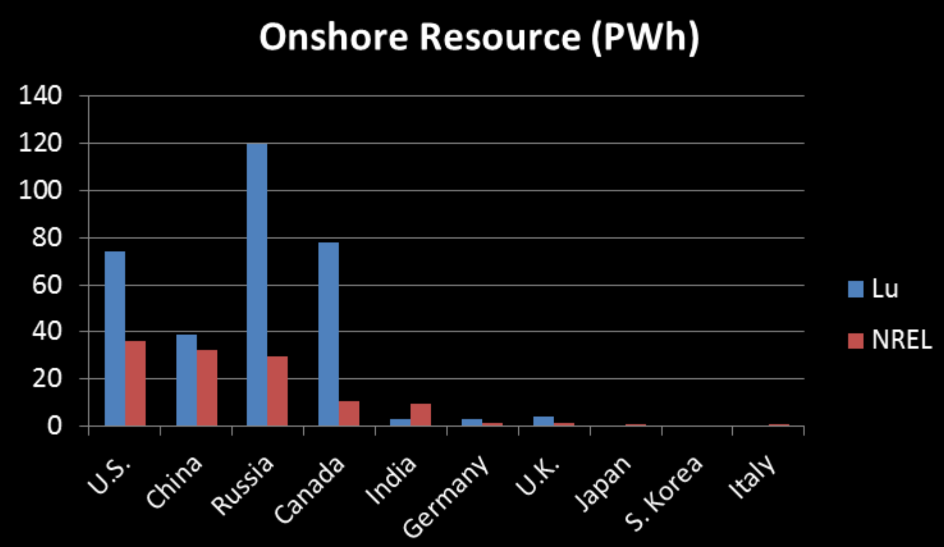
Onshore

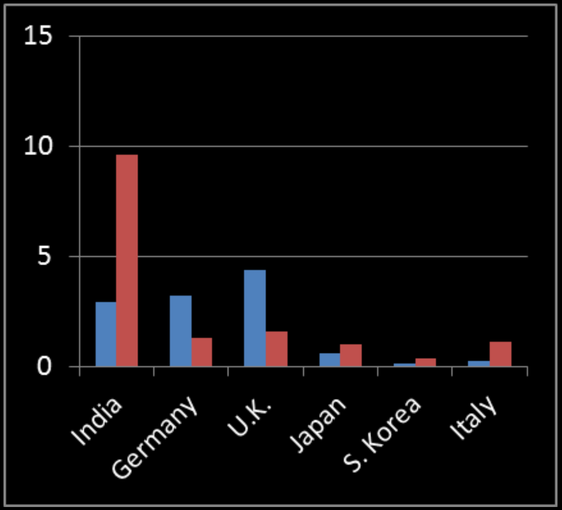
- Wind potential is classified according to:
  - Wind Class (based on net annual average CF)
  - Distance to Grid (LANDSCAN 2011)
  - Country
- Exclusions:
  - Permafrost (Global Permafrost Zonation Index Map)
  - Protected Areas (Protected Planet)
  - Elevation and Slope
  - Land Use/Land Cover (partial exclusions, GLOBCOVER 2009)

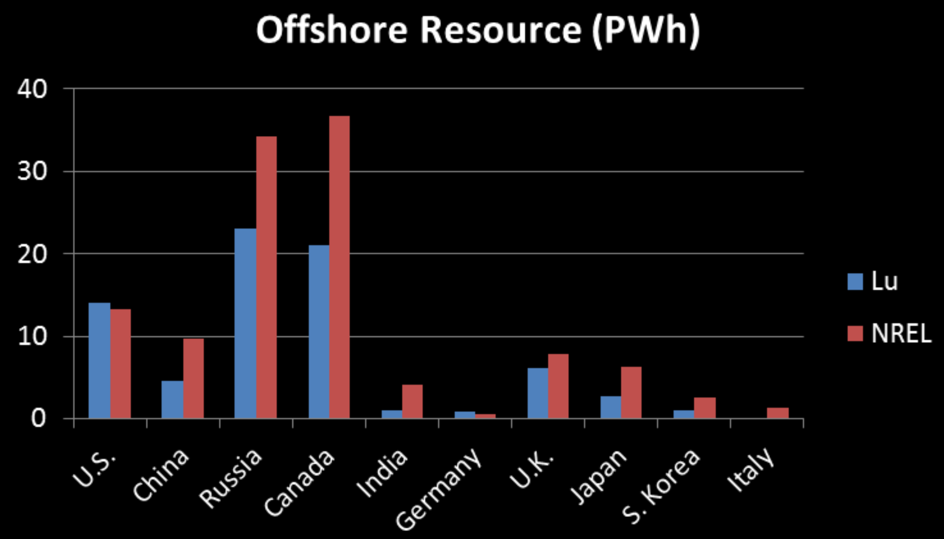
Offshore

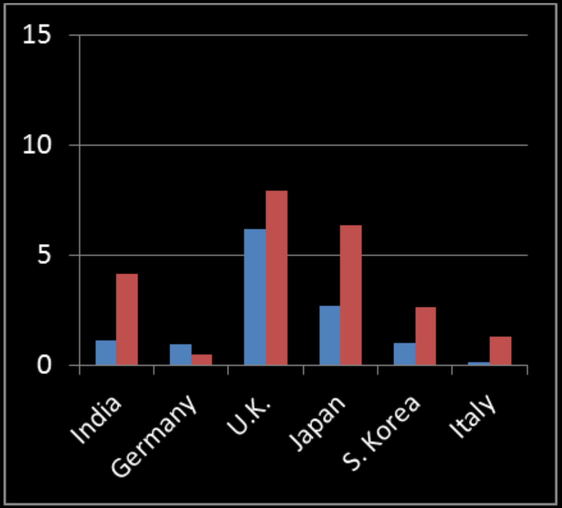
- Wind resource is classified according to:
  - Wind Class (based on net annual average CF)
  - Bathymetry
  - Distance to Shore
  - Exclusive Economic Zones (EEZs)
- Exclusions:
  - Sea Ice (National Snow and Ice Data Center)
  - Marine Protected Areas (Protected Planet)
  - Minimum/Maximum Distance to Shore
  - Maximum Marine Depth (ETOPO1 Global Relief Model)

Comparison: Lu, et al. 2009









Lu, X.; McElroy, M. B.; Kiviluoma, J. Global potential for wind-generated electricity. Proc. Natl. Acad. Sci. 2009.

Comparison: GCAM; Zhou, et al. 2012

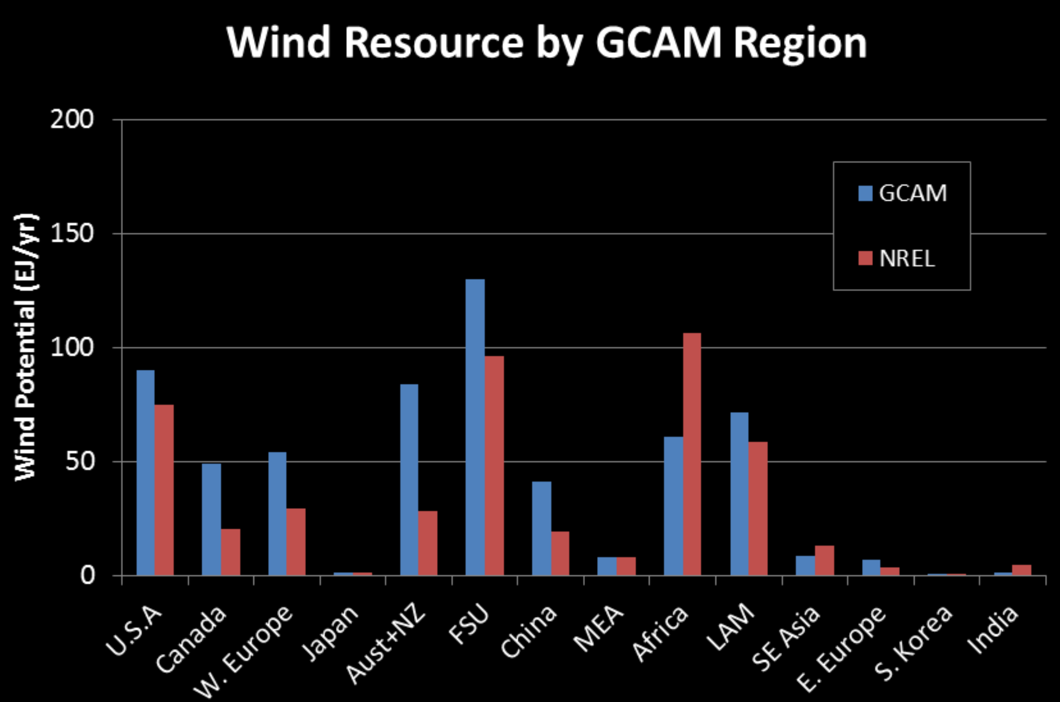
Comparison of GCAM resource available for <103 $/MWh to estimated comparable NREL/CFDDA resource.

Zhou writes "a [gross] capacity factor of 30% is equal to a generation cost of 11 cents/kWh."

For NREL/CFDDA comparison, use nCF>26% for near and mid distance to transmission, nCF>30% for far.

Global total:

GCAM 606 EJ/yr
NREL 464 EJ/yr



Zhou, Y., Luckow, P., Smith, S. J., & Clarke, L. (2012). Evaluation of global onshore wind energy potential and generation costs. *Environmental science & technology*, *46*(14), 7857-7864.

References

- ***Cholesky Decomposition for Correlated Random Numbers***
    - *http://quantcorner.wordpress.com/2012/02/29/generation-of-correlated-random-numbers-recommended-article/*
    - *http://code.activestate.com/recipes/576512-generating-correlated-random-numbers/*
    - *http://en.wikipedia.org/wiki/Cholesky_decomposition#cite_note-Matlab_documentation-1*
    - *http://www.sitmo.com/article/generating-correlated-random-numbers/#comment-325*
    - *http://math.stackexchange.com/questions/163470/generating-correlated-random-numbers-why-does-cholesky-decomposition-work*

- **Correlated Random *Numbers***
    - *http://www.cmu.edu/biolphys/deserno/pdf/corr_gaussian_random.pdf*
    - *http://web.ics.purdue.edu/~hwan/IE680/Lectures/Chap08Slides.pdf*
    - *http://www.columbia.edu/~mh2078/MCS04/MCS_framework_FEegs.pdf*

- **Lasse Svenningsen. *Proposal of an Improved Power Curve Correction.* European Wind Energy Conference & Exhibition 2010, April 2010, Warsaw, Poland.**

- **Manobianco, J.; Alonge, C.; Frank, J.; Brower, M. (2010). Development of Regional Wind Resource and Wind Plant Output Datasets for the Hawaiian Islands. 37 pp.; NREL Report No. SR-550-48680. http://www.nrel.gov/docs/fy10osti/48680.pdf**

- **IEC 61400-1 (2005). Wind Turbines – Part I: Design Requirements.**

- **Musial, W.; Ram, B. (2010). *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*. NREL/TP-500-40745. Golden, CO: National Renewable Energy Laboratory.**