Net Zero Emissions
Why and How

Paul Debevec (debevec@uiuc.edu)
Osher Lifelong Learning Institute at
University of Illinois

Lecture 4

Issues from previous lectures
Why not 100% renewable wind and solar?
A little about storage
Transmission

Paul Debevec (debevec@uiuc.edu)

Osher Lifelong Learning Institute at

University of Illinois

February 24, 2020

Lecture 4 Outline

- Weather-climate quiz (at end if time allows)
- Three issues from Lecture 3
  - U.S. oil imports and exports
  - Trees
  - Solar resource management
- One issue from Lecture 1: billion dollar disasters
- Why not just 100% wind and solar renewables?
- A little about storage
- Transmission projects
- Summary

Climate versus Weather Quiz

How Much Do You Know About Weather and Climate?

How much do you know about weather, climate, and how they're different? Put your knowledge to the test.

TAKE QUIZ

Issues from Lecture 3

Back to the U.S. Oil Imports and Exports

U.S. petroleum consumption by sector and share of total in 2018

69%
14.16 million barrels per day
transportation

25%
5.13 million barrels per day
industrial

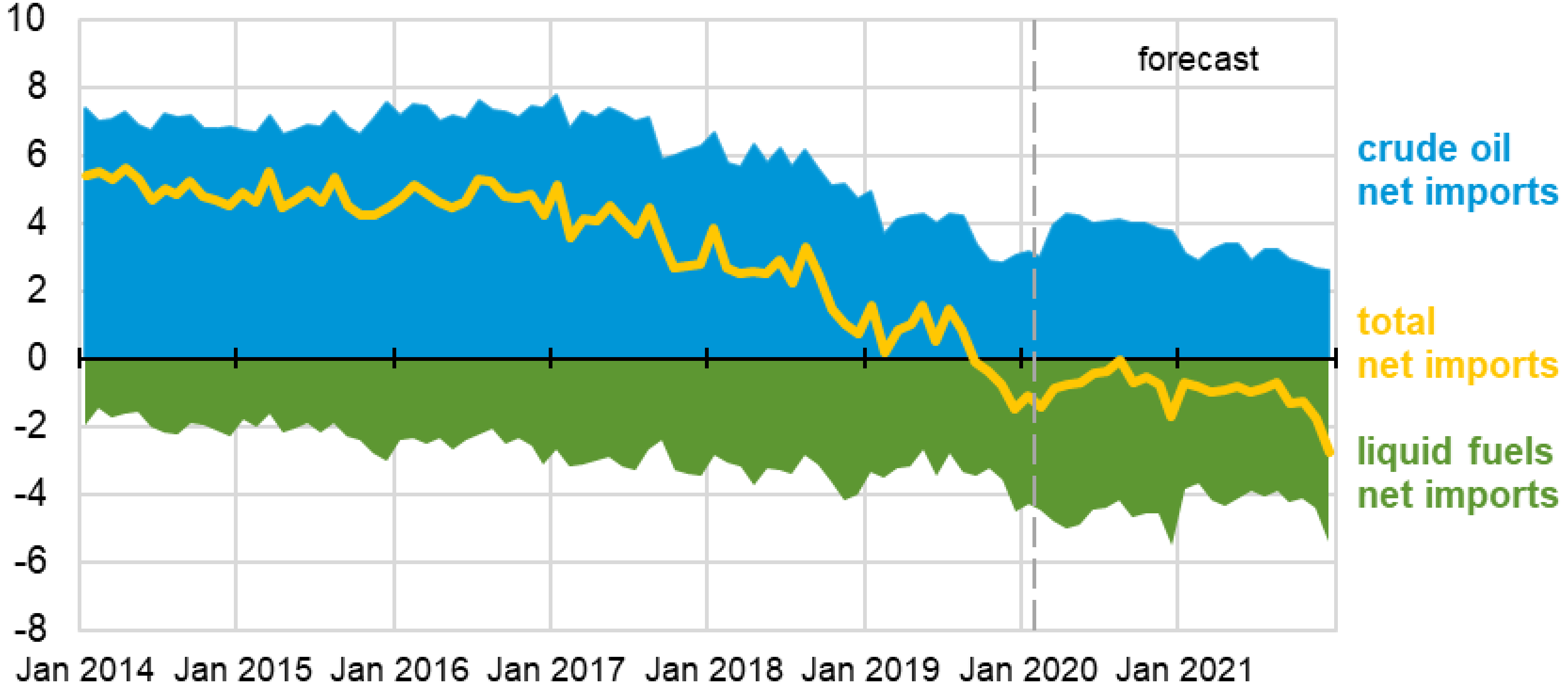
3%
0.56 million barrels per day
residential

2%
0.48 million barrels per day
commercial

1%
0.11 million barrels per day
electric power

U.S. net imports of crude oil and liquid fuels

million barrels per day



Note: Liquids fuels include: gasoline, distillate fuels, hydrocarbon gas liquids, jet fuel, residual fuel oil, unfinished oils, other hydrocarbons/oxygenates, and other oils.

Source: Short-Term Energy Outlook, February 2020

Top sources and amounts of U.S. petroleum imports (percent share of total), respective exports, and net imports, 2018

million barrels per day

Import sources	Gross imports	Exports	Net imports
Total, all countries	9.94	7.60	2.34
OPEC countries	2.89 (29%)	0.31	2.58
Persian Gulf countries	1.58 (16%)	0.05	1.53
Top five countries[1]			
Canada	4.29 (43%)	1.02	3.27
Saudi Arabia	0.90 (9%)	<0.01	0.90
Mexico	0.72 (7%)	1.19	-0.48
Venezuela	0.59 (6%)	0.12	0.46
Iraq	0.52 (5%)	<0.01	0.52

Note: Ranking in the table is based on gross imports by country of origin. Net imports volumes in the table may not equal gross imports minus exports because of independent rounding of data.

Back to the Forest
Trillion Trees


TREES ARE THE ANSWER
Brought to you by..
J. FRANK SCHMIDT & SON CO.

THE HILL

February 2, 2020

GOP bill will seek to commit US to planting 3.3 billion trees annually

The New York Times

February 12, 2020
How a Trillion Trees Triumphed Over Trump's Climate Denialism

Marc Benioff, chairman of Salesforce, at the World Economic Forum in Davos, Switzerland, where President Trump embraced his Trillion Trees climate initiative.

Ronald Reagan, September 1980

"Approximately 80 percent of our air pollution stems from hydro-carbons released by vegetation, so let's not go overboard in setting and enforcing tough emission standards from man-made sources."

"Trees cause more pollution than automobiles do."

The New York Times

June 11, 2019

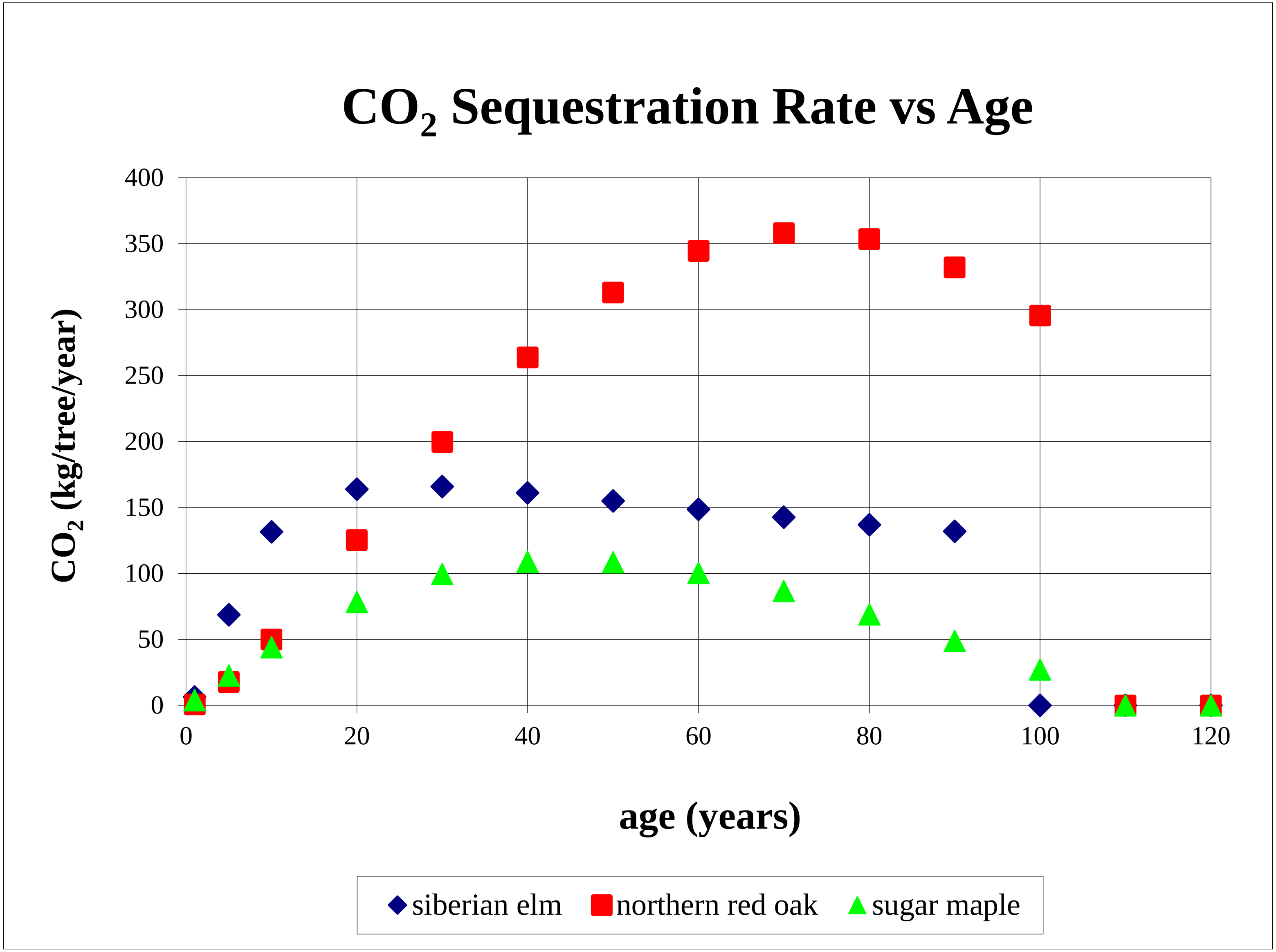
Oak Tree Given to Trump by French President Has Died

U.S. FOREST SERVICE
Caring for the land and serving people

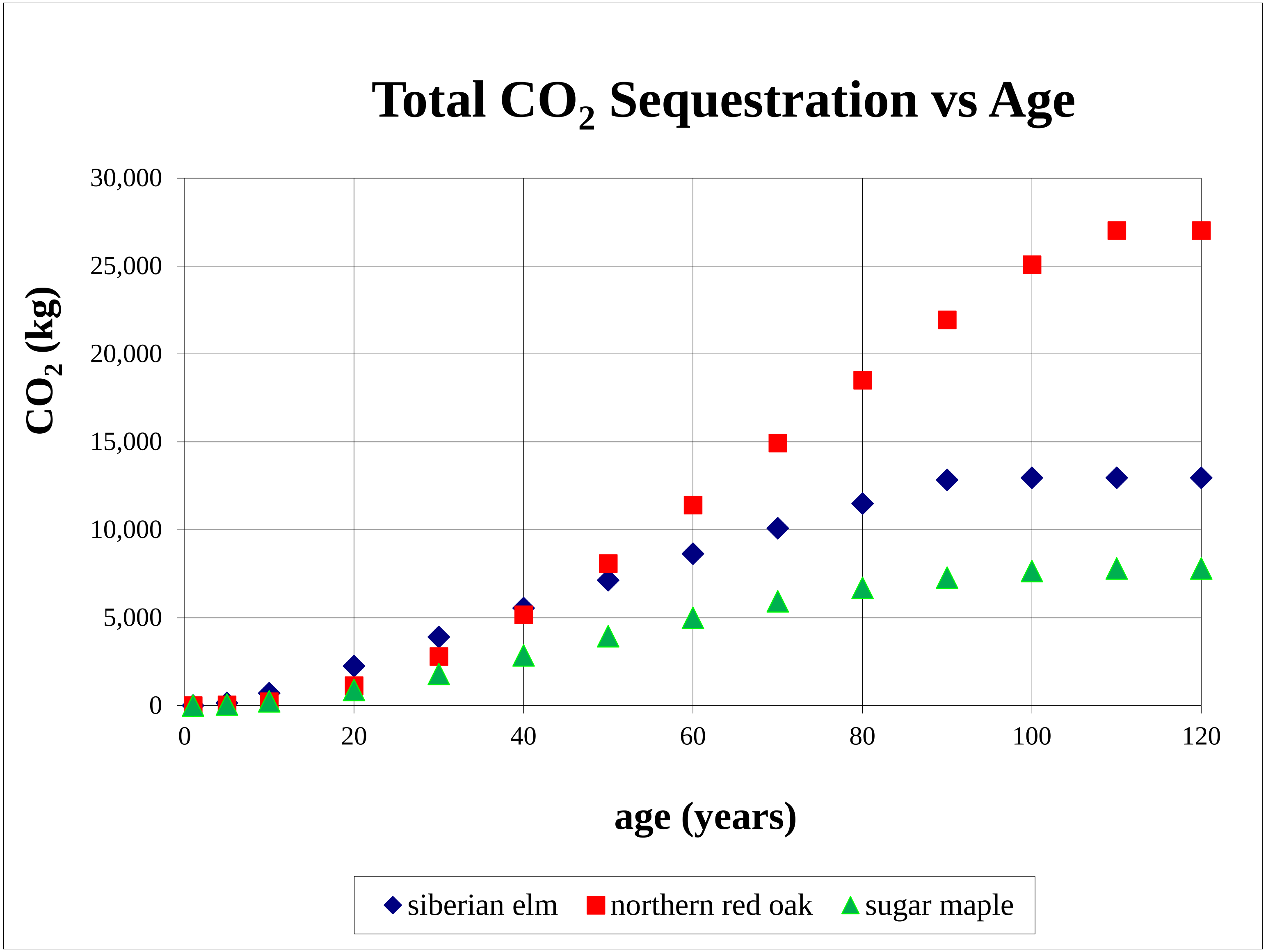
United States Department of Agriculture

Climate Change Resource Center

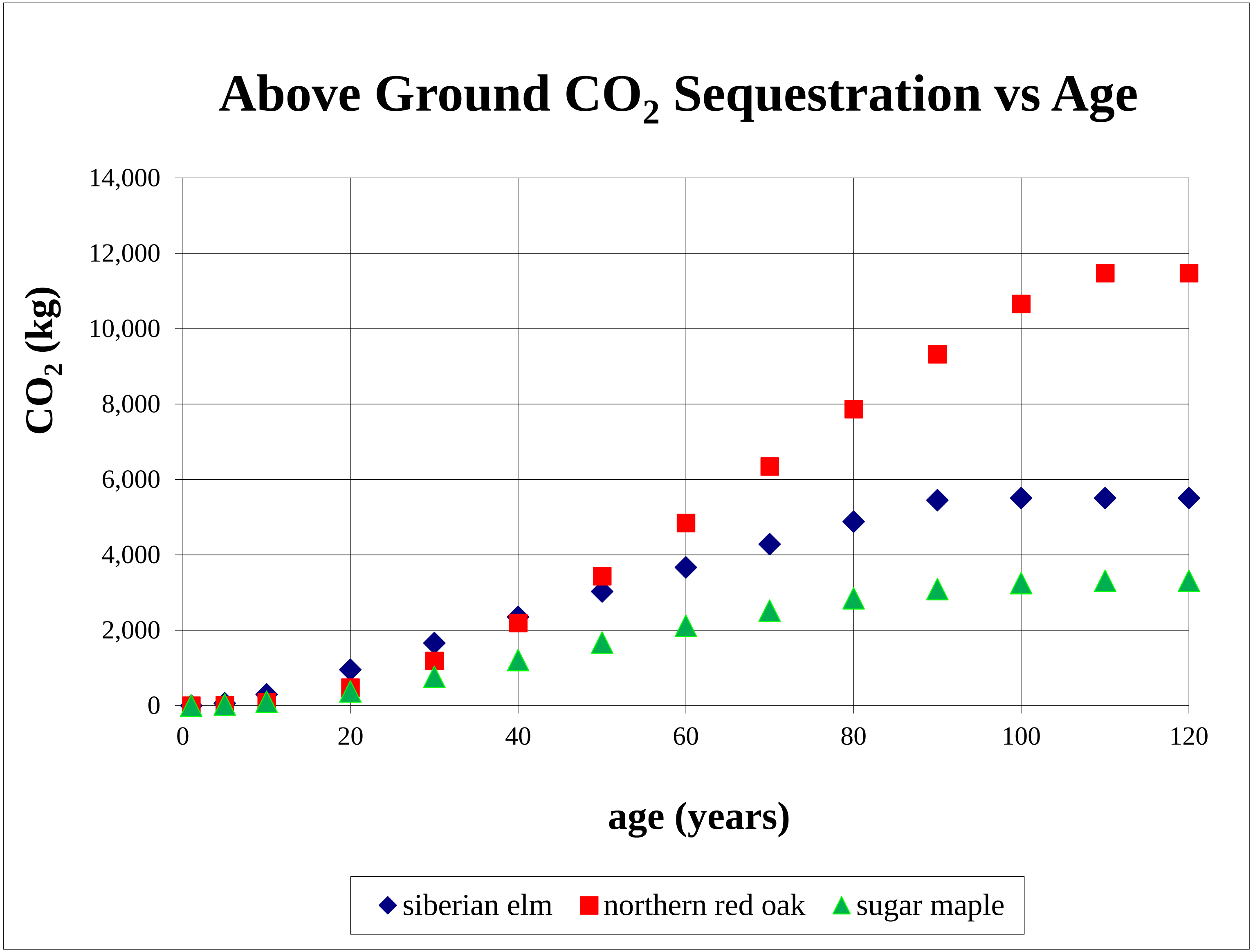
CUFR Tree Carbon Calculator (CTCC)



For US forests 2.2 – 9.5 tonne CO_2/acre/y sequestered.

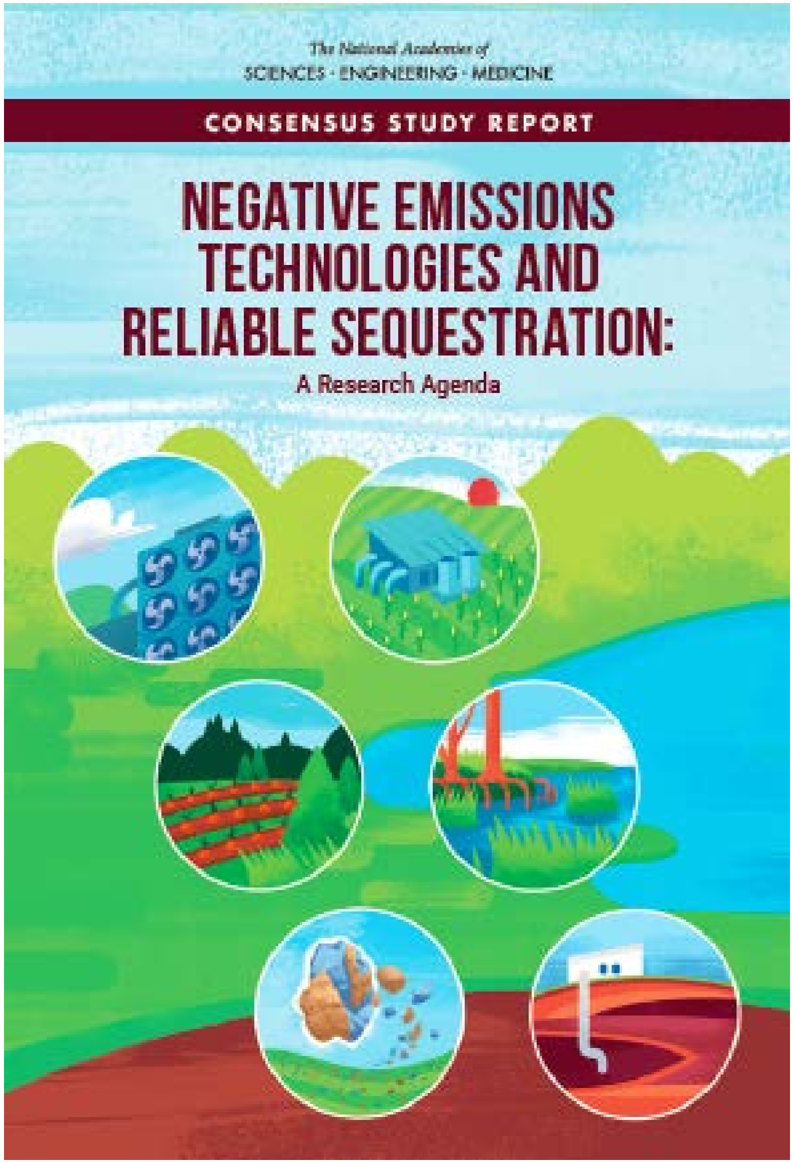


For US forests 2.2 – 9.5 tonne CO_2/acre/y sequestered.



For US forests 2.2 – 9.5 tonne CO_2/acre/y sequestered.

National Academy of Sciences, 2019



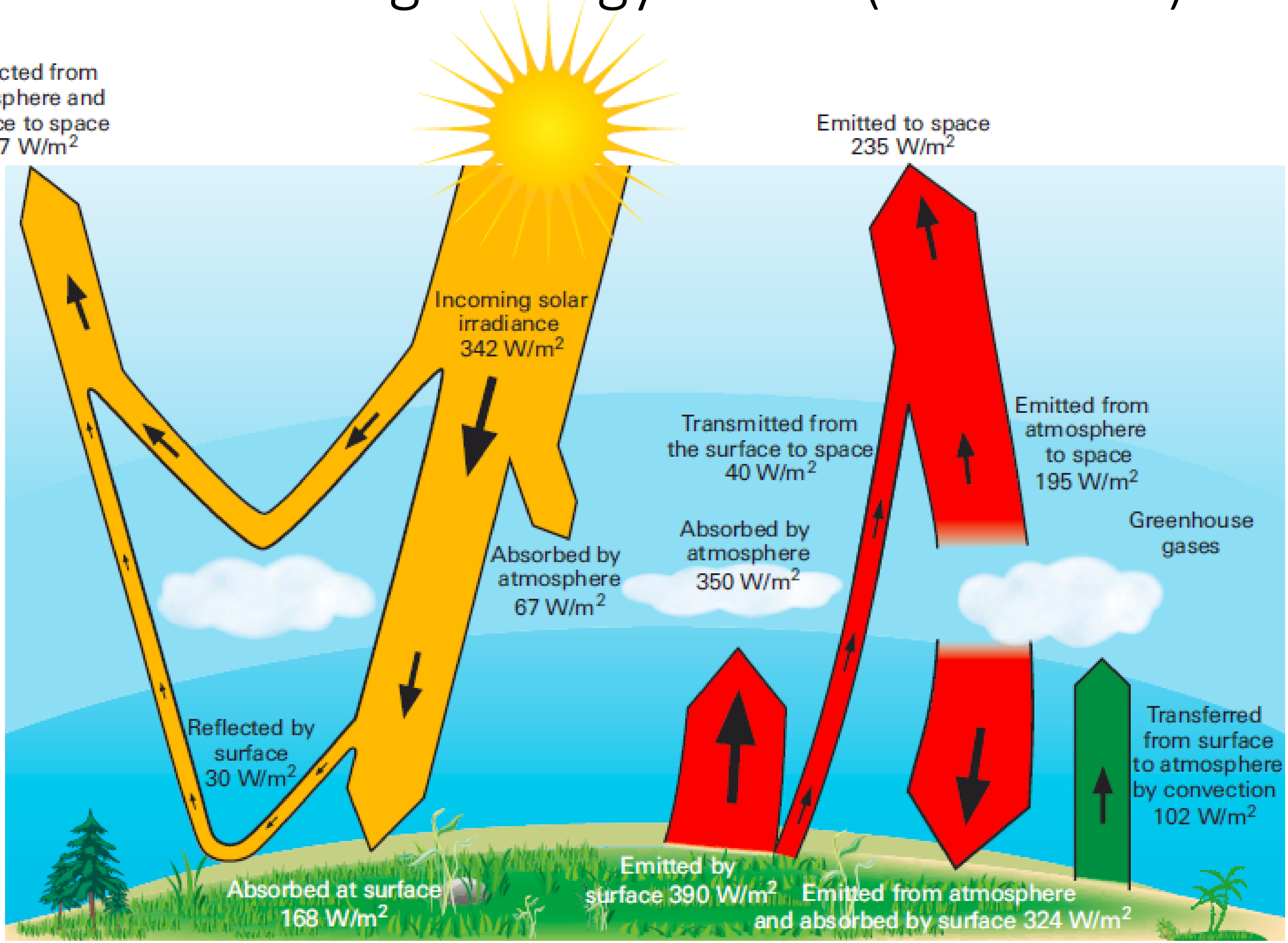
National Academy of Sciences, 2019

- Sequester 150 Mt CO_2 per year requires 9.9 million acres of new forest
  - Area as large as Maryland
  - Can never be harvested
  - In competition with farming, food production, logging, and other uses
  - Full growth in approximately 40 years
- U.S. emission 5.8 Gt CO_2 per year requires 370 million acres
  - Twice the area of Texas
- NAS estimates 250 Mt CO_2 per year "practically achievable"

Geoengineering
Solar Radiation Management
Marine Cloud Brightening

Climate Science

Global Average Energy Fluxes (in Balance)



SRM Example:
Marine Cloud Brightening

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

CrossMark click for updates

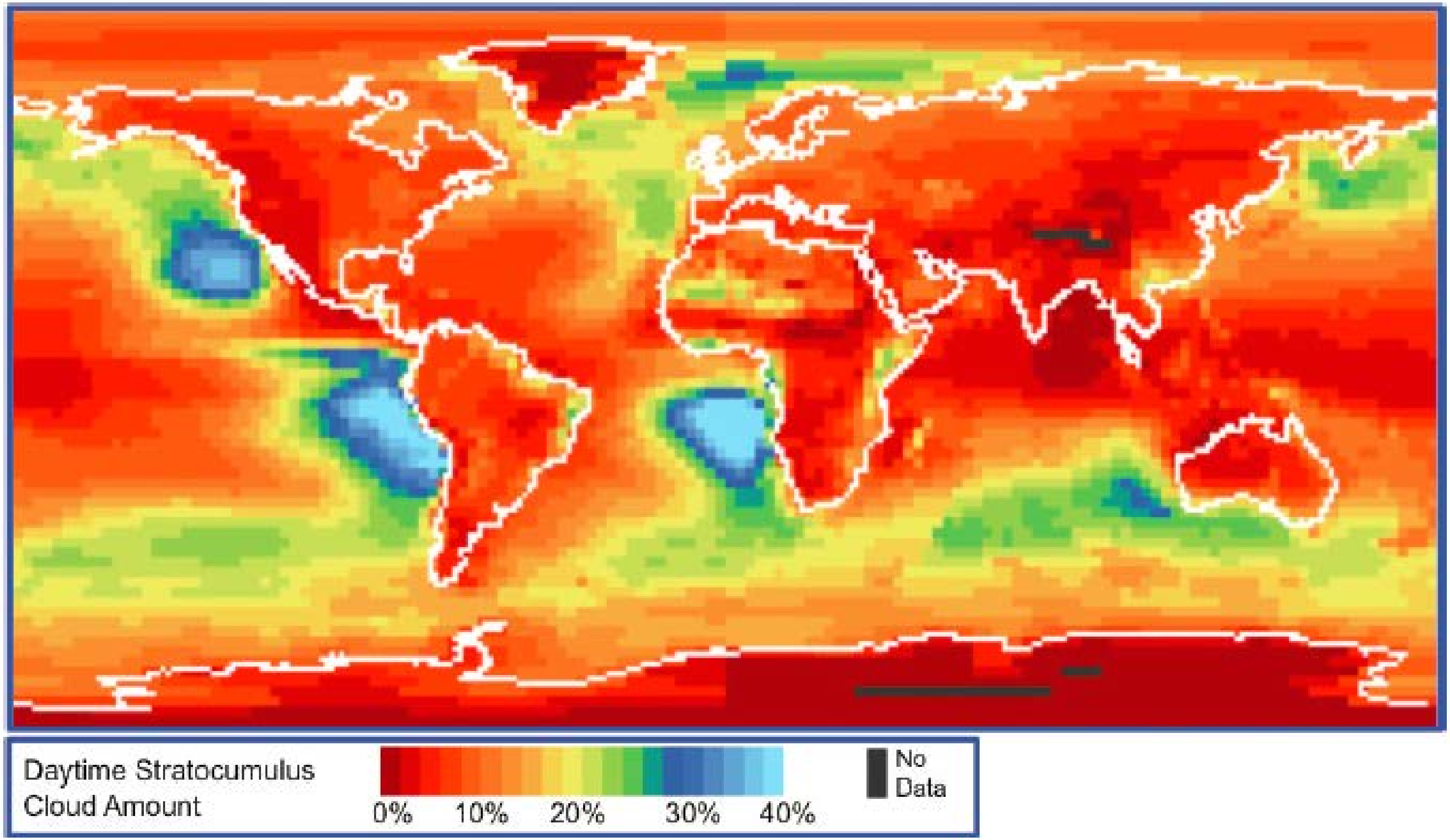
Phil. Trans. R. Soc. A (2012) **370**, 4217–4262
doi:10.1098/rsta.2012.0086

Marine cloud brightening

By John Latham[1,4], Keith Bower[4], Tom Choularton[4], Hugh Coe[4], Paul Connolly[4], Gary Cooper[7], Tim Craft[5], Jack Foster[7], Alan Gadian[6,*], Lee Galbraith[8], Hector Iacovides[5], David Johnston[8], Brian Launder[5], Brian Leslie[8], John Meyer[8], Armand Neukermans[8], Bob Ormond[8], Ben Parkes[6], Phillip Rasch[3], John Rush[8], Stephen Salter[7], Tom Stevenson[7], Hailong Wang[3], Qin Wang[8] and Rob Wood[2]

[1]*National Centre for Atmospheric Research, Boulder, CO 80301, USA*
[2]*Department of Atmospheric Sciences, University of Washington, Seattle, WA 98105, USA*
[3]*Climate Science, Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[4]*School of Earth and Atmospheric Sciences, University of Manchester, Manchester M13 9PL, UK*
[5]*MACE, University of Manchester, Manchester M13 9PL, UK*
[6]*NCAS, SEE, University of Leeds, Leeds LS2 9JT,UK*
[7]*Department of Engineering, University of Edinburgh, Edinburgh EH9 3JL, UK*
[8]*FICER, CA, USA*

Daytime Stratocumulus Cloud Amount 1983 - 2009

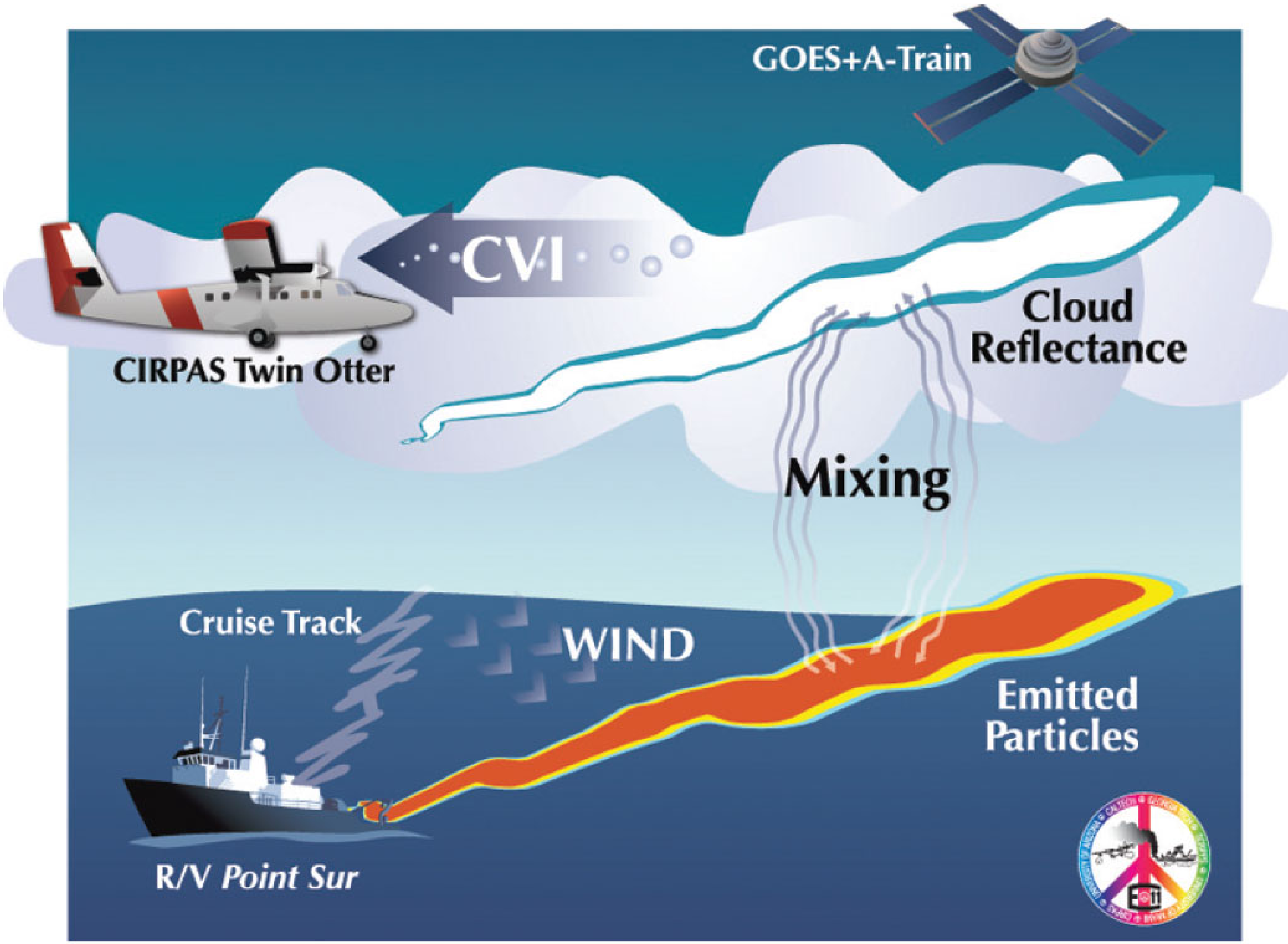


Cloud Brightening

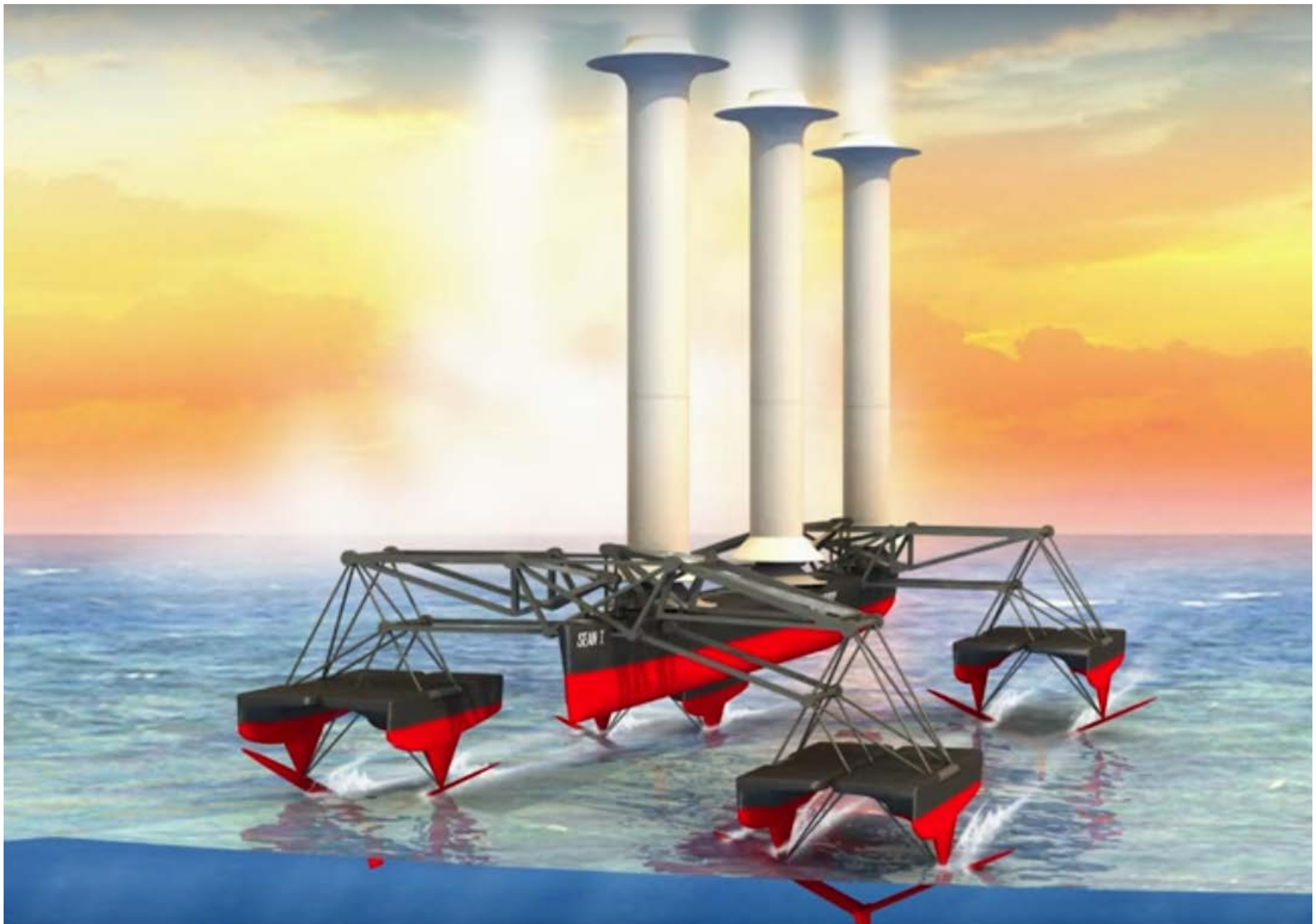
Cloud Brightening

https://www.youtube.com/watch?v=cgJyw2cTrW4

Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) July-August 2011

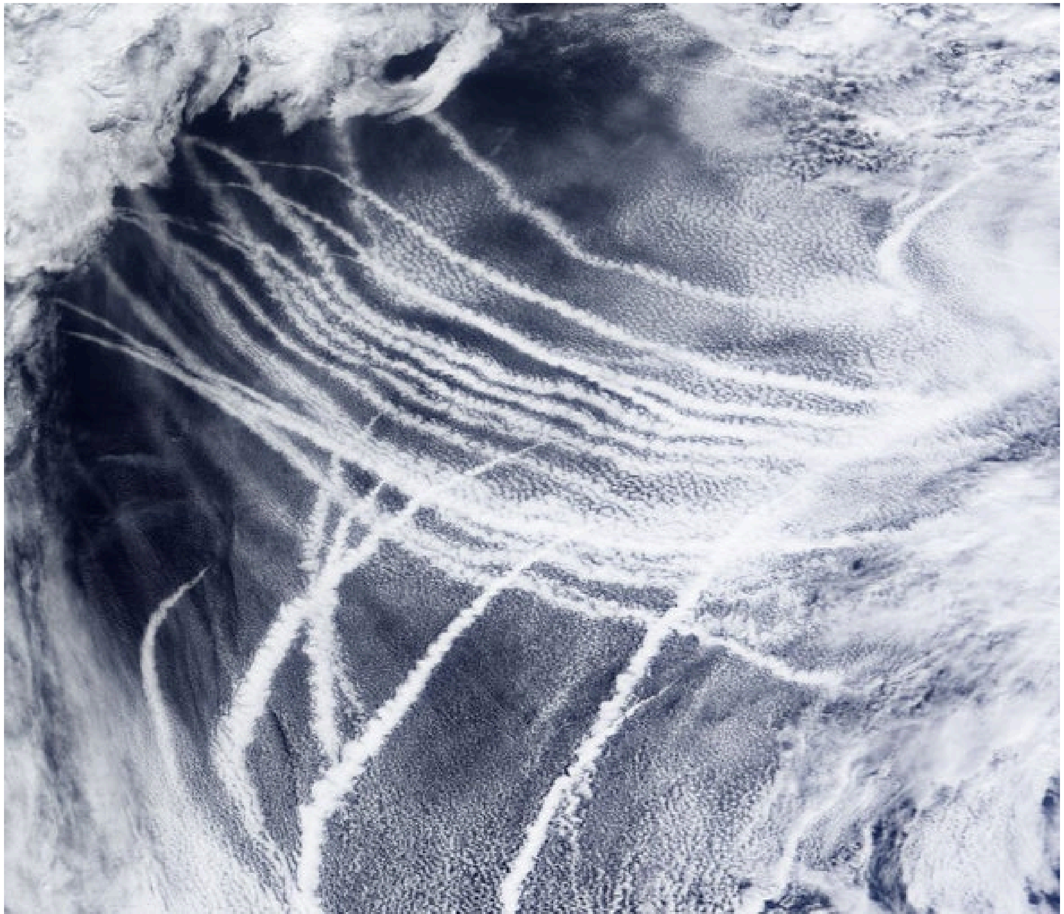


Marine Cloud Brightening
Stephen Salter, TEDx, October, 2016



SCIENTIFIC AMERICAN™

January 23, 2020
NOAA Gets Go-Ahead to Study Controversial Climate Plan B



Royal Society, September 2009
Geoengineering the Climate

"The proposal to whiten marine clouds has a number of advantages over most alternative approaches to reducing absorbed insolation. Firstly, should unforeseen problems arise, spraying could be stopped and within ten days nearly all of the salt particles would rain or settle out of the atmosphere; secondly, sea spray occurs naturally in large quantities. Moreover, at different times of the year different regions of the oceans can be covered offering scope for targeted cooling in particularly sensitive areas."

Cloud albedo enhancement		
Effectiveness	Feasibility (production of sufficient CCN) and effectiveness still uncertain Limited maximum effect and limited regional distribution SRM method so does nothing to counter ocean acidification	Low to Medium
Affordability	Very uncertain: short aerosol lifetime at low altitude so requires continual replenishment of CCN material, but at lower cost per unit mass	Medium
Timeliness	Once deployed would start to reduce temperatures within one year Could be deployed within years/decades (but basic science and engineering issues need to be resolved first)	Medium
Safety	Non-uniformity of effects—may affect weather patterns and ocean currents Possible pollution by CCN material (if not sea-salt)	Low

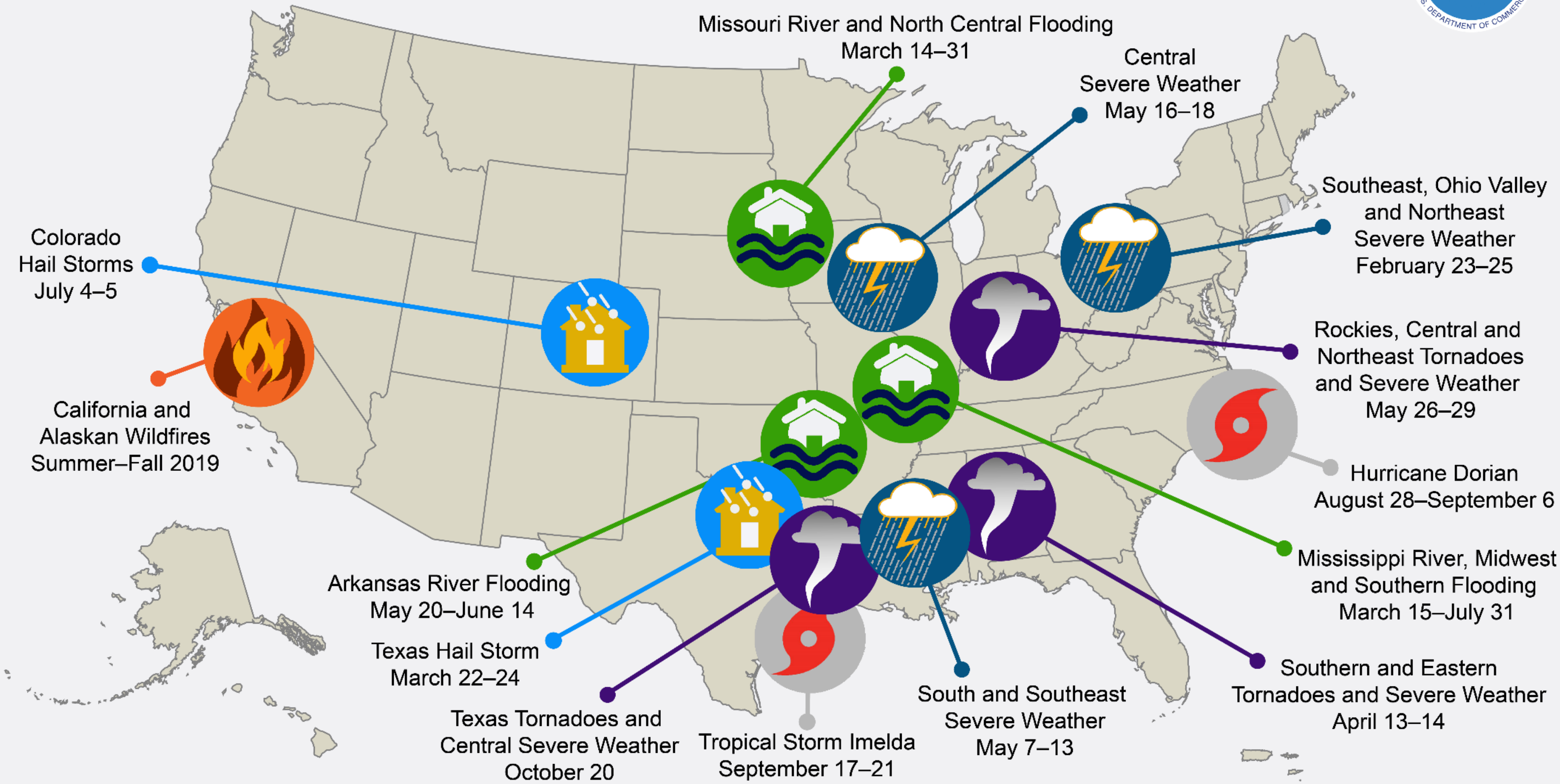
One issue from Lecture 1
Billion dollar weather and climate disasters

NOAA

NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

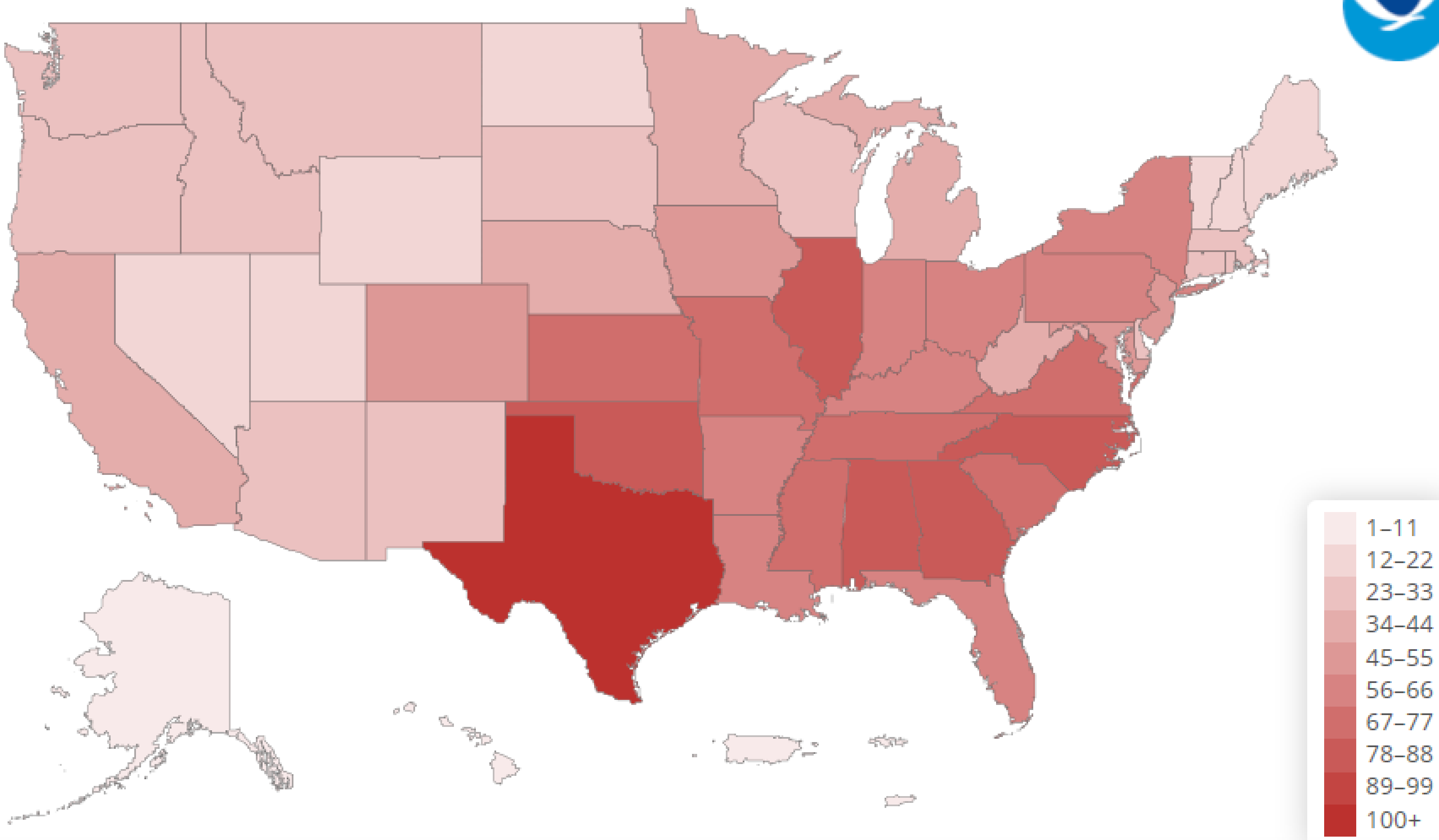
2019 Billion-Dollar Weather and Climate Disasters

U.S. 2019 Billion-Dollar Weather and Climate Disasters



This map denotes the approximate location for each of the ***14 separate billion-dollar weather and climate disasters*** *that impacted the United States* ***during 2019****.*

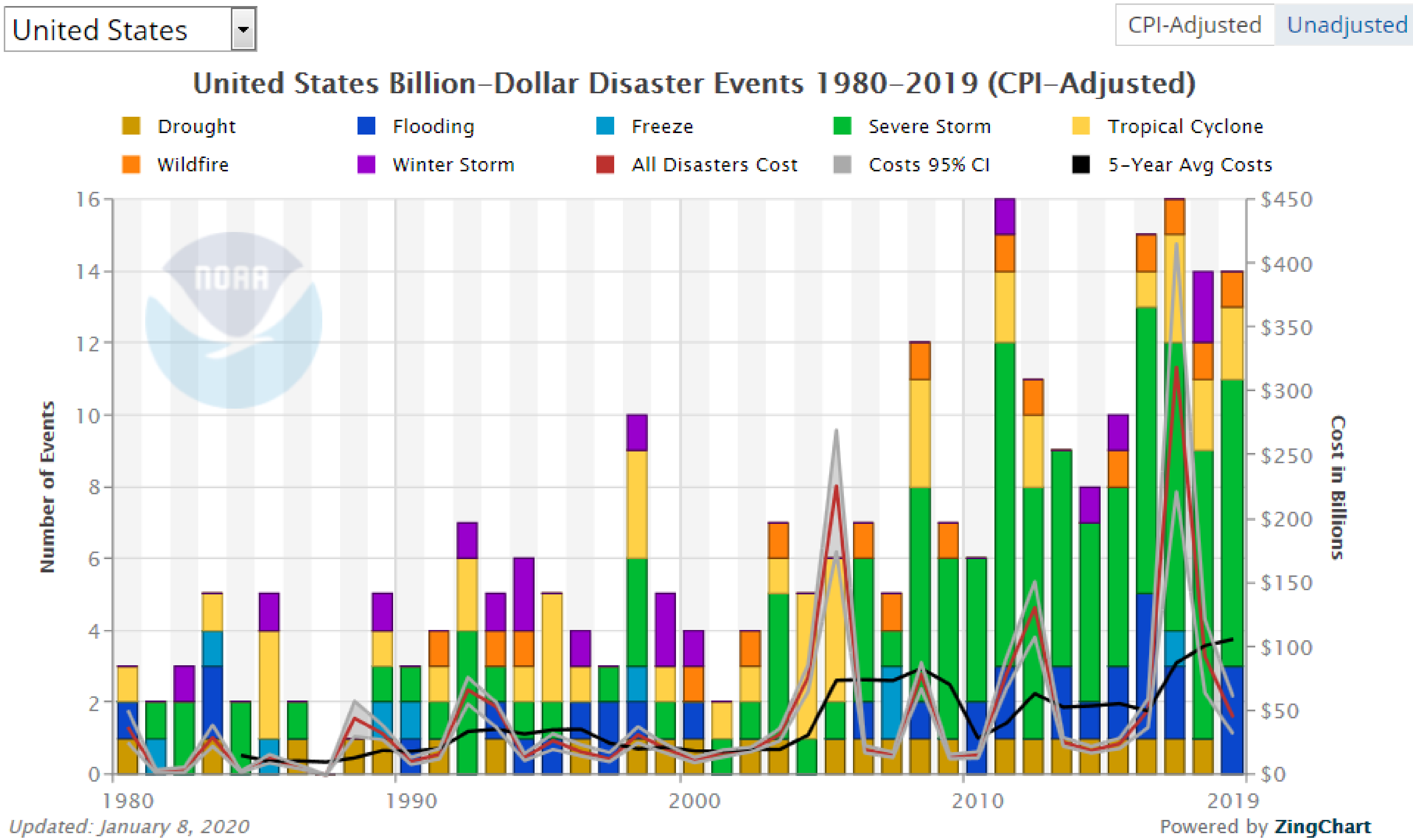
1980-2019 Billion-Dollar Weather and Climate Disasters (CPI-Adjusted)



United States

Drought: 26	Flooding: 32	Freeze: 9	Severe Storm: 113
Tropical Cyclone: 44	Wildfire: 17	Winter Storm: 17	All Disasters: 258

Please note that the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event).



United States
CPI-Adjusted
Unadjusted
United States Billion-Dollar Disaster Events 1980-2019 (CPI-Adjusted)
Drought
Flooding
Freeze
Severe Storm
Tropical Cyclone
Wildfire
Winter Storm
All Disasters Cost
Costs 95% CI
5-Year Avg Costs
Number of Events
Cost in Billions
0
2
4
6
8
10
12
14
16
$0
$50
$100
$150
$200
$250
$300
$350
$400
$450
1980
1990
2000
2010
2019
Updated: January 8, 2020
Powered by ZingChart

Billion-dollar events to affect the U.S. from 1980 to 2019 (CPI-Adjusted)

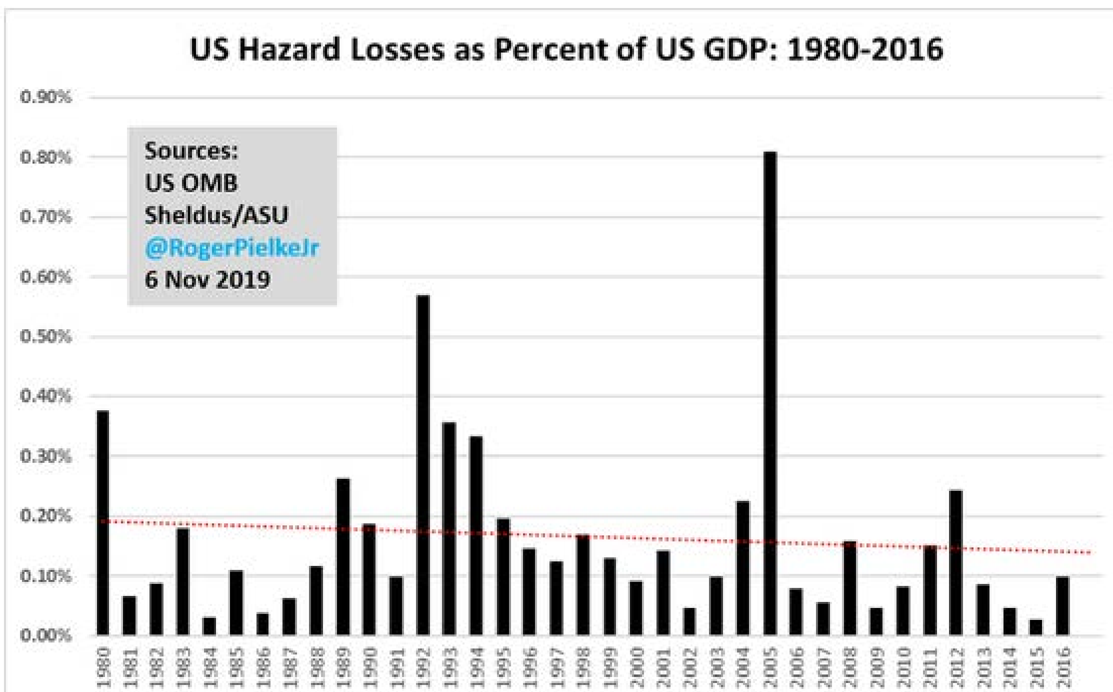
DISASTER TYPE	NUMBER OF EVENTS	PERCENT FREQUENCY	CPI-ADJUSTED LOSSES *(BILLIONS OF DOLLARS)*	PERCENT OF TOTAL LOSSES	AVERAGE EVENT COST *(BILLIONS OF DOLLARS)*	DEATHS
Drought	26	10.1%	$249.7 CI	14.2%	$9.6	2,993†
Flooding	32	12.4%	$146.5§ CI	8.3%§	$4.6§	555
Freeze	9	3.5%	$30.5 CI	1.7%	$3.4	162
Severe Storm	113	43.8%	$247.8 CI	14.1%	$2.2	1,642
Tropical Cyclone	44	17.1%	$945.9 CI	53.9%	$21.5	6,502
Wildfire	17	6.6%	$84.9 CI	4.8%	$5.0	347
Winter Storm	17	6.6%	$49.3 CI	2.8%	$2.9	1,048
All Disasters	**258**	**100.0%**	**$1,754.6** CI	**100.0%**	**$6.8**	**13,249**

†Deaths associated with drought are the result of heat waves. (Not all droughts are accompanied by extreme heat waves.)

§Flooding statistics do not include inland flood damage caused by tropical cyclone events.

The confidence interval (CI) probabilities (75%, 90% and 95%) represent the uncertainty associated with the disaster cost estimates. Monte Carlo simulations were used to produce upper and lower bounds at these confidence levels (Smith and Matthews, 2015).

November 7, 2019
Roger Pielke: Everything You Hear About Billion-Dollar Disasters Is Wrong



U.S. hazard losses as a percentage of GDP, 1980 to 2016. Sources linked in text. R. PIELKE JR.

Natural Hazards 67(2013)387
US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases
Adam B. Smith and Richard W. Katz

"the billion-dollar dataset is only adjusted for the CPI over time, not currently incorporating any changes in exposure (e.g., as reflected by shifts in wealth or population). Normalization techniques for exposure have been limited by the lack of data on a relevant spatial scale. Yet, a number of studies have concluded that population growth, increased value of property at risk and demographic shifts are major factors behind the increasing losses from specific types of natural hazards (Downton and Pielke 2005; Brooks and Doswell 2001). The magnitude of such increasing trends is greatly diminished when applied to data normalized for exposure (Pielke et al. 2008)."

Empower Results®

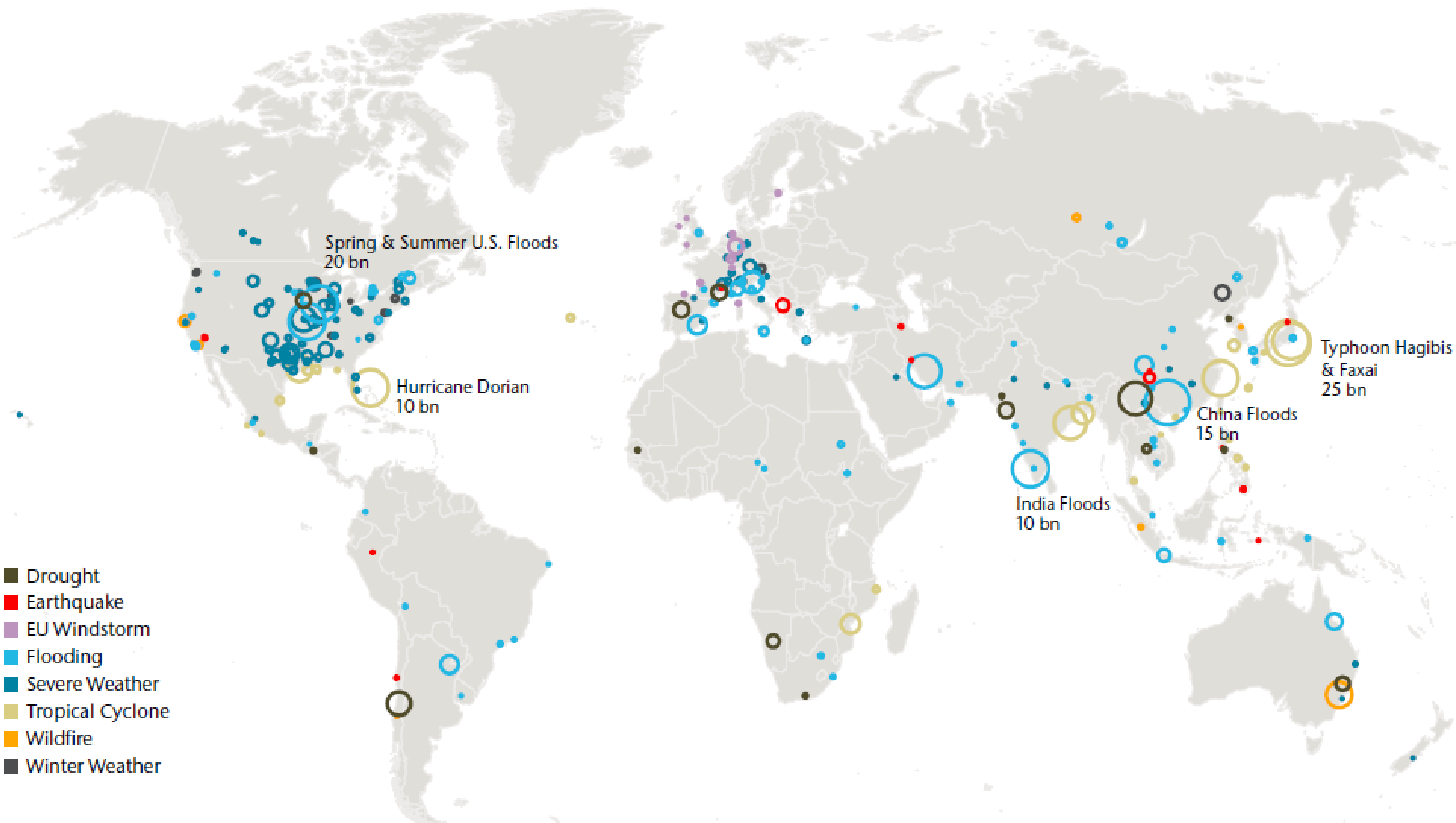
Weather, Climate & Catastrophe Insight

2019 Annual Report

Top 10 Global Economic Loss Events

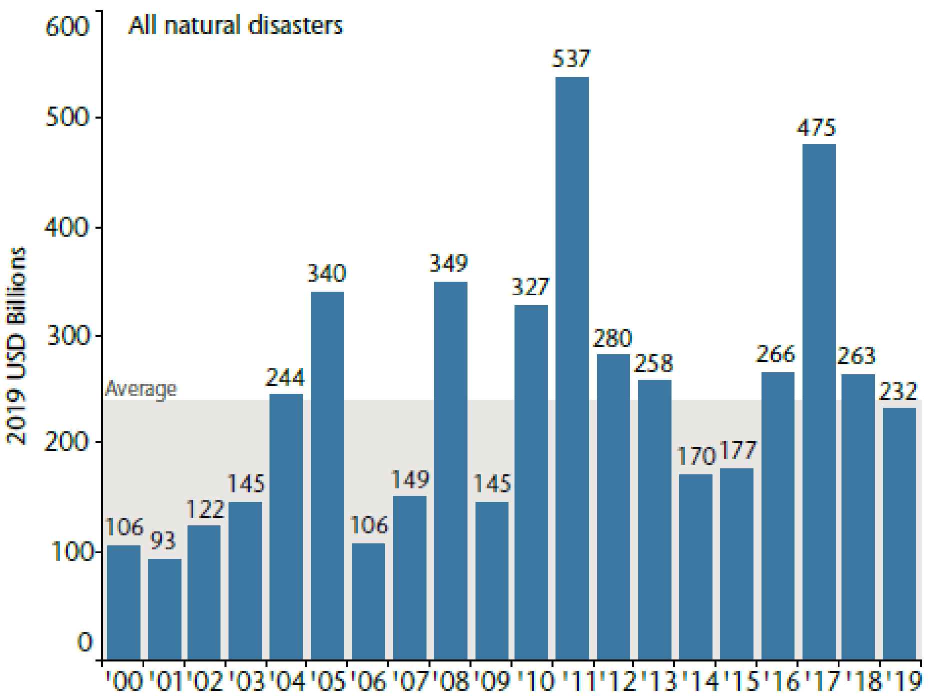
Date(s)	Event	Location	Deaths	Economic Loss (USD billions)	Insured Loss (USD billions)
October 6-12	Typhoon Hagibis	Japan	99	15.0	9.0
June - August	Monsoon Floods	China	300	15.0	0.7
September 7-9	Typhoon Faxai	Japan	3	10.0	6.0
May – July	Mississippi Basin Floods	United States	0	10.0	4.0
Aug 25 – Sep 7	Hurricane Dorian	Bahamas, Caribbean, US, Canada	83	10.0	3.5
March 12-31	Missouri Basin Floods	United States	10	10.0	2.5
June – October	Monsoon Floods	India	1,750	10.0	0.2
August 6-13	Typhoon Lekima	China, Philippines, Japan	101	9.5	0.8
March - April	Flooding	Iran	77	8.3	0.2
May 2-5	Cyclone Fani	India, Bangladesh	81	8.1	0.5
			All Other Events	126 billion	44 billion
			Totals	**232 billion**[1]	**71 billion**[1,2]

Significant 2019 Economic Loss Events

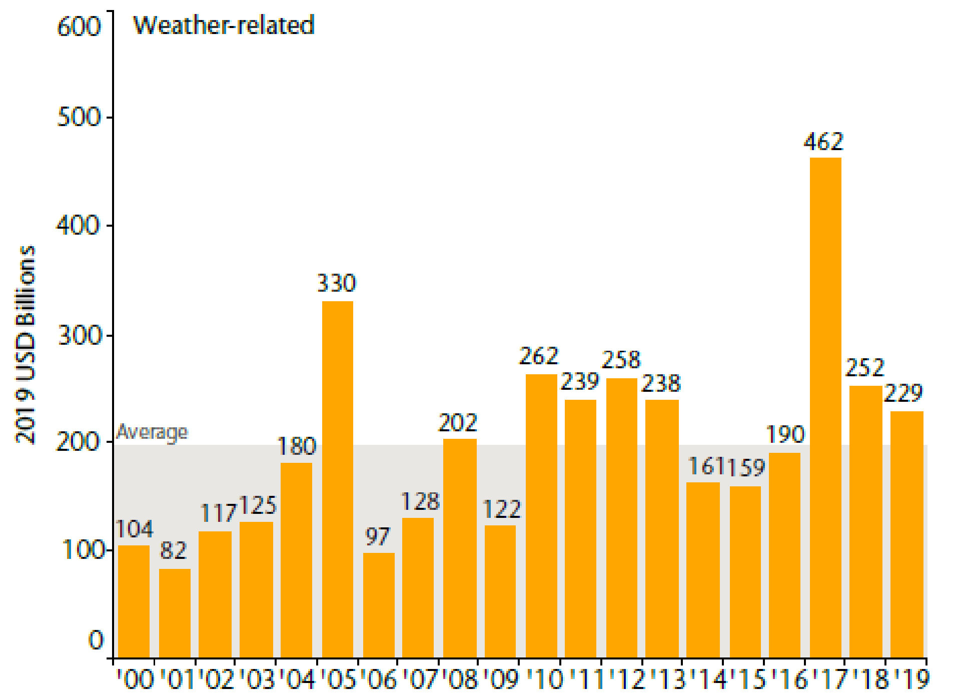


[1] Subject to change as loss estimates are further developed
[2] Includes losses sustained by private insurers and government-sponsored programs
[3] Based on events that incurred economic loss equal to or greater than USD50 million. Position of an event is determined by the most affected administrative unit or epicenter.

Global Economic Losses



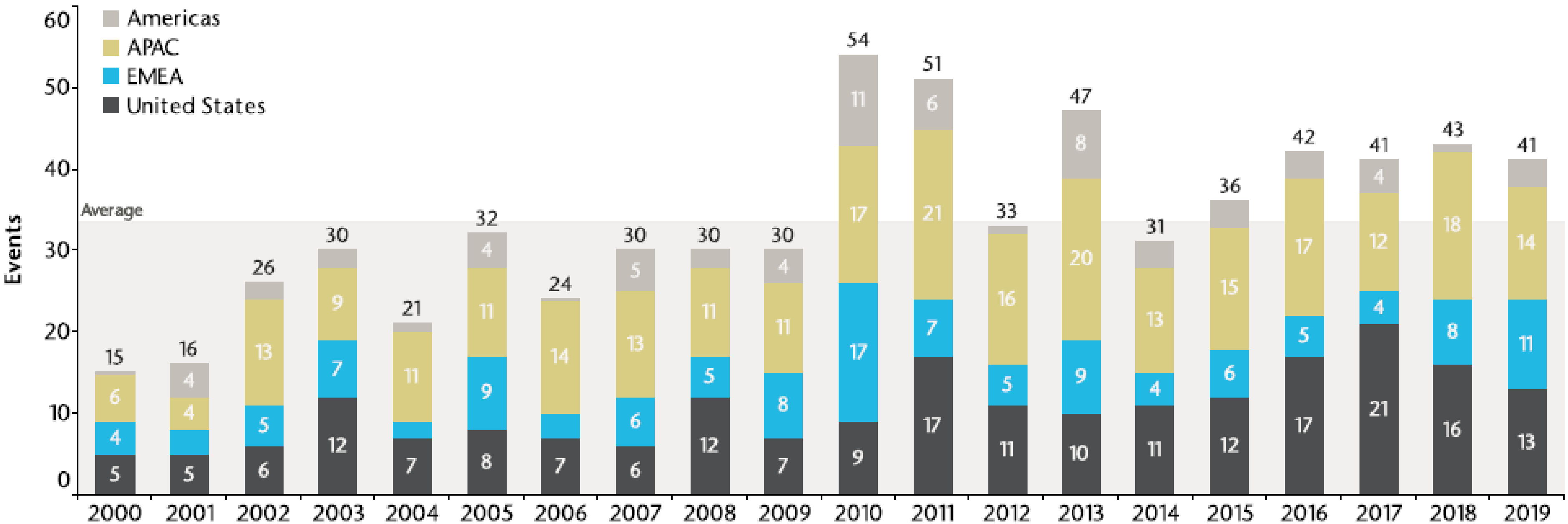
All natural disasters



Weather related

Global Billion-Dollar Economic Loss Events

Exhibit 6: Global Billion-Dollar Economic Loss Events



Note: Exhibit 6 includes events which reached the billion-dollar-plus (USD) threshold after an inflation-adjustment based on the 2019 U.S. Consumer Price Index.

Americas: non-U.S.
APAC: Asia and Oceania
EMEA: Europe, Middle East and Africa
United States: U.S.

Typhoon Hagibis, Japan, 10/6 – 10/12, $15 billion, 99 killed
Flooding, China, Jun - Aug, $15 billion, 300 killed
Hurricane Dorian, 8/25 – 9/7, Bahamas, U.S., Caribbean, Canada, $10 billion, 83+ killed
Typhoon Faxai, Japan, 9/7 – 9/9, $10 billion, 3 killed
Flooding, India, Jun - Oct, $10 billion, 1750 killed
Flooding, Mississippi Basin U.S., May - Jul, $10 billion, 0 killed
Flooding, Missouri Basin U.S., 3/12 – 3/31, $10 billion, 10 killed
Typhoon Lekima, China, Philippines, Japan, Aug 6 - 13, $9.5 billion, 101 killed
Flooding, Iran, Mar - Apr, $8.3 billion, 77 killed
Cyclone Fani, India, Bangladesh, 5/3 – 5/5, $8.1 billion, 89 killed
Drought, China, Jan - Dec, $8 billion
Wildfires, Australia, 11/8 – 12/31, $5 billion, 29 killed
Severe Weather, Rockies, Plains, Midwest U.S., 5/27 – 5/30, $4.5 billion, 0 killed
Tropical Storm Imelda, Texas/Louisiana (U.S.), 9/17 – 9/20, $3.5 billion, 5 killed
Flooding, Italy and Austria, 11/11 – 11/19, $3.5 billion, 3 killed
Cyclone Bulbul, India and Bangladesh, 11/8 – 11/11, $3.4 billion, 72 killed
Severe Weather, Plains, Southeast U.S., 10/20 – 10/21, $2.75 billion, 4 killed
Cyclone Idai, Mozambique, Zimbabwe, Malawi, 3/3 - 3/18, $2.7 billion, 1303 killed
Flooding, Spain, 9/11 – 9/15, $2.5 billion, 7 killed
Flooding, Argentina, Uruguay, 1/1 - 1/20, $2.3 billion, 5 killed
Flooding, China, 8/18 – 8/21, $2.3 billion, 45 killed
Drought, Chile, Jan - Dec, $2 billion
Flooding, Australia, 1/28 - 2/7, $1.9 billion, 3 killed
Severe Weather, Plains, Midwest U.S., 3/23 – 3/25, $1.8 billion, 0 killed
Drought, India, Jan - Dec, $1.75 billion
Drought & Heatwave, Western & Central Europe, Jun - Aug, $1.7 billion, N/A killed
Drought, Spain, Jan - Dec, $1.7 billion
Windstorm Eberhard, Central & Western Europe, 3/10, $1.6 billion, 2 killed
Severe Weather, Plains, Midwest, Southeast U.S., 5/4 – 5/10, $1.5 billion, 1 killed
Drought, U.S., Jan - Dec, $1.5 billion, 0 killed
Drought, Australia, Jan - Dec, $1.4 billion
Severe Weather, Central/Eastern U.S., 2/22 - 2/26, $1.4 billion, 4 killed
Severe Weather, Plains, Midwest, Southeast, Northeast U.S., 4/12 – 4/15, $1.3 billion, 9 killed
Flooding, Italy and France, 11/21 – 11/24, $1.2 billion, 9 killed
Flooding, Indonesia, 12/31 – 1/3, $1.15 billion, 30 killed
Severe Weather, Rockies, Plains, U.S., 7/4 – 7/5, $1.1 billion, 0 killed
Severe Weather, Central Europe, 6/10 – 6/12, $1.1 billion, 0 killed
Drought, Uruguay, Jan - Dec, $1.1 billion
Severe Weather, Plains, Midwest, Southeast U.S.

SCIENTIFIC AMERICAN™

January 22, 2020

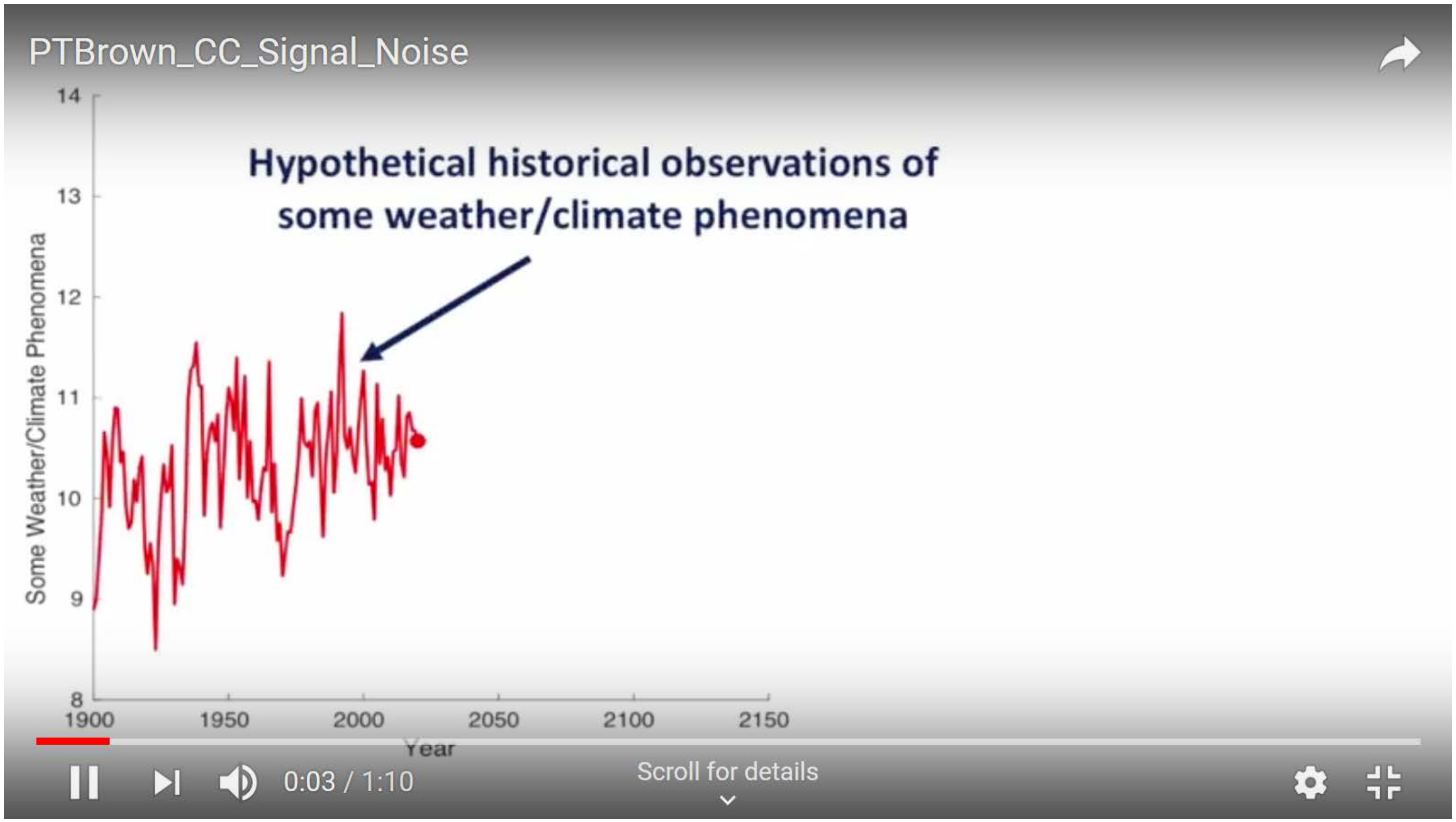
Earth's 40 Billion-Dollar Weather Disasters of 2019: 4th Most Billion-Dollar Events on Record

Most Expensive non-U.S. Weather Disasters Since 1990

Rank	Disaster	Year	Deaths	Damage (2020 dollars)
1.	China Floods	1998	3656	$48 billion
2.	Thailand Floods	2011	813	$47 billion
3.	North Korea Floods	1995	68	$27 billion
4.	China Winter Weather	2008	145	$26 billion
5.	China Drought	1994	104	$24 billion
6.	China Floods	2016	475	$23 billion
7.	China Floods	2010	1691	$22 billion
8.	China Floods	1996	2775	$21 billion
9.	Japan Typhoon Mireille	1991	66	$19 billion
10.	India Monsoon Floods	2014	298	$18 billion
11.	Germany Floods	2002	27	$17 billion
12.	Italy Floods	1994	68	$16 billion
13.	Japan Typhoon Hagibis	2019	99	$15 billion
13.	China Floods	2019	300	$15 billion

Source: EM-DAT and Aon

Climate Change Signal And Noise
Prof. Patrick T. Brown
San Jose State University



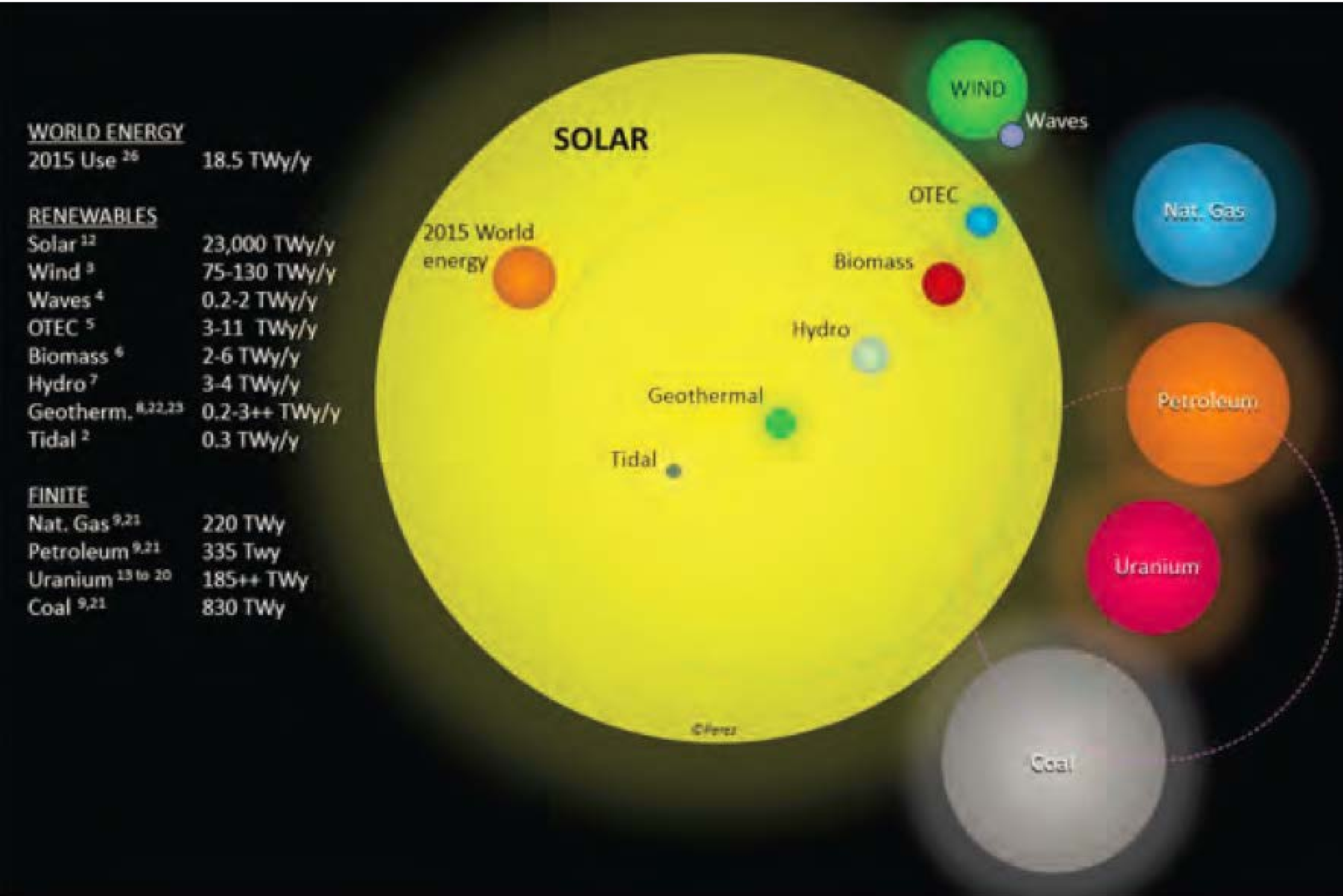
https://www.youtube.com/watch?v=qJSNbXFUQGs

Why not 100% wind and solar renewables?

Variability and Intermittency of Wind and Solar

- Renewables examples
- Bonneville Power Administration example
- Champaign County wind example
- Champaign County solar example
- Wind plus solar example
- Aggregation
- Battery storage
- How much storage is needed?
- Summary

Global Renewable Resources for Electricity Generation


WORLD ENERGY
2015 Use [26] 18.5 TWy/y
RENEWABLES
Solar [12] 23,000 TWy/y
Wind [3] 75-130 TWy/y
Waves [4] 0.2-2 TWy/y
OTEC [5] 3-11 TWy/y
Biomass [6] 2-6 TWy/y
Hydro [7] 3-4 TWy/y
Geotherm. [8,22,23] 0.2-3++ TWy/y
Tidal [2] 0.3 TWy/y
FINITE
Nat. Gas [9,21] 220 TWy
Petroleum [9,21] 335 Twy
Uranium [13 to 20] 185++ TWy
Coal [9,21] 830 TWy
SOLAR
2015 World energy
WIND
Waves
OTEC
Biomass
Hydro
Geothermal
Tidal
Nat. Gas
Petroleum
Uranium
Coal

Energy Transition
The German Energiewende

May 11, 2016

Germany nearly reached 100 percent renewable power on Sunday

theguardian

July 10, 2016

Wind power generates 140% of Denmark's electricity demand

theguardian

May 18, 2016

Portugal runs for four days straight on renewable energy alone

theguardian

April 22, 2017

British power generation achieves first ever coal-free day

July 19, 2019
Scotland generating enough wind energy to power two Scotlands

August 2, 2019
El Hierro Island 8 days at 100 % renewables

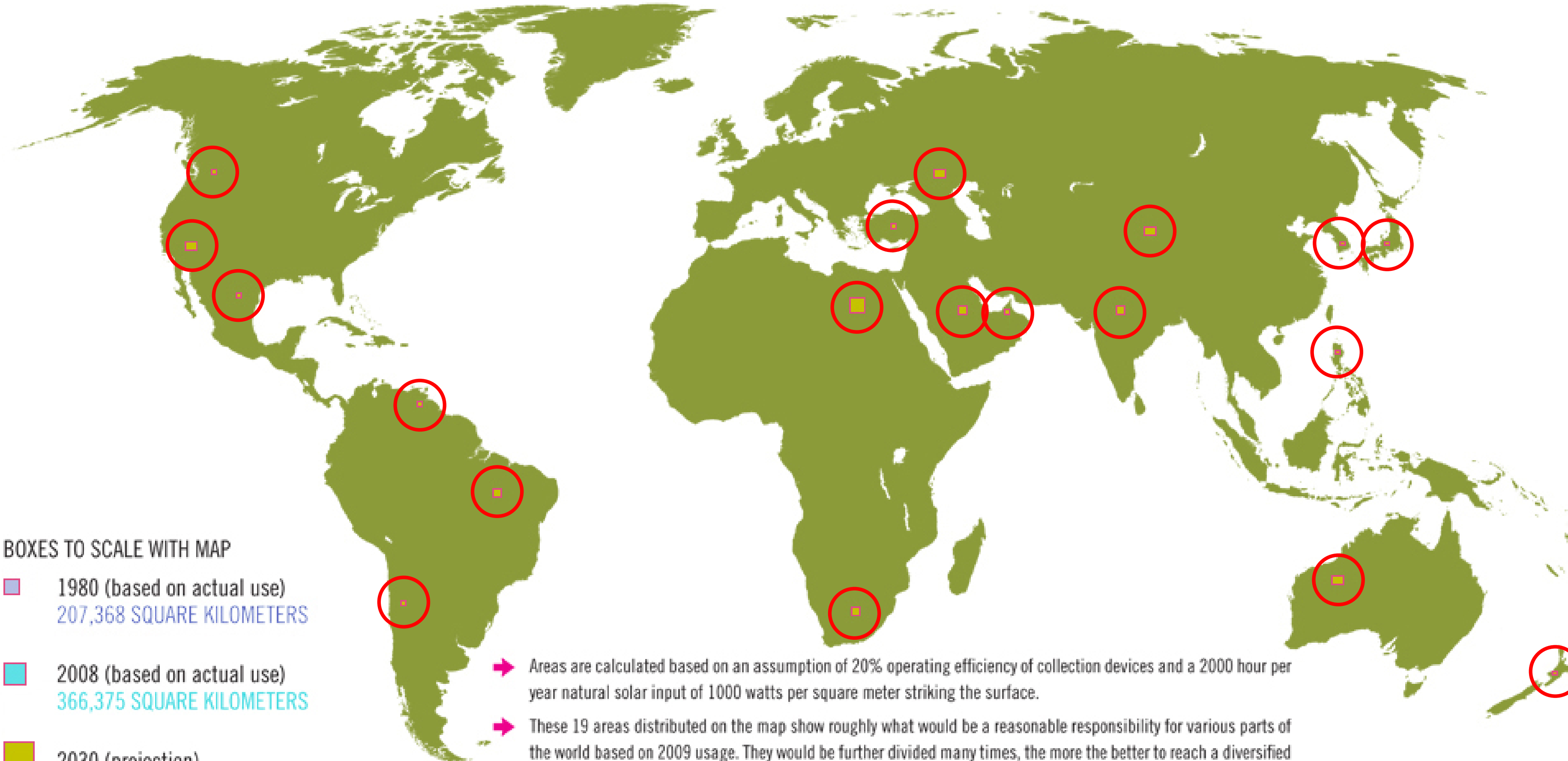
February 2, 2020

Costa Rica celebrates 300 days living alone with renewable energy

SURFACE AREA REQUIRED TO POWER THE WORLD

WITH ZERO CARBON EMISSIONS AND WITH SOLAR ALONE

www.landartgenerator.org



BOXES TO SCALE WITH MAP

1980 (based on actual use)
207,368 SQUARE KILOMETERS

2008 (based on actual use)
366,375 SQUARE KILOMETERS

2030 (projection)
496,805 SQUARE KILOMETERS

Required area that would be needed in the year 2030 is shown as one large square in the key above and also as distributed around the world relative to use and available sunlight.

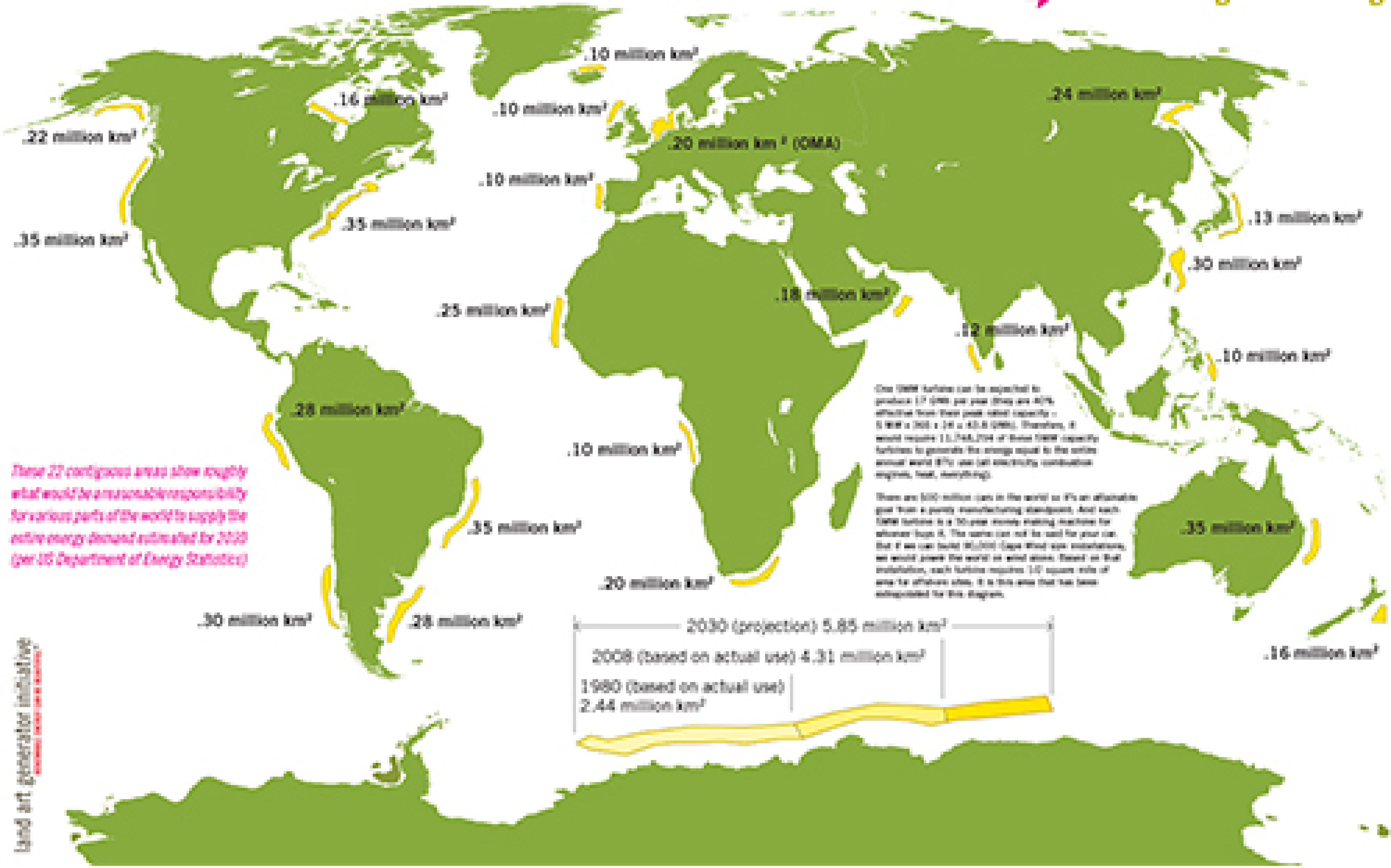
- Areas are calculated based on an assumption of 20% operating efficiency of collection devices and a 2000 hour per year natural solar input of 1000 watts per square meter striking the surface.
- These 19 areas distributed on the map show roughly what would be a reasonable responsibility for various parts of the world based on 2009 usage. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.
- The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is 18 times less than the total area of that desert.
- The definition of "power" covers the fuel required to run all electrical consumption, all machinery, and all forms of transportation. It is based on the US Department of Energy statistics of worldwide Btu consumption and estimates the 2030 usage (678 quadrillion Btu) to be 44% greater than that of 2008.
- Area calculations do not include magenta border lines.

LAND ART GENERATOR INITIATIVE

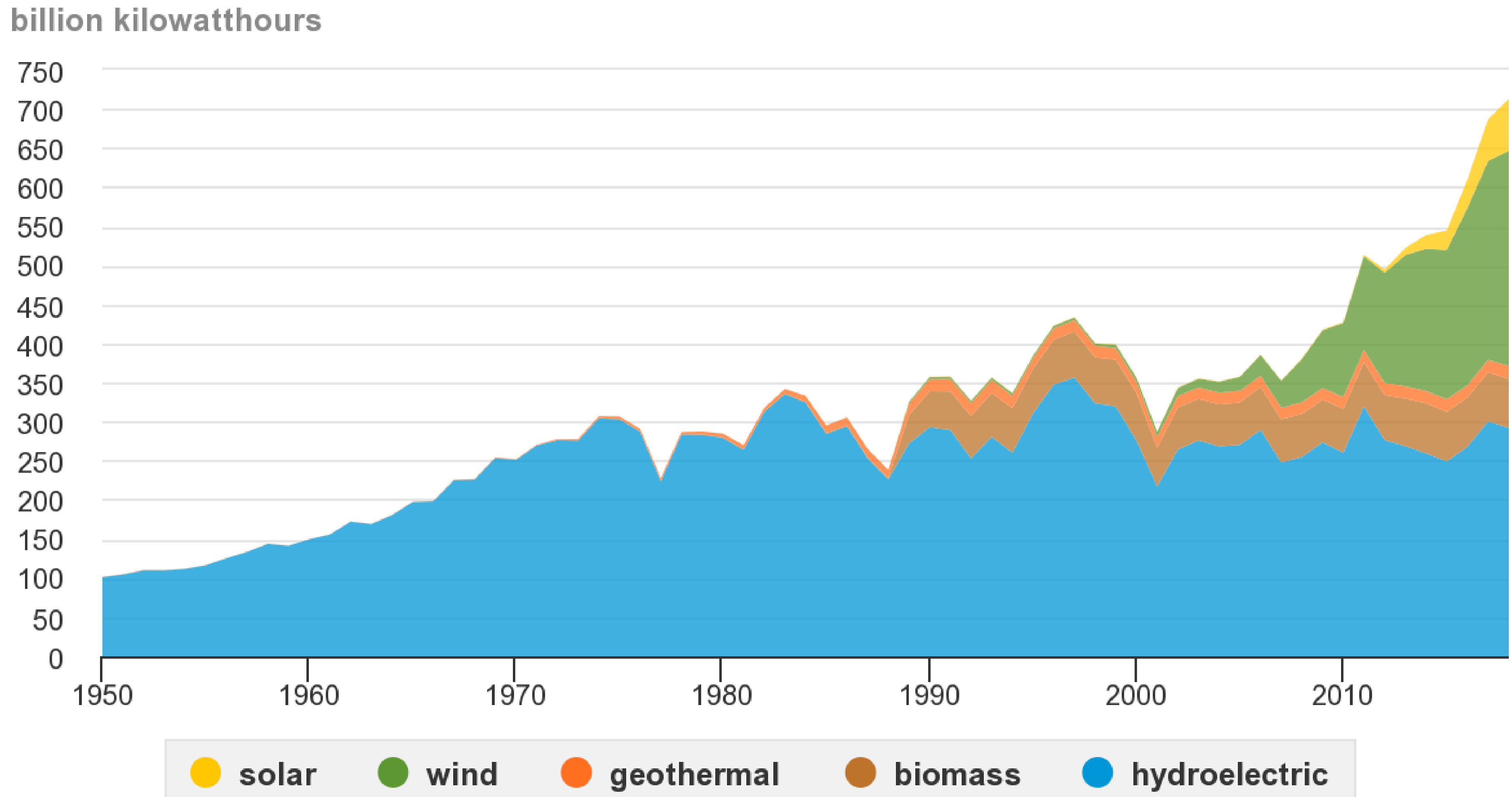
SURFACE AREA REQUIRED TO POWER THE WORLD

WITH ZERO CARBON EMISSIONS AND WITH OFFSHORE WIND ALONE

www.landartgenerator.org



U.S. Electricity Generation from Renewables 1950-2018



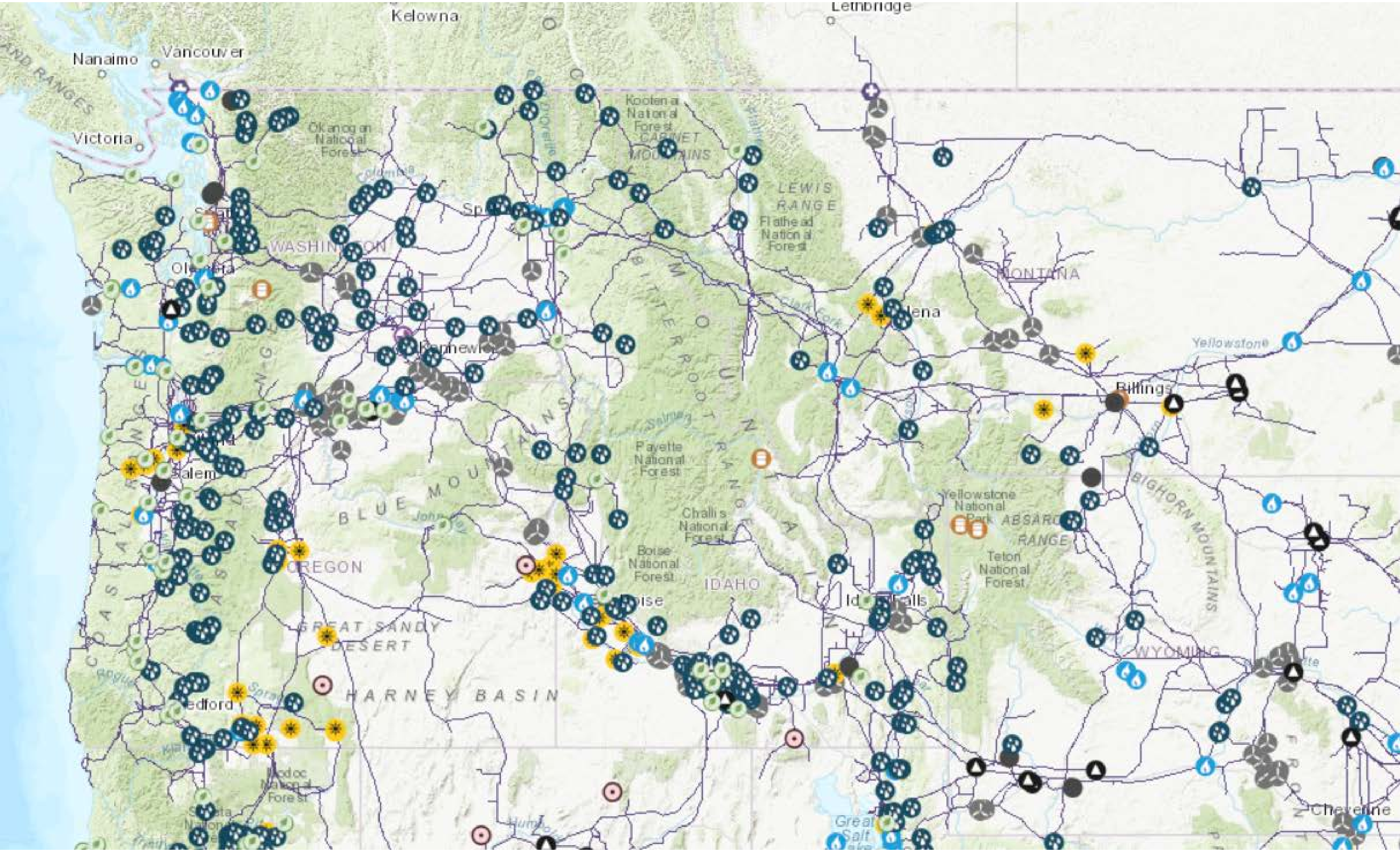
Note: Electricity generation from utility-scale facilities. Hydroelectric is conventional hydropower.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, March 2019

So Why Not All Renewables?

- Cost compared to fossil fuels
- Variability
- Intermittency
- Grid inadequacy
- Lack of storage
- Inertia from capital investments in fossil fuel generators

Variability and Intermittency of Wind
Example of Bonneville Power Administration

Bonneville Power Administration Wind Facilities



BPA Balancing Administration Load and Total Wind, Hydro, and Thermal Generation, Near-Real-Time February 12, 2018 – February 19, 2018

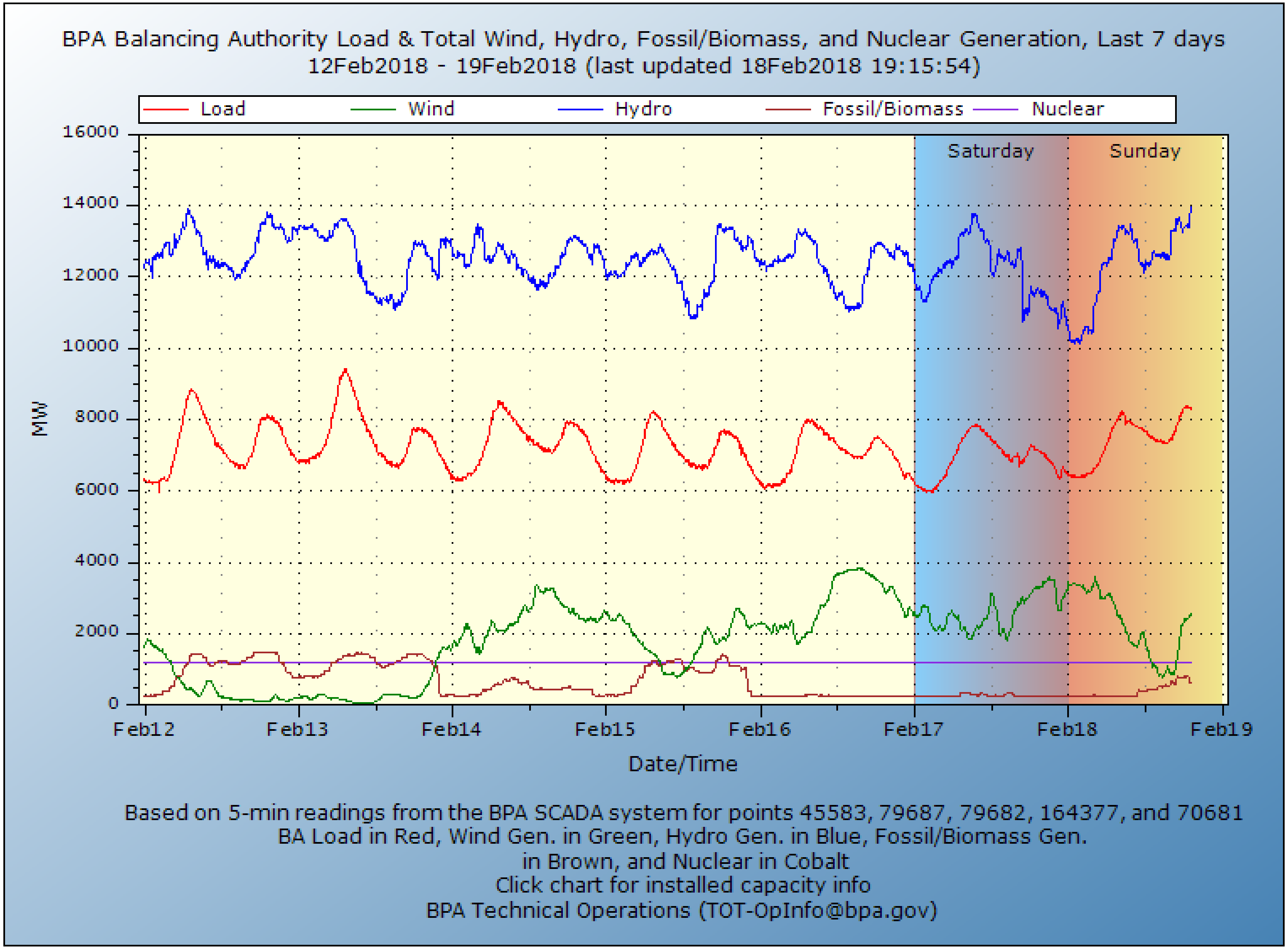
Hydro

Load

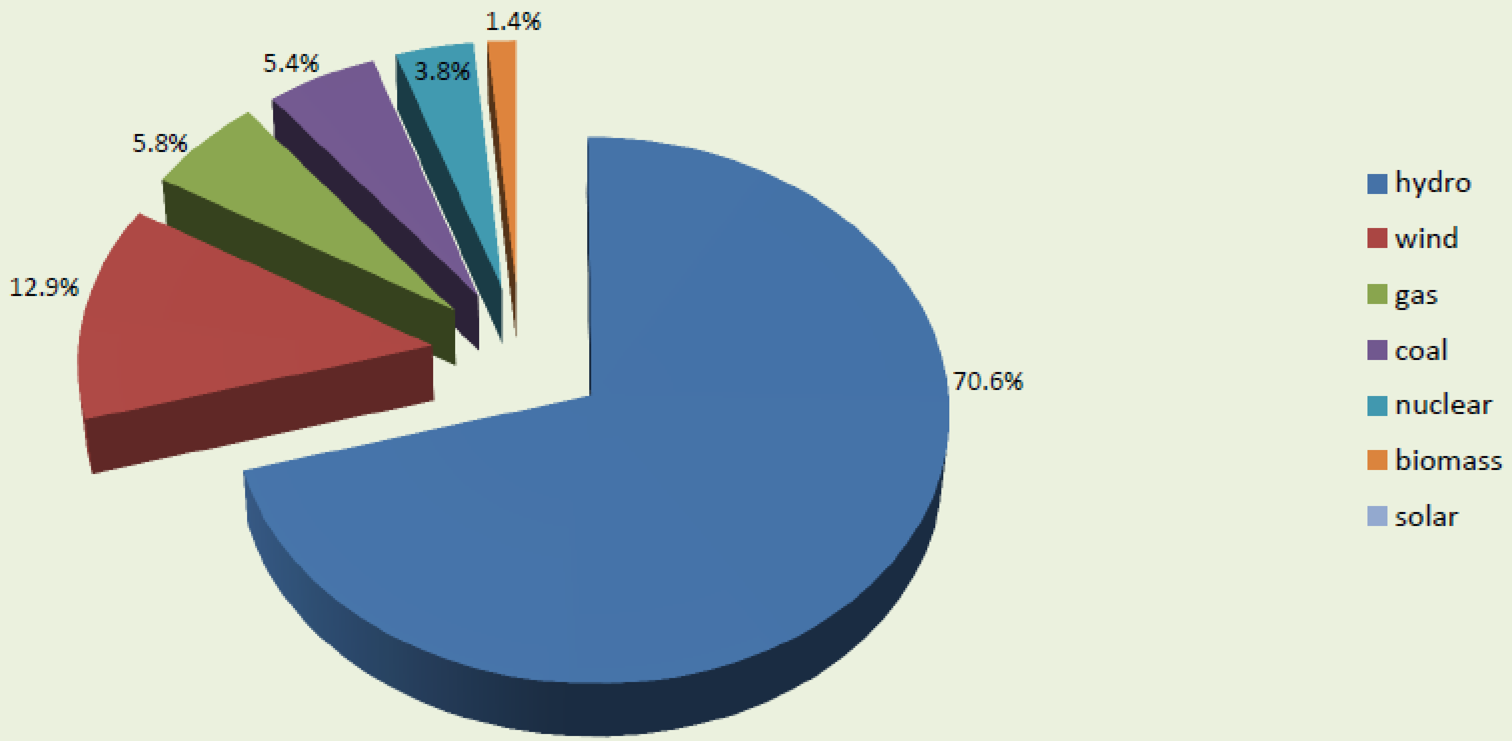
Wind

Nuclear

Thermal



Generation Capacity Within The BPA Balancing Authority Area, By Type

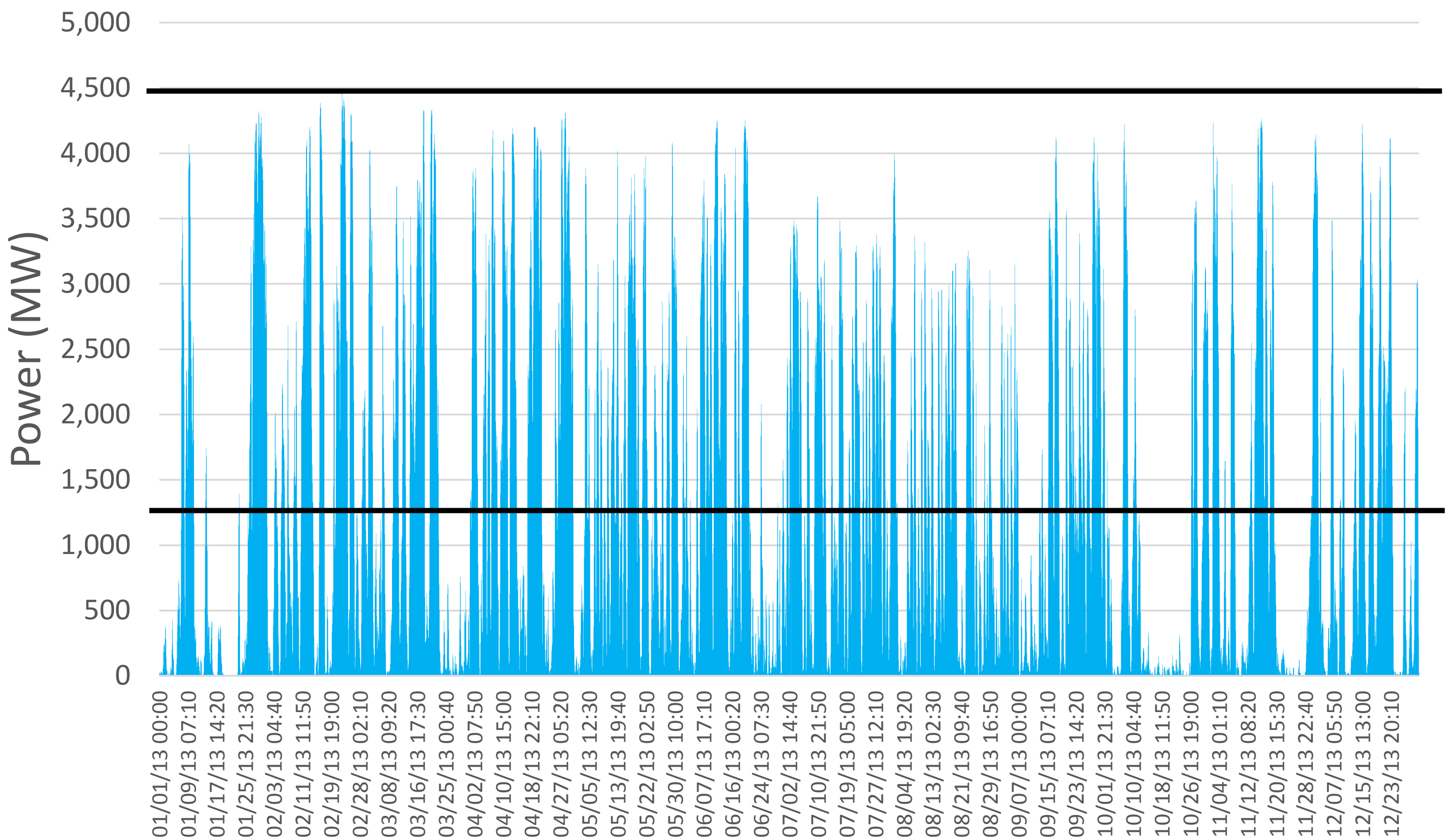


Total Nameplate Generation = 31434 MW, as of 14 December, 2017; BPA/Technical Operations/TOOC

Bonneville Power Administration
Wind Power Hourly Average
January 1 - December 31, 2013

maximum power
4,512 MW

average power
1,261 MW

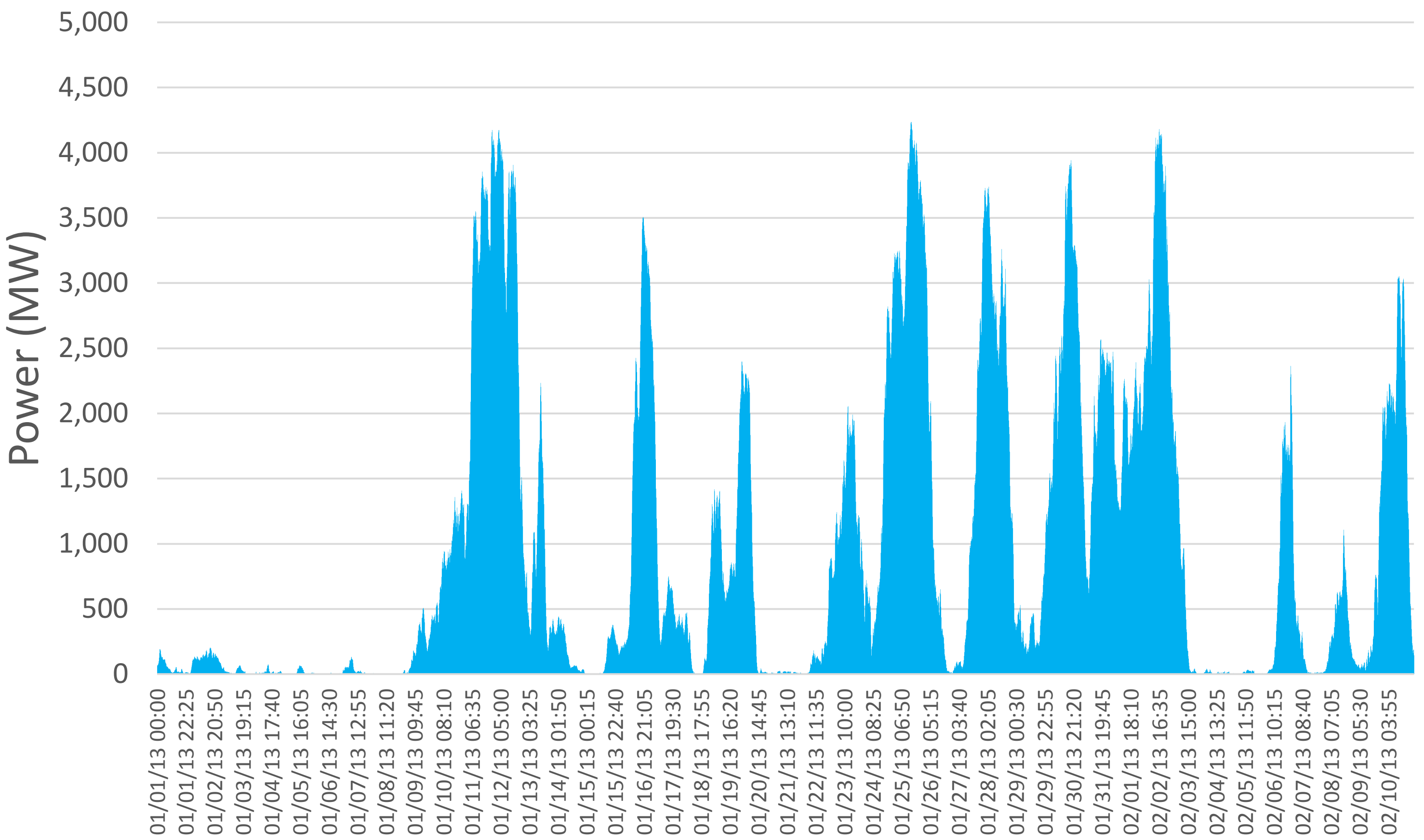


January 1

capacity factor =
1,261 MW /4,512 MW =
28%

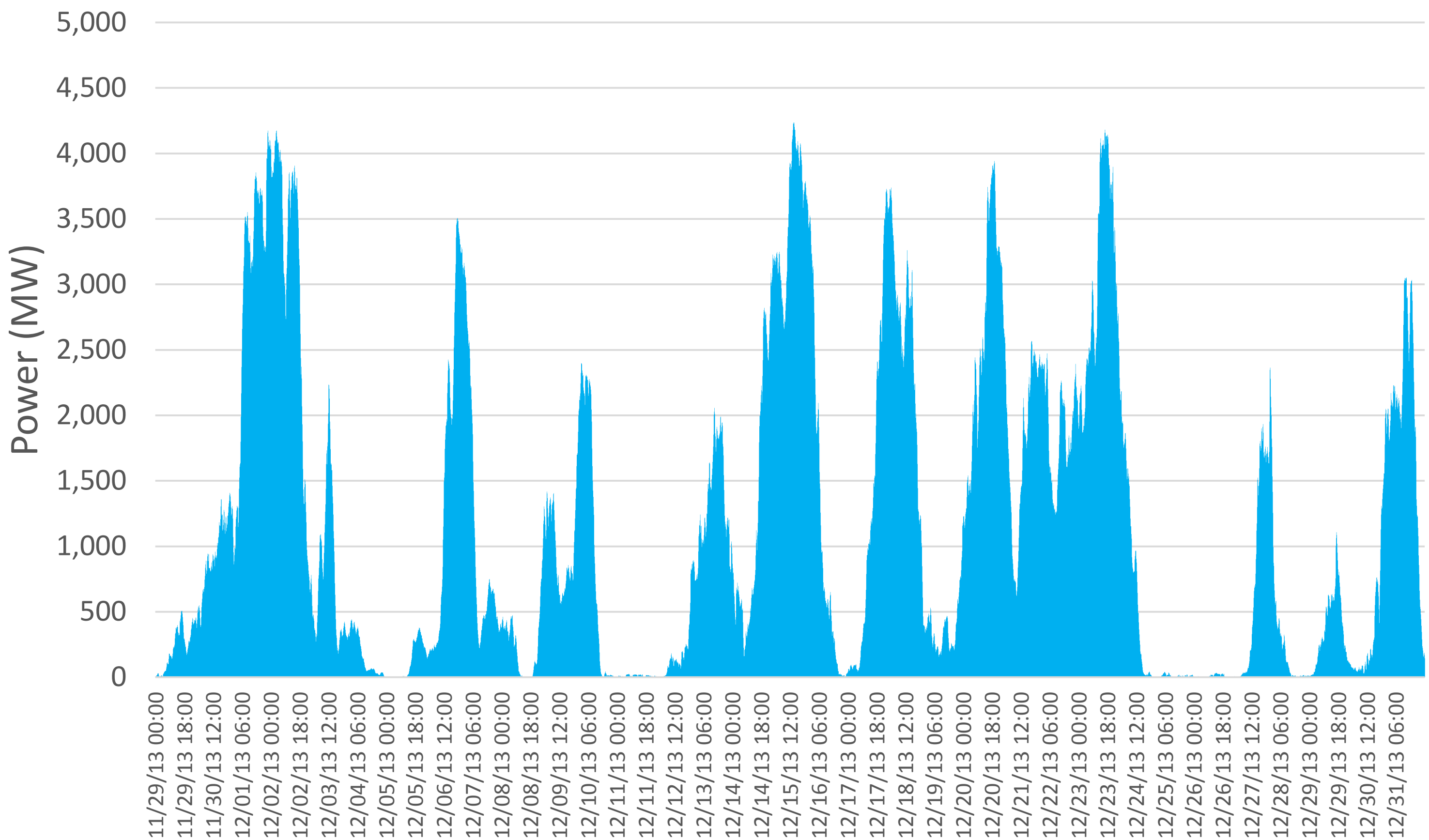
December 31

Bonneville Power Administration
Wind Power 5 Minute Average
January 1, 2013 - February 10, 2013



January 1 February 10

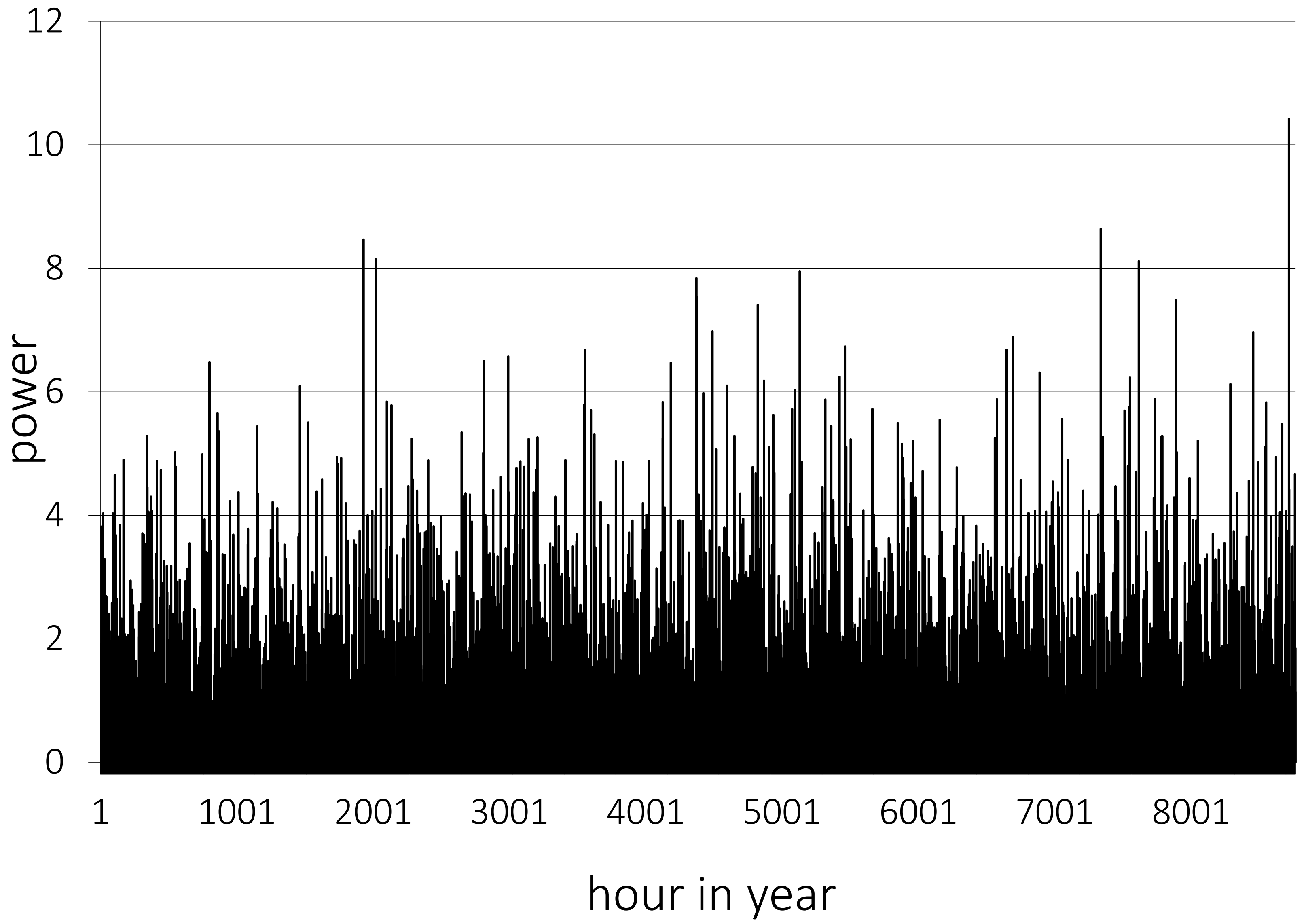
Bonneville Power Administration
Wind Power 5 Minute Average
November 29, 2013 - December 31, 2013

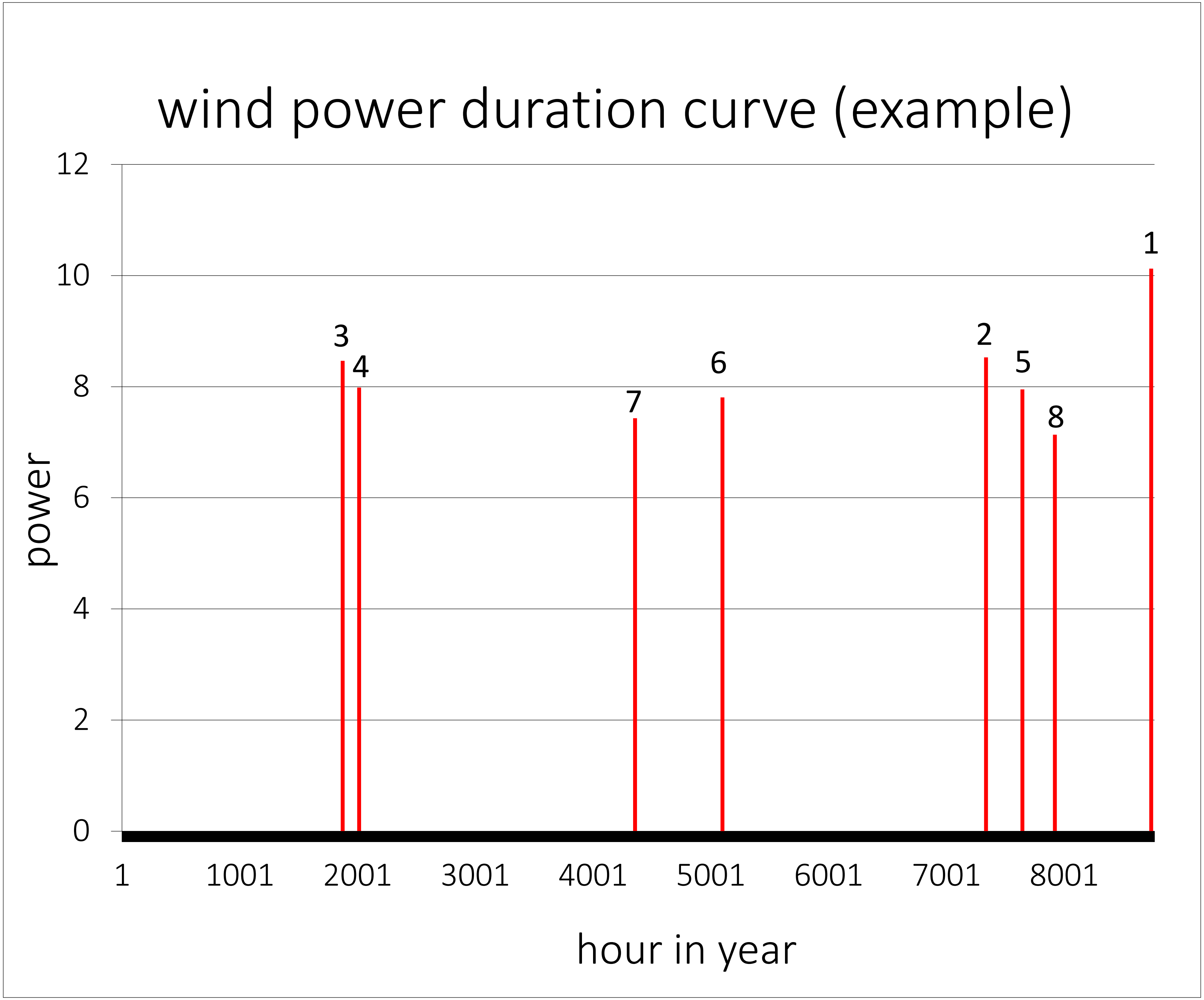


November 29 December 31

Wind Power Duration Curve Example

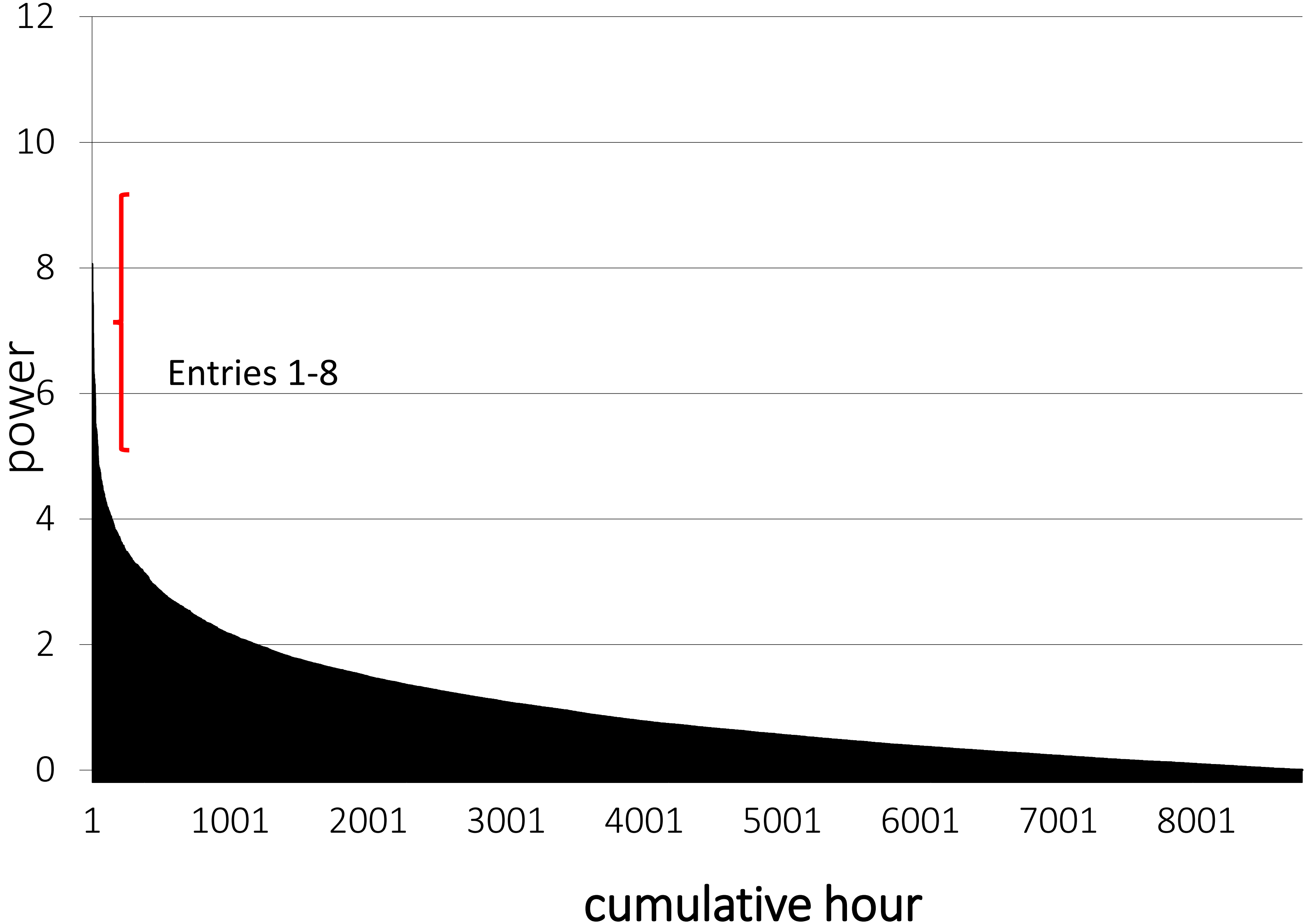
wind power duration curve (example)



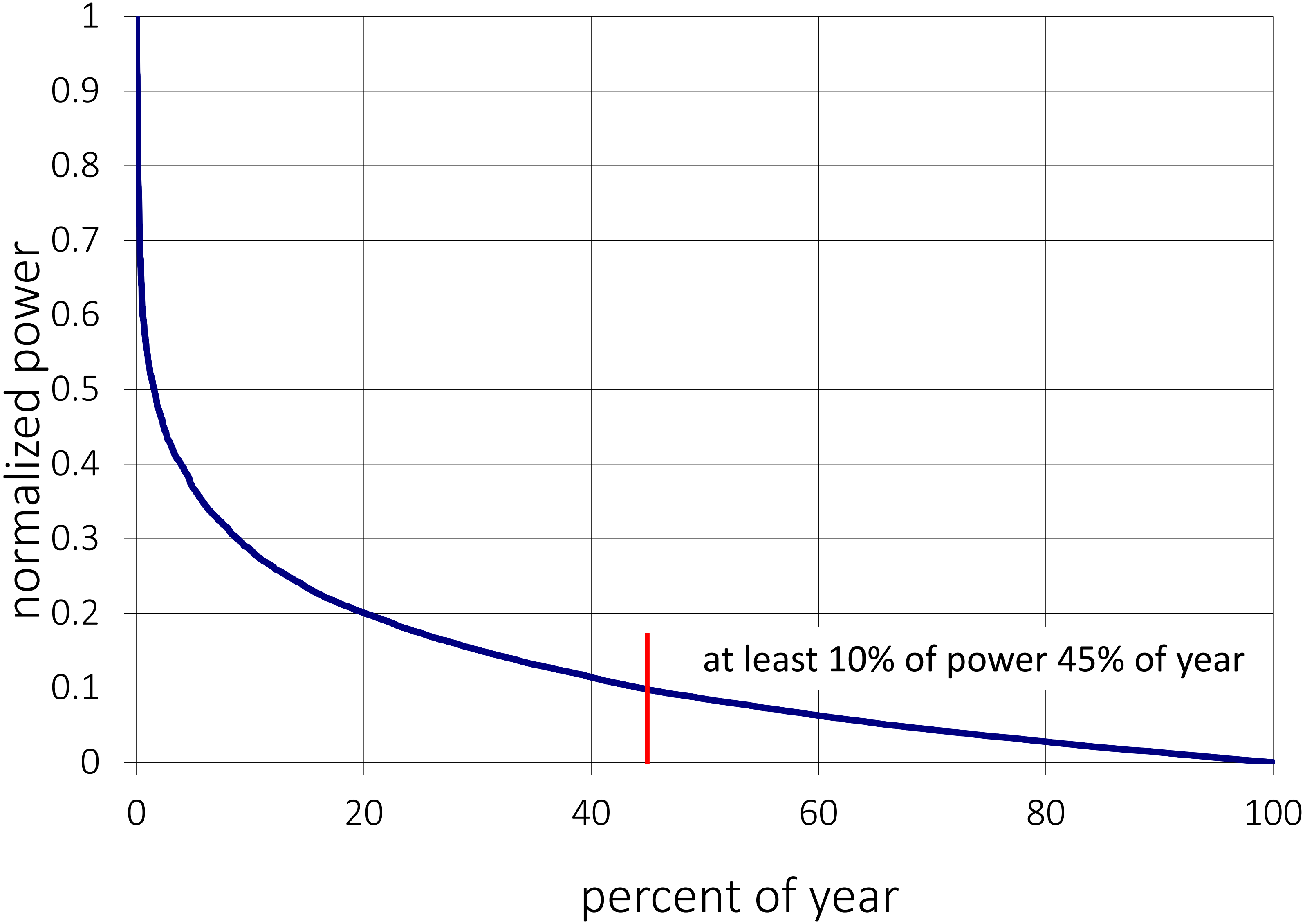


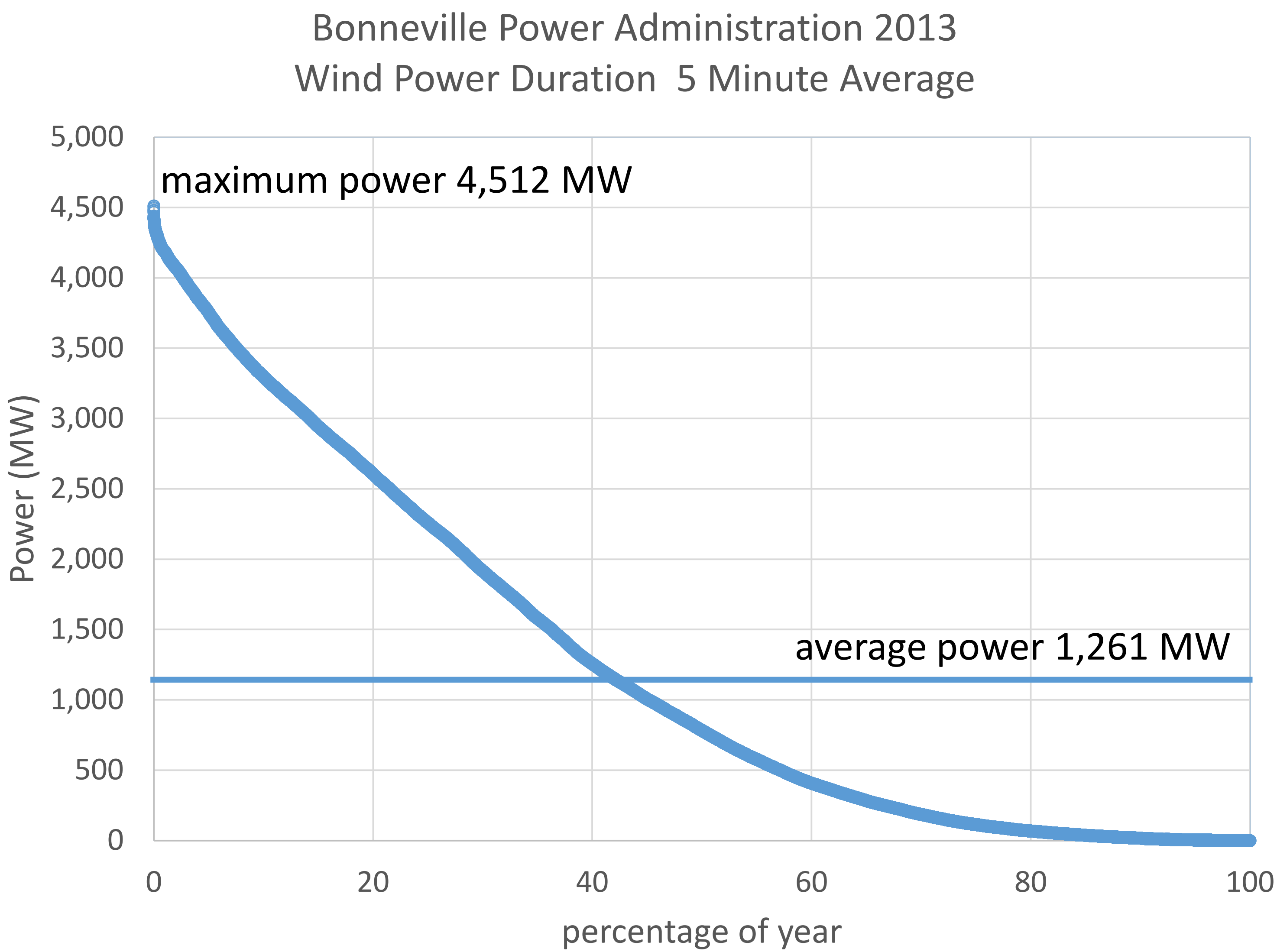
wind power duration curve (example)
12
10
8
6
4
2
0
power
1
1001
2001
3001
4001
5001
6001
7001
8001
hour in year
1
2
3
4
5
6
7
8

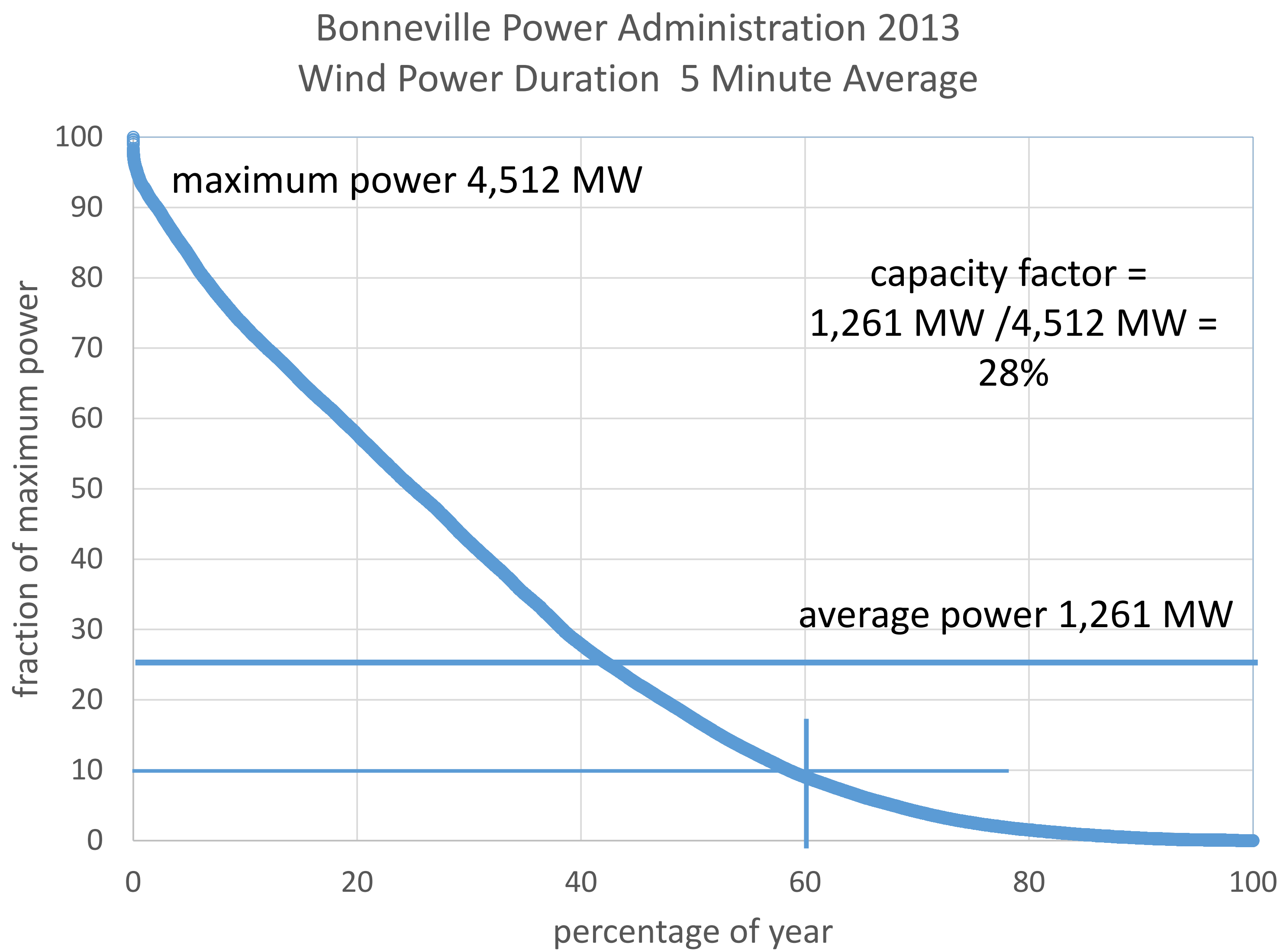
wind power duration curve (example)



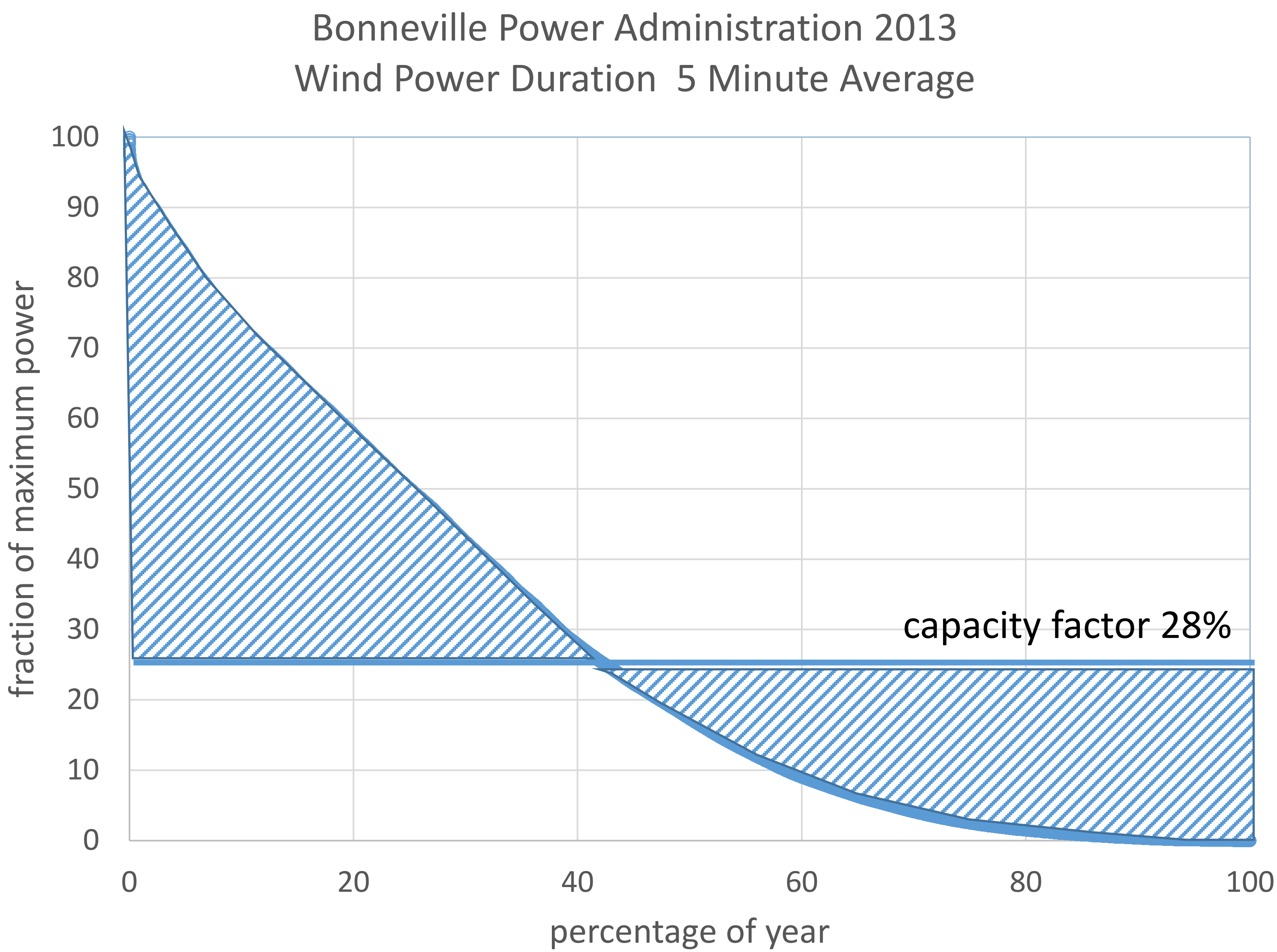
wind power duration curve (example)




Bonneville Power Administration 2013
Wind Power Duration 5 Minute Average
maximum power 4,512 MW
average power 1,261 MW
Power (MW)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
20
40
60
80
100
percentage of year



at least 10% of the capacity is available 60% of the year

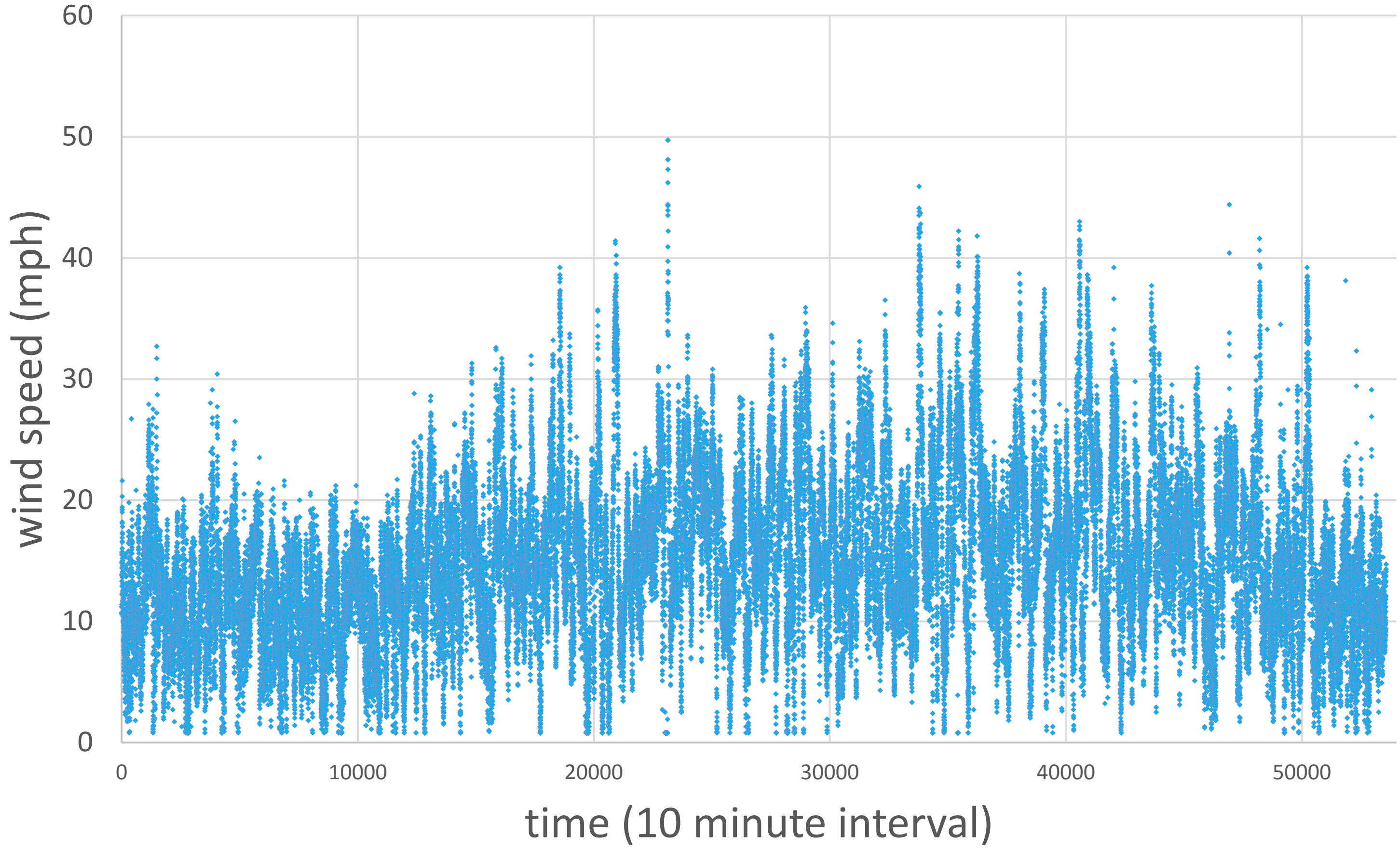


areas above and below average line are equal to 4,840 GWh

total generation = 11,050 GWh

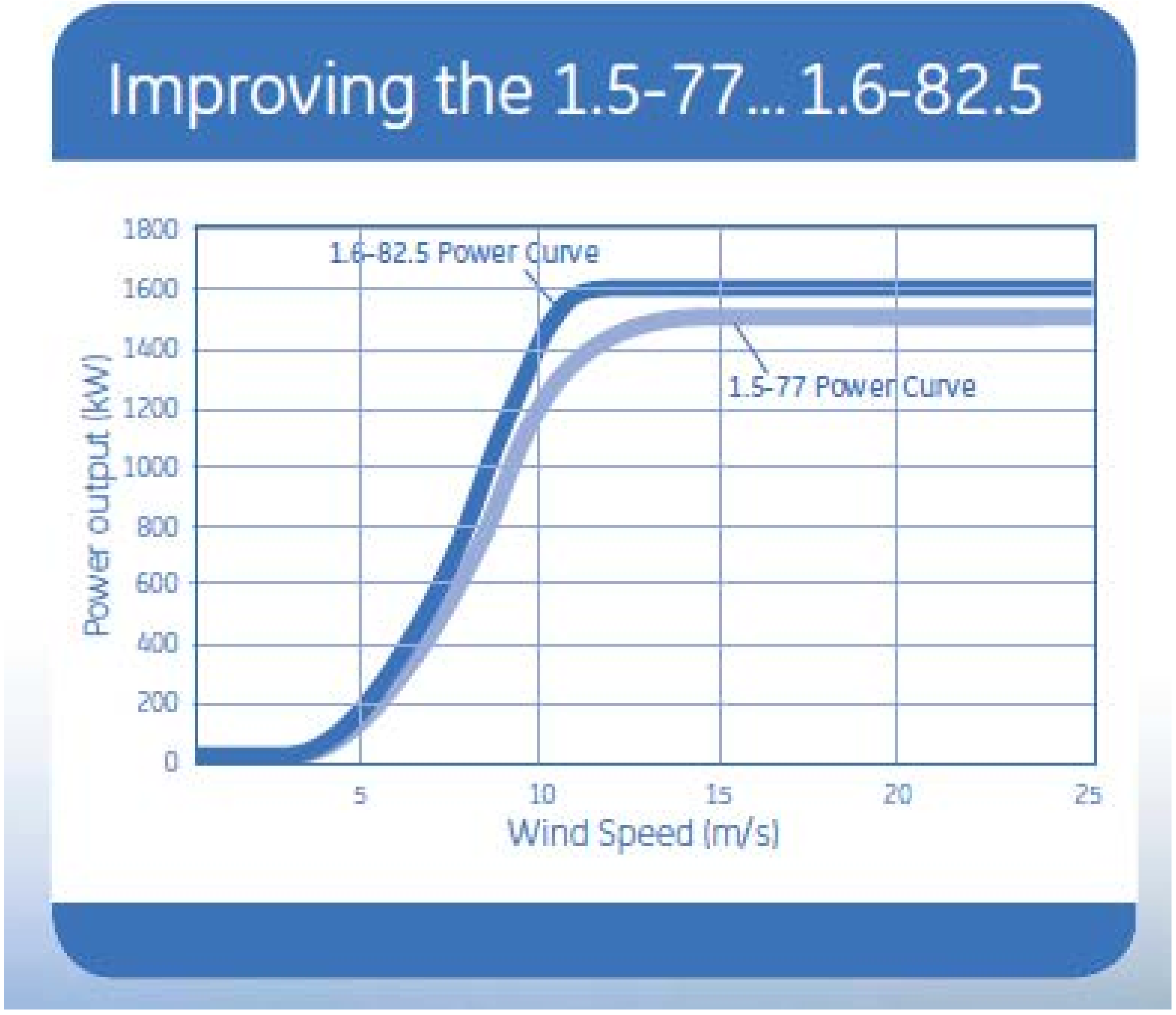
Champaign County Wind

Champaign County Wind Speed at 100m
July 2011 –June 2012

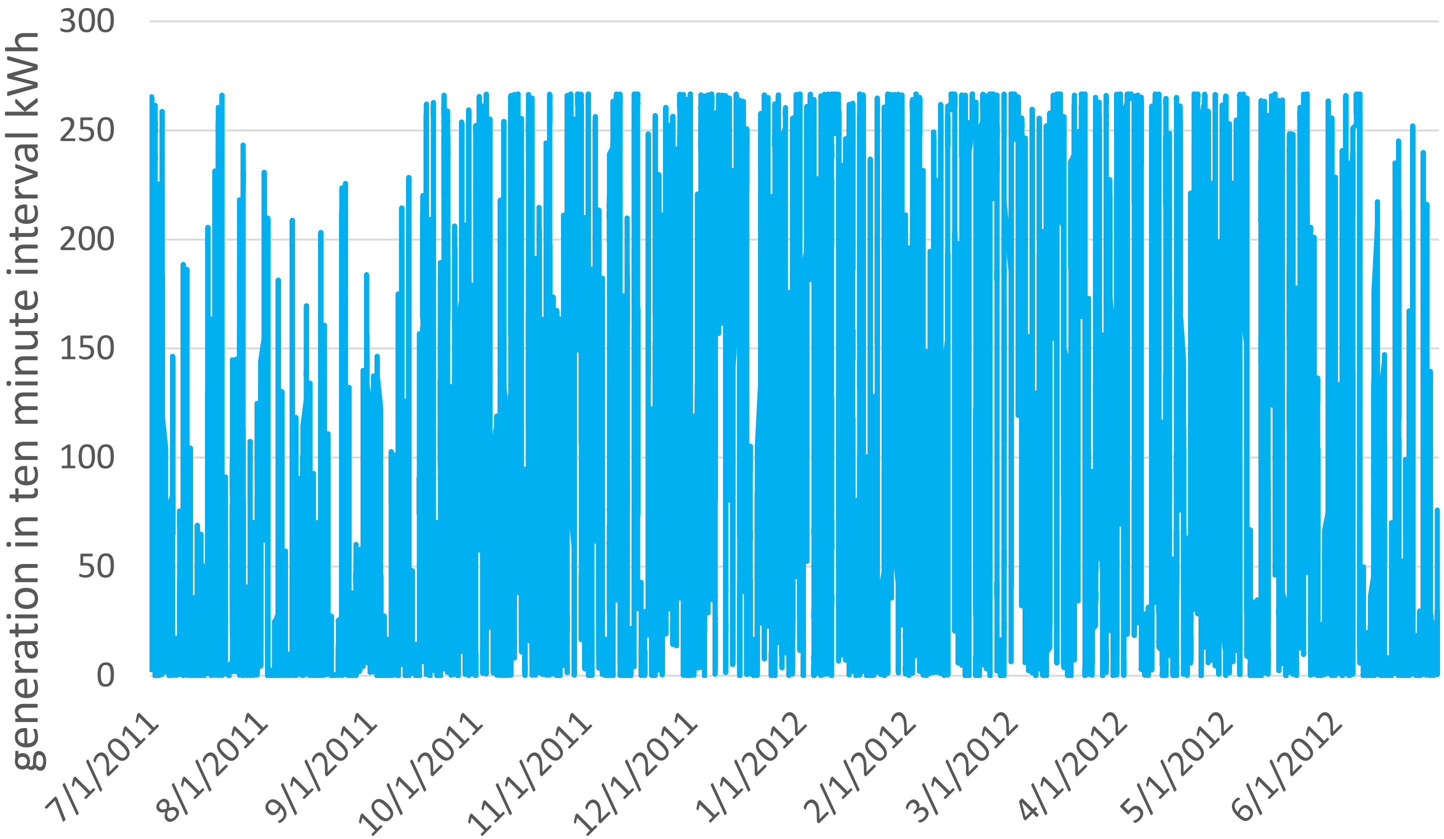


July 2011 June 2012

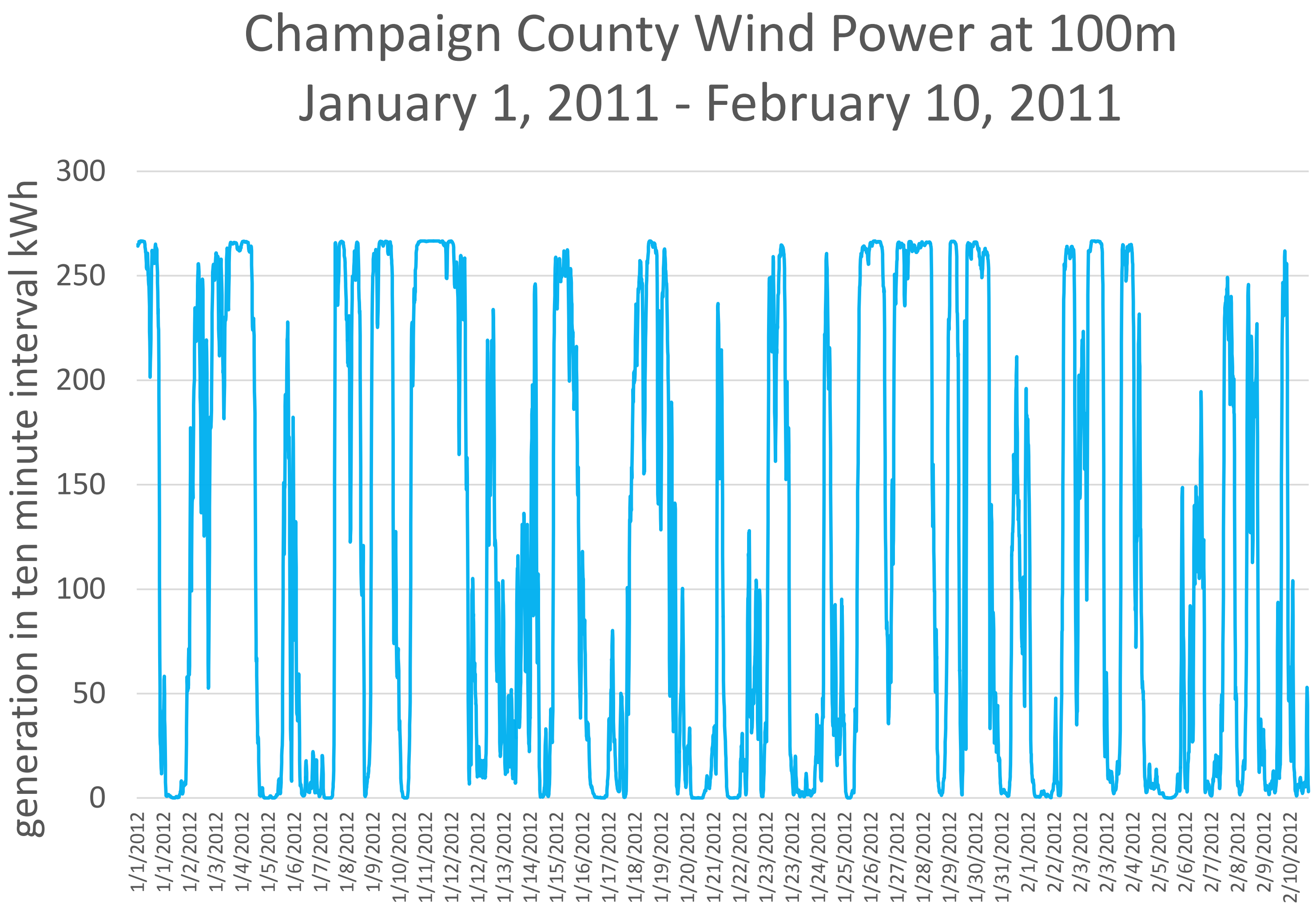
GE 1.5-77 1.6-82.5 Turbine Power Curve



Champaign County Wind Power July 2011 –June 2012

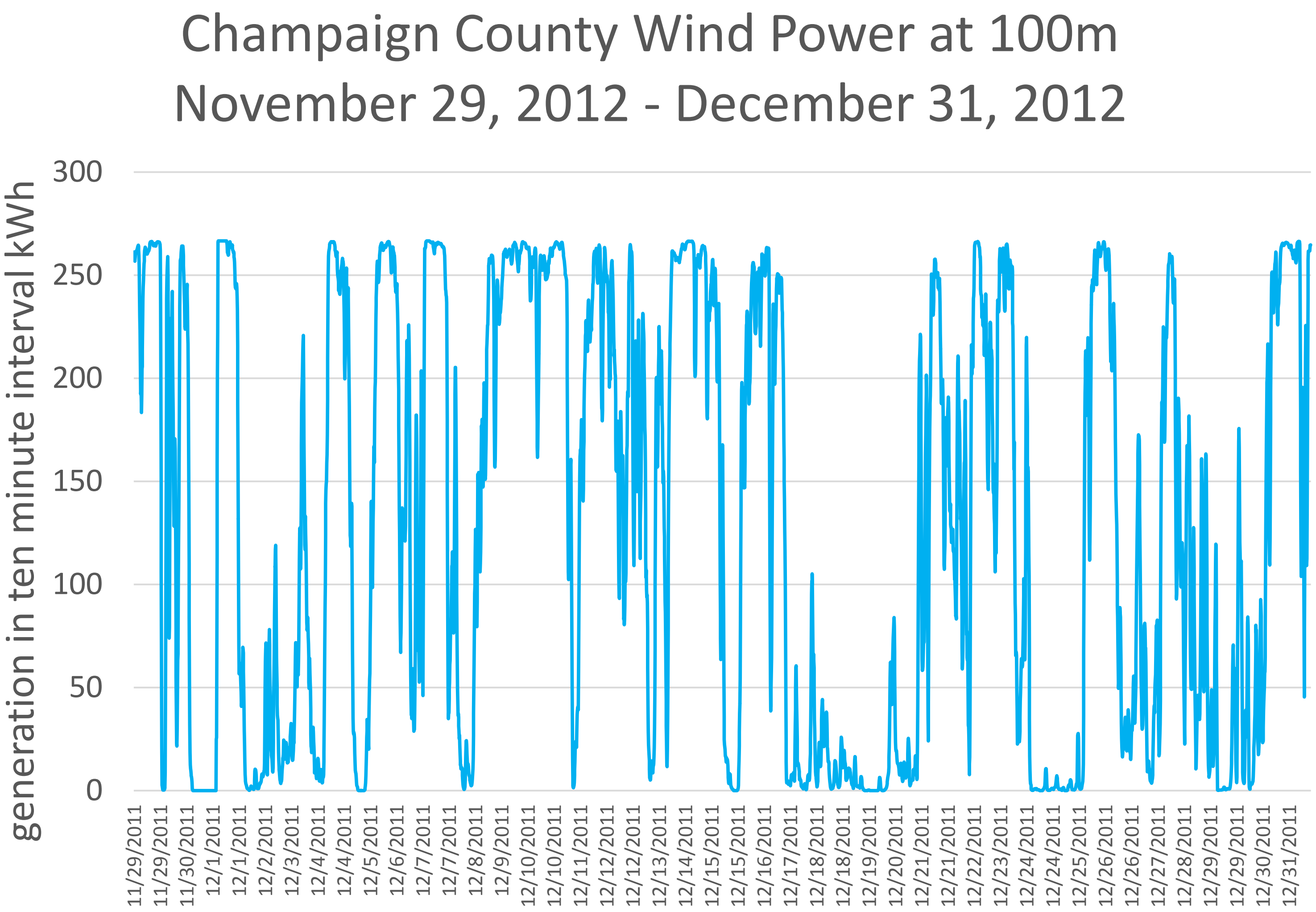


July 2011 June 2012

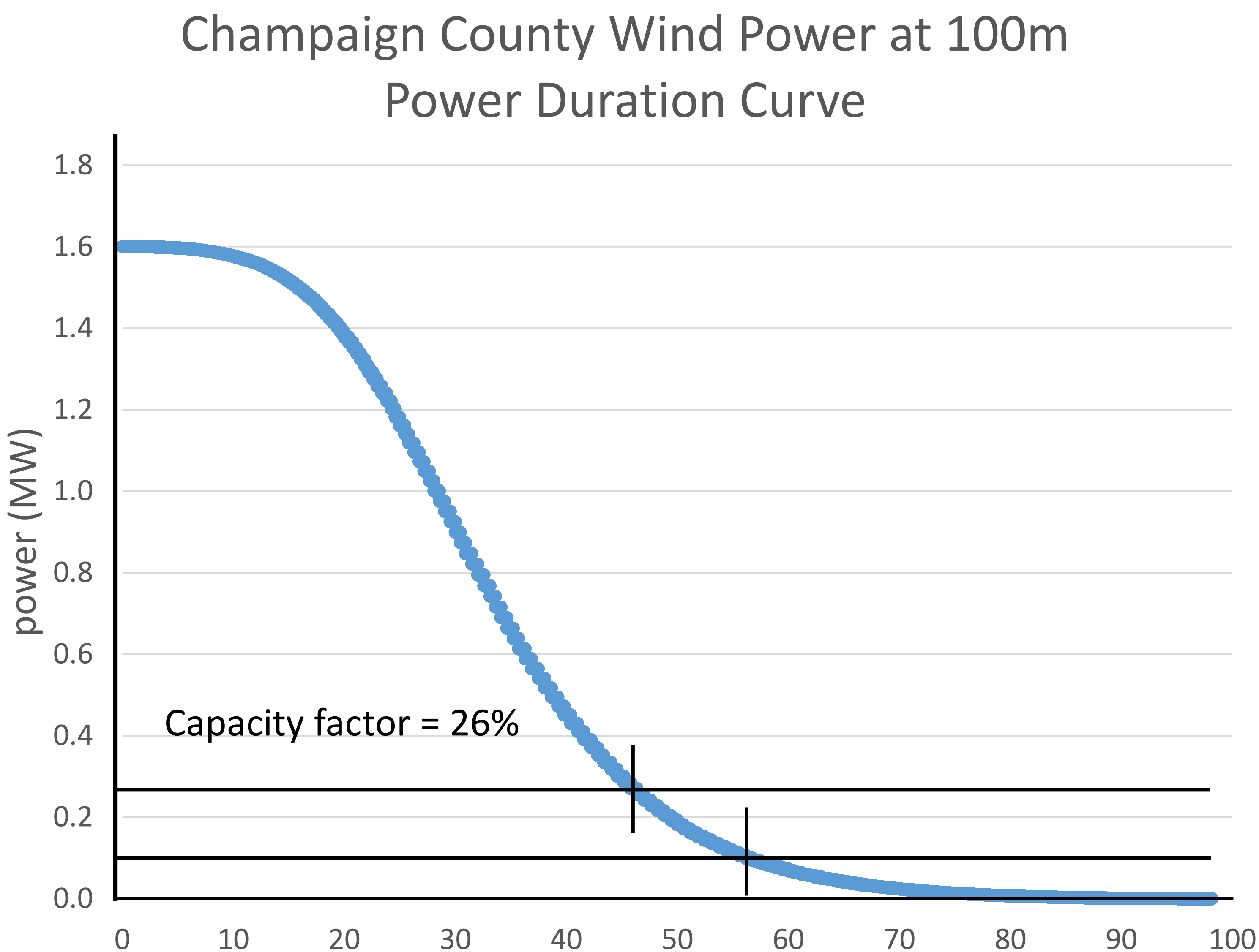


January 1

February 10



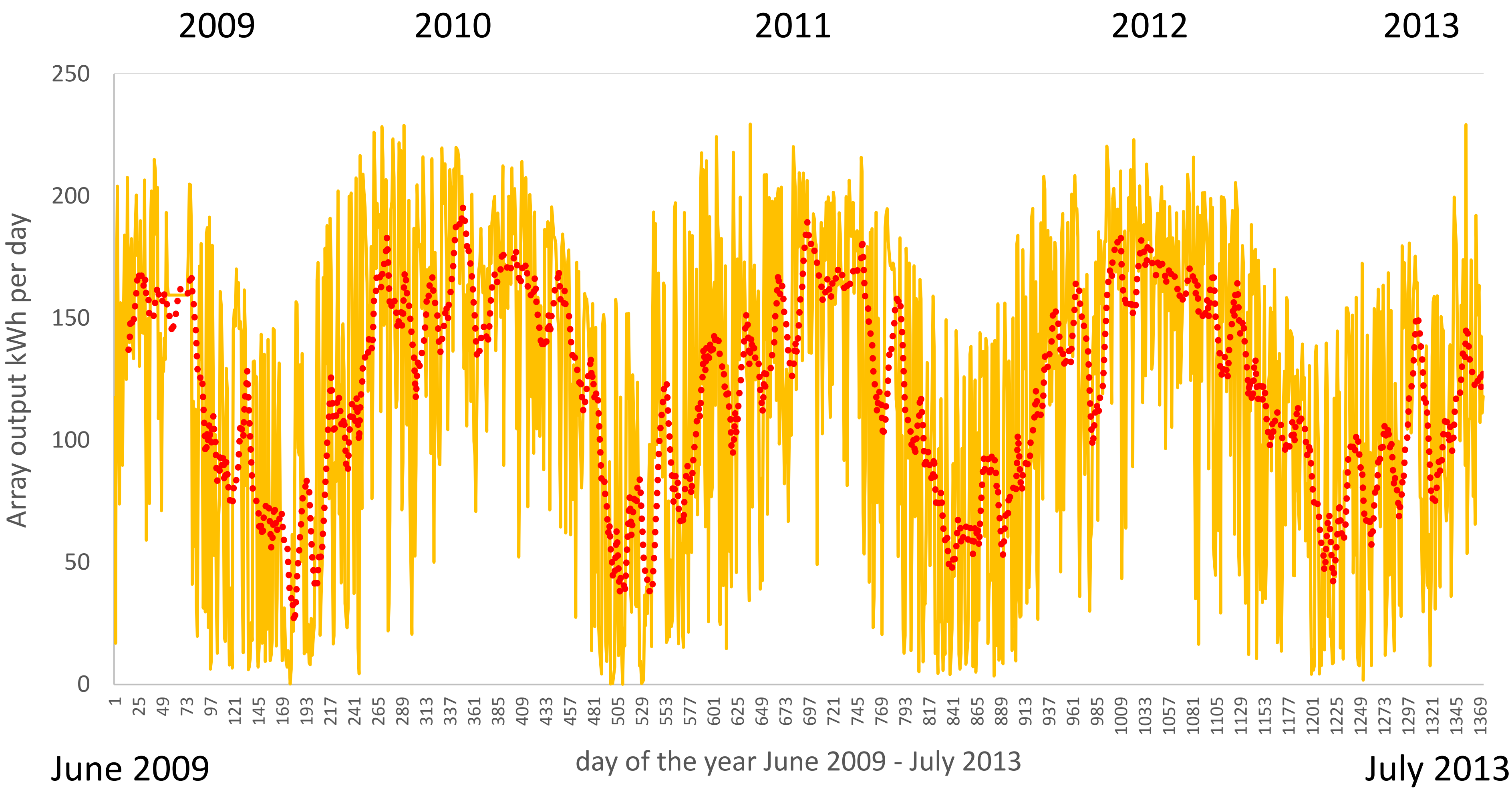
November 29 December 31



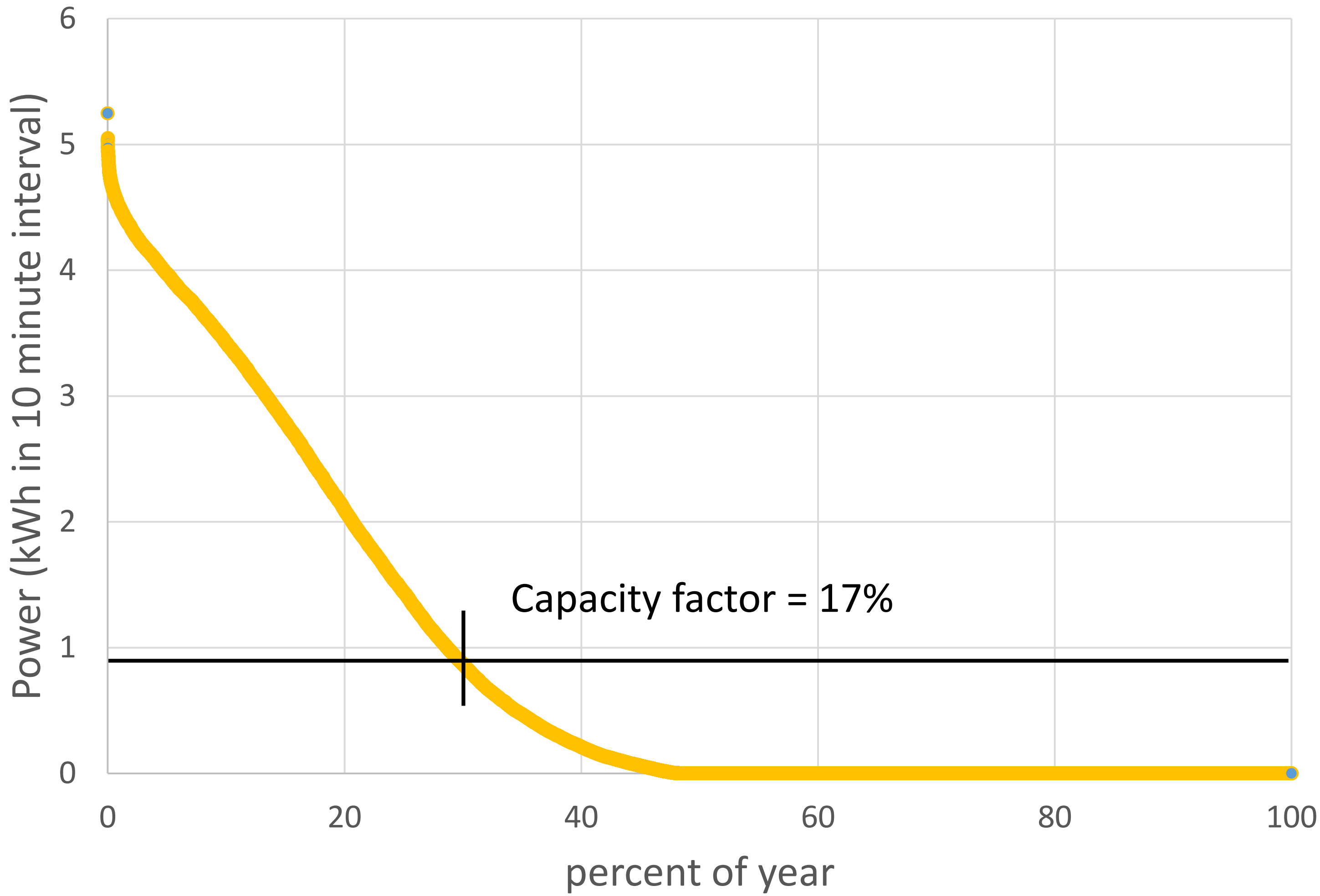
At least 10% of capacity available 55% of the year

Champaign County Solar
Gies College of Business
Solar Panel Array

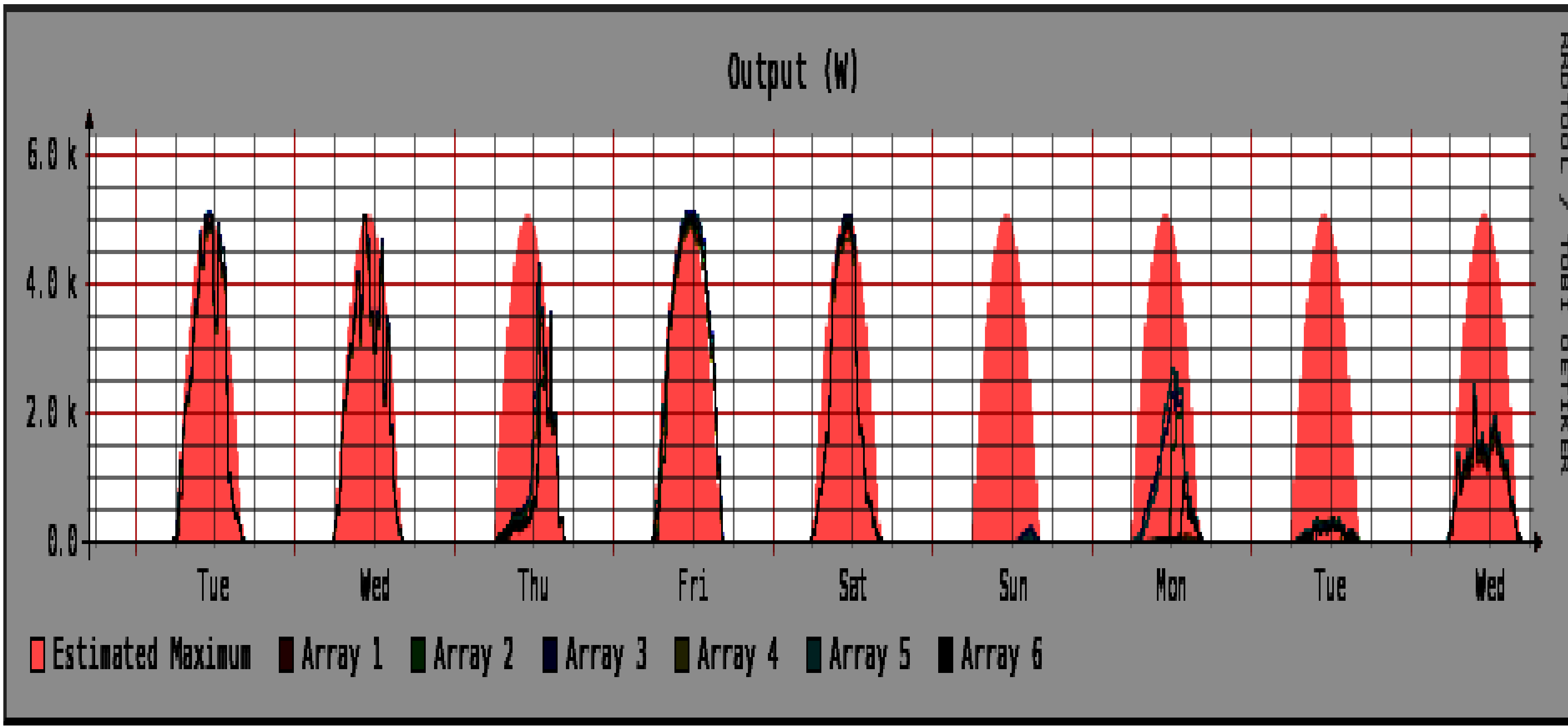
Gies College of Business
Solar Panel Array Four Year History
June 2009 – July 2013



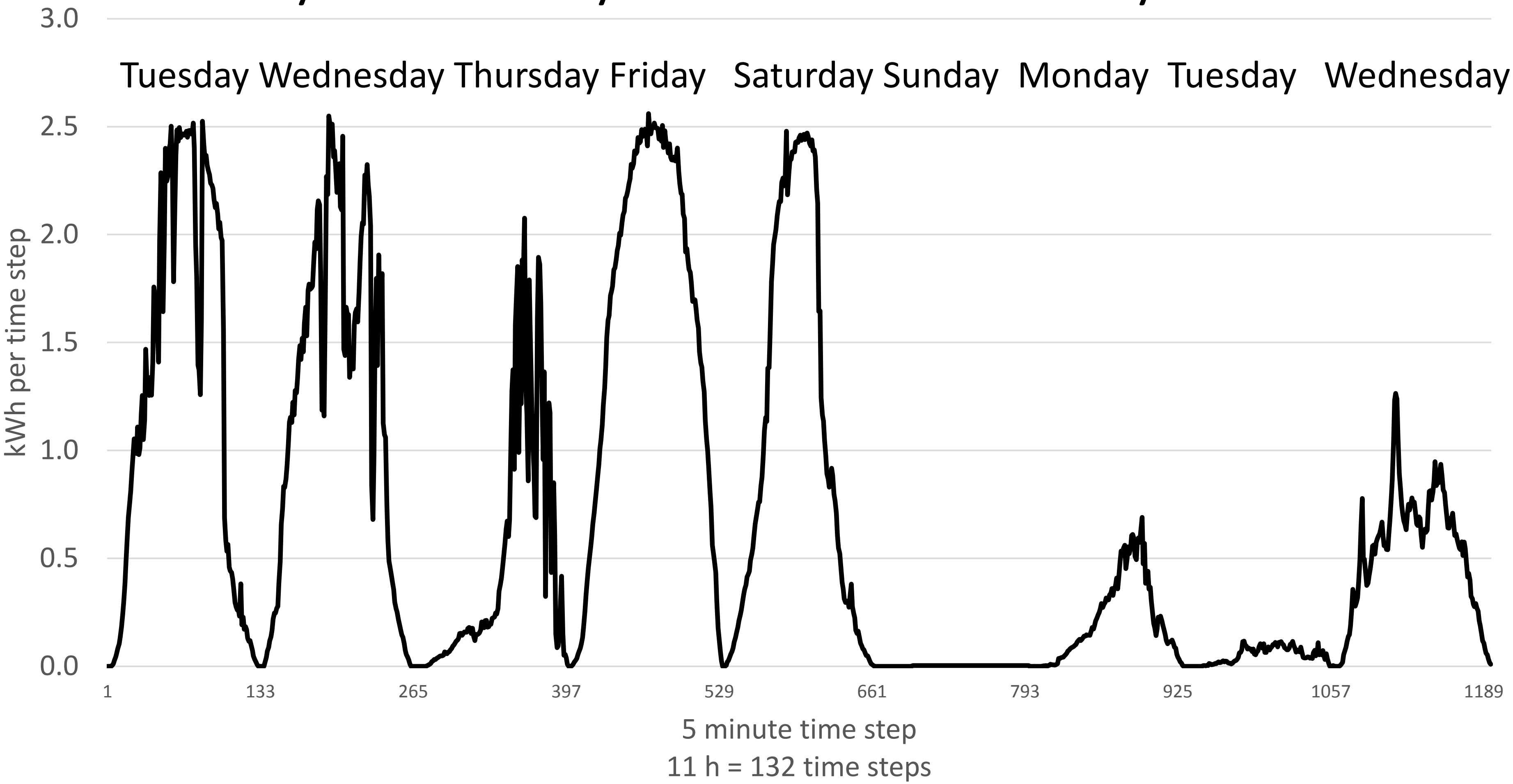
Gies College of Business
Power Duration



Gies College of Business
Single Solar Panel Array (one of six)
Tuesday February 24, 2015 – Wednesday March 4, 2015

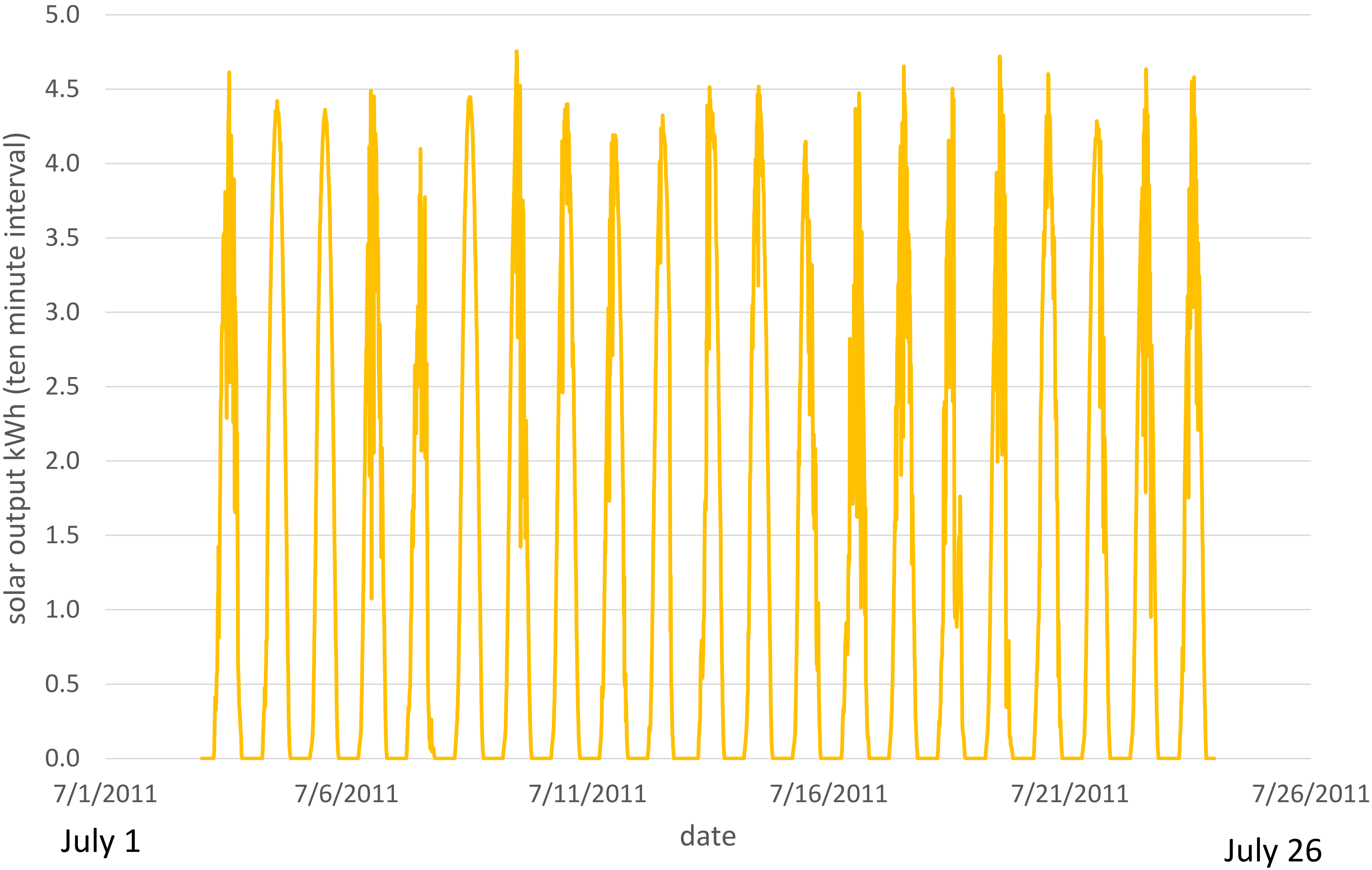


Gies College of Business
Single Solar Panel Array Output
Tuesday February 24 – Wednesday March 4



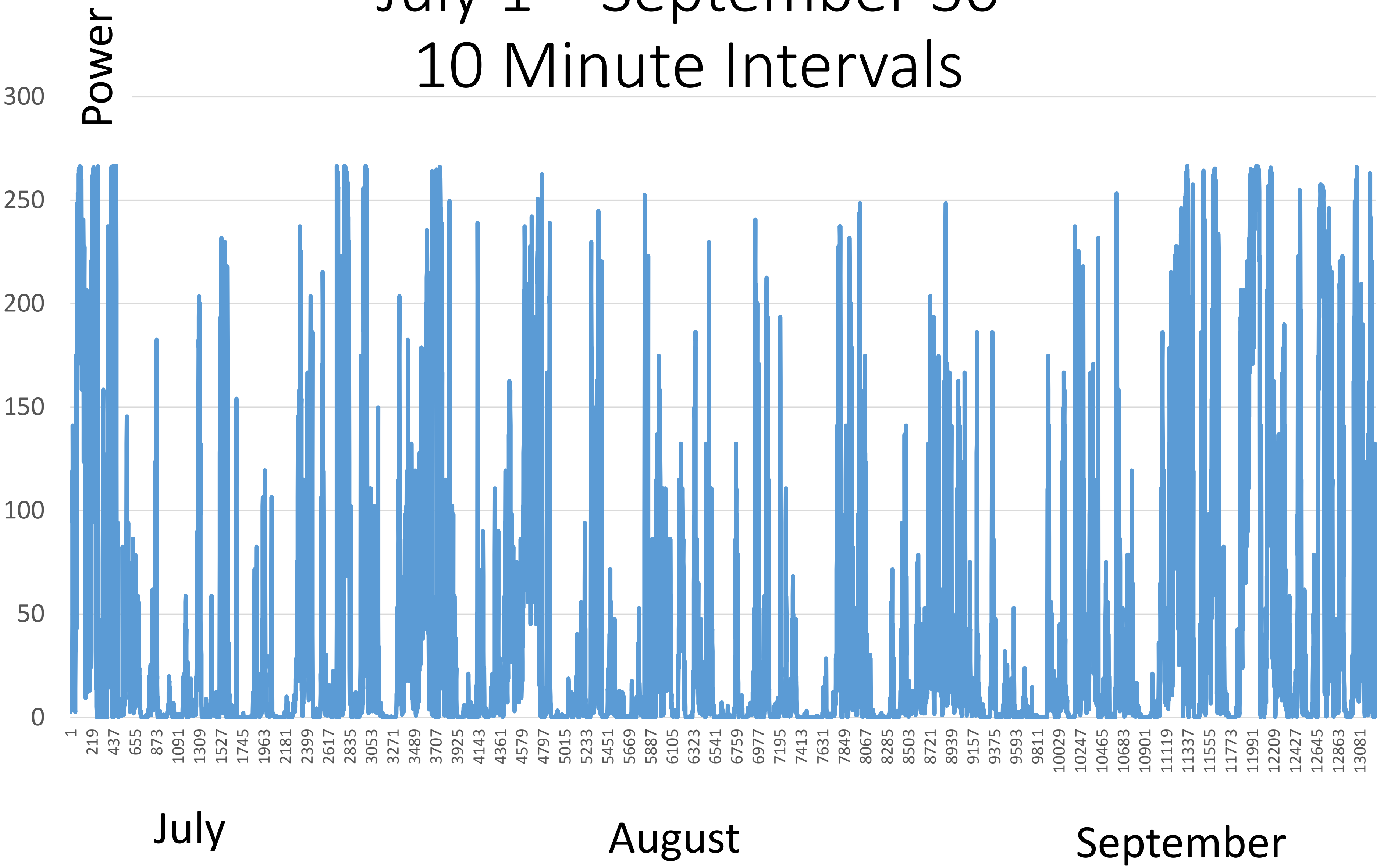
Friday, February 27 was a good day. Sunday, March 1 was not sunny.

Gies College of Business Solar Panels "Best Weeks"

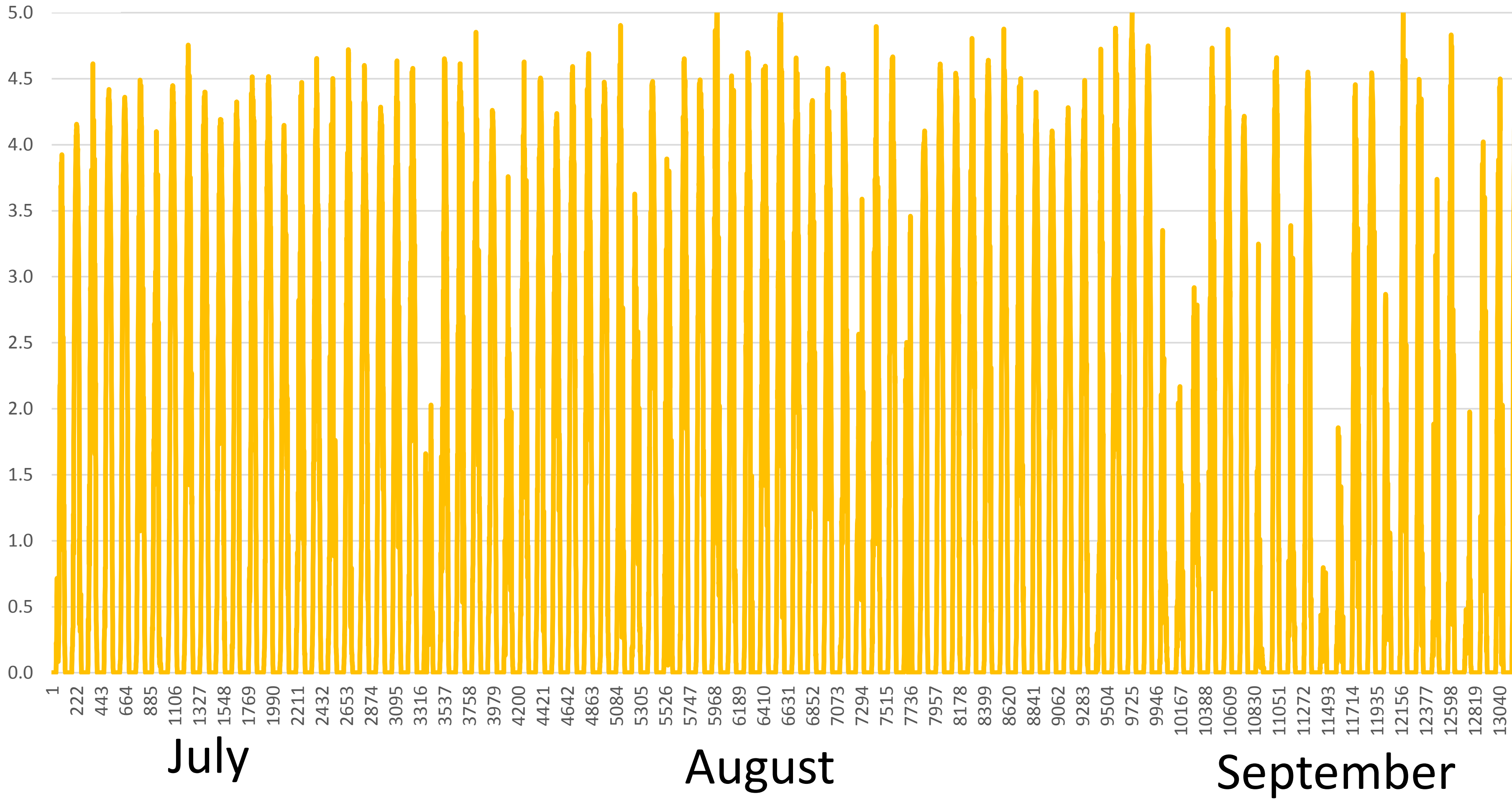


Wind Plus Solar

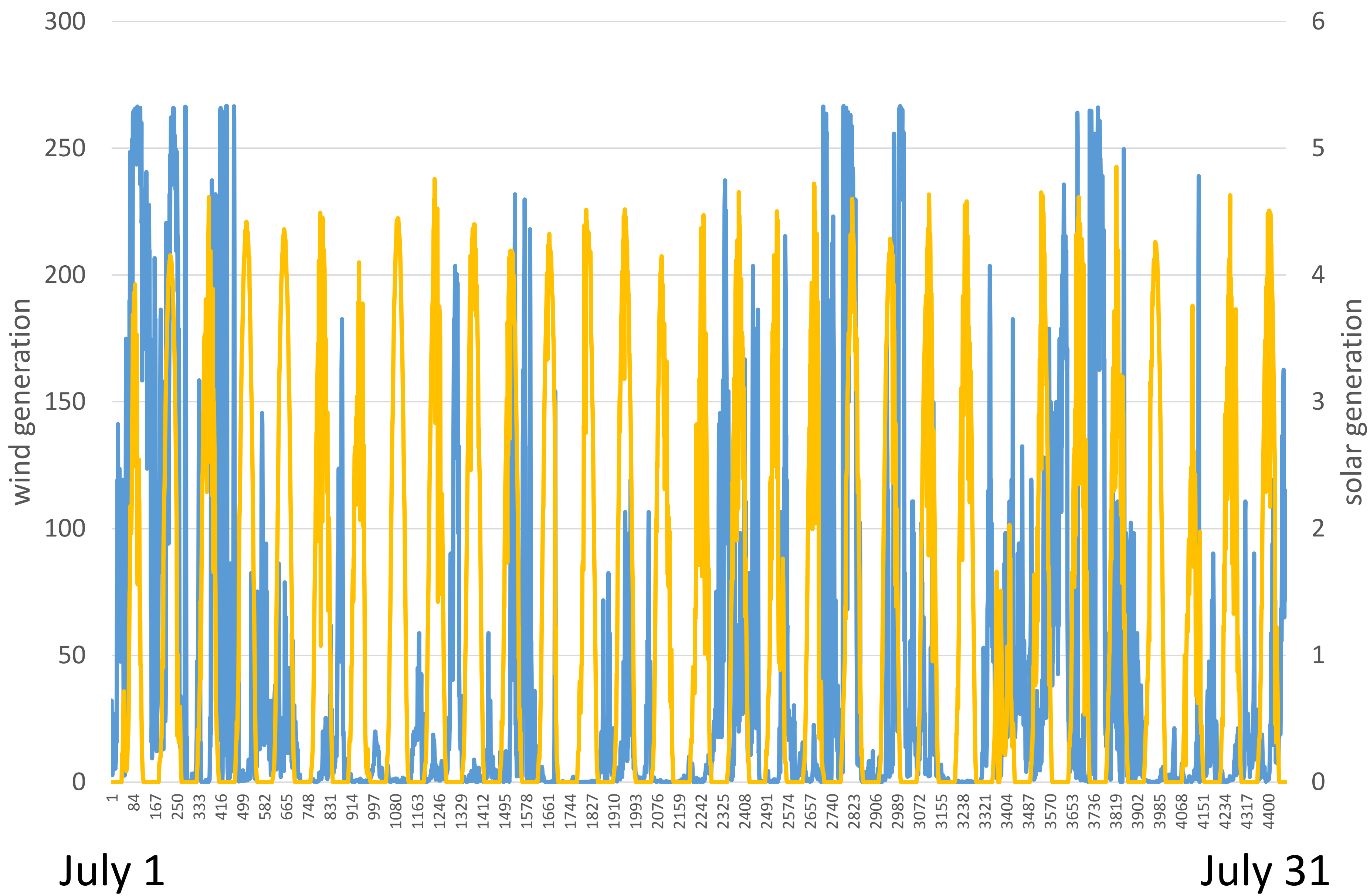
Wind Power Generation Champaign County July 1 – September 30 10 Minute Intervals



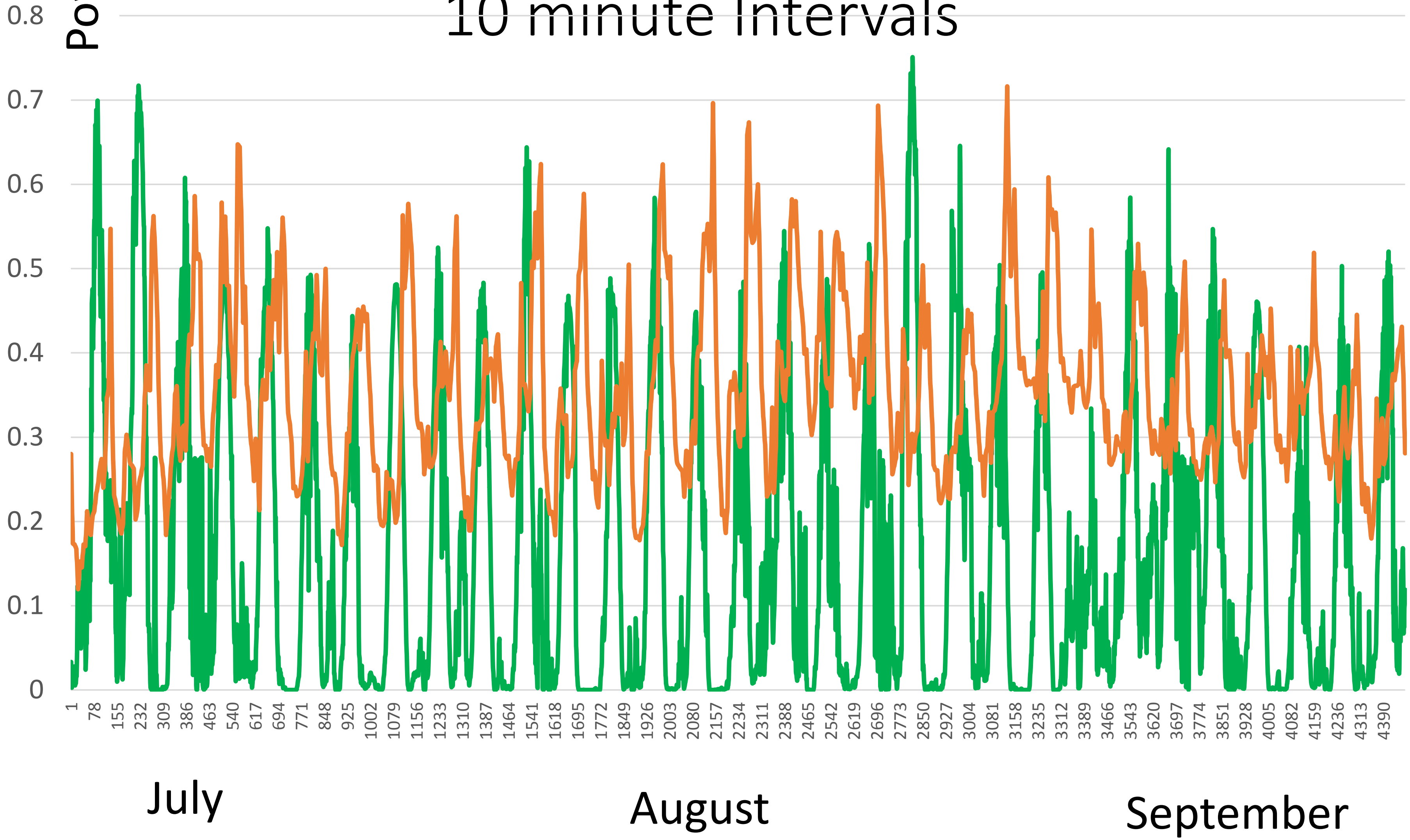
Solar Power Generation
Gies College of Business
July 1 – September 30
10 minute intervals



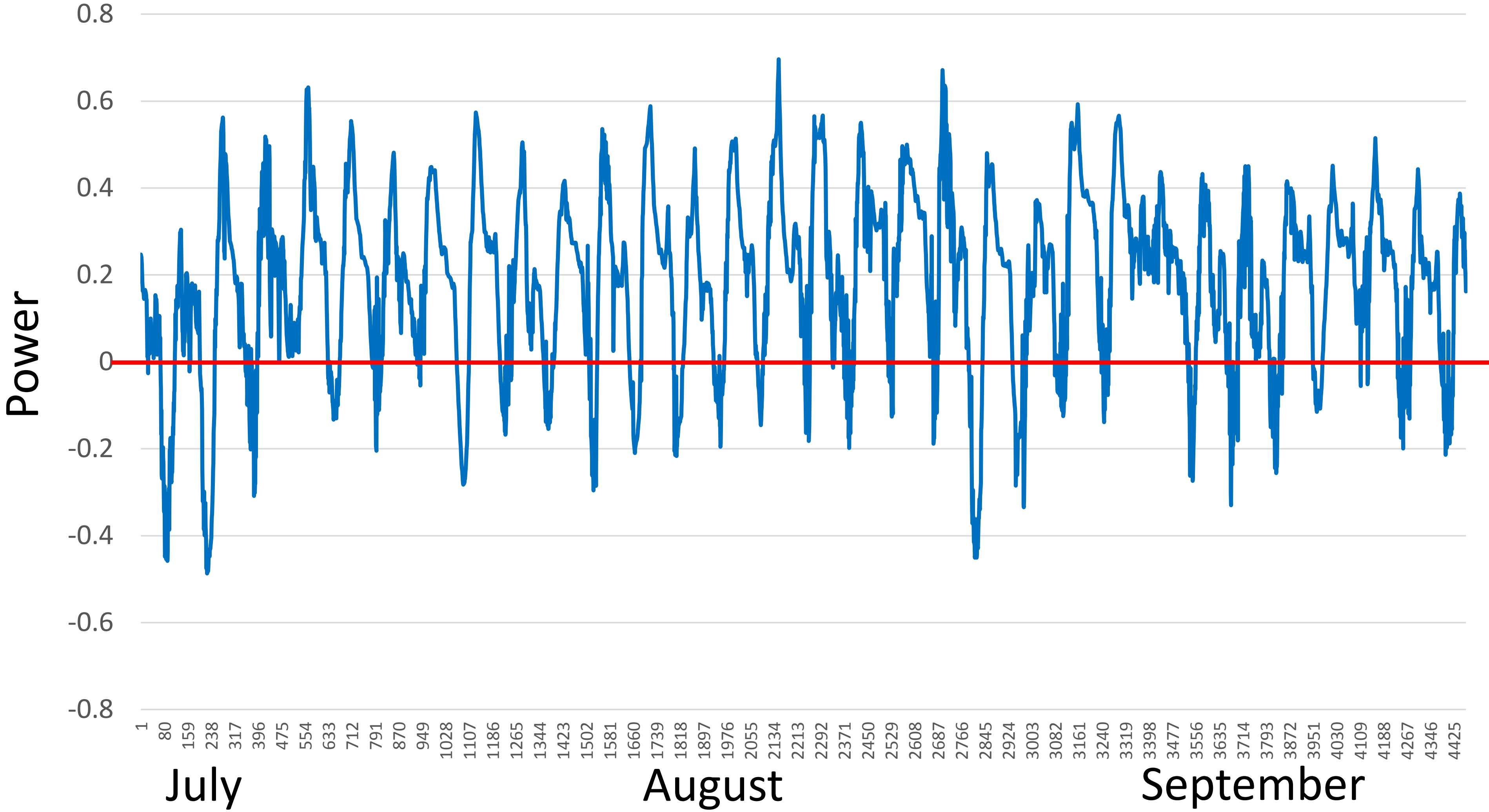
Champaign County July Wind and Gies July Solar



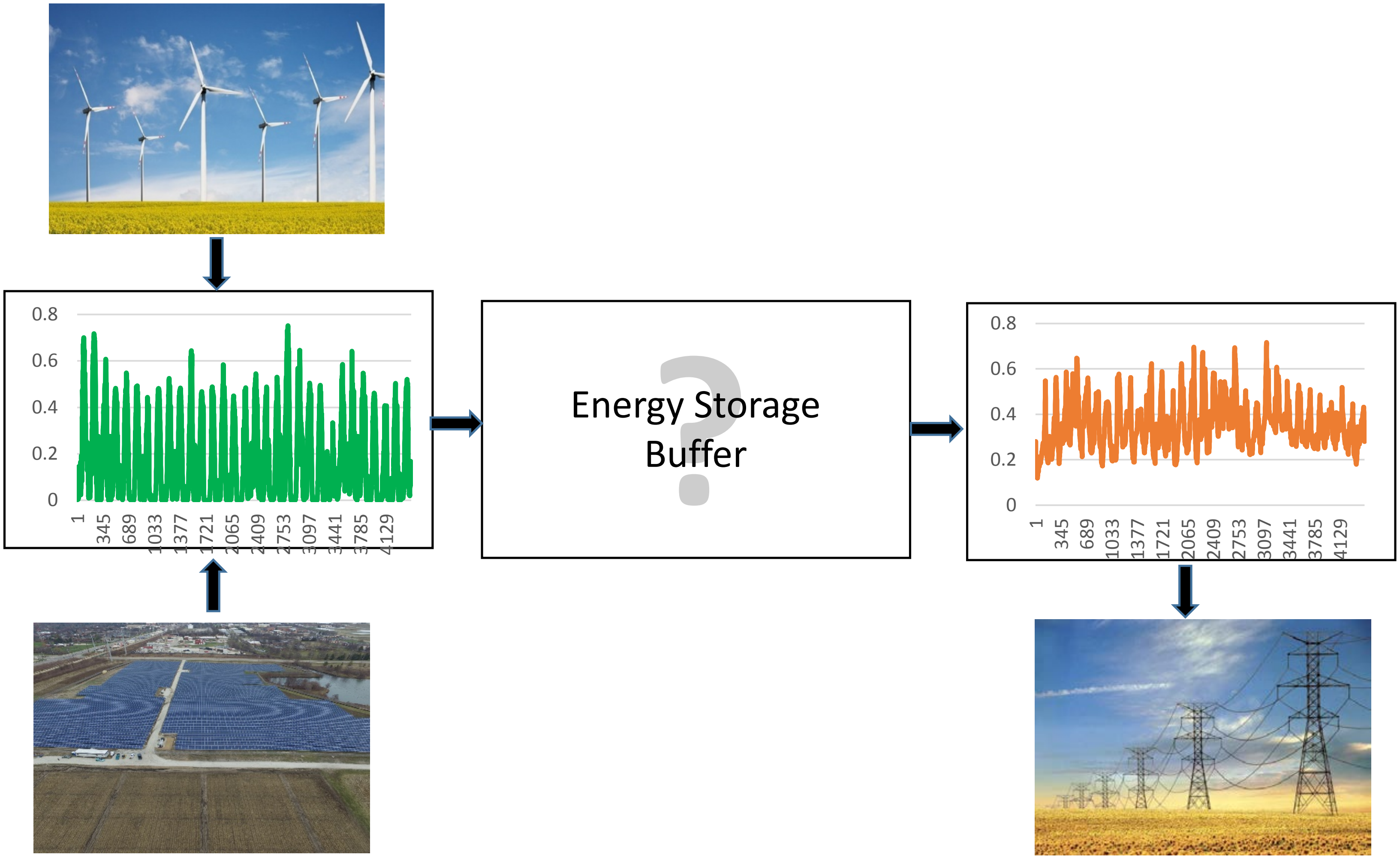
Normalized Wind + Solar Compared to Normalized Residential Load
July 1 – September 30
10 minute Intervals



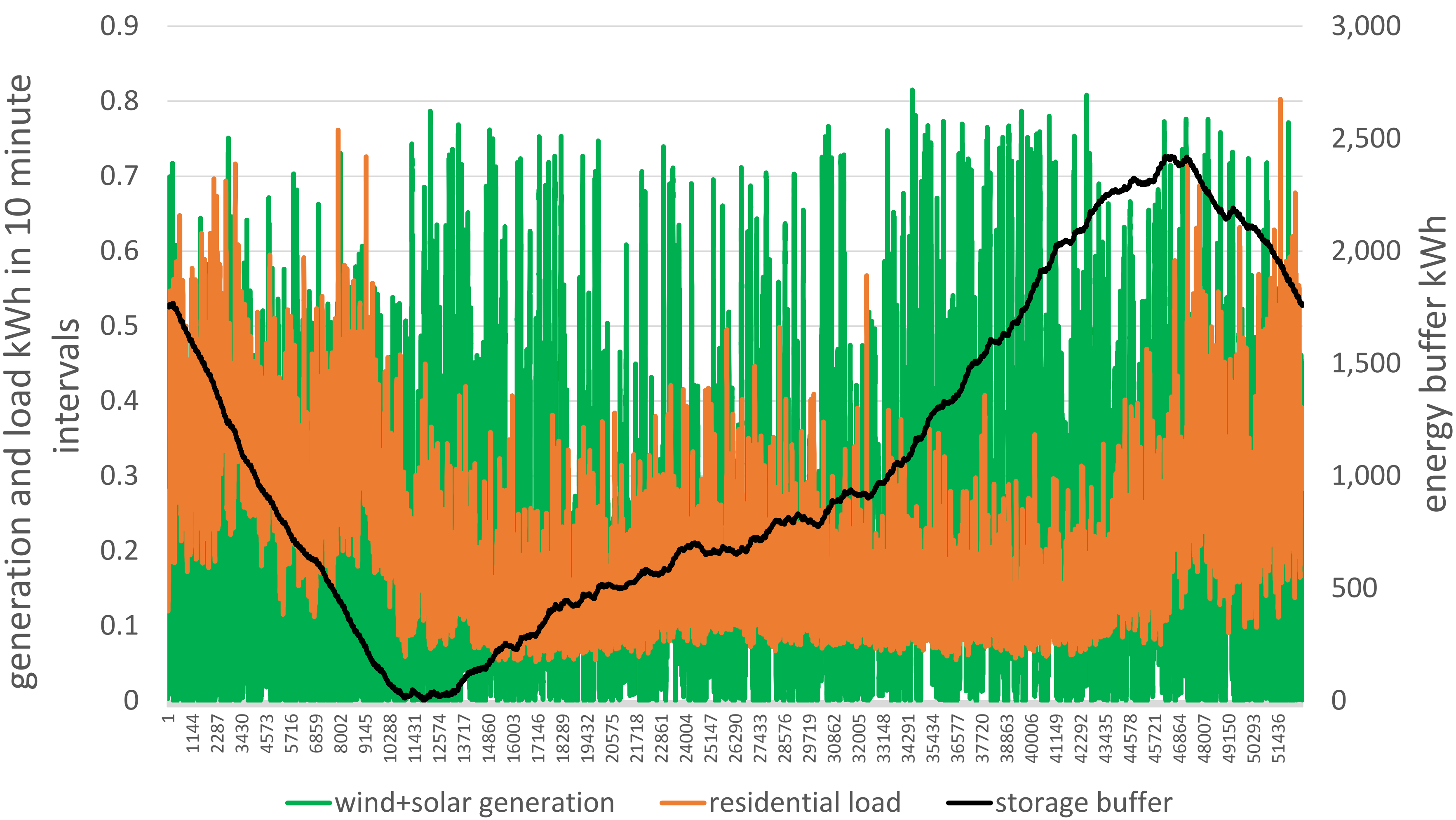
Mismatch of Load and Generation
July 1 – September 30
10 minute Intervals



Wind + Solar + Storage = Load



Wind+Solar, Load, Storage Buffer



July 2011

June 2012

Geophysical constraints on the reliability of solar and wind power in the United States

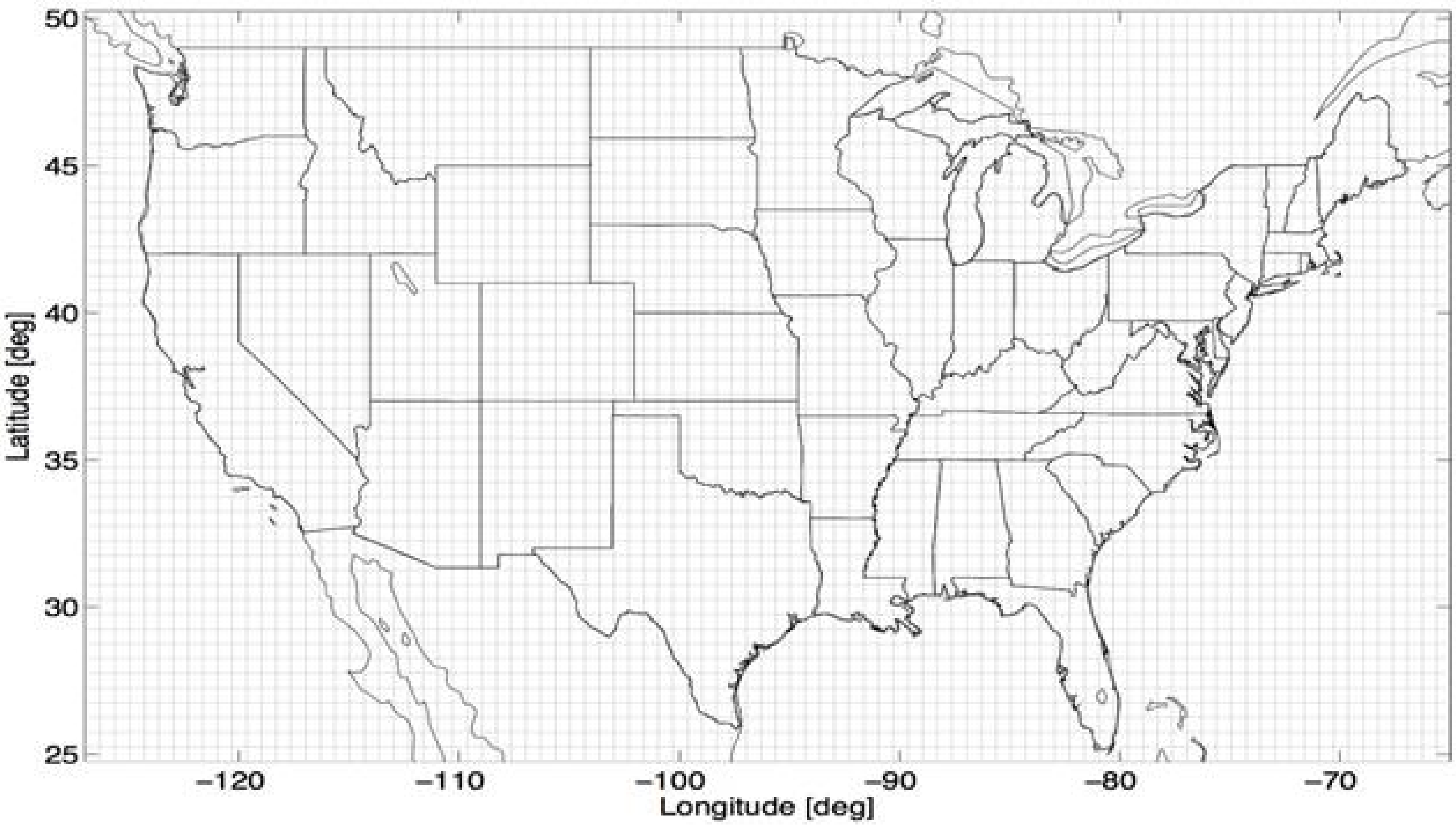
M R. Shaner et al.

Energy & Environmental Science

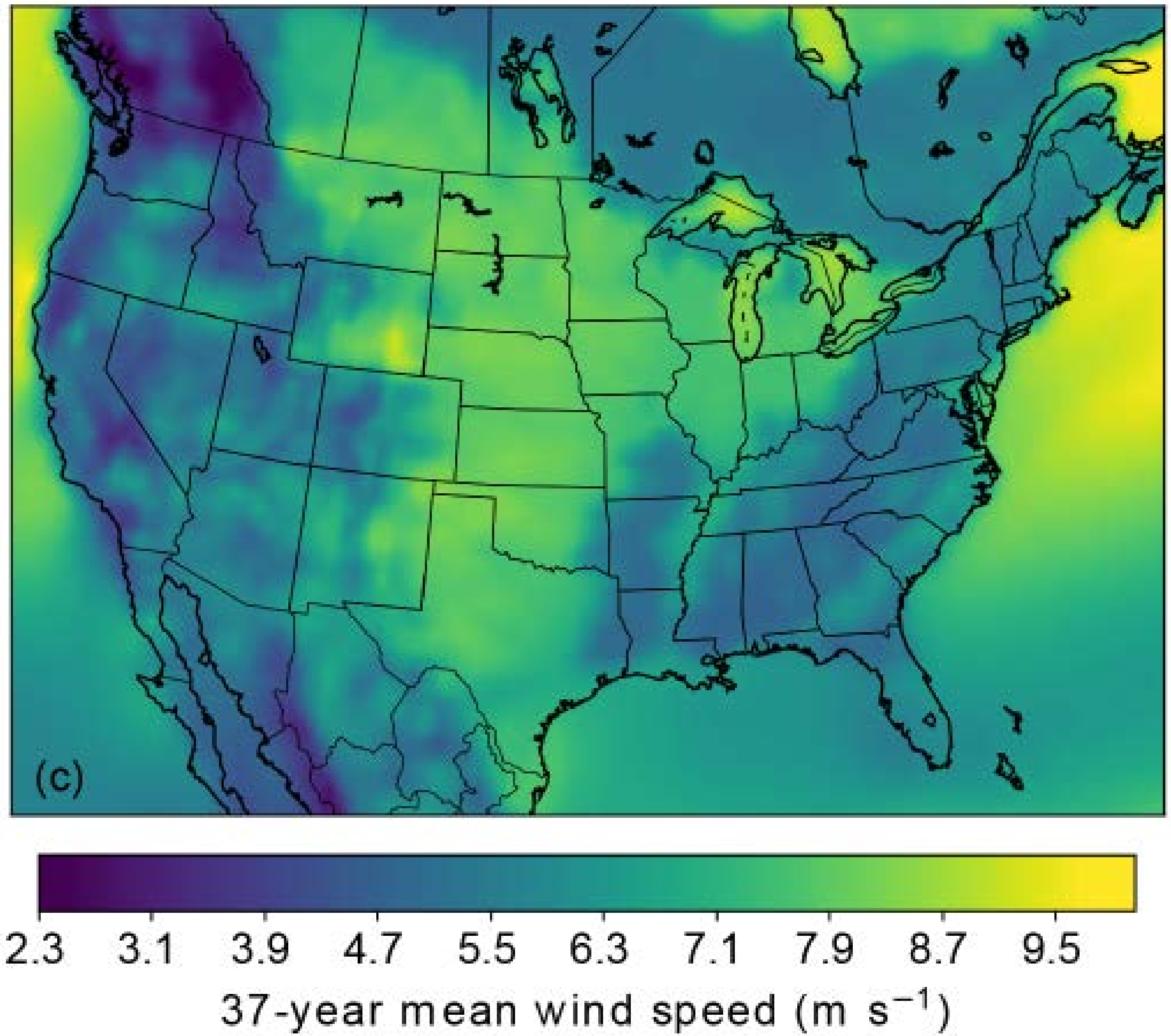
11(2018)914

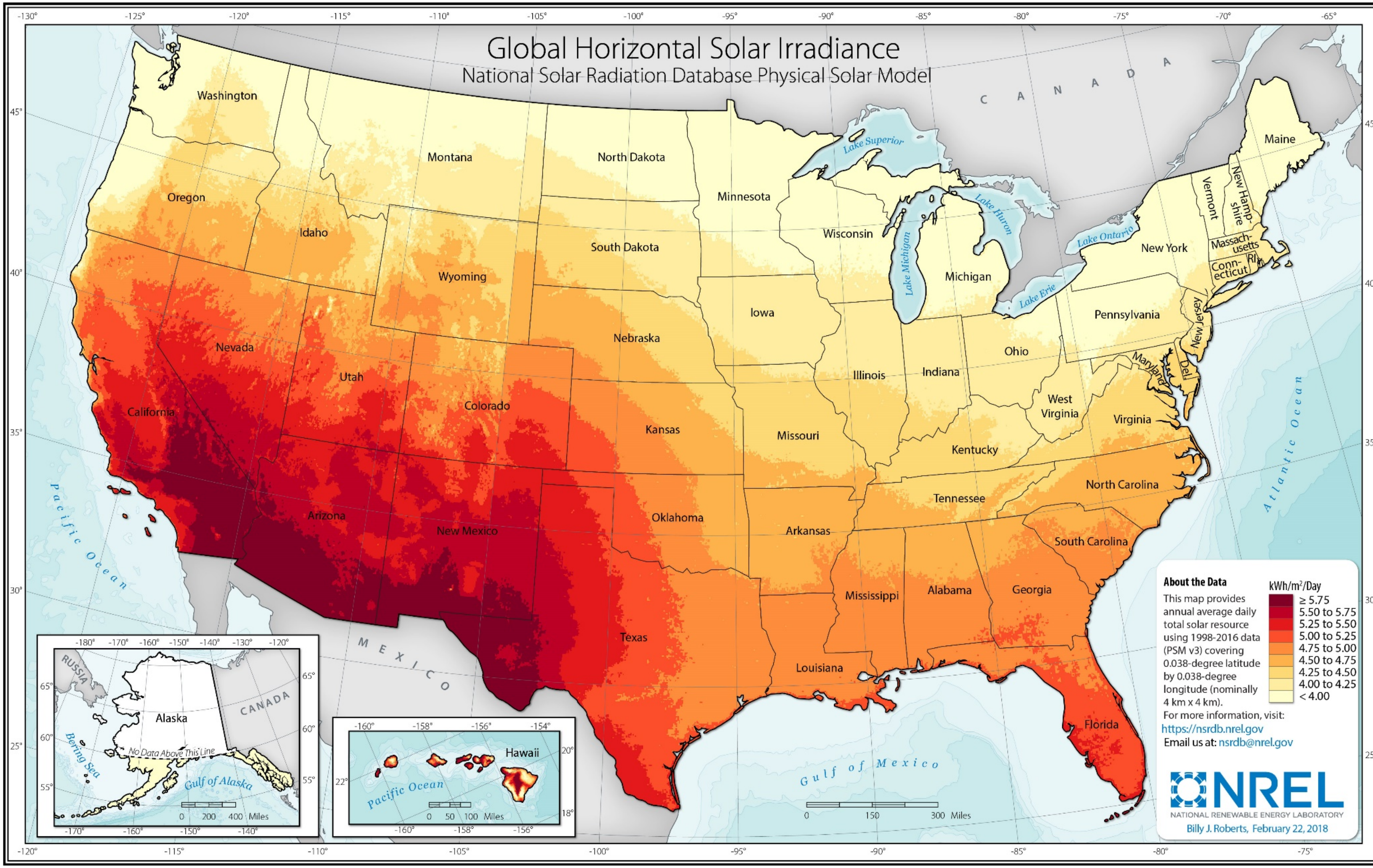
MERRA-2 Grid

Modern-Era Retrospective analysis for Research and Applications, Version 2



MERRA-2 37-Year Mean Wind Speed





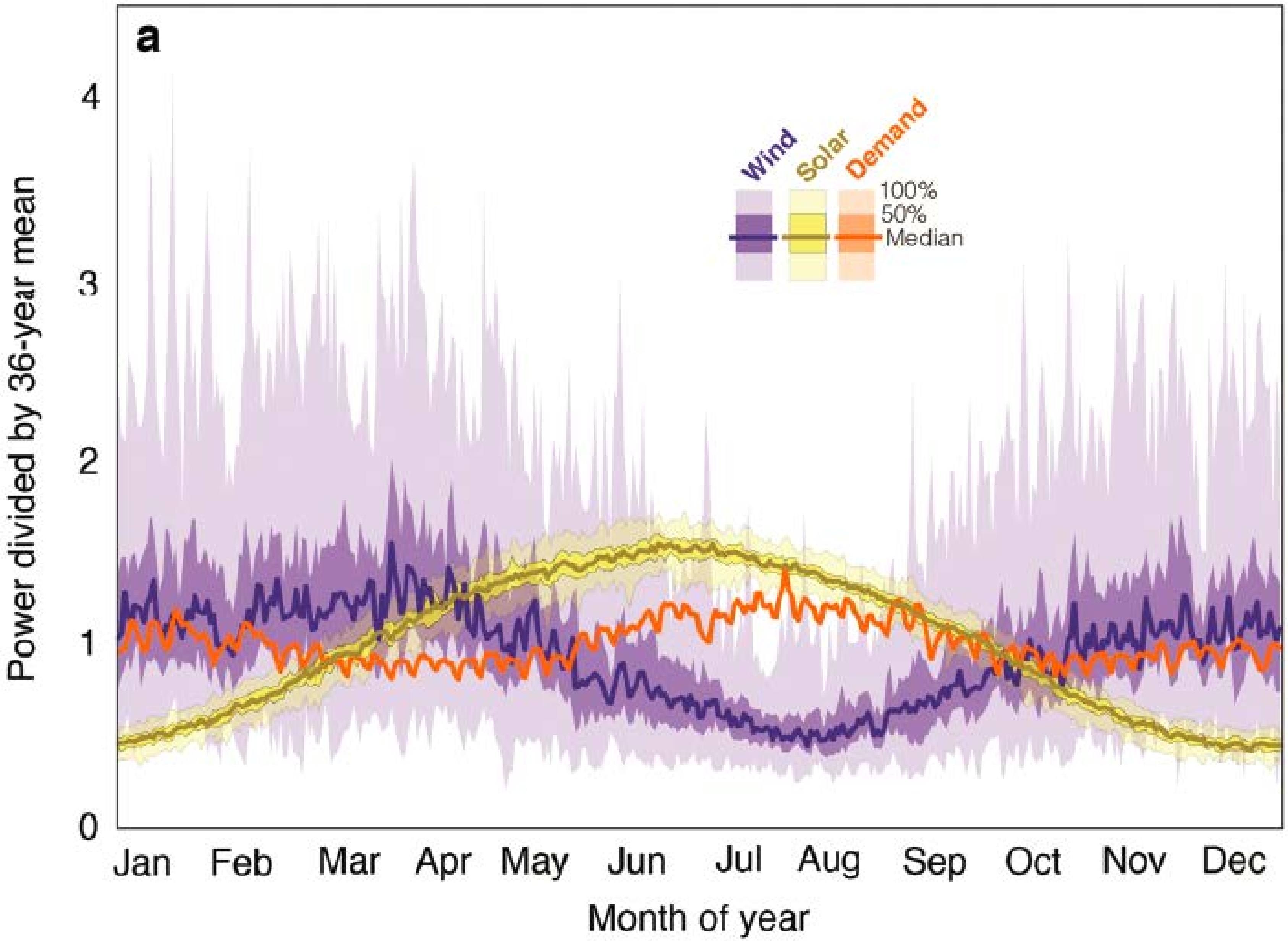
Global Horizontal Solar Irradiance
National Solar Radiation Database Physical Solar Model
Washington
Oregon
California
Nevada
Idaho
Montana
Wyoming
Utah
Arizona
Colorado
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
West Virginia
Maryland
Del.
New Jersey
Pennsylvania
New York
Vermont
New Hampshire
Maine
Massachusetts
Connecticut
RI
C A N A D A
M E X I C O
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
Pacific Ocean
Atlantic Ocean
Gulf of Mexico
Alaska
RUSSIA
CANADA
Bering Sea
Gulf of Alaska
No Data Above This Line
Hawaii
Pacific Ocean
About the Data
This map provides annual average daily total solar resource using 1998-2016 data (PSM v3) covering 0.038-degree latitude by 0.038-degree longitude (nominally 4 km x 4 km).
For more information, visit:
https://nsrdb.nrel.gov
Email us at: nsrdb@nrel.gov
kWh/m²/Day
≥ 5.75
5.50 to 5.75
5.25 to 5.50
5.00 to 5.25
4.75 to 5.00
4.50 to 4.75
4.25 to 4.50
4.00 to 4.25
< 4.00
0 150 300 Miles
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Billy J. Roberts, February 22, 2018

MERRA-2 Data Set

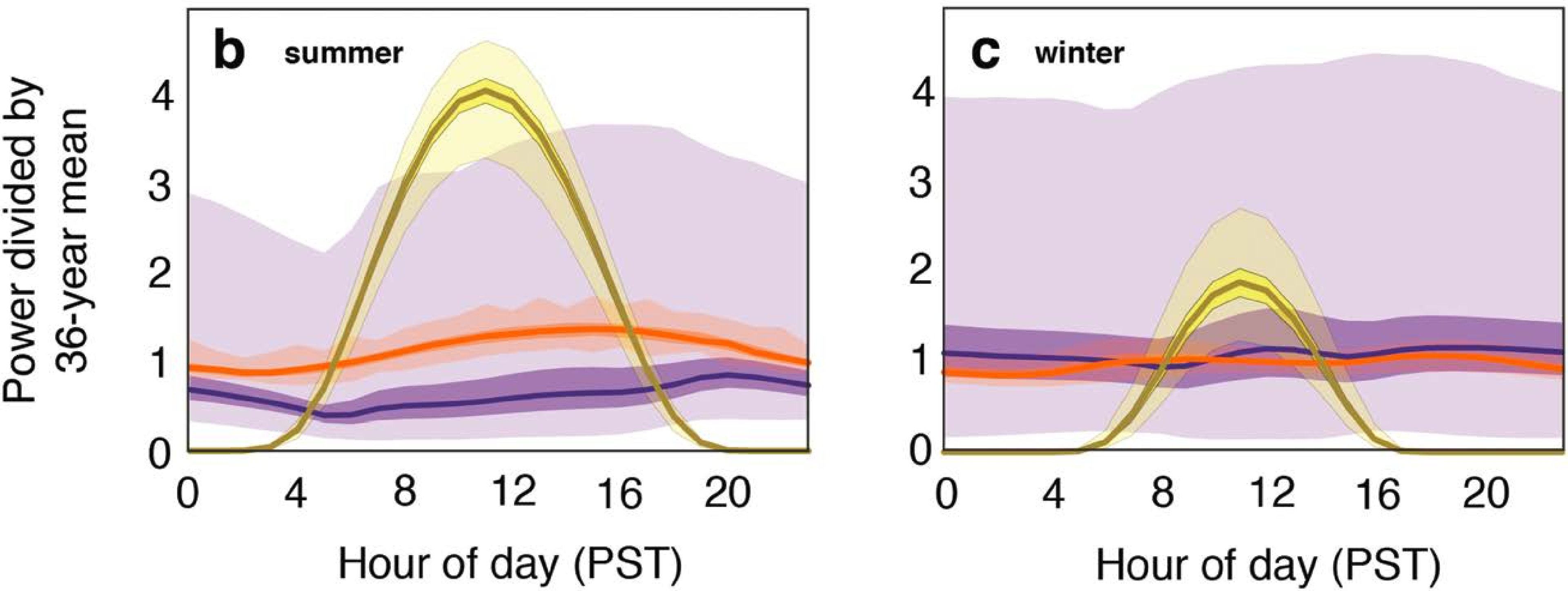
$$\begin{pmatrix} Demand \\ Solar\ Insolation \\ Wind\ Speed \end{pmatrix} \left(location_i , hour_j , day_k , year_l \right)$$

- Sum over locations assuming ideal transmission
- Convert isolation and speed to electrical capacity
- Mean total power demand is 450 GW. One year is 3.94 TWh
- Mix X% solar with (100-X)% wind
- Set total generation to some multiple of demand ×1 to ×4
- Assume storage of hours to days
- Determine reliability, i.e. fraction of time demand is not met

Average Daily Variability 1980-2015



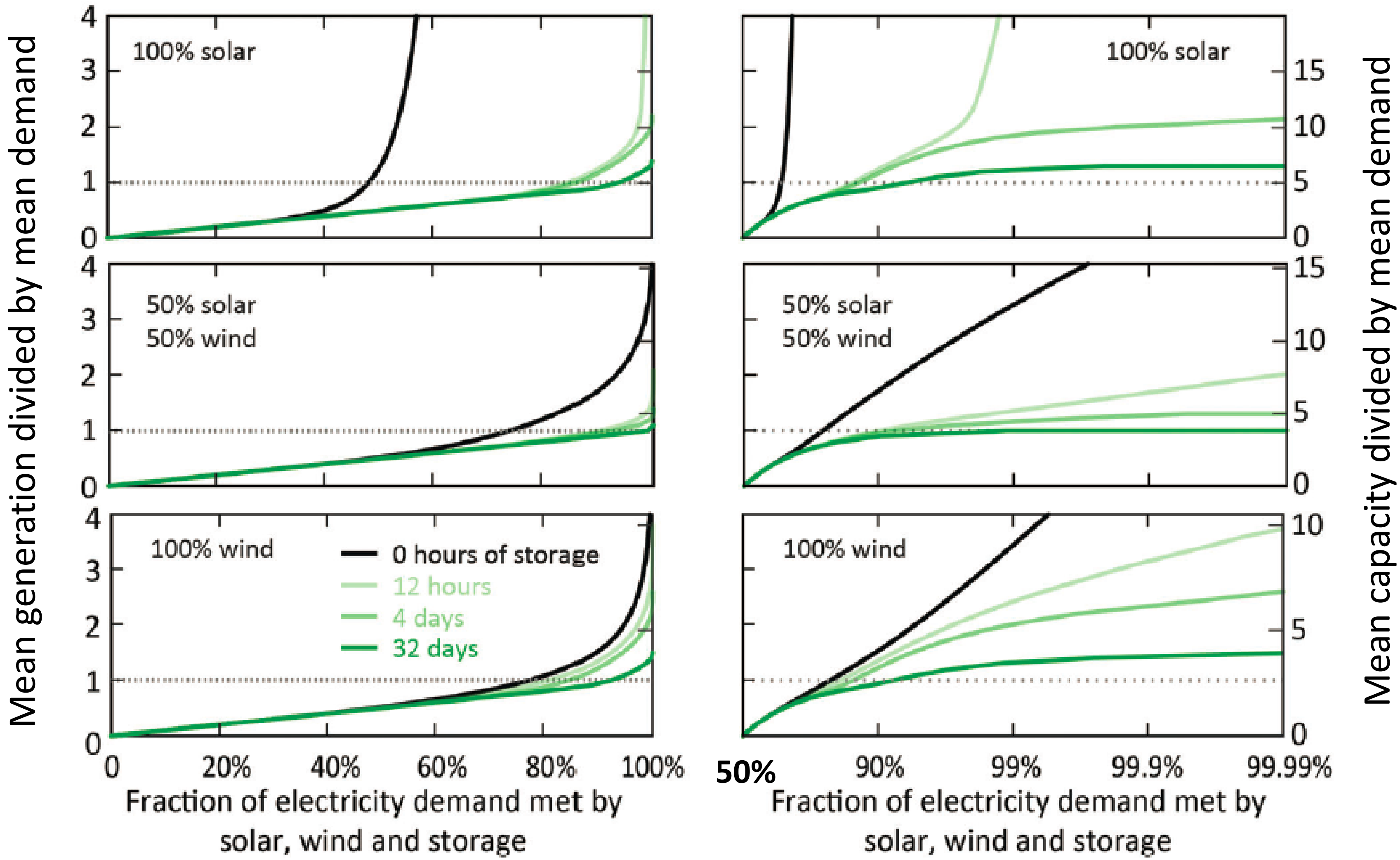
Summer and Winter Hourly Variability 1980-2015



Strategies to Meet Demand (Note: North American Electric Reliability Corporation (NERC) Reliability Standard Is 99.97%)

- Limit demand – demand response
- Employ widespread transmission
- Employ some dispatchable generation
  - Hydropower
  - Nuclear power
  - Biomass resource
  - Fossil fuels with capture and sequestration
- Overbuild renewable generation
- Employ storage

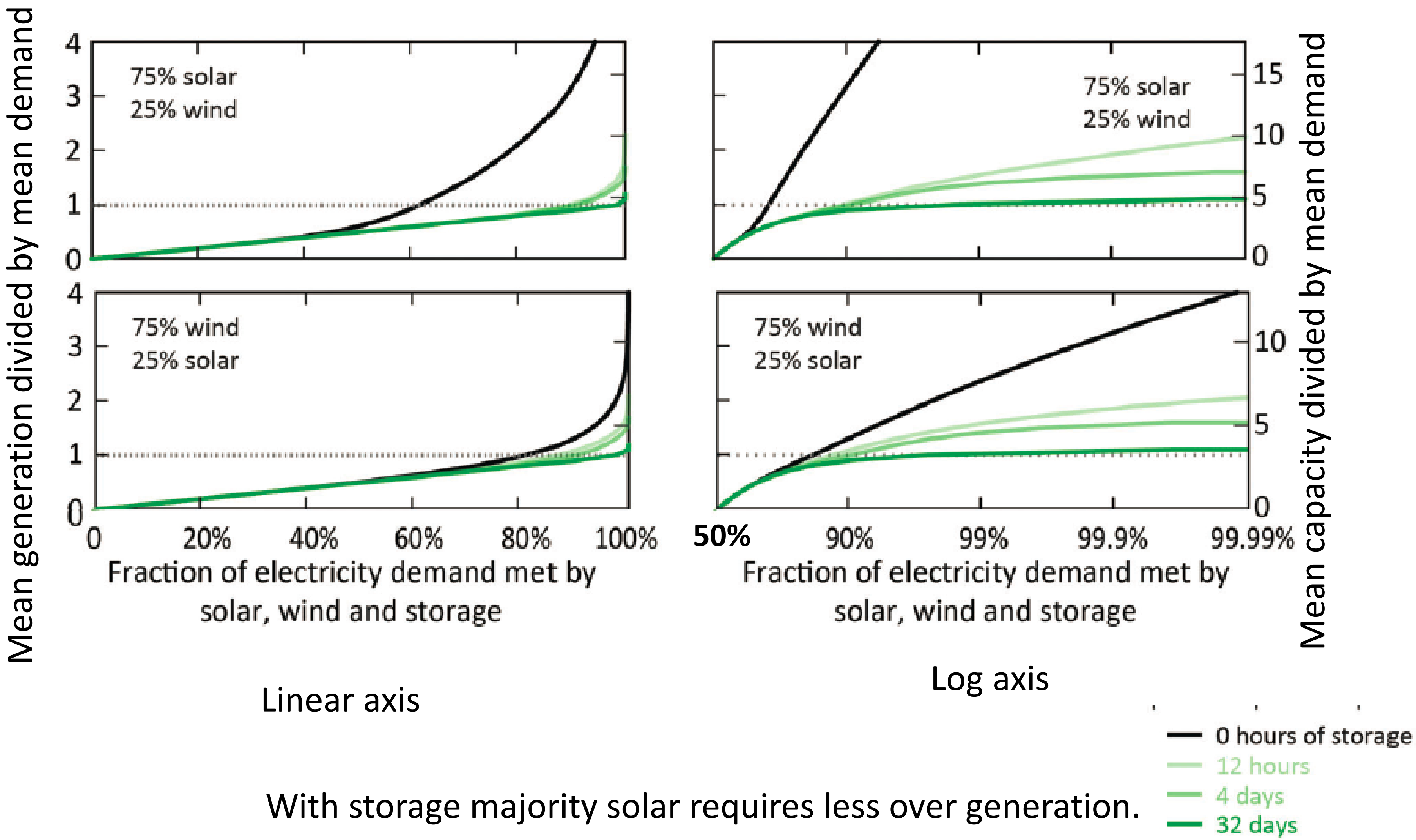
Reliability as Function of Generation and Storage



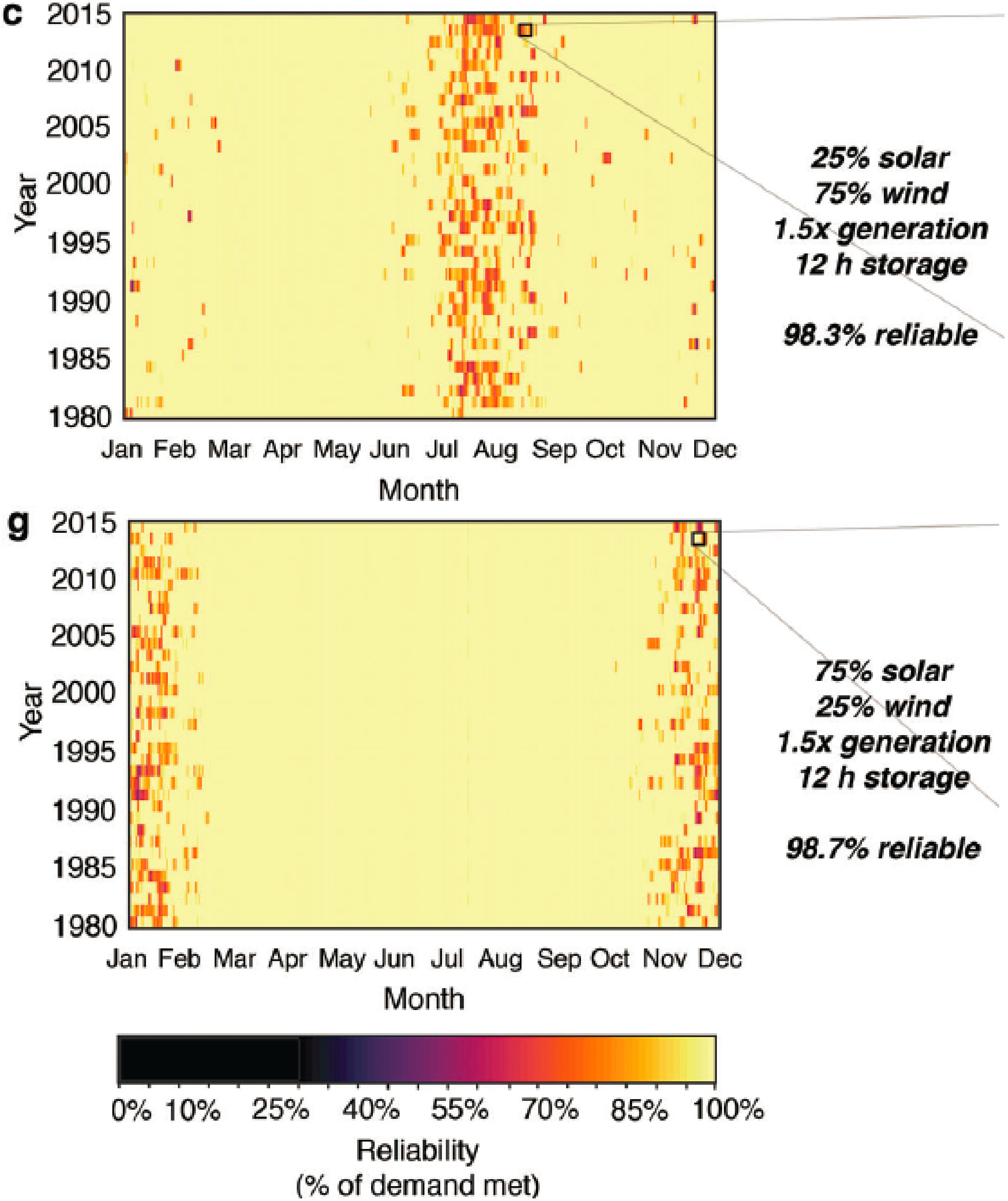
Linear axis

Log axis

Reliability as Function of Generation and Storage



With storage majority solar requires less over generation.



Daily demand met as a function of resource mix, generation and energy storage.

A Few Numbers

- For 450 GW_e generation from wind 11.1% of CONUS
- For 450 GW_e generation from solar 1.03% of CONUS
- Current (2017 data) wind generation 6.3%
- Current (2017 data) solar generation 1.9%
- At 38% capacity factor 1180 GW of wind required
- At 21% capacity factor 2140 GW solar required
- Capital cost for 1180 GW of wind 1,590 G$
- Capital cost for 2140 GW solar 2,350 G$
- Capital cost for 24 hours of battery storage 2,590 G$
- Capital cost for 7 coast-to-coast HVDC lines 410 G$

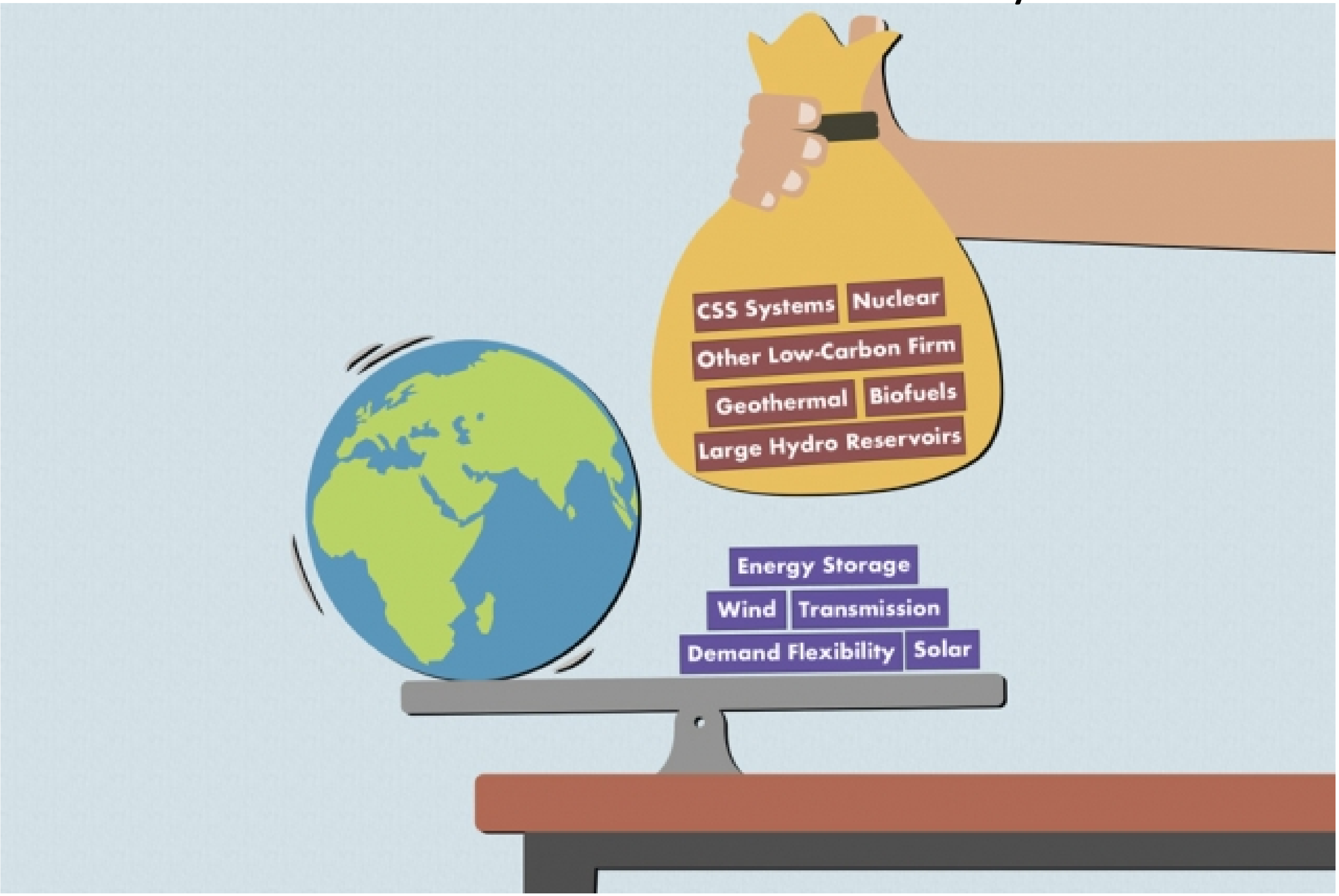
Summary so Far

- Capacity factors of wind and solar in optimal locations are approximately 30%
- Both wind and solar are variable and are intermittent
- Aggregation over distance improves capacity factor and lowers intermittency
- Aggregation of wind and solar also lowers intermittency
- Aggregation alone is not sufficient for reliability.
- Some sort of storage is necessary. How much storage is not well determined.
- Storage at current prices is expensive.

MIT News

September 6, 2018

Adding power choices reduces cost and risk of carbon-free electricity



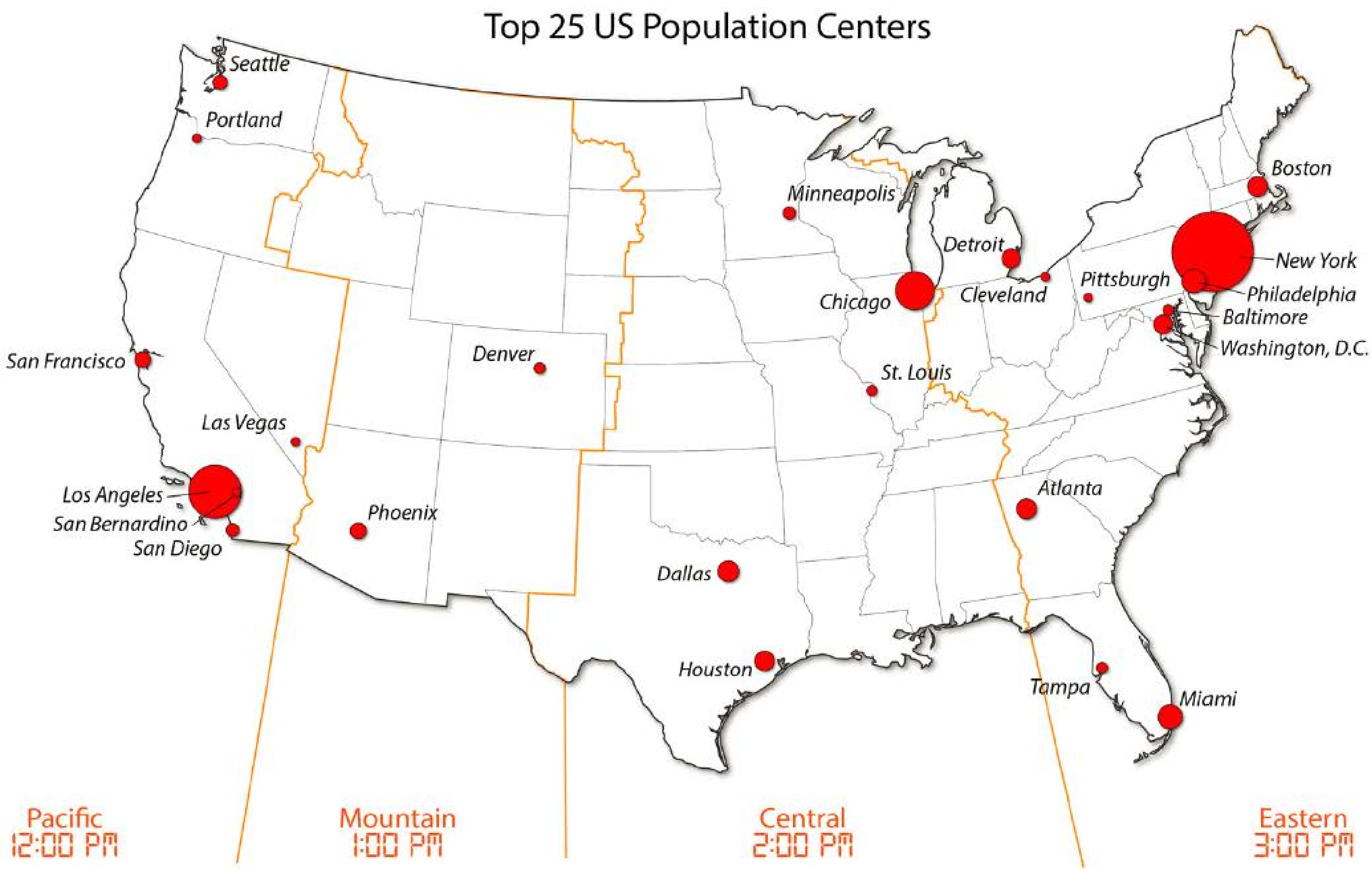
Carbon-Neutral Electricity Generating Options Other Than Wind + Solar + Storage

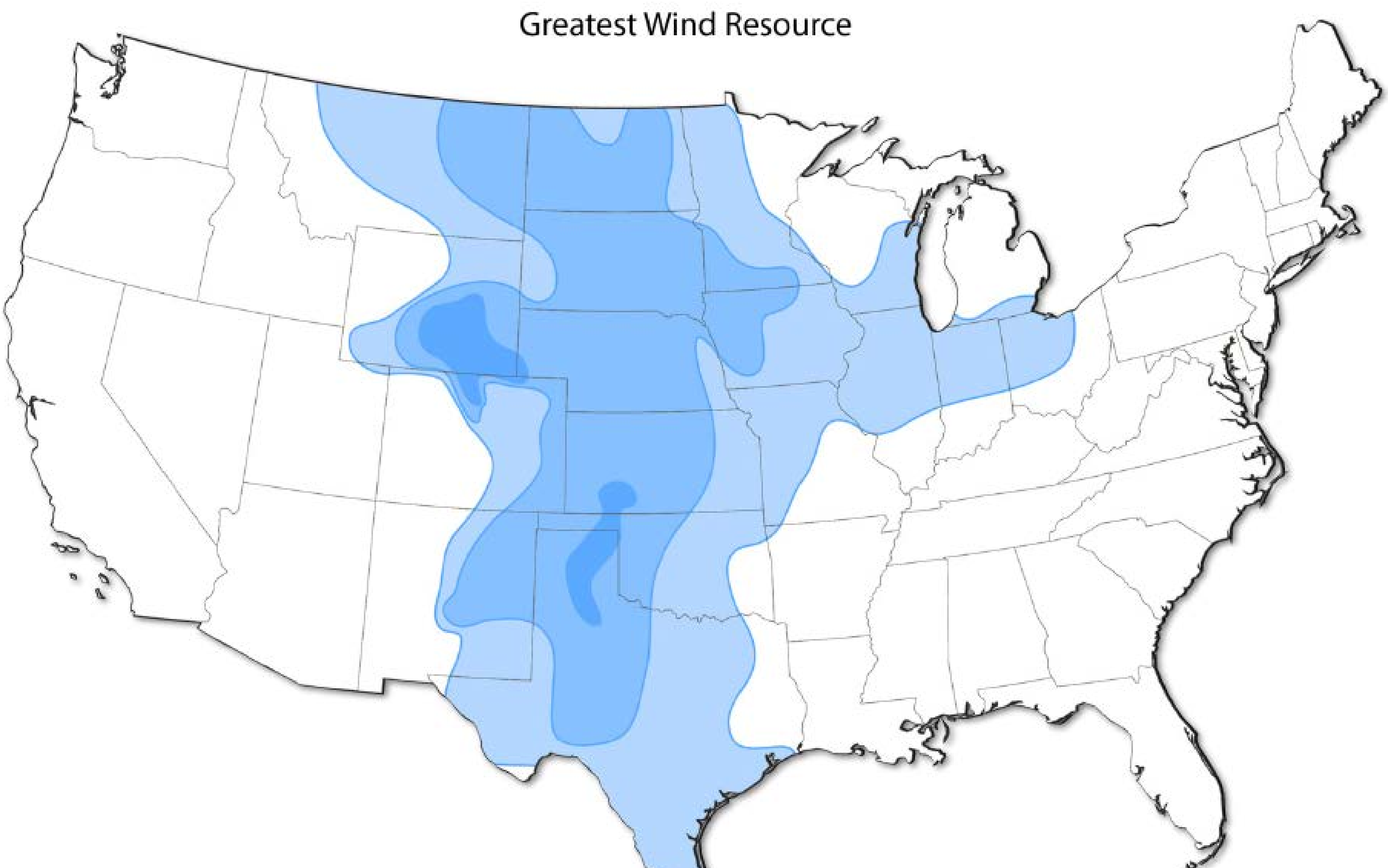
- Geothermal
- Hydropower
- Biomass
- Nuclear
    - Use $9,000/kW for nuclear power
    - Replace 7.50 TWh per day (310 GW) of fossil fuel generation with nuclear generation for 2.8 T$
    - Wind + solar = 1.8 T$
    - Wind + solar + 2 days of storage = 4.5 T$

Transmission Projects

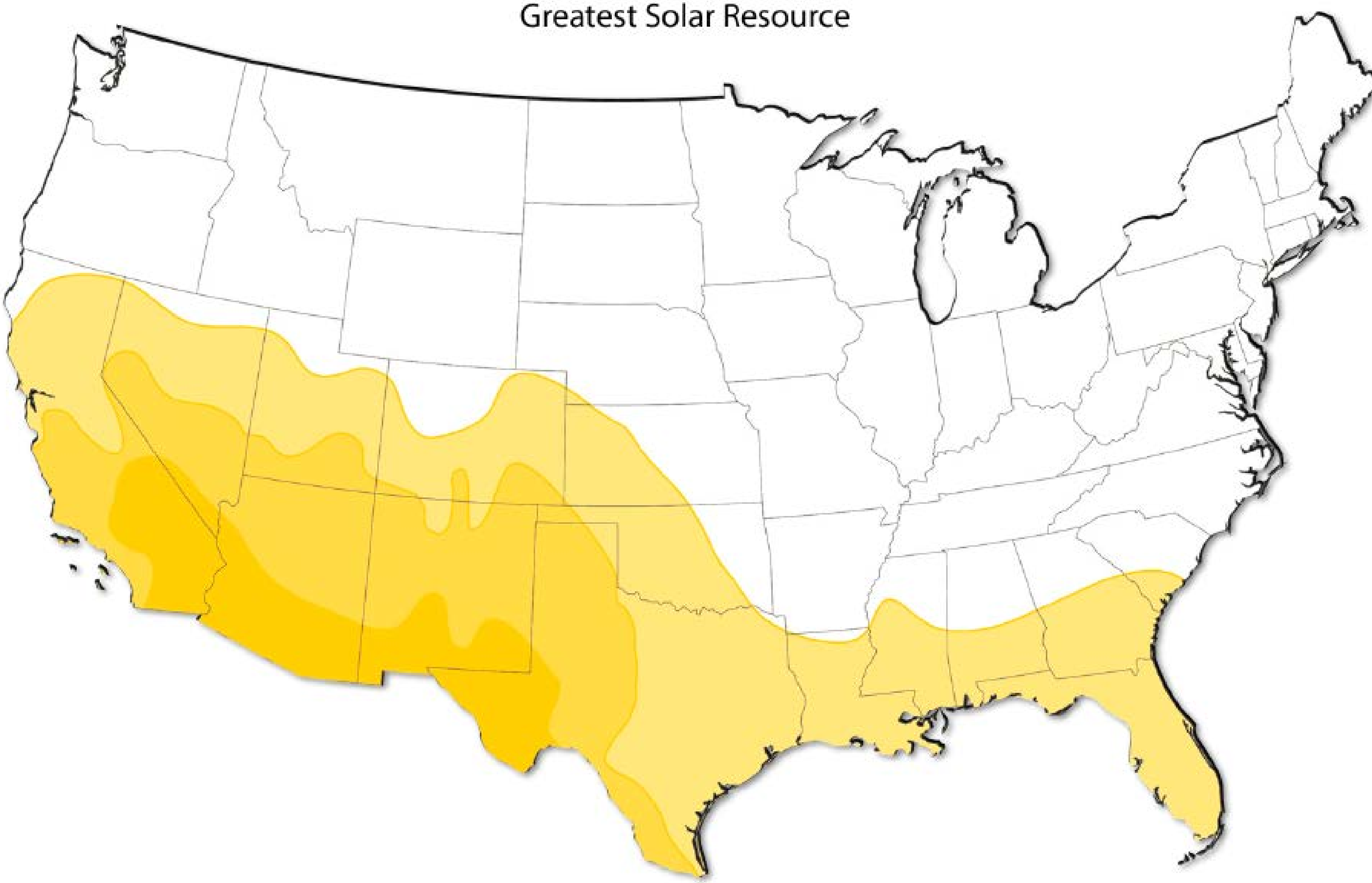
NREL Interconnection Seams Study (2018)

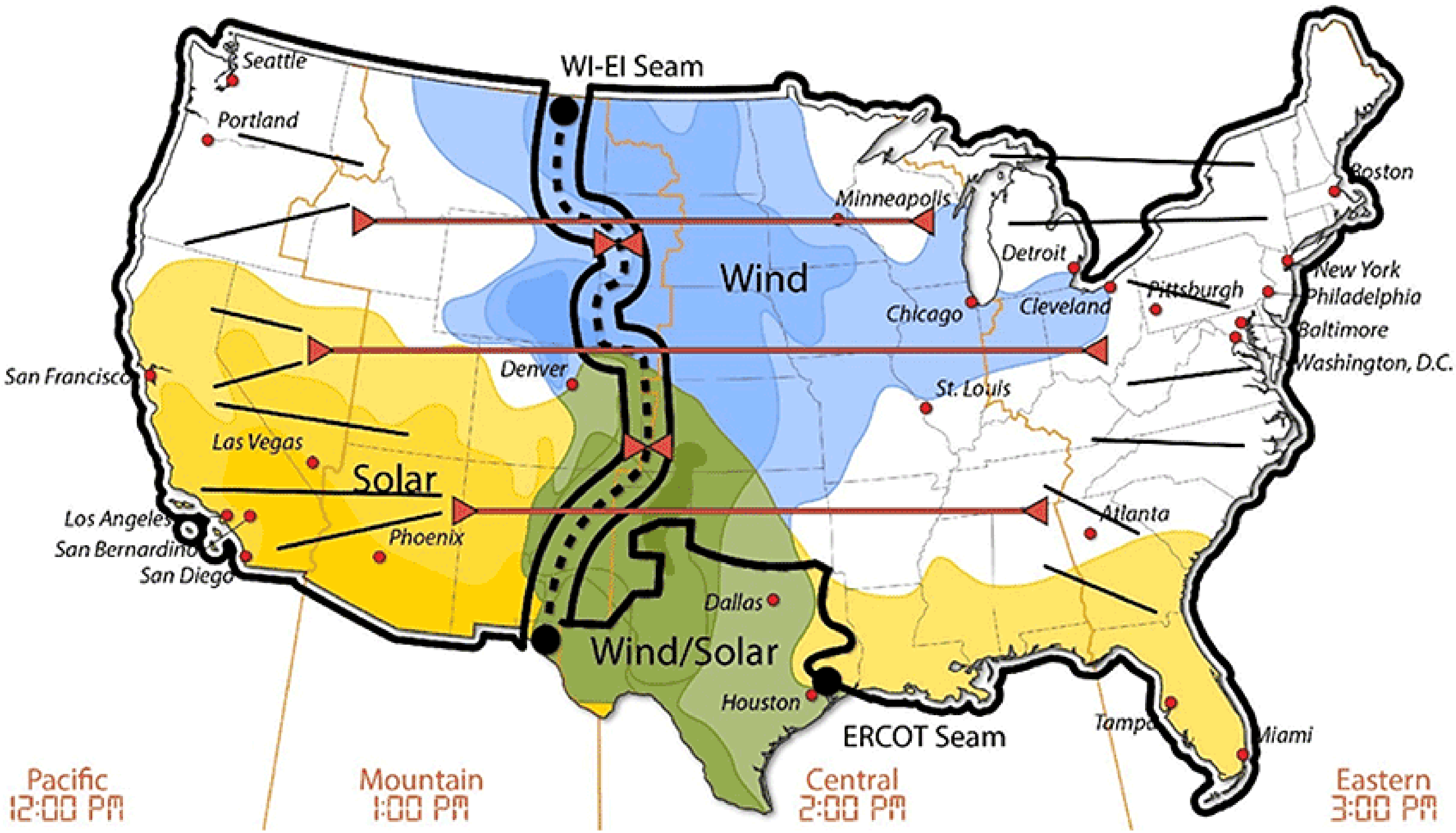
NREL Interconnection Seams Study (2018)




Greatest Wind Resource

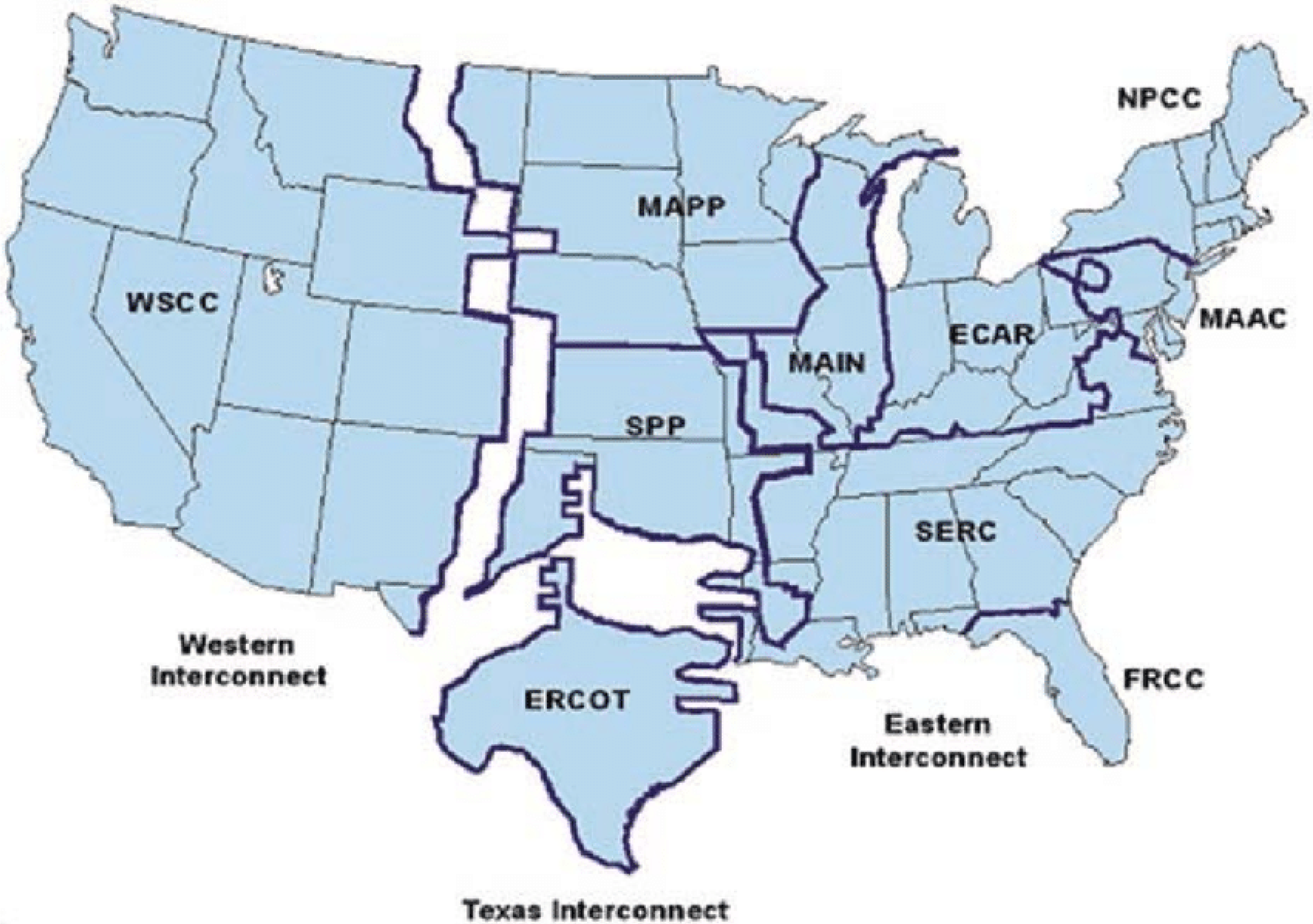
Greatest Solar Resource



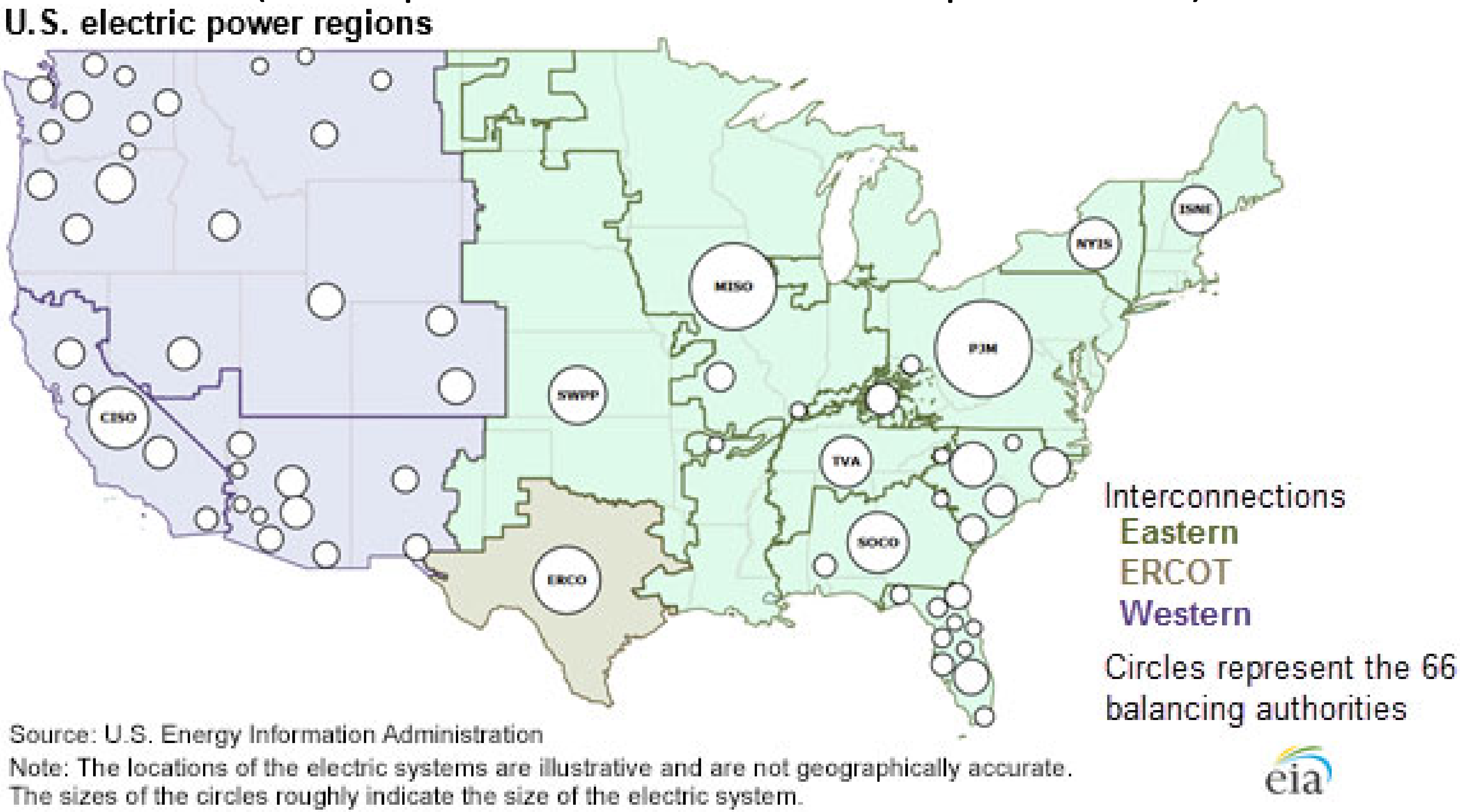

WI-EI Seam
Seattle
Portland
Minneapolis
Boston
Detroit
New York
Wind
Pittsburgh
Philadelphia
Chicago
Cleveland
Baltimore
Washington, D.C.
San Francisco
Denver
St. Louis
Las Vegas
Solar
Los Angeles
San Bernardino
Phoenix
Atlanta
San Diego
Dallas
Wind/Solar
Houston
ERCOT Seam
Tampa
Miami
Pacific
12:00 PM
Mountain
1:00 PM
Central
2:00 PM
Eastern
3:00 PM

North American Regional Reliability Council

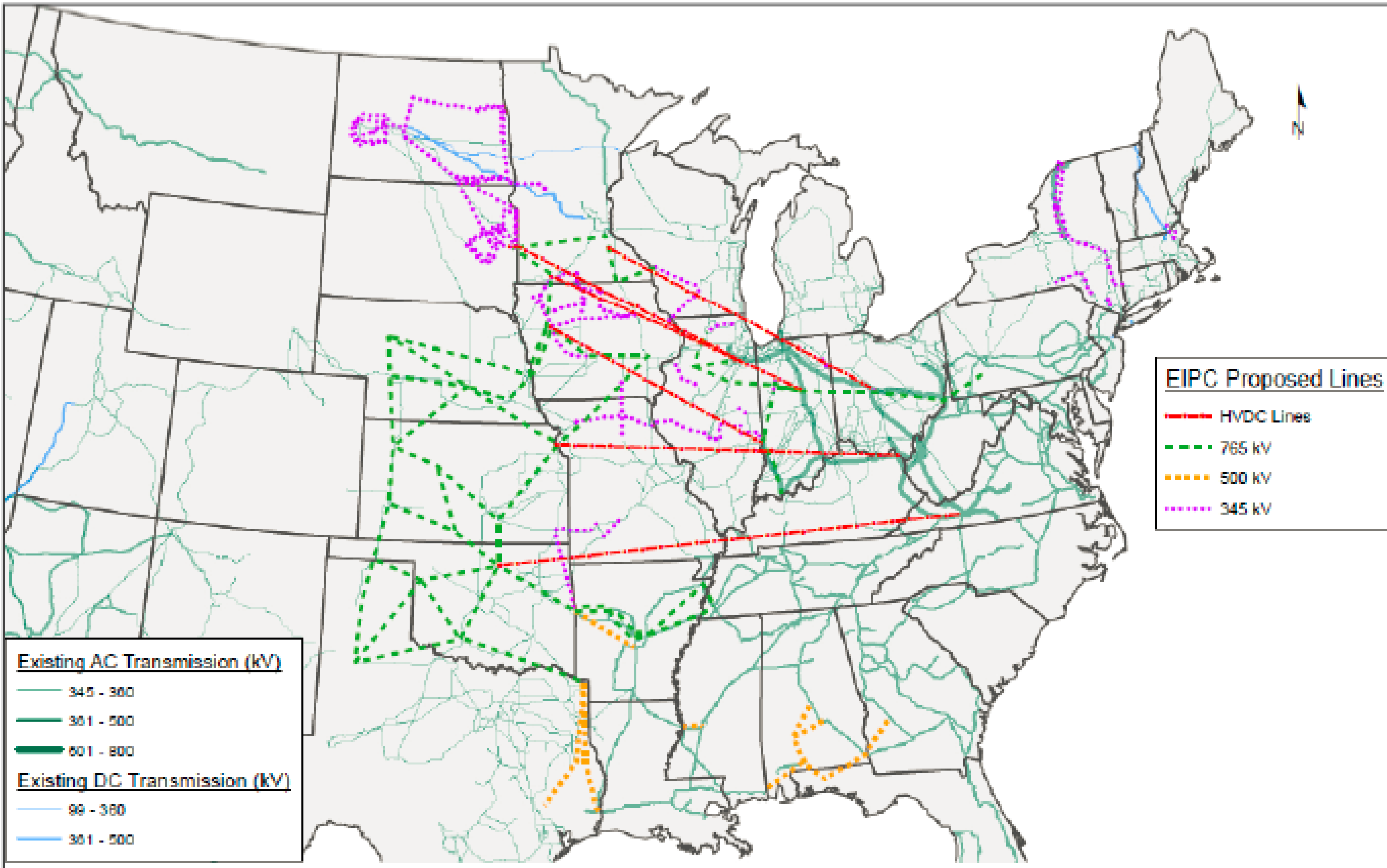
Eastern, Western and Texas Grids



Regional Transmission Organizations (Independent Service Operators)



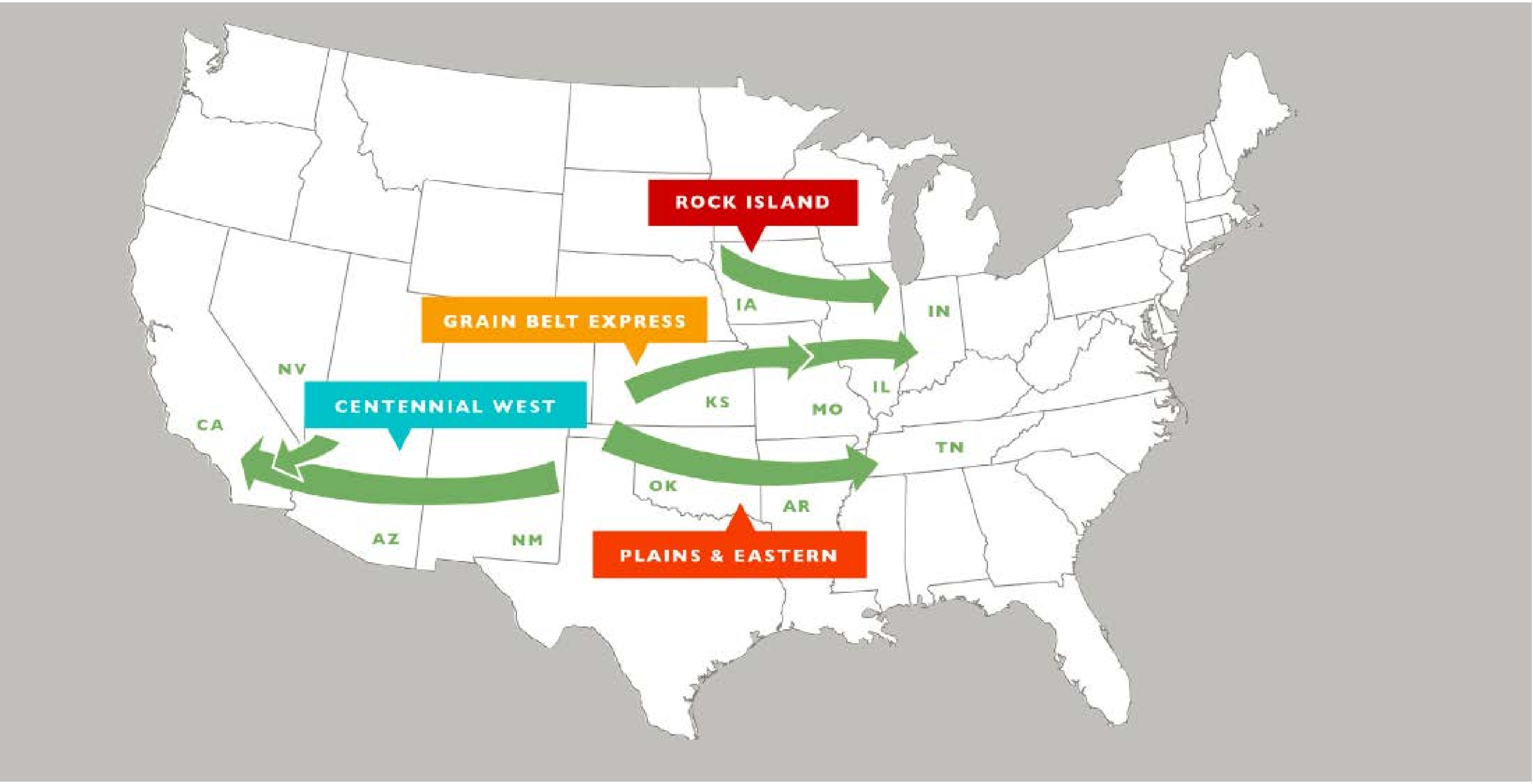
Eastern Interconnection Planning Collaborative Proposal (2012)



Great Plains Projects

CLEAN LINE ENERGY PARTNERS

Houston, TX
2012 Project Brochure



Transmission Expansion

Illinois Wind Working Group

Charlie Ary, Clean Line Energy

July 18, 2012

CLEAN LINE
ENERGY PARTNERS


CLEAN LINE ENERGY PROJECTS
Houston-based Clean Line Energy is working to permit three transmission lines that it says will be used to take wind power from the Heartland to population centers farther east. In Missouri, up to 500 megawatts of wind would be pumped into the grid if regulators approve the project.
Rock Island
IOWA
NEBRASKA
INDIANA
OHIO
ILLINOIS
Grain Belt Express
KANSAS
MISSOURI
KENTUCKY
TENNESSEE
Plains & Eastern
OKLAHOMA
ARKANSAS
Where the transmission line would cross Missouri
St. Joseph
CALDWELL
CHARITON
MONROE
RALLS
BUCHANAN
CLINTON
CARROLL
RANDOLPH
Kansas City
Missouri Rver
MISSOURI
St. Louis

Grain Belt Express
TRANSMISSION LINE

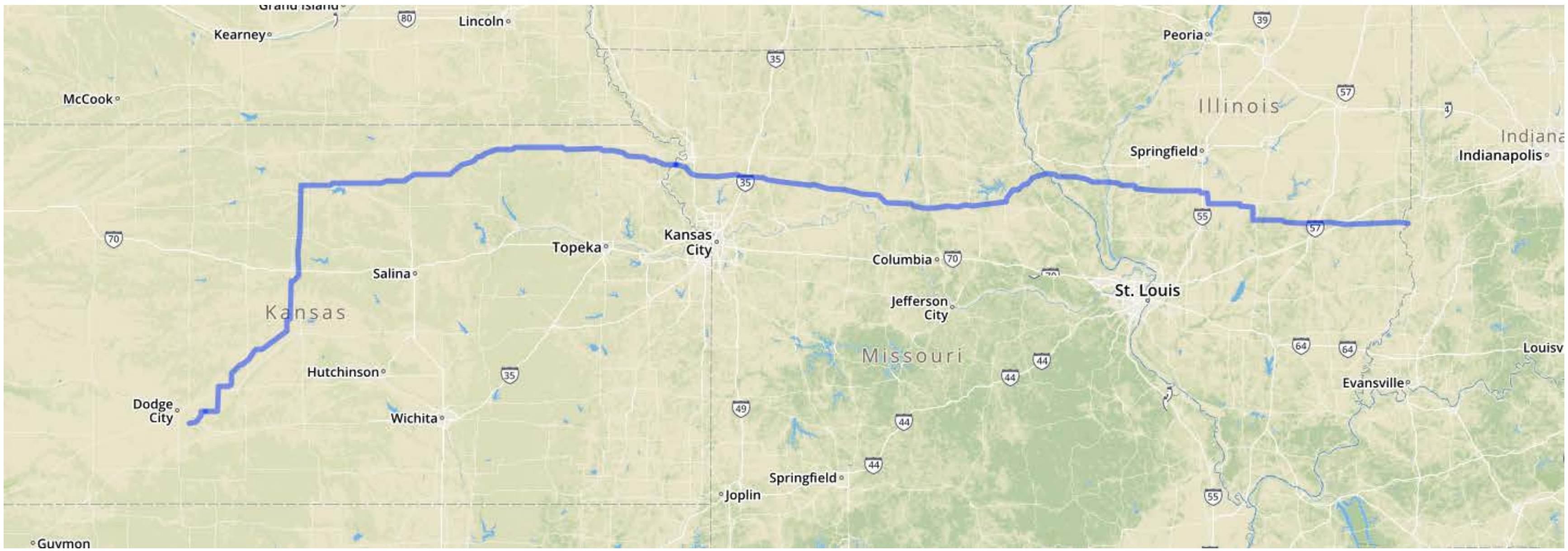
Home | Overview | FAQs | Learn More | Stay Connected

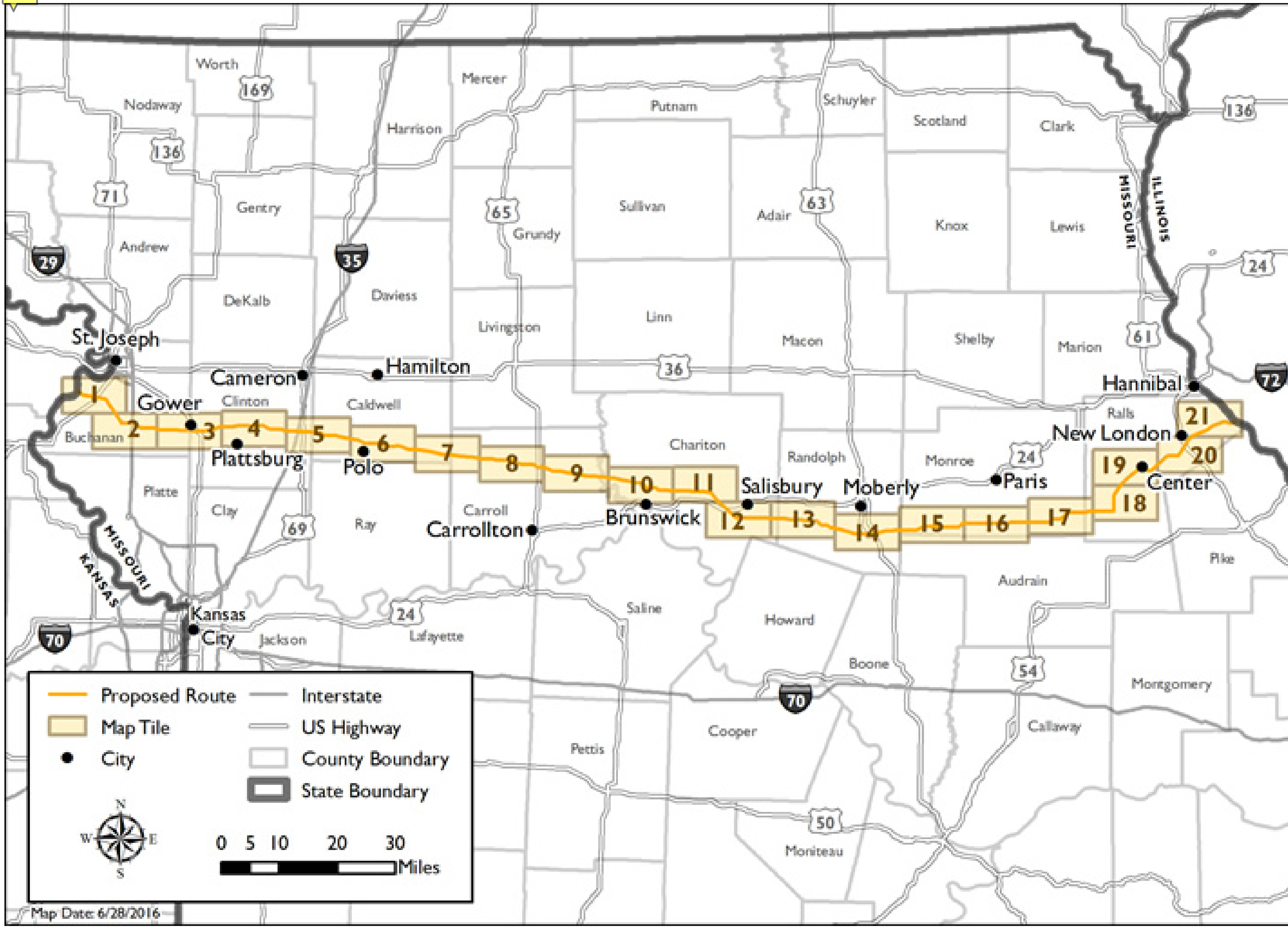
Grain Belt Express

moving energy from source to market

Grain Belt Express is an approximately 800-mile, 600-kilovolt high voltage direct current (HVDC) transmission line project. When built, it will deliver up to 4,000 megawatts (MW) of low-cost sustainable power from western Kansas and the surrounding area to customers in Missouri and states farther east.

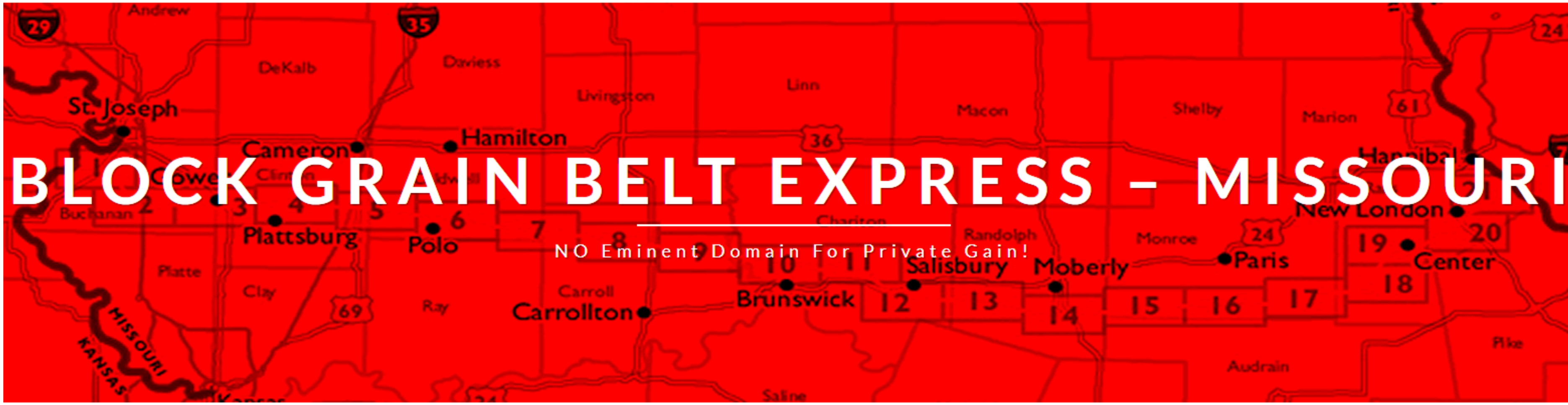
Grain Belt Express Transmission Line




Worth
Nodaway
Mercer
Harrison
Putnam
Schuyler
Scotland
Clark
Gentry
Andrew
Grundy
Sullivan
Adair
Knox
Lewis
DeKalb
Daviess
Livingston
Linn
Macon
Shelby
Marion
MISSOURI
ILLINOIS
St. Joseph
Cameron
Hamilton
Hannibal
Gower
Clinton
Caldwell
Ralls
Buchanan
Plattsburg
Polo
Chariton
Randolph
Monroe
New London
Paris
Center
Salisbury
Moberly
Brunswick
Carrollton
Platte
Clay
Ray
Carroll
Pike
Audrain
MISSOURI
KANSAS
Kansas City
Jackson
Lafayette
Saline
Howard
Boone
Montgomery
Callaway
Cooper
Pettis
Moniteau
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
169 136 71 29 35 65 63 36 24 61 72 69 70 54 50
Proposed Route
Map Tile
City
Interstate
US Highway
County Boundary
State Boundary
N S E W
0 5 10 20 30
Miles
Map Date: 6/28/2016

FAQ: Is Grain Belt Express a regulated entity?

Grain Belt Express is regulated by the Kansas Corporation Commission, the Missouri Public Service Commission, and the Indiana Utility Regulatory Commission, and will seek utility status from the Illinois Commerce Commission. Grain Belt Express is also regulated by the Federal Energy Regulatory Commission (FERC). In addition, Grain Belt Express will obtain additional permits from a variety of state and federal agencies prior to construction.



"If approved, the use of eminent domain for a project with little or no benefit to our state would be a violation of property rights. The transmission line would place an enormous burden on landowners, as it would greatly decrease property values and farm productivity, while negatively impacting the quality of our lives and potentially affecting our health, safety and environment."

"Finally, the approval of the line would set a very dangerous precedent as other private companies will likely ask for the power of eminent domain for their business ventures with or **without any benefit to the state of Missouri**."

ST. LOUIS POST-DISPATCH

July 11, 2015

Missouri blocks Grain Belt Express wind project

"The Missouri Public Service Commission's 3-2 vote to deny the Grain Belt Express project's route could derail the entire line, which already won approval from Kansas and Indiana."

ST. LOUIS POST-DISPATCH

July 12, 2016

Missouri review of Grain Belt transmission application delayed 60 days

ST. LOUIS POST-DISPATCH

August 17, 2017

Despite giving vocal support, state regulators again deny Grain Belt Express transmission line, citing court ruling

ST. LOUIS POST-DISPATCH

February 27, 2018

Case over stalled transmission line for wind energy advances to Missouri Supreme Court

ST. LOUIS POST-DISPATCH

July 17, 2018

Missouri Supreme Court says state regulators erred in denial of Grain Belt Express transmission line

ST. LOUIS POST-DISPATCH

March 20, 2019

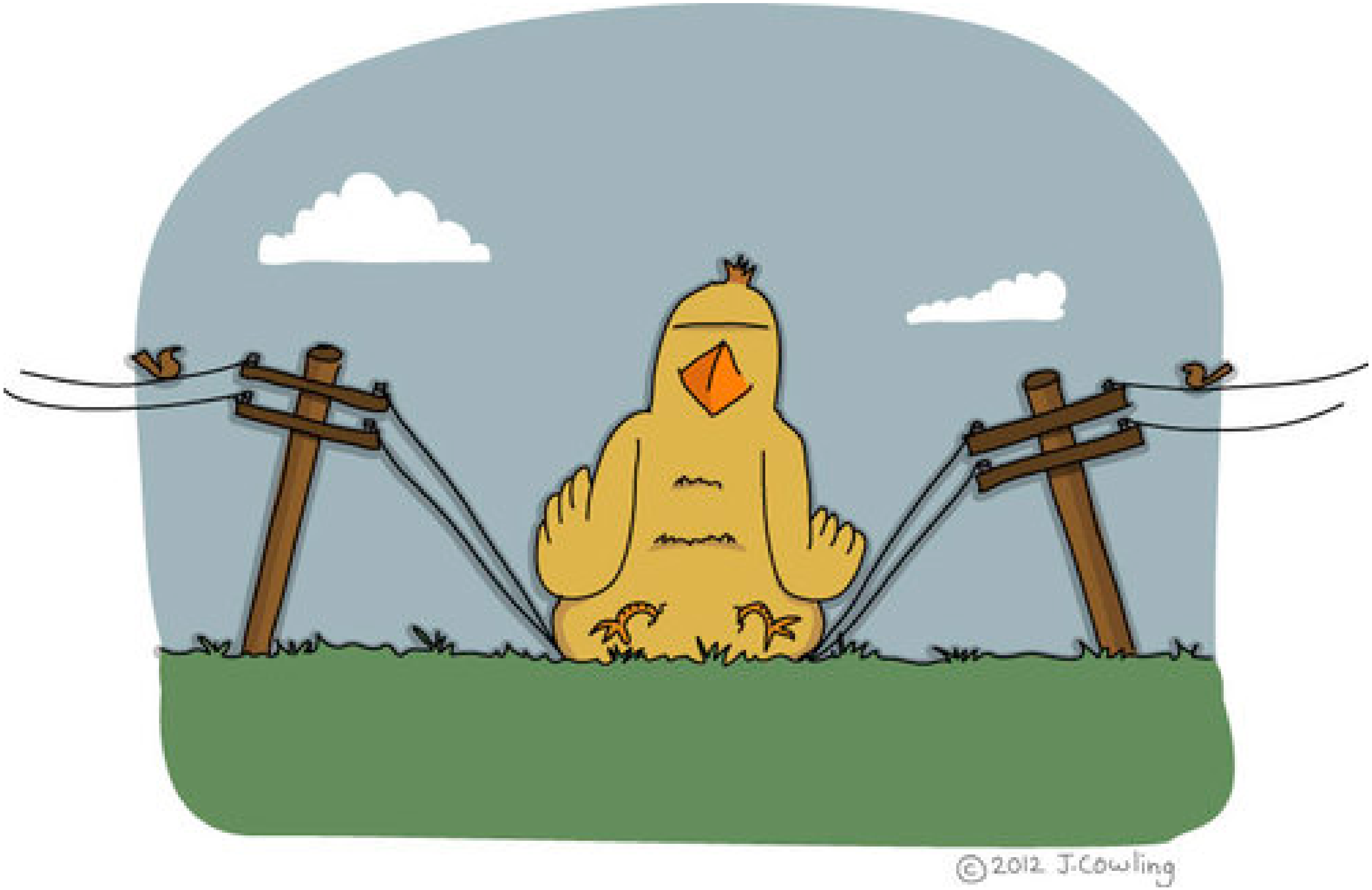
After years of rejection, Missouri regulators give nod to Grain Belt Express transmission line

ST. LOUIS POST-DISPATCH

January 28, 2020

Grain Belt Express power line gets thumbs down in Missouri House

Failure to Connect



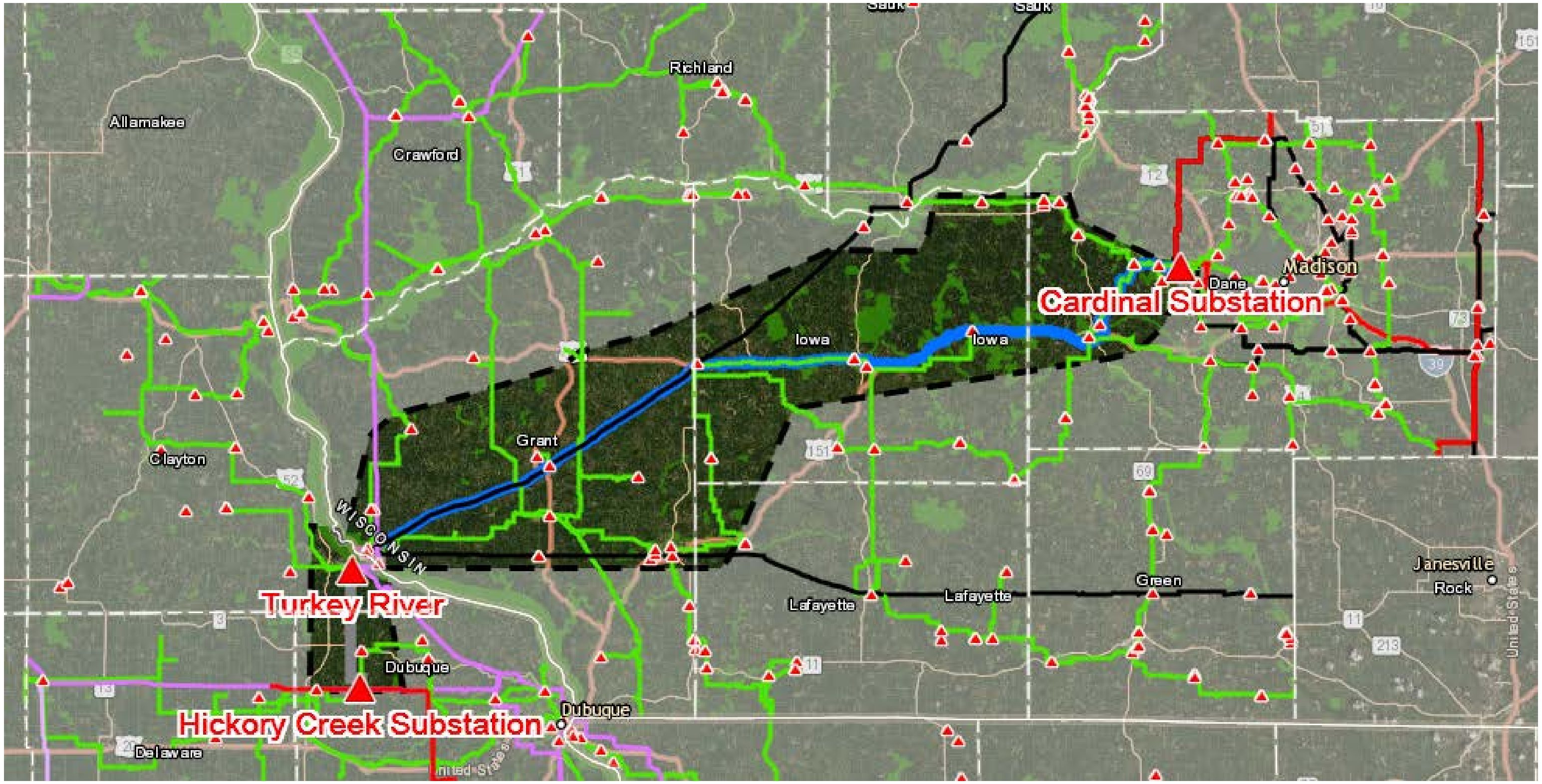
Eminent Domain Decision
Susette Kelo, et al. v. City of New London, CT et al.
545 U.S. 469 (2005)

Wisconsin Project

ENERGY NEWS NETWORK

January 22, 2019

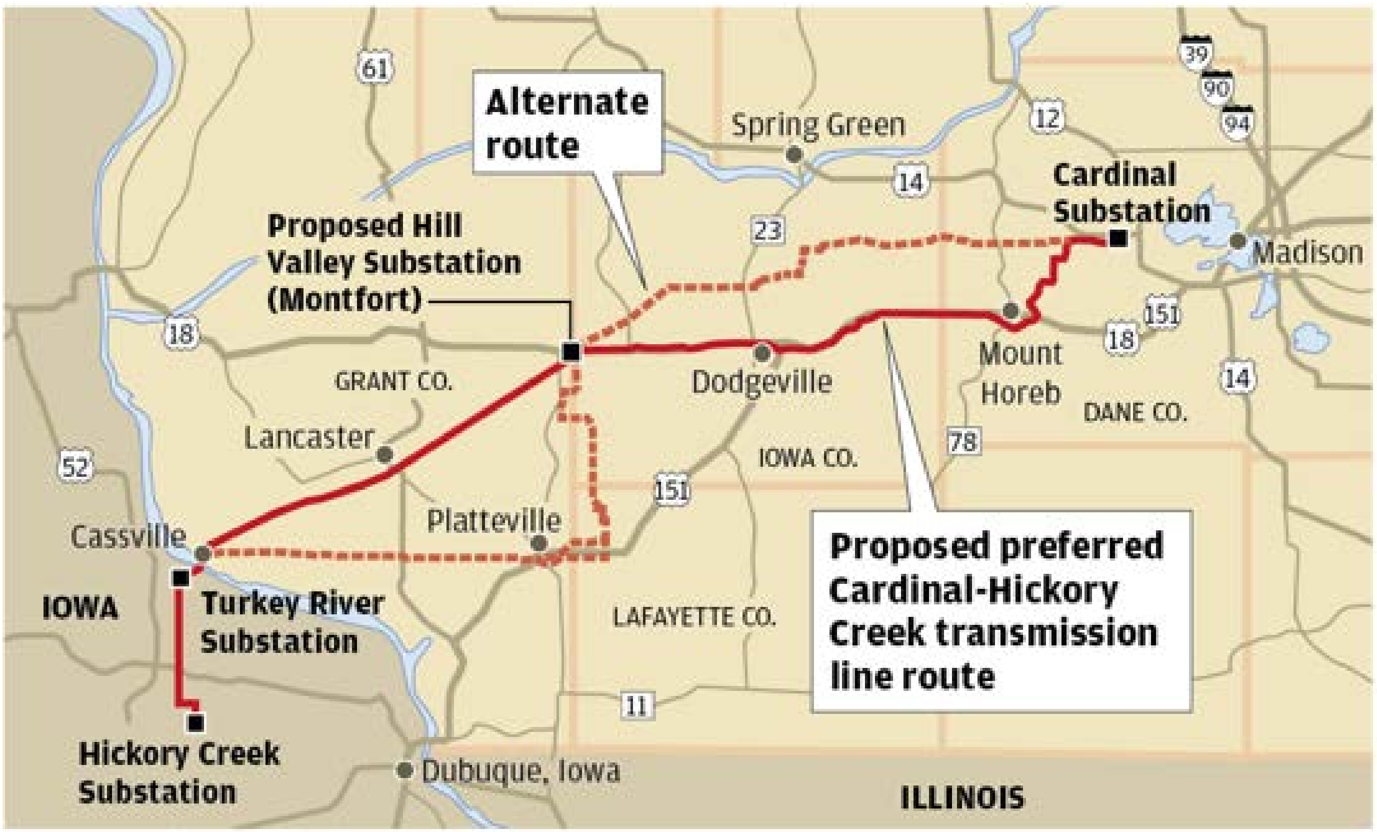
In Wisconsin, many oppose transmission line to bring western wind power



WISCONSIN STATE JOURNAL

July 26, 2019

Illinois, Michigan urge rejection of high-voltage power line in southwestern Wisconsin



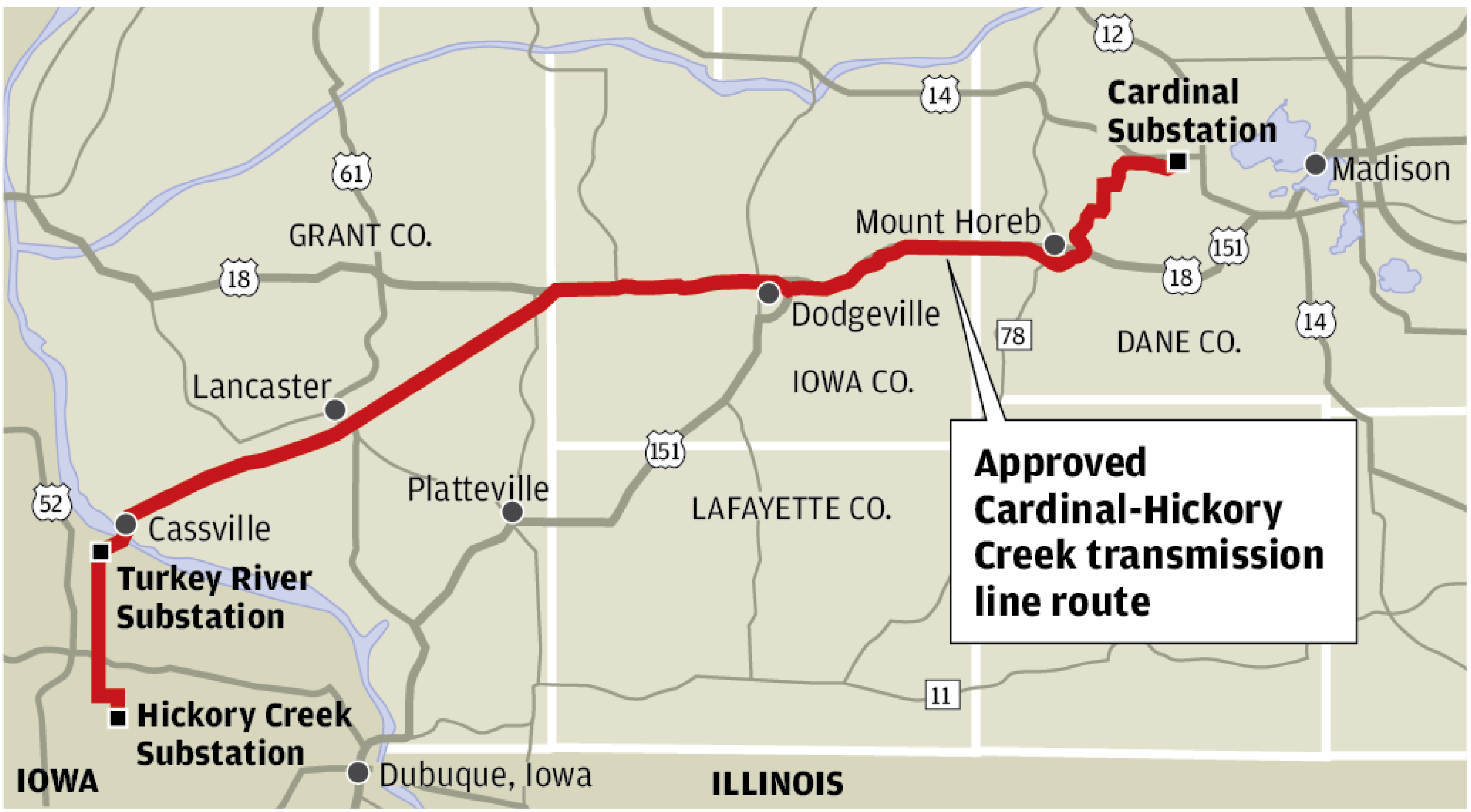
SOURCE: American Transmission Company

State Journal

WISCONSIN STATE JOURNAL

October 19, 2019

Residents seek reconsideration of power line approval
Iowa County votes to sue PSC



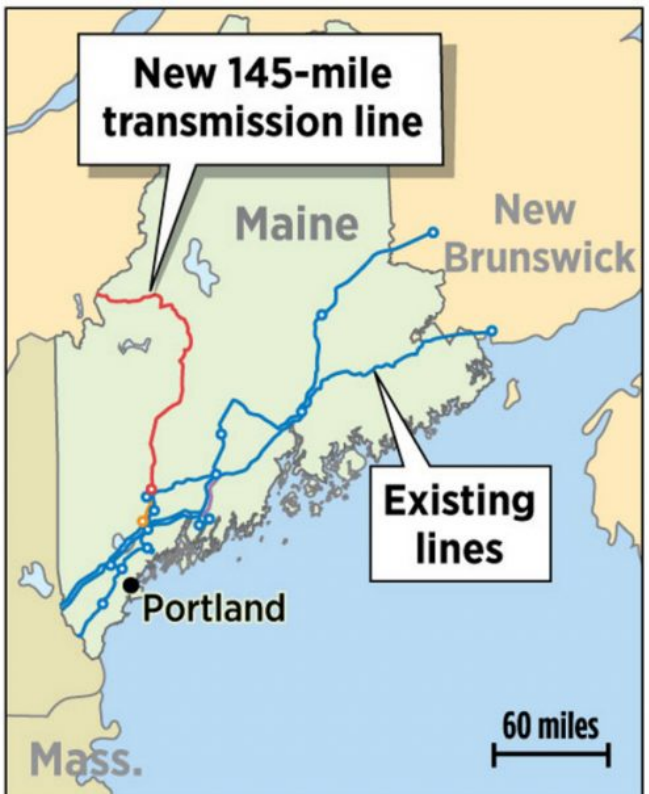
SOURCE: American Transmission Company

State Journal

New England Project

August 15, 2017

Should Northern New England Host Massachusetts' Renewable Energy Extension Cord?

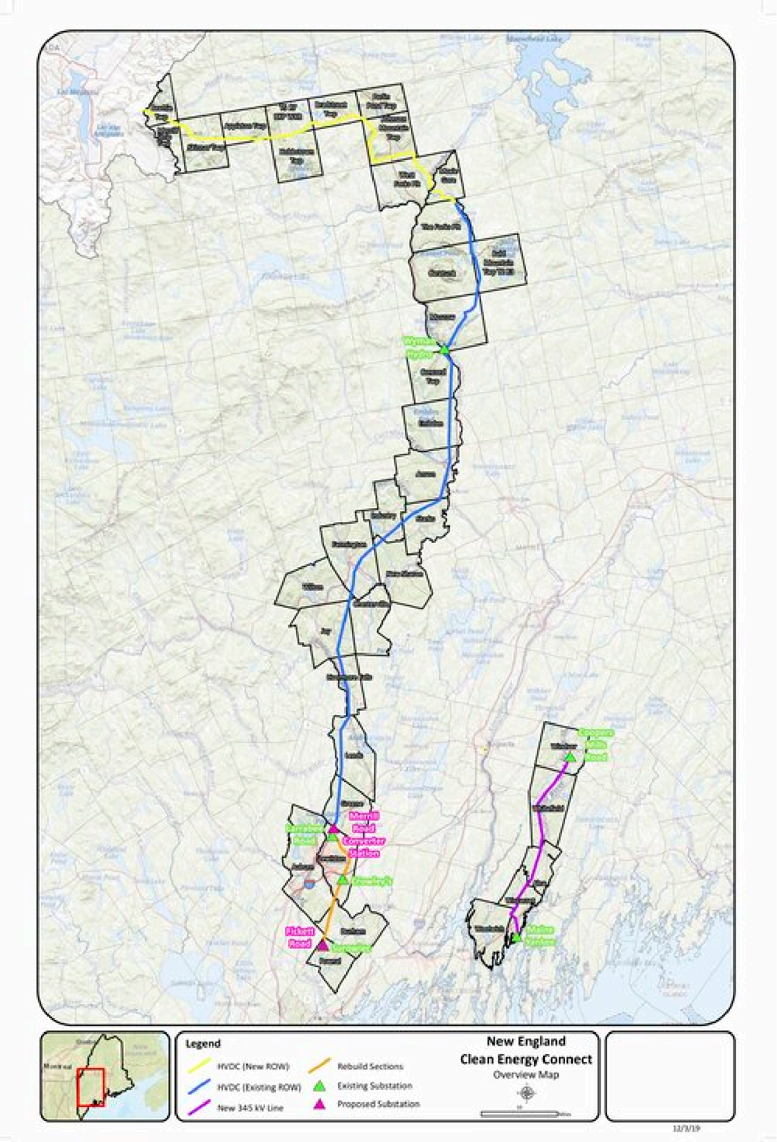


STAFF GRAPHIC | PETE GORSKI

Proposed transmission line

Massachusetts energy officials said Wednesday they will work toward a deal with Central Maine Power Co. for its New England Clean Energy Connect line. The project calls for a 145-mile transmission line to deliver hydropower from Quebec to Massachusetts. The line would extend from Beattie Township to Lewiston to deliver green power to Massachusetts utilities.

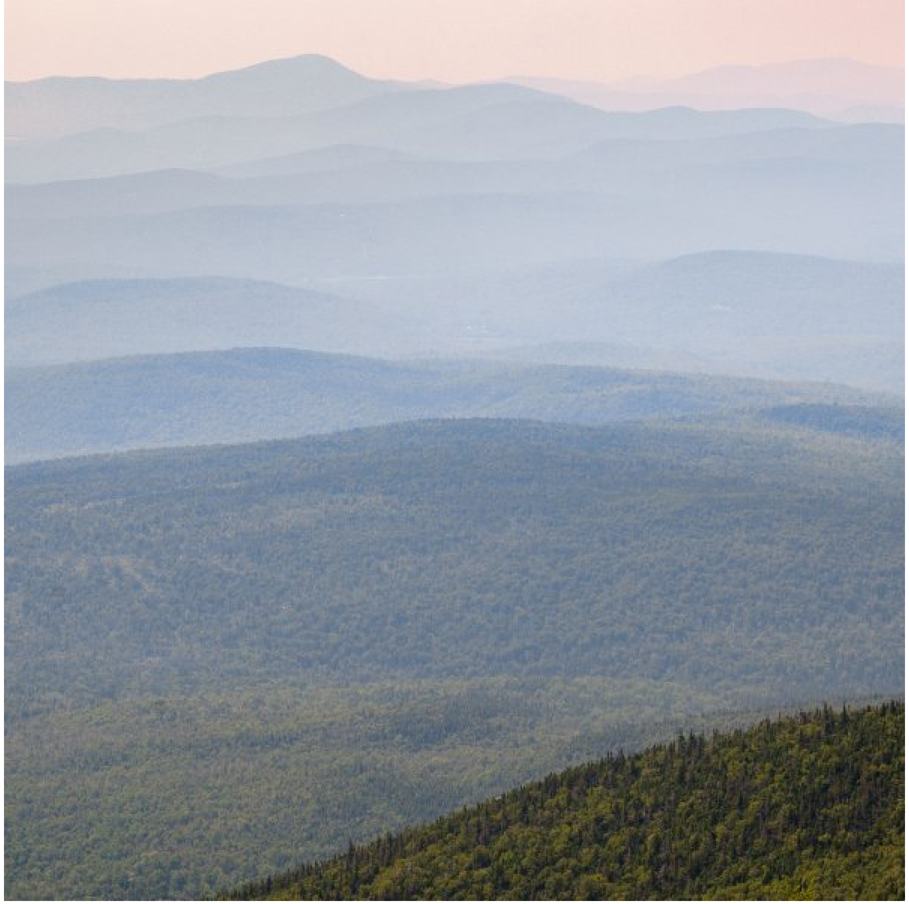
Central Maine Power
New England Clean Energy Connect



Outside

July 12, 2019

Is a Green Future Worth Spoiling the Appalachian Trail?



The Westerly Sun

February 3, 2020

Transmission line foes submit signatures for referendum

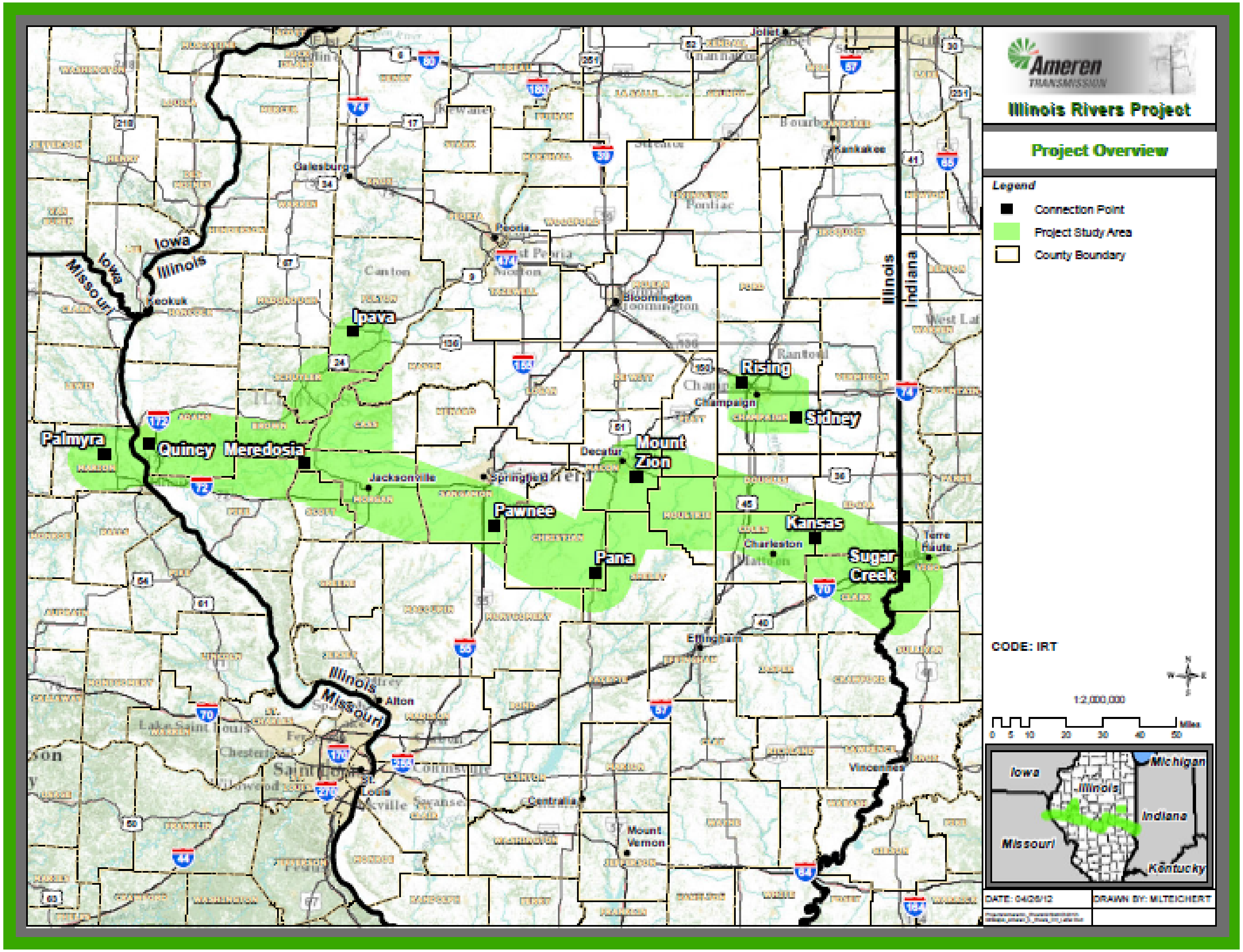
Illinois Project

Illinois Public Media™

January 28, 2013

Senator Rose Cites Concerns with Ameren Line Plans

Ameren Illinois Rivers Project



No wires, no wind.

But, it is not just transmission lines.

Wind farm example (among many)

The Globe

February 27, 2019

Worthington, Iowa

Rural landowners air opposition to industrial wind farms

Solar farm example (among many)

npr

March 25, 2019

Spotsylvania County, Virginia

A Battle Is Raging Over The Largest Solar Farm East Of The Rockies


IT *IS* HARD WALKIN' ON THIS STUFF.
YEP, SON, WE HAVE MET THE ENEMY AND HE IS US.