Grid Integration Challenges for 100% Conversion to Wind, Water, and Sun

Mark Z. Jacobson
Atmosphere/Energy Program
Dept. of Civil & Environmental Engineering
Stanford University

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Grid Integration of Renewables Workshop

Stanford University, January 13, 2011

Cleanest Solutions to Global Warming, Air Pollution, Energy Security – Energy & Env. Sci, 2, 148 (2009)

Recommended – Wind, Water, Sun (WWS)

Electric Power

1. Wind
2. CSP
3. Geothermal
4. Tidal
5. PV
6. Wave
7. Hydroelectricity

Vehicles

WWS-Battery-Electric

WWS-Hydrogen Fuel Cell

Not Recommended

Electric Power

Nuclear

Coal-CCS

Vehicles

Corn ethanol

Cellulosic ethanol

Hydrogen Fuel Cell Ships & Tractors; Liquid Hydrogen Aircraft

Air-Source Heat Pump, Air Source Electric Water Heater, Solar Water Pre-Heater

Heat pump water heater

Powering the World on Renewables

Global end-use power demand 2010

12.5 TW

Global end-use power demand 2030 with current fuels

16.9 TW

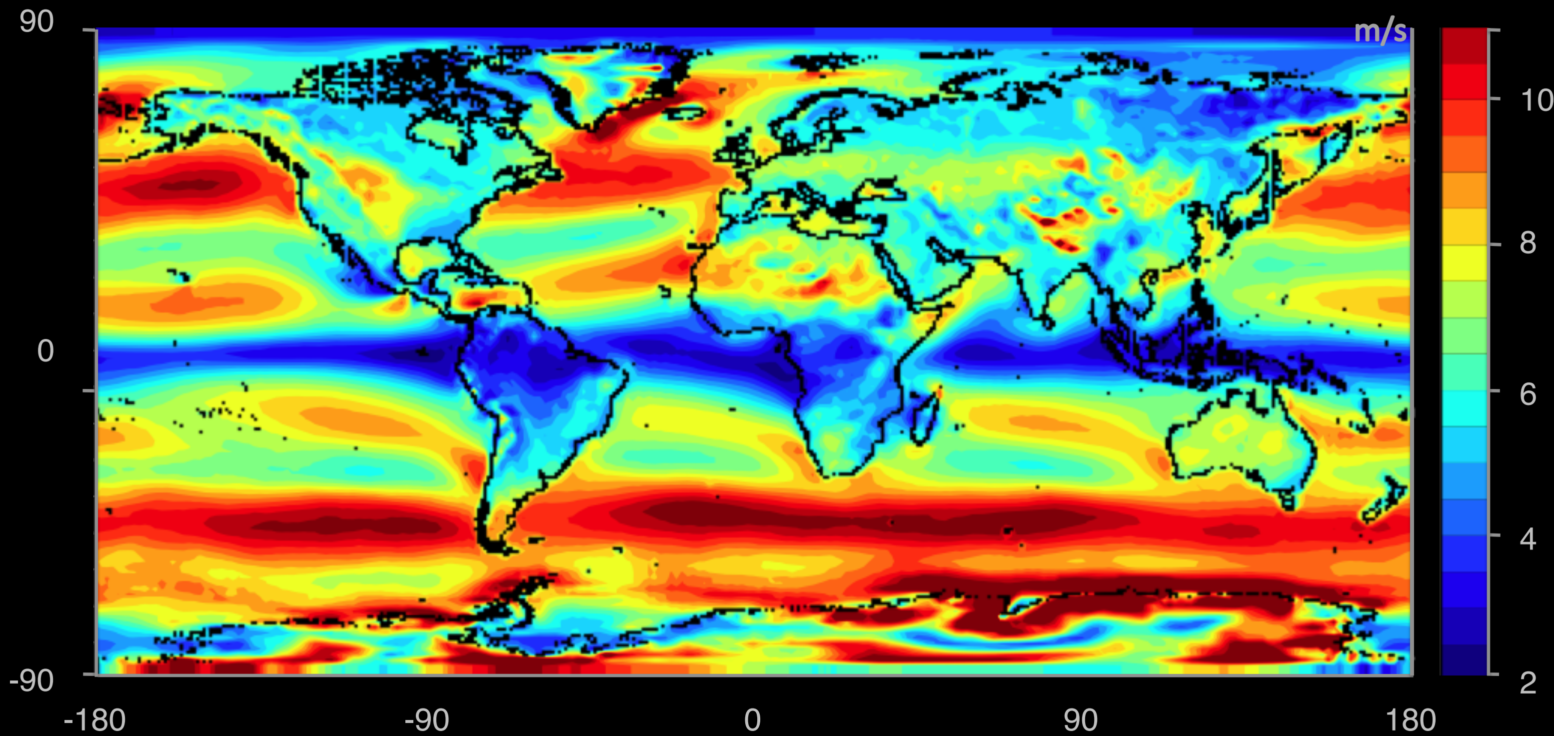
Global end-use power demand 2030 converting all energy to wind-water-sun (WWS) and electricty/H_2

11.5 TW (30% reduction)

Number of Plants or Devices to Power World

Technology	Percent Supply 2030	Number
5-MW wind turbines	50%	3.8 mill. (0.8% in place)
0.75-MW wave devices	1	720,000
100-MW geothermal plants	4	5350 (1.7% in place)
1300-MW hydro plants	4	900 (70% in place)
1-MW tidal turbines	1	490,000
3-kW Roof PV systems	6	1.7 billion
300-MW Solar PV plants	14	40,000
300-MW CSP plants	20	49,000
	100%	

World Wind Speeds at 100m

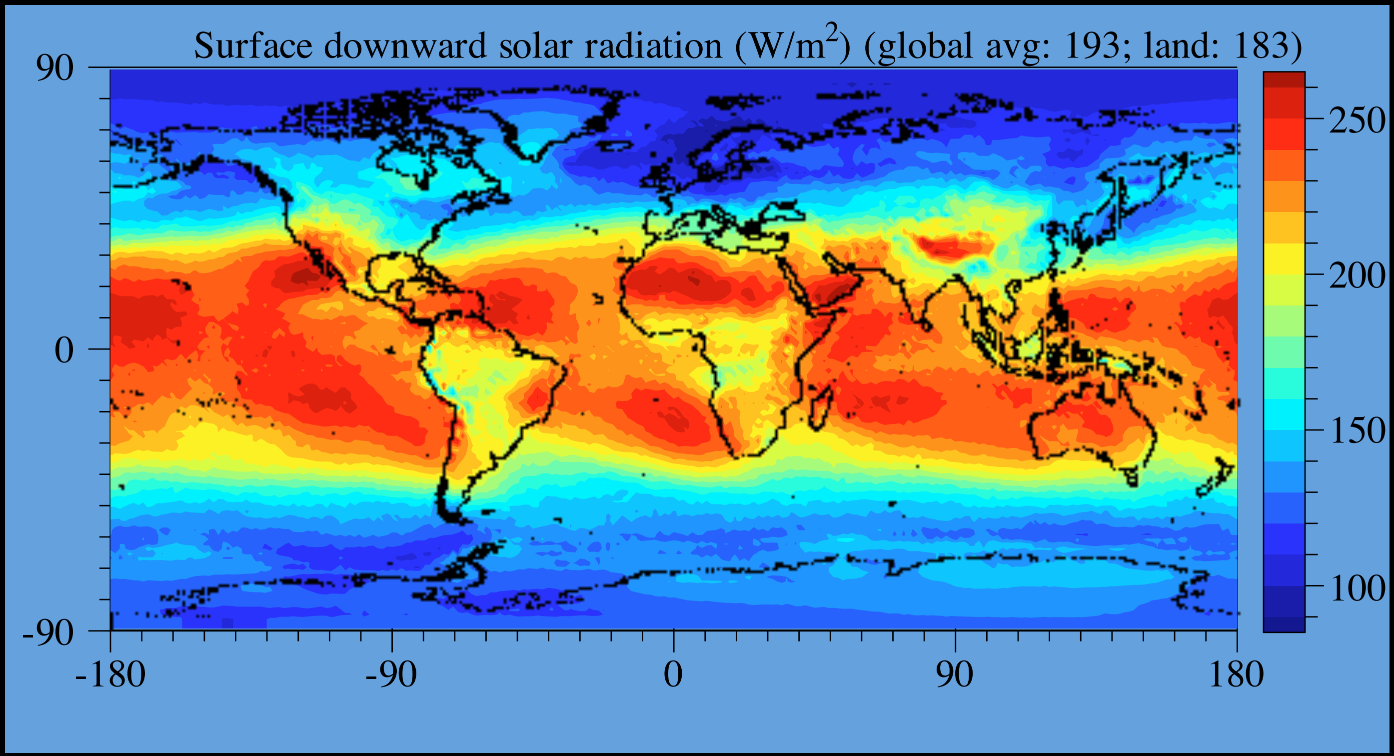


All wind worldwide: 1700 TW;

All wind over land in high-wind areas outside Antarctica ~ 70-170 TW

World power demand 2030: 16.9 TW

World Surface Solar



All solar worldwide: 6500 TW;

All solar over land in high-solar locations~ 340 TW

World power demand 2030: 16.9 TW

Methods of addressing variability of WWS

1. Interconnecting geographically-dispersed WWS resources

2. Bundling WWS resources as one commodity and using hydroelectricity to fill in gaps in supply

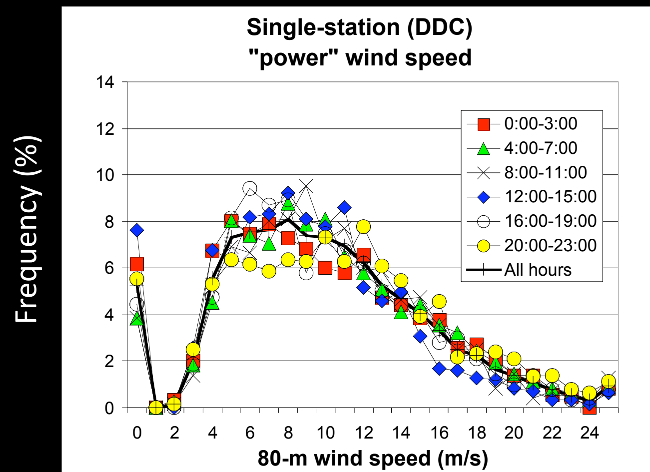
3. Using demand-response management

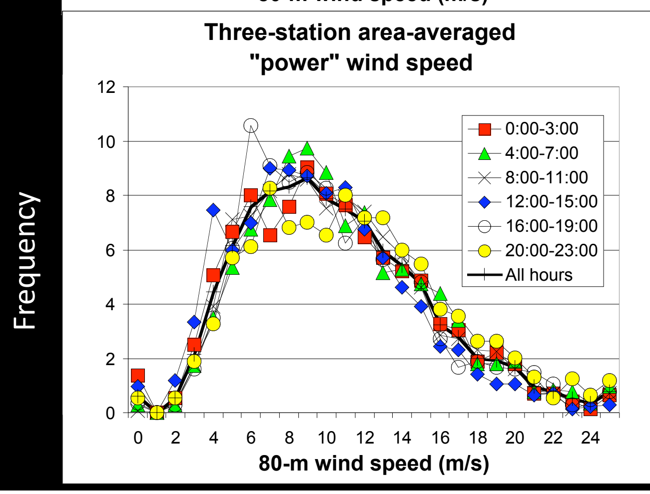
4. Oversizing peak generation capacity and producing hydrogen with excess for industry, transportation

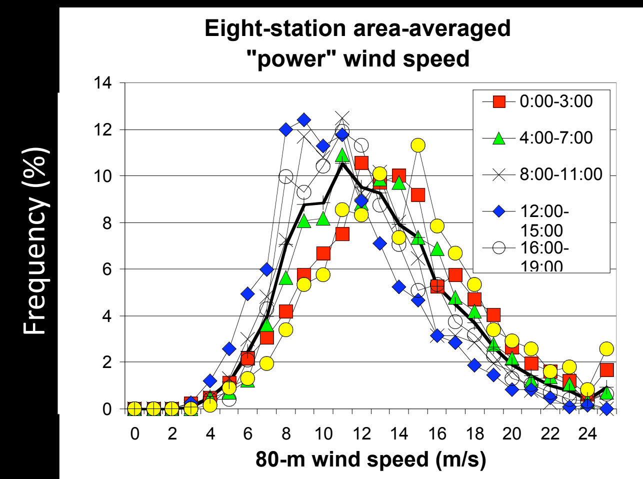
5. Storing electric power on site or in BEVs (e.g., VTG)

6. Forecasting winds and cloudiness better to reduce reserves

Interconnecting Geographically-Dispersed Farms



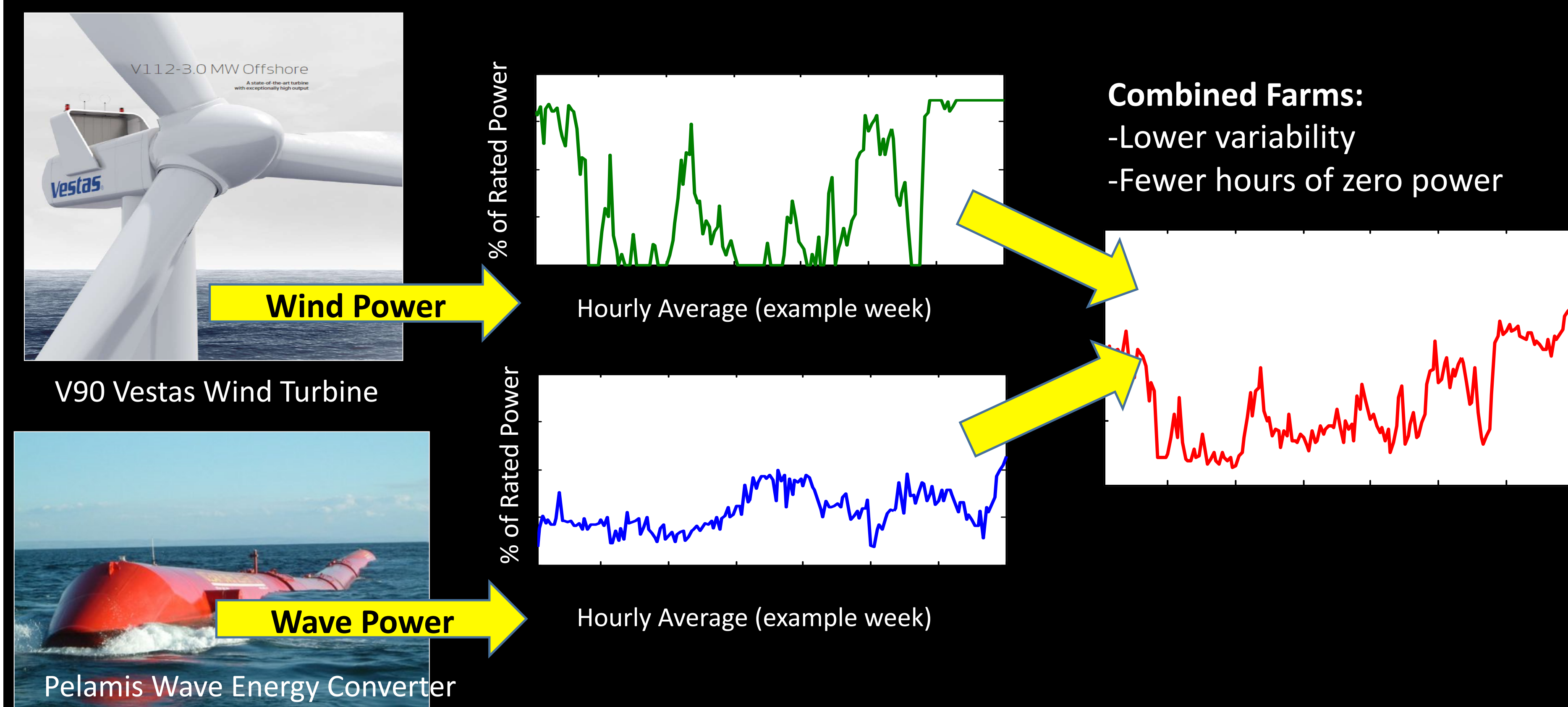




Interconnection (over 550 km x 700 km region) eliminated no-wind hours in aggregate and narrowed the range of the wind speed frequency distribution

Archer and Jacobson (2003)

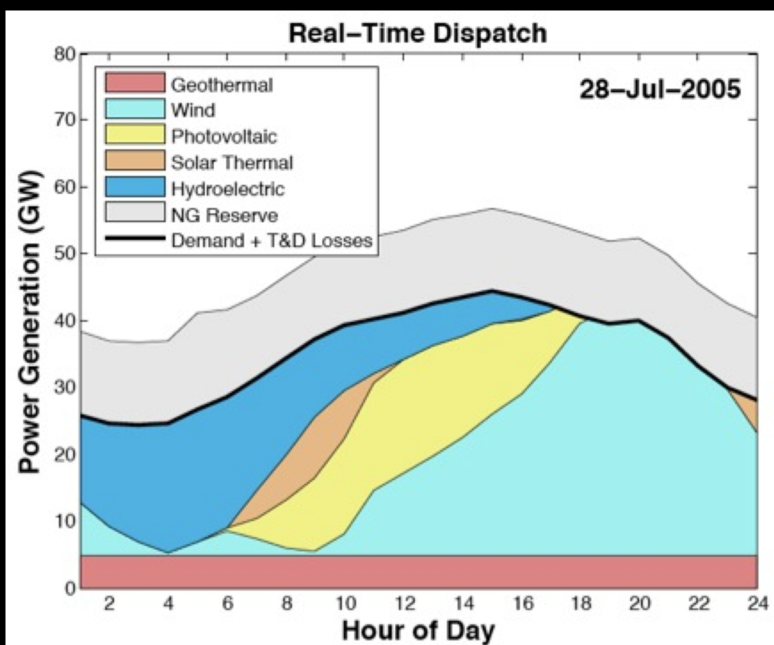
BUNDLING MARINE RENEWABLE RESOURCES

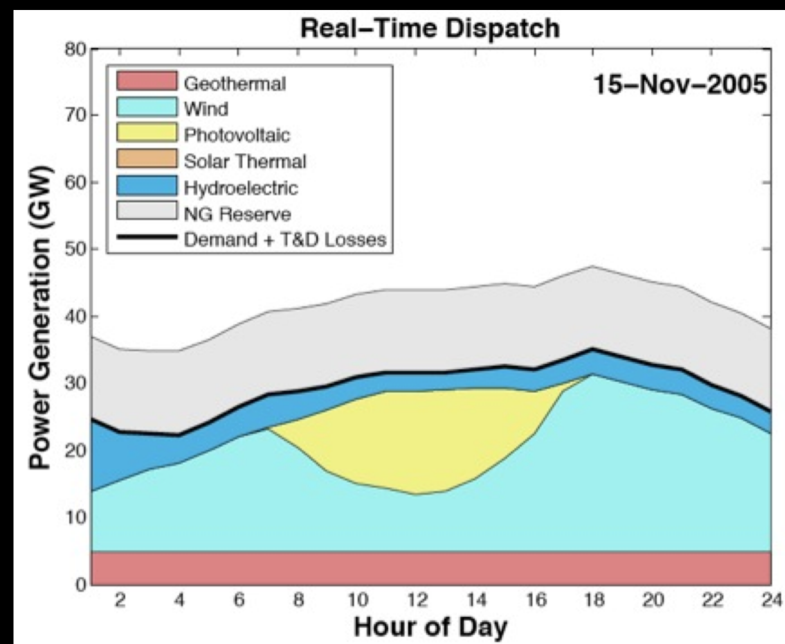


Stoutenburg, E.D., Jenkins, N., Jacobson, M.Z., *Renewable Energy*, doi:10.1016/j.renene.2010.04.033, 2010. Photo credit: NOAA NDBC, Vestas Wind Systems A/S, Pelamis Wave Power Ltd

Matching Hourly Demand With WWS Supply by Aggregating Sites and Bundling WWS Resources – Least Cost Optimization for California

For 99.8% of all hours in 2005, 2006, delivered CA elec. carbon free. Can oversize WWS capacity, use demand-response, forecast, store to reduce NG backup more

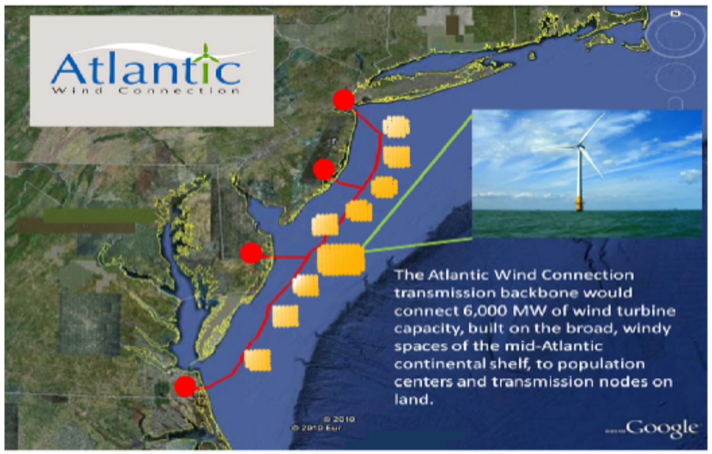


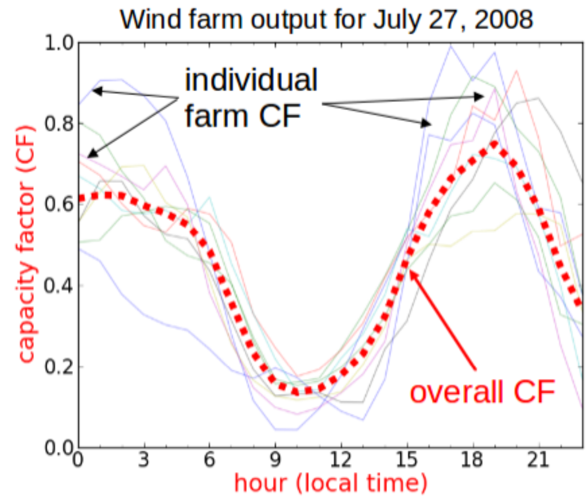


Hart and Jacobson (2011); www.stanford.edu/~ehart/

Modeling the Atlantic offshore grid

Nov. 2008, 90 m avg. wind speed at farm locations
v mean=8.6-9.8 m/s





6 PM

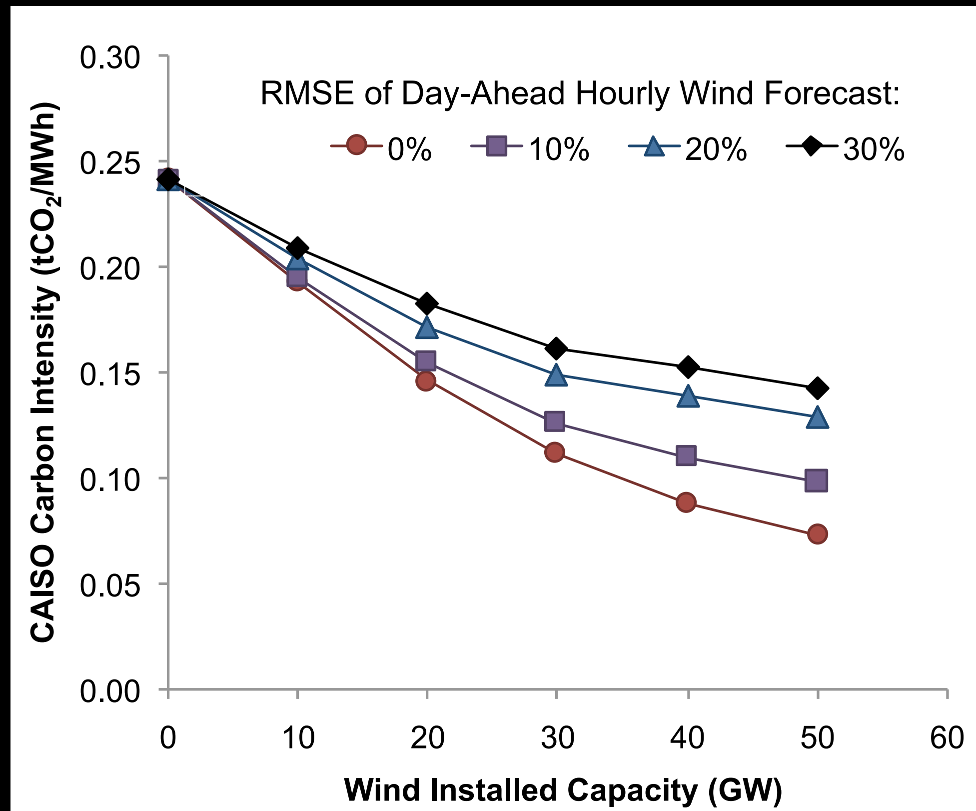
- Strong East Coast offshore wind resource
- Grid can be designed to use peak coincident sea breezes

(Dvorak et al., 2011)

Forecast Accuracy Effects on Reserve Needs

Reducing root-mean-square forecast errors (RMSE) reduces the required spinning reserve capacity from NG, reducing system-wide carbon emissions for 2005-6

Scenario includes 4.8 GW geothermal, 17 GW in+out state hydro, 3.7 GW pumped storage hydro, 35-60 GW NG, no solar



Hart and Jacobson (2011)

Reserve Base for NdO (Tg) Used in Permanent Magnets for Wind Turbine Generators

Country	Reserve Base	Needed to power 50% of world with wind
U.S.	2.1	
Australia	1.0	
China	16.0	
CIS	3.8	
India	0.2	
Others	4.1	
World	27.3	4.4 (0.1 Tg/yr for 44 years)

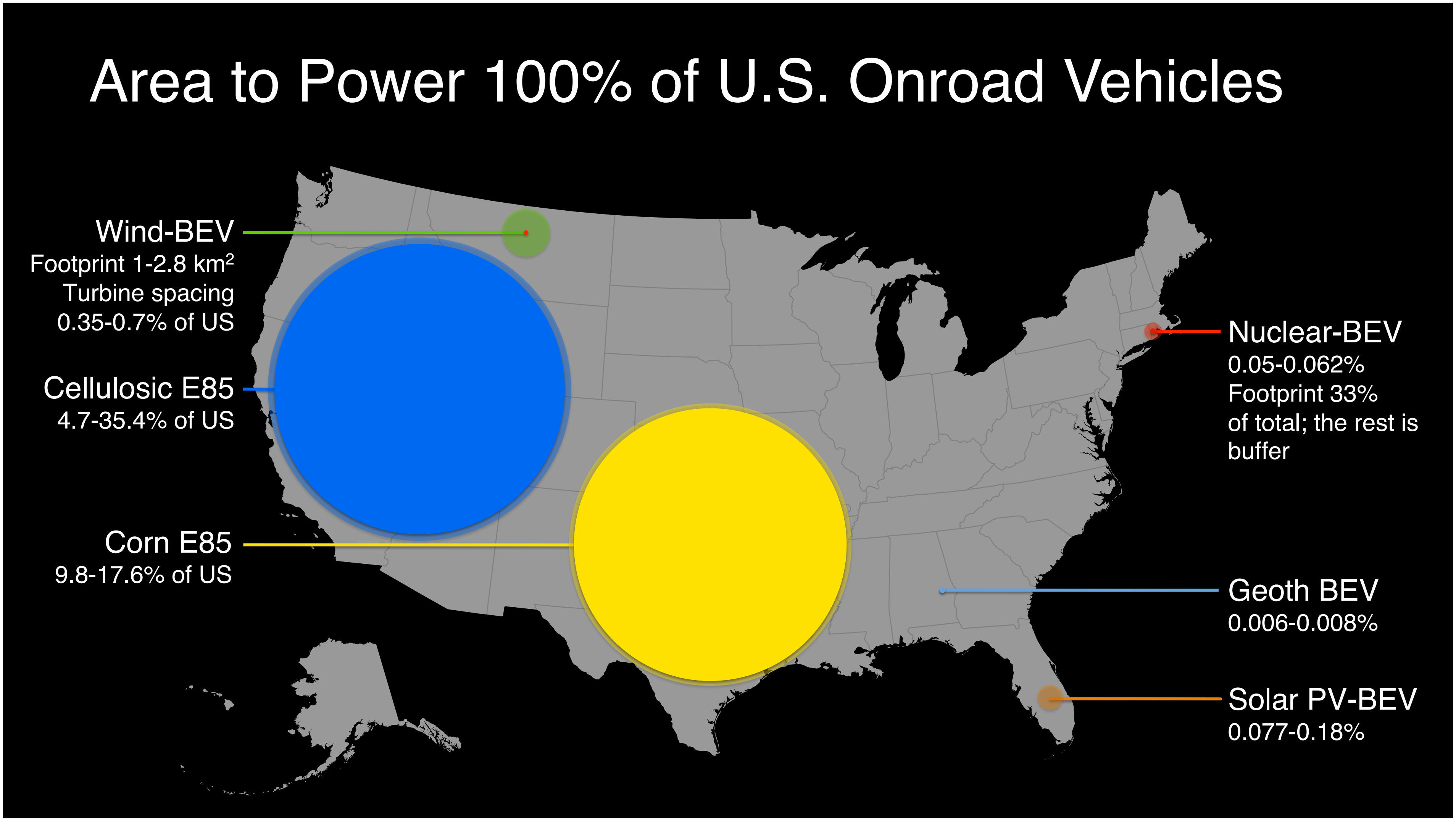
Current production: 0.022 Tg/yr

Jacobson & Delucchi (2010)

Reserve Base for Lithium (Tg) Used in Batteries

Country	Reserve Base	Possible number of vehicles @10kg/each with current known land reserves
U.S.	0.41	
Australia	0.22	
China	1.1	
Bolivia	5.4	
Chile	3.0	
Argentina	?	
Afghanistan	?	
World land	11+	1.1 billion+ (currently 800 million)
Oceans	240	

Jacobson & Delucchi (2010)


Area to Power 100% of U.S. Onroad Vehicles
Wind-BEV
Footprint 1-2.8 km2
Turbine spacing
0.35-0.7% of US
Cellulosic E85
4.7-35.4% of US
Corn E85
9.8-17.6% of US
Nuclear-BEV
0.05-0.062%
Footprint 33%
of total; the rest is
buffer
Geoth BEV
0.006-0.008%
Solar PV-BEV
0.077-0.18%

Long-Distance Transmission Costs (2007 $US)

Component	Low	Med	High
Transmission distance (km)	1200	1600	2000
Power capacity (MW)	5000	5000	5000
Wind capacity factor	0.45	0.38	0.33
Line, land, tower cost ($/MW)	240,000	450,000	680,000
Station equipment ($/MW)	120,000	150,000	180,000
Transmission loss (%/1000 km)	3	4	6
Transmission line lifetime (yrs)	70	60	50
Station equipment lifetime (yrs)	30	30	30
Discount rate (%/yr)	3	7	10
Cost of l.d. transmission (¢/kWh)	0.3	1.2	3.2

Delucchi & Jacobson (2010)

Costs of Energy, Including Transmission (¢/kWh)

Energy Technology	2005-2010	2020-2030
Wind onshore	4-7	≤4
Wind offshore	10-17	8-13
Wave	>>11	4-11
Geothermal	4-7	4-7
Hydroelectric	4	4
CSP	11-15	8
Solar PV	>20	10
Tidal	>>11	5-7
Conventional (+Externalities)	7 (+5)=12	5-7 (+5.5) =10.5-12.5

Delucchi & Jacobson (2010)

Summary

2030 electricity cost 4-10¢/kWh for most, 8-13 for some WWS , vs. fossil-fuel 5-7 + 5.5 externality = 10.5-12.5¢/kWh

Includes long-distance transmission (1200-2000 km) ~1¢/kWh

Requires only 0.41% of world land for footprint; 0.59% for spacing (compared with 40% of world land for cropland and pasture)

→Eliminates 2.5-3 million air pollution deaths/year

→Eliminates global warming, provides energy stability

Summary, cont.

Converting to Wind, Water, & Sun (WWS) and electricity/H_2 will reduce global power demand by 30%

Methods of addressing WWS variability: (a) interconnecting geographically-dispersed WWS; (b) bundling WWS and using hydro to fill in gaps; (c) demand-response; (d) oversizing peak capacity and producing hydrogen with excess for industry, vehicles; (e) on-site storage; (f) forecasting

Materials are not limits although recycling may be needed.

Barriers : up-front costs, transmission needs, lobbying, politics.

New papers:
www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html

New Electric Power Generation 2009

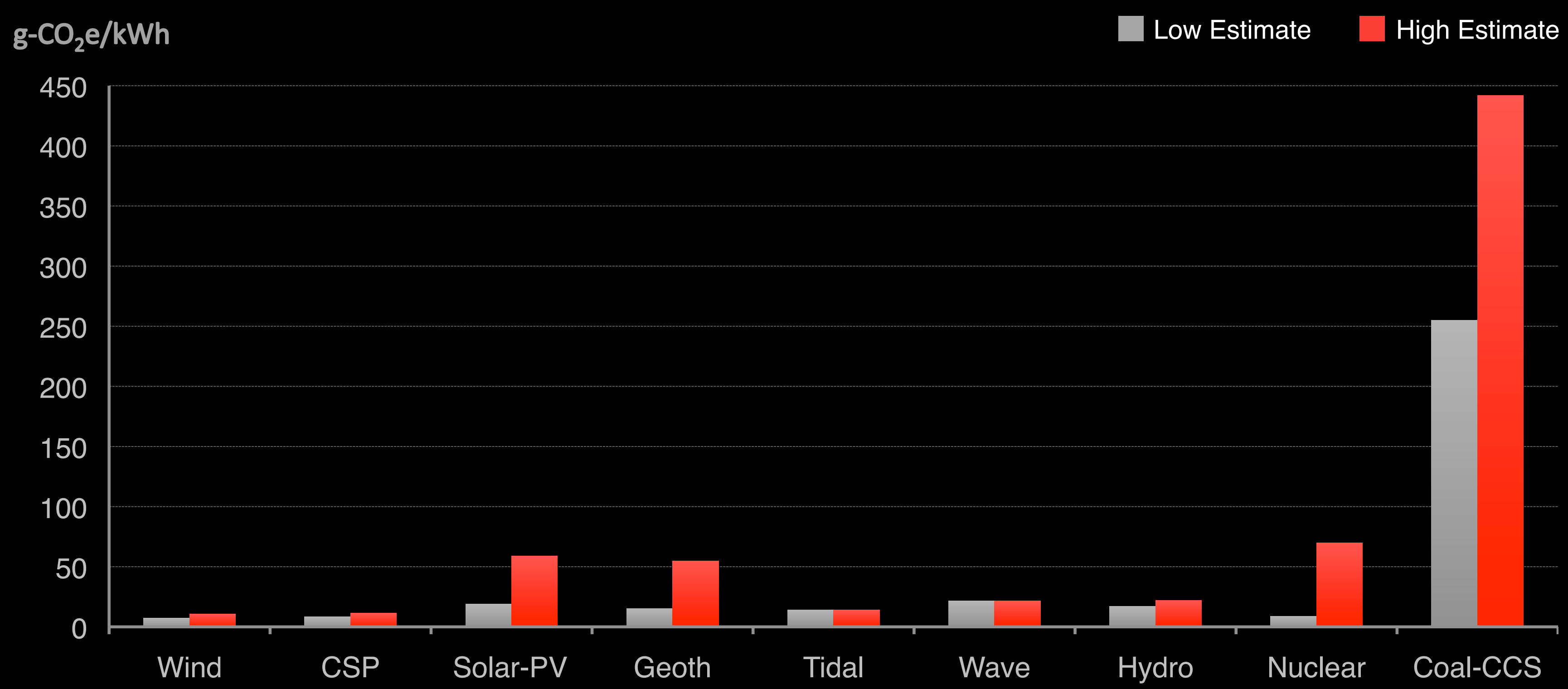
U.S.

1. Natural Gas (41%)
2. Wind (39%)
3. Coal

E.U.

1. Wind (39%)
2. Natural Gas (26%)
3. Solar (16%)
4. More coal, nuclear decommissioned than installed

Lifecycle CO_2e of Electricity Sources

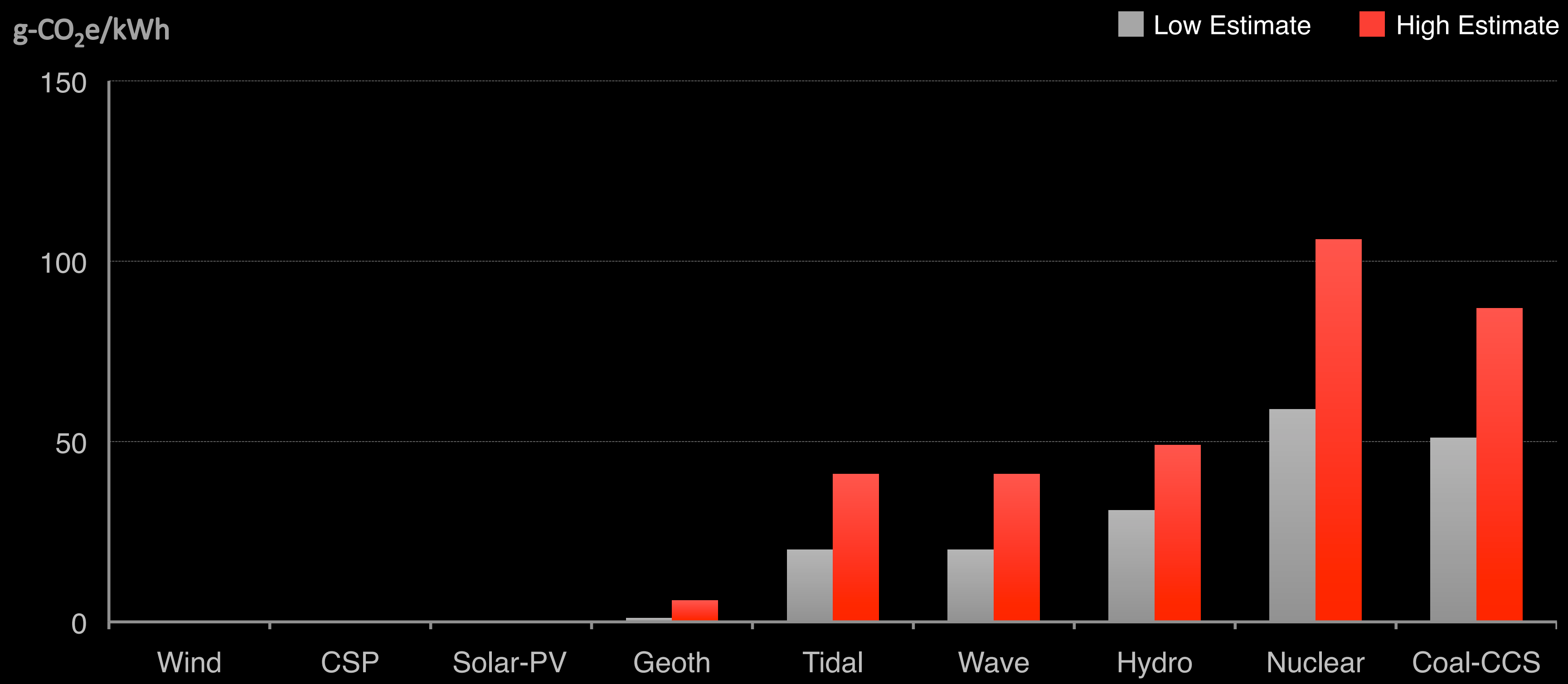


Time Between Planning & Operation

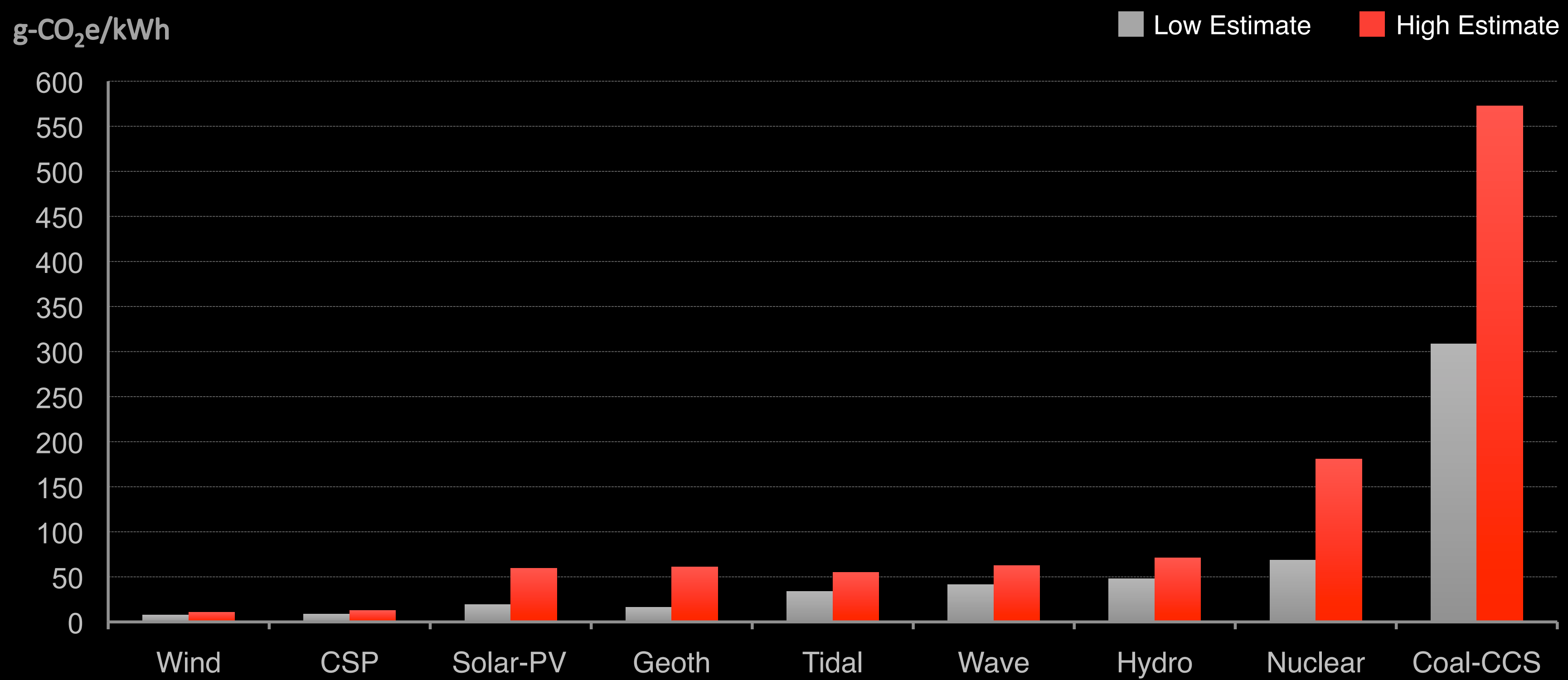
Nuclear:	10 - 19 y (life 40 y)
	Site permit: 3.5 - 6 y
	Construction permit approval and issue 2.5 - 4 y
	Construction time 4 - 9 years

Hydroelectric:	8 - 16 y (life 80 y)
Coal-CCS:	6 - 11 y (life 35 y)
Geothermal:	3 - 6 y (life 35 y)
Ethanol, CSP, Solar-PV, Wave, Tidal, Wind:	2 - 5 y (life 40 y)

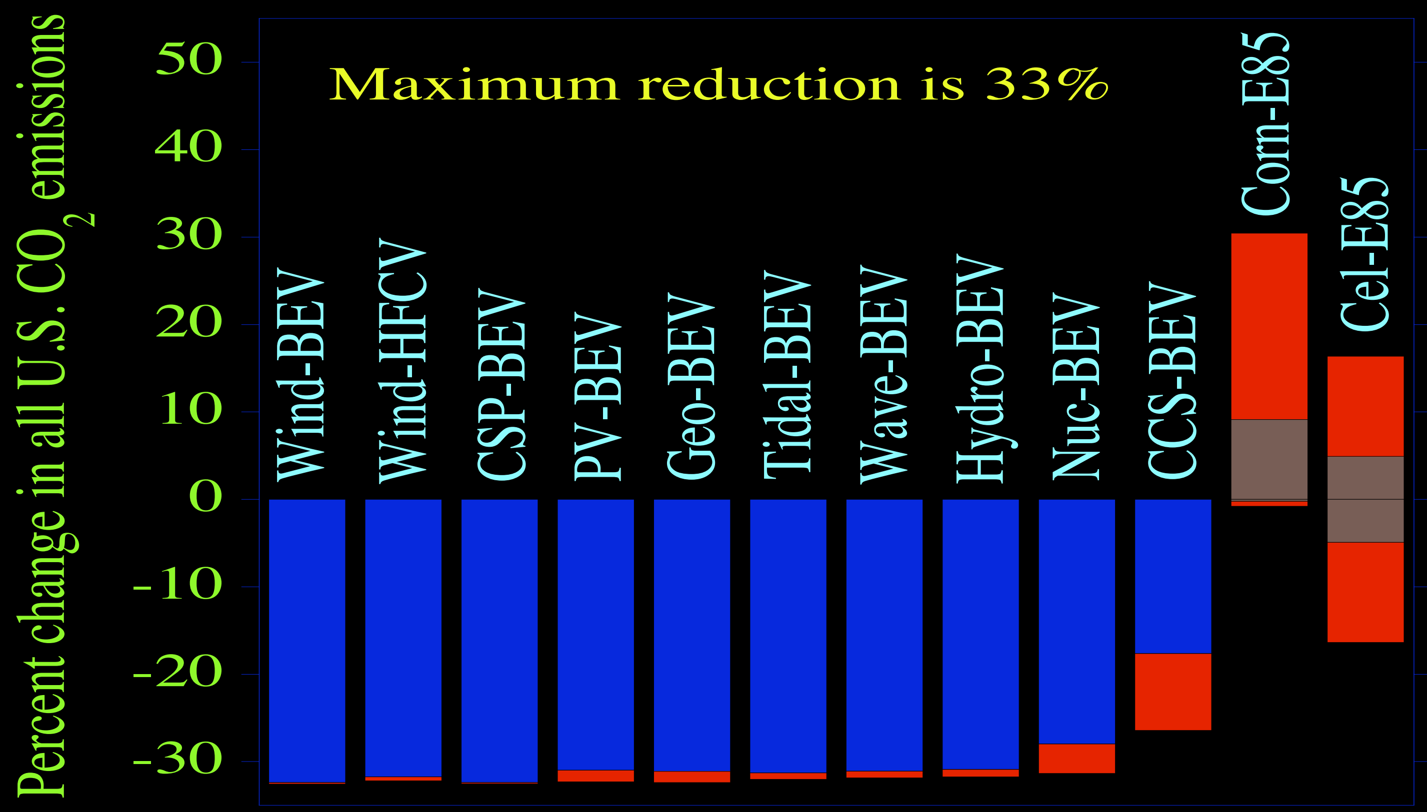
CO_2e From Current Power Mix due to Planning-to-Operation Delays, Relative to Wind



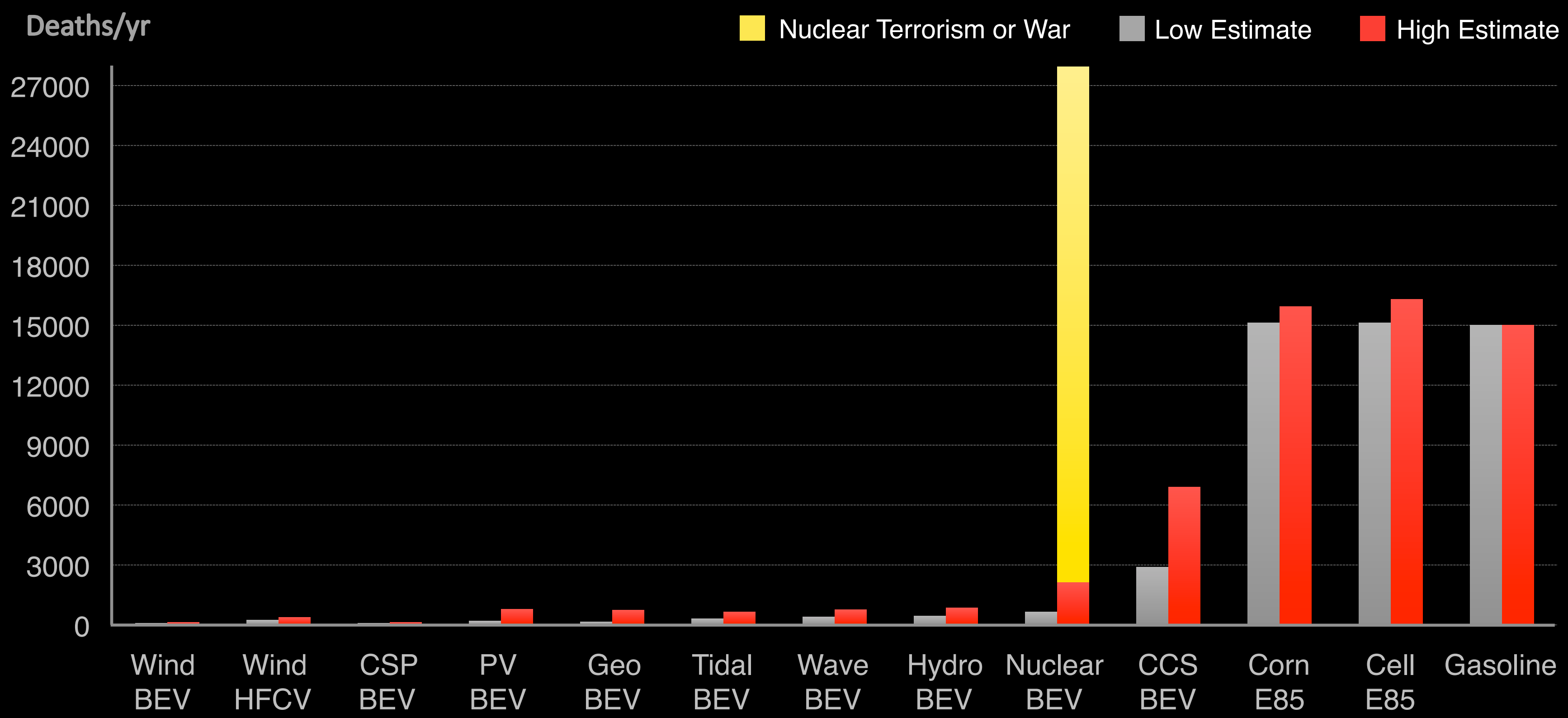
Total CO_2e of Electricity Sources



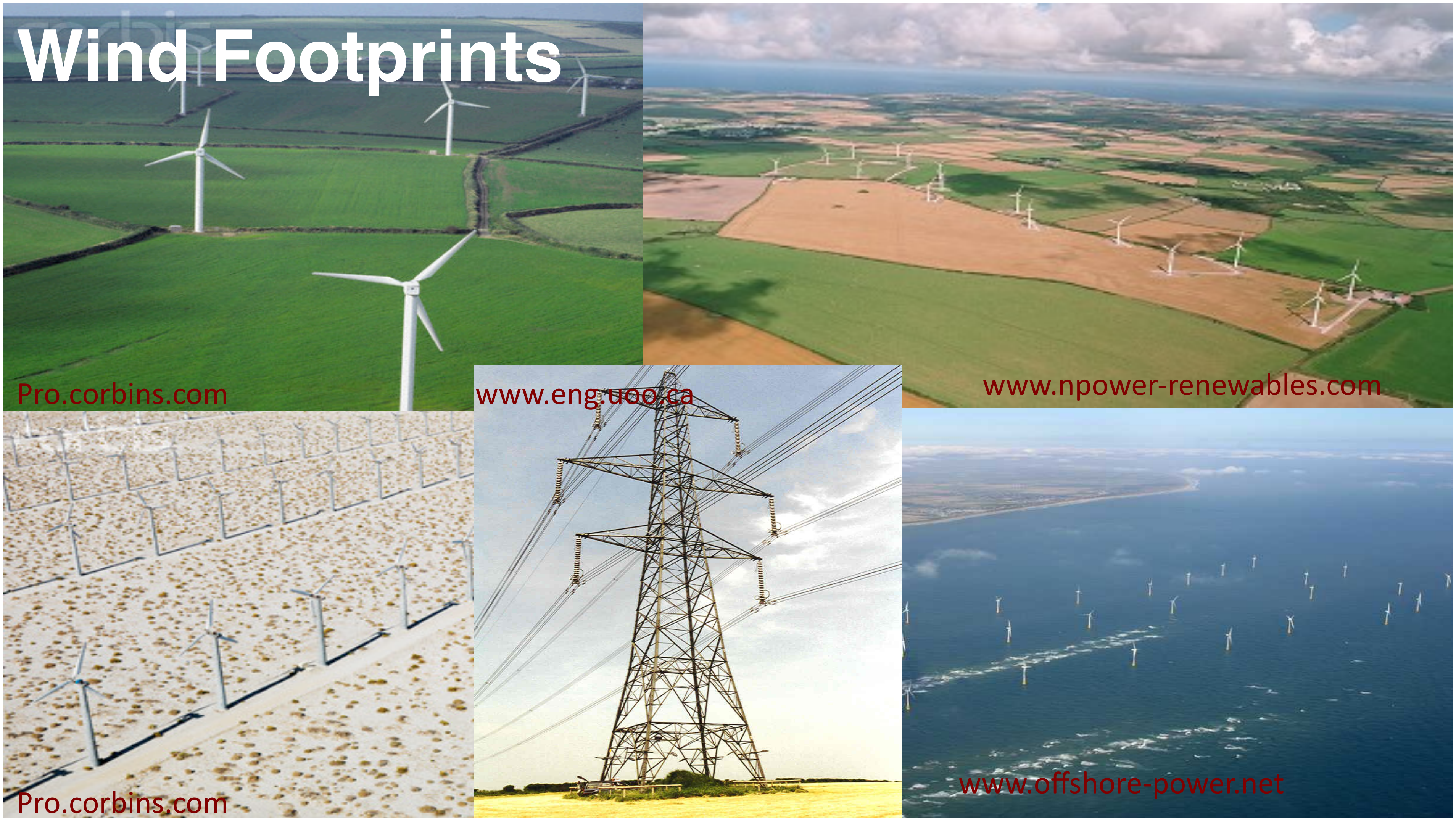
Change in U.S. CO_2 (%) From Converting to BEVs, HFCVs, or E85



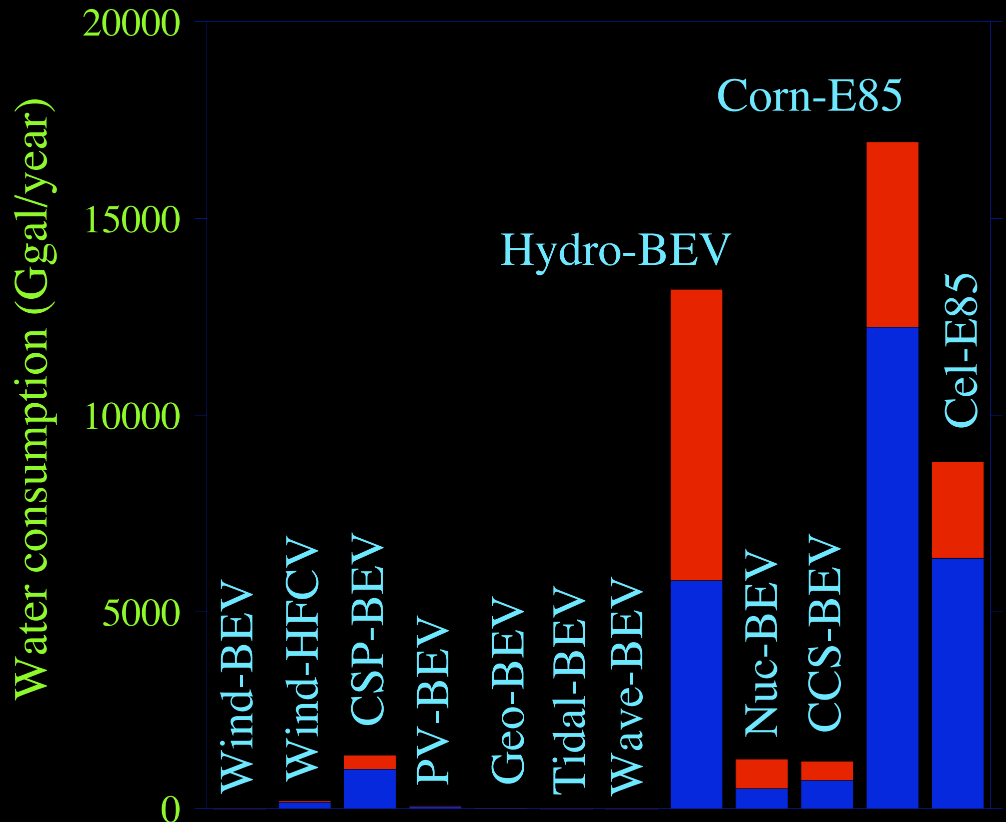
Low/High U.S. Air Pollution Deaths/yr For 2020 Upon Conversion of U.S. Vehicle Fleet



Wind Footprints



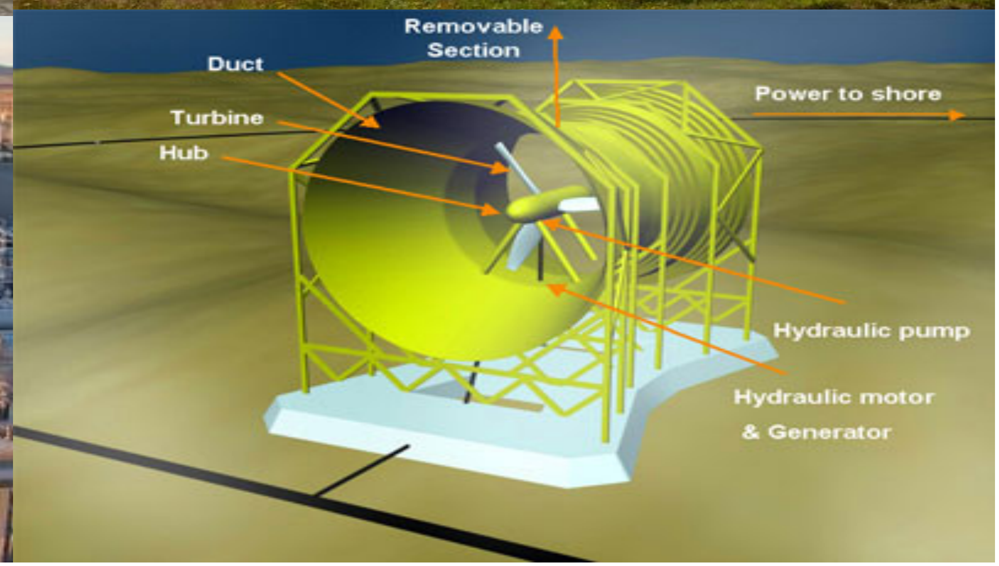
Water Consumed to Run U.S. Vehicles



U.S. water demand = 150,000 Ggal/yr

Wind Power, Wind-Driven Wave Power

Hydroelectric, Geothermal, Tidal Power



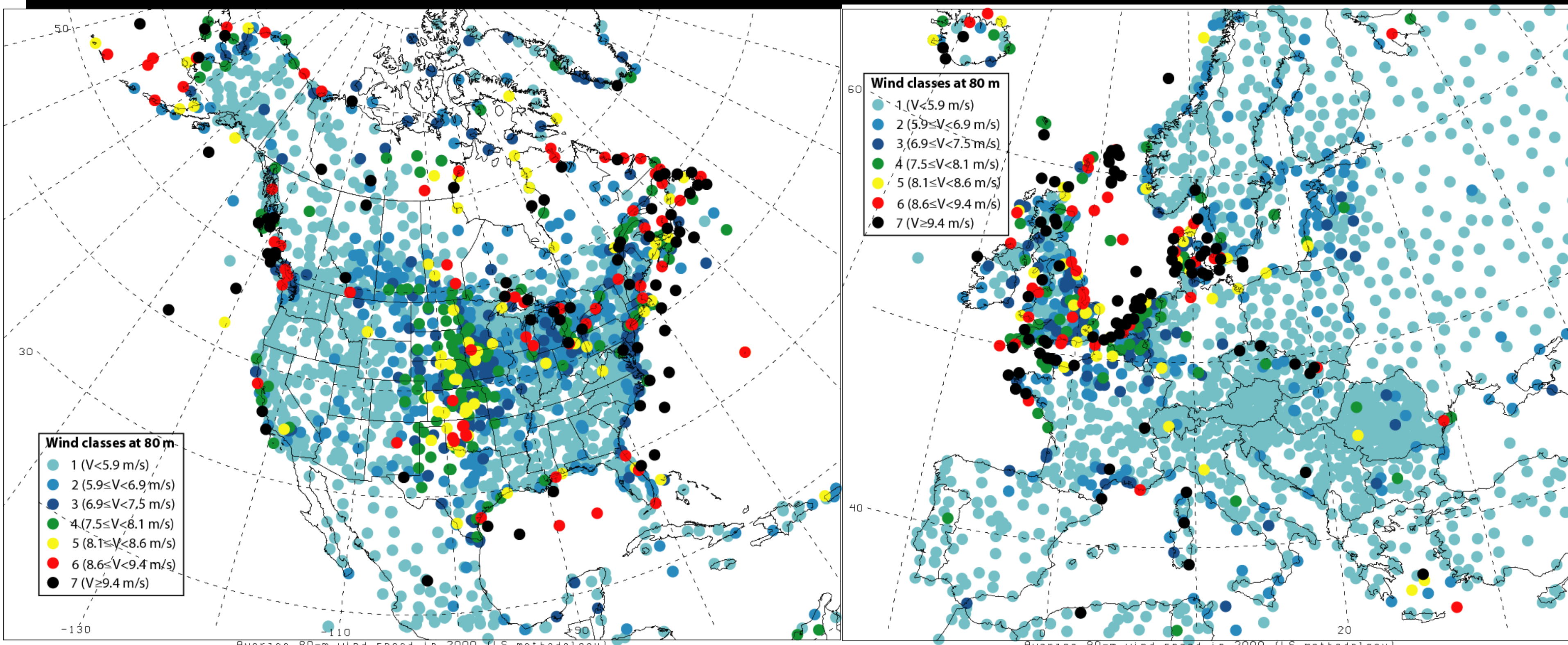
Concentrated Solar Power, PV Power

Materials

- Wind
  - Steel/concrete for towers, steel for rotors
    - No real limits -- 98% of steel currently recycled
  - Neodymium for permanent magnets in generators
    - Enough for wind to power 50% of world for 100 years without recycling
- Solar
  - Silver (used as an electrode), germanium (used in multi junction cells)
    - Silver presents challenges but not a limit, particularly with recycling
    - Substitute more abundant gallium for germanium

- Lithium for batteries
  - Known land resources over 28 million tonnes
  - Enough land supply for 52 million vehicles/yr for over 25 yrs.
  - Ocean contains another 240 million tonnes.

80-m Wind Speeds From Data



Archer and Jacobson (2005) www.stanford.edu/group/efmh/winds/