100% Clean, Renewable Energy and Storage for Everything

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Leonardo Energy Webinar

February 24, 2021

What are the Problems? Why act Quickly?

Fossil-fuel and biofuel air pollution cause ~7 million air pollution deaths per year worldwide costing ~$30 trillion/year

Global warming will cost the world ~$25-30 trillion per year by 2050.

Fossil fuels will become scarce over time, increasing energy prices and economic, political, and social instability

Drastic problems require immediate solutions

Wind, Water, Solar (WWS) Solution

Electrify or Provide Direct Heat For All Sectors and Provide the Electricity and Heat with 100% WWS

ELECTRICITY	TRANSPORTATION	HEATING/COOLING	INDUSTRY
Wind	Battery-electric	Electric heat pumps	Electric arc furnaces
Solar PV/CSP	H_2 fuel cell	Solar heat	Induction furnaces
Geothermal		Geothermal heat	Resistance furnaces
Hydro		District heat/cold	Dielectric heaters
Tidal/Wave			Electron beam heaters

Onshore and Floating Offshore Wind

Solar Photovoltaics (PV)

Electric & Hydrogen Fuel Cell Transportation

Tesla Semi-electric (850km)

Nikola Tre Semi-hydrogen fuel cell (1200 km)

Fjellstrand electric ferry

Protera electric bus

Planes: Replace w/Battery Electric & Hydrogen Fuel Cell

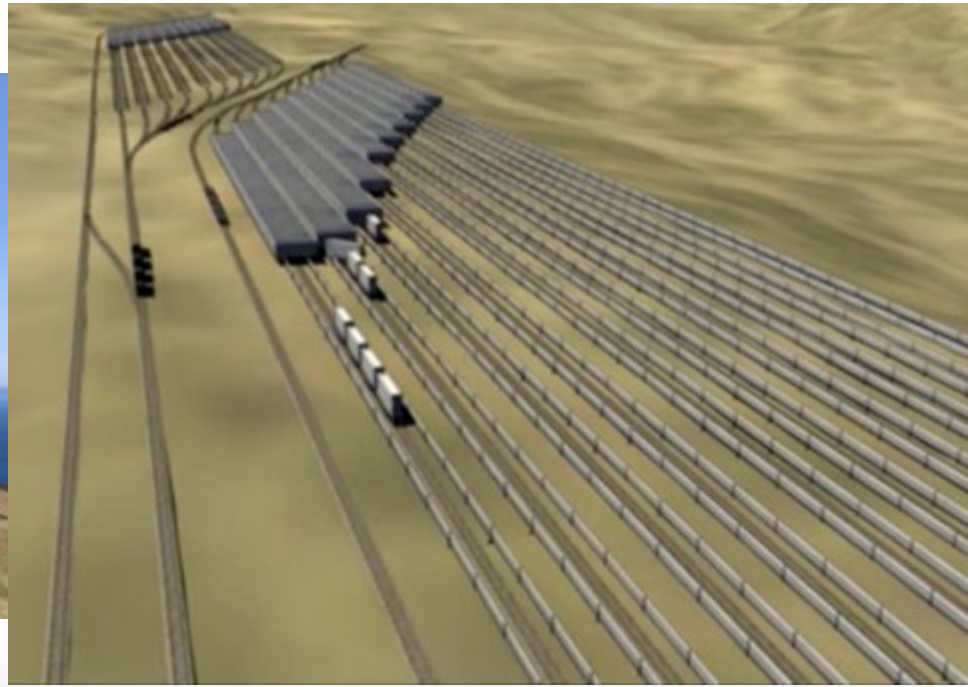
9-seat battery electric-MagniX

4-seat hydrogen fuel cell aircraft

Types of Storage for a 100% WWS System

ELECTRICITY	HEATING/COOLING	OTHER
CSP with storage	Water tank	Hydrogen
Pumped hydro storage	Ice	
Existing hydroelectric	Underground	
Batteries	Borehole	
Flywheels	Water Pit	
Compressed air	Aquifer	
Gravitational Storage	Building materials	

Gravitational Storage With Solid Masses



Stanford University 4th Generation District Heating System

Seasonal Heat Storage in Underground Boreholes
Okotoks, Canada

http://www.sustainapedia.com/drake-landing-solar-community/ https://www.leidos.com/project/north-america's-first- Mark Z. Jacobson (2015) right

Seasonal District Heat Storage in Covered Water Pit
Vojens, Denmark

Nighttime Storage in Ice for Daytime Air Cooling

Transitioning an Individual Home to Run on WWS Electricity/Storage and No Gas

Rooftop Solar Plus Battery Storage

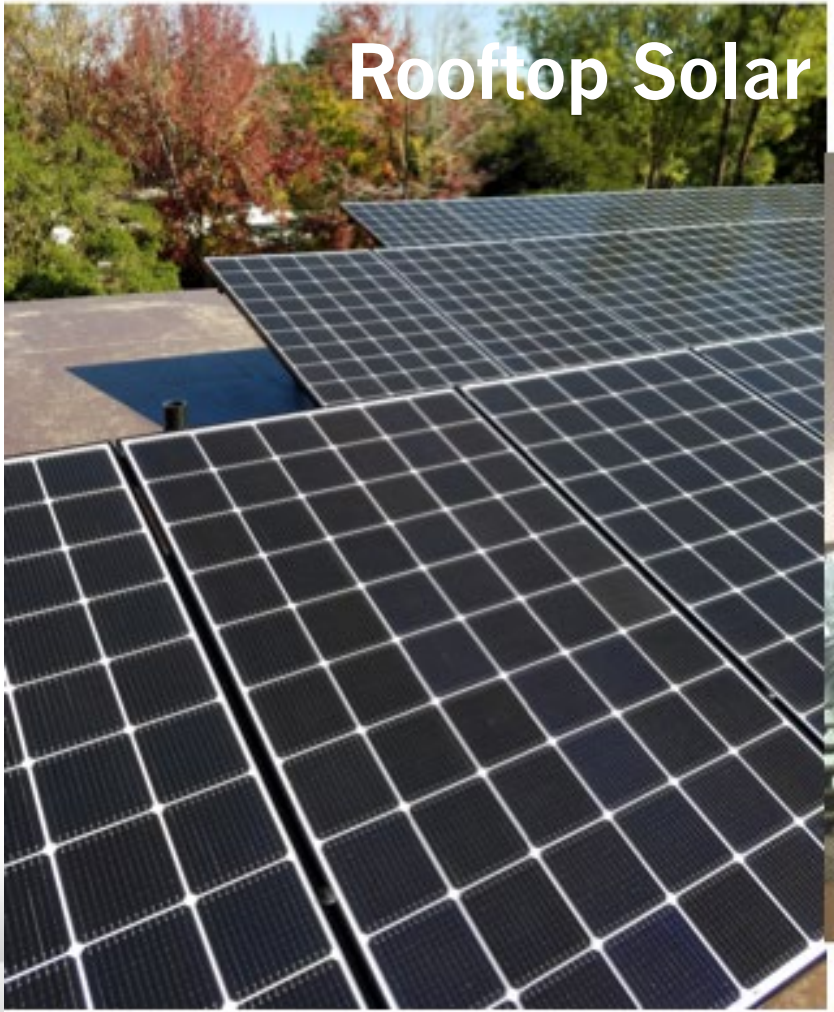


Photo by M.Z. Jacobson

Ductless Mini-Split Electric Heat Pump Air Heater / Air Conditioner

M.Z. Jacobson

Electric Heat Pump Water Heater

Photo by M.Z. Jacobson

Electric Induction Cooktop

Photo by M.Z. Jacobson

Three Years of Energy Use

Generated 120% of all home and vehicle energy

→ No electric bill, natural gas bill, or gasoline bill

Received average $700/yr from CCA for excess electricity to grid

Avoided costs of all-electric home

Gas hookup fee: 3-8 K

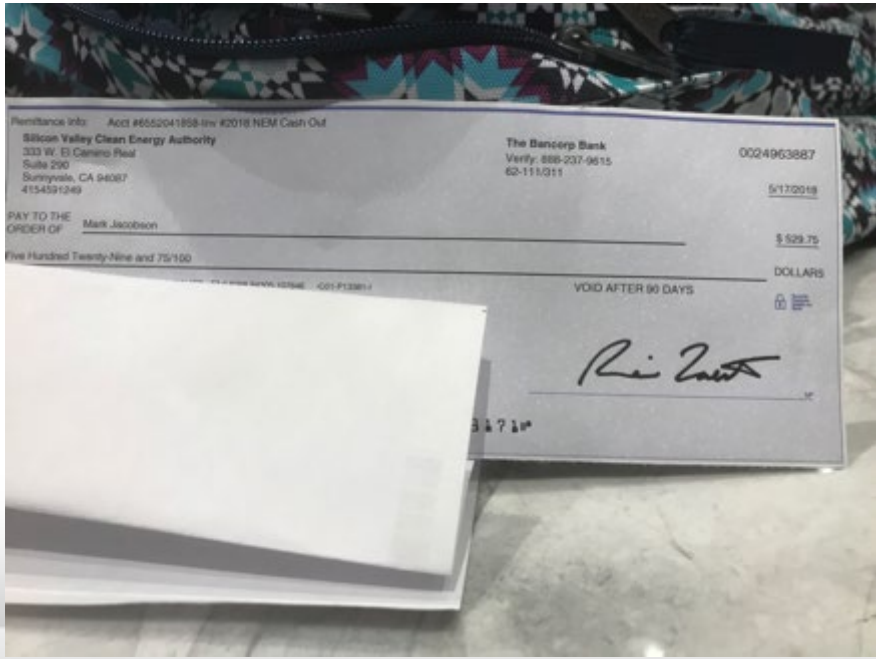
Gas pipes: 1-7 K

Electric bill 1-3 K per year

Natural gas bill 1-3 K per year

Vehicle fuel bill 1-4 K per year

Total: 4-15 K plus 3-10 K per year



No Blackout on Hottest Day of Year

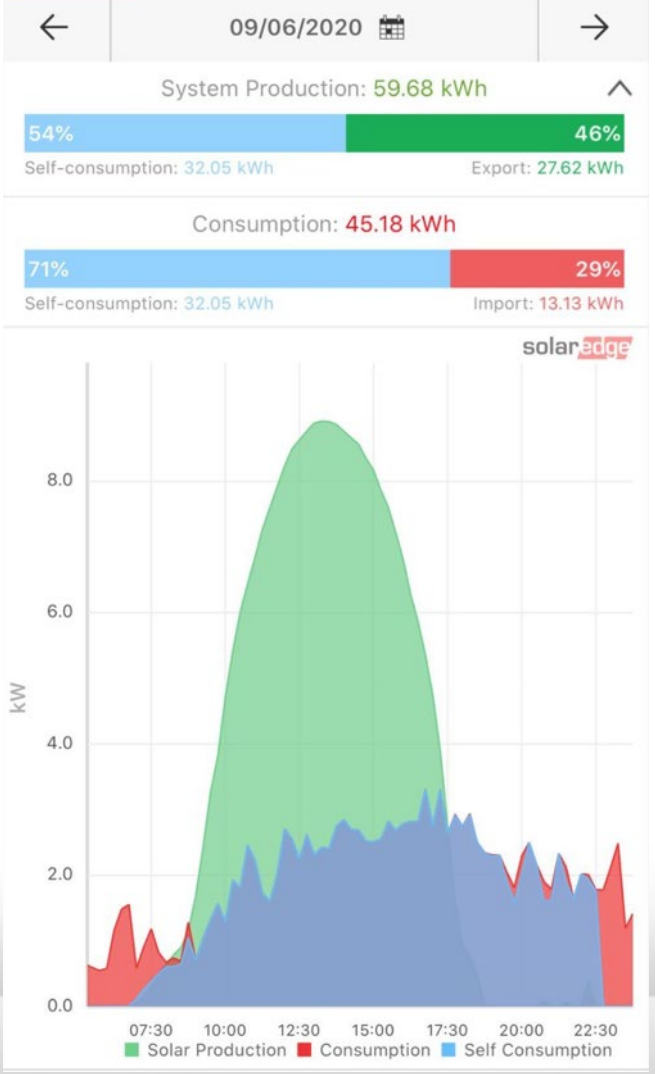
Sept. 6, 2020

Outside temperature: 106 F

Inside temperature: 77 F

Blue=consumption by solar during day or batteries after sunset (2-3.3 kW/6.4 kWh)

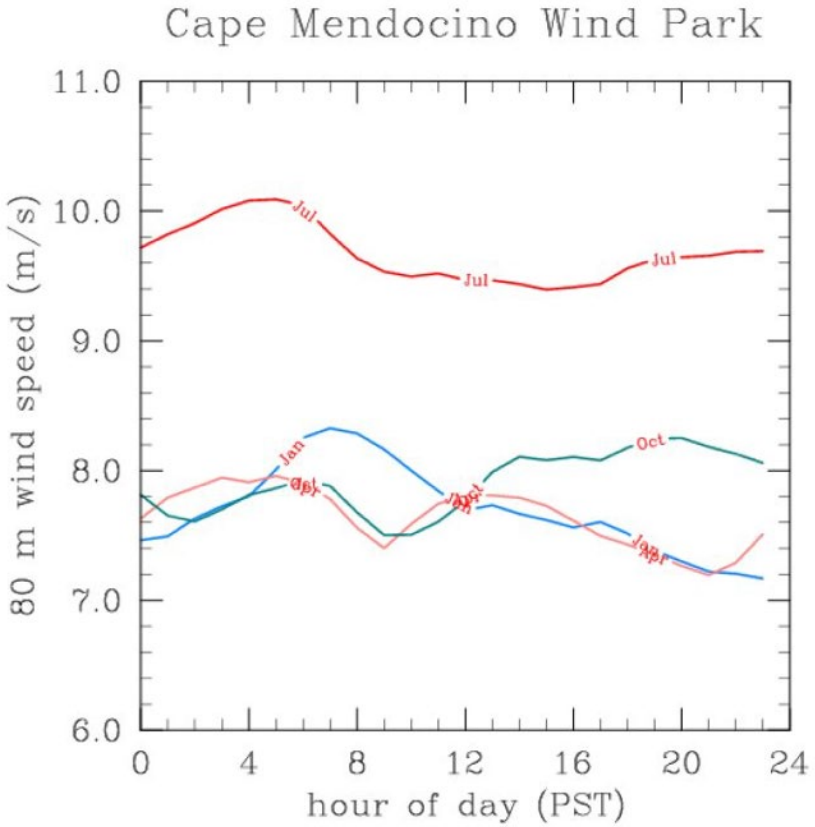
Red=grid electricity



Jacobson

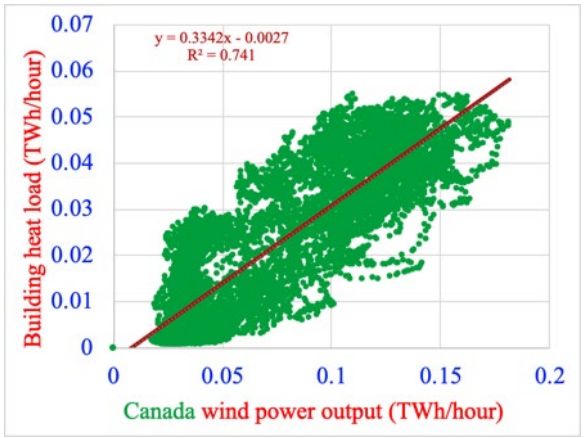
How to Meet California Heat Wave Peak Air Conditioning Load With Offshore Wind

Mean 80-m wind speed from MM5 for 2005-6

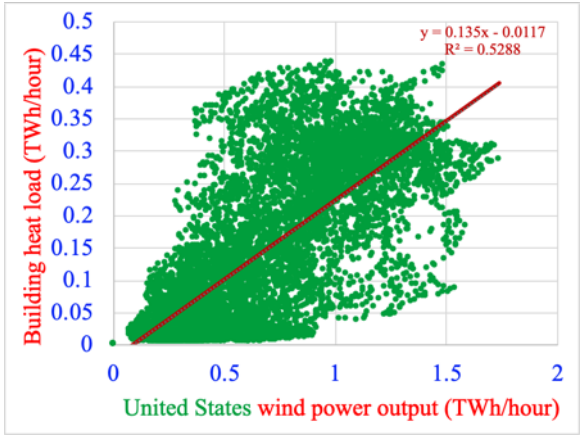


Dvorak et al., 2010

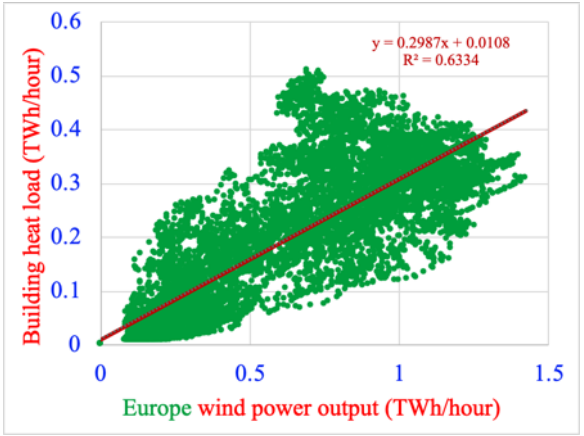
Strong Correlation Between Wind Power Output and Building Heat Load



Canada



U.S.



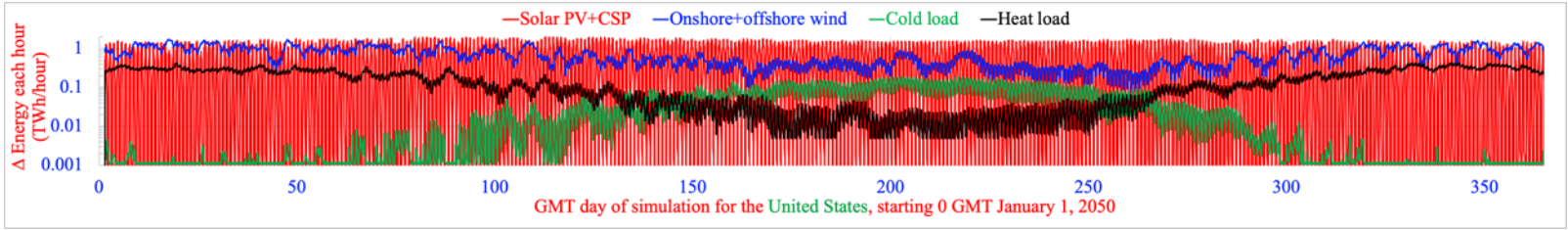
Europe

Dvorak et al., 2010

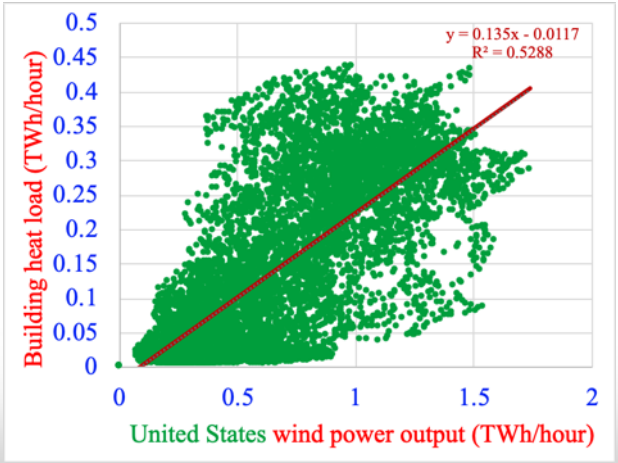
Wind Power Output Correlates With Heat Load in Cold Climates

2050 U.S. Heat Load, Cold Load, Solar Output, Wind Output

All year



Wind Power v. Heat Load
R=0.73



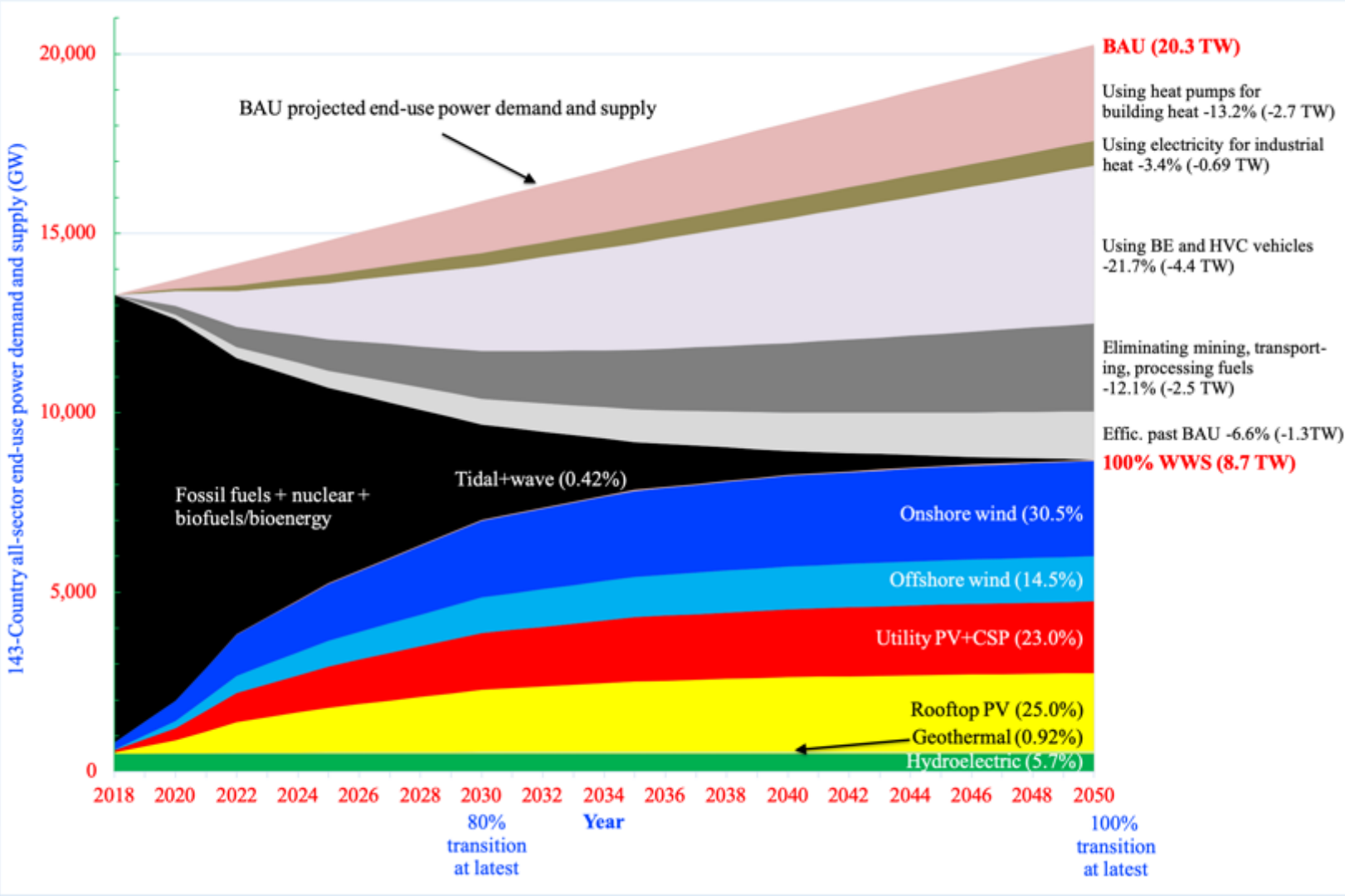
Can the World Transition to 100%, Clean, Renewable Energy for all Purposes?

Roadmaps for 143 Countries

All-Purpose End-Use Power Demand

Year and Fuel Type	143-Countries
2016 End-use demand	12.6 TW
2050 Demand with current fuels (BAU)	20.3 TW
2050 Demand with WWS	8.7 TW
2050 Demand reduction w/ WWS 21.7% efficiency of BE, HFC v. ICE 3.4% efficiency of electric industry 13.2% efficiency of heat pumps 12.1% eliminating fuel mining 6.6% efficiency beyond BAU	57.1%

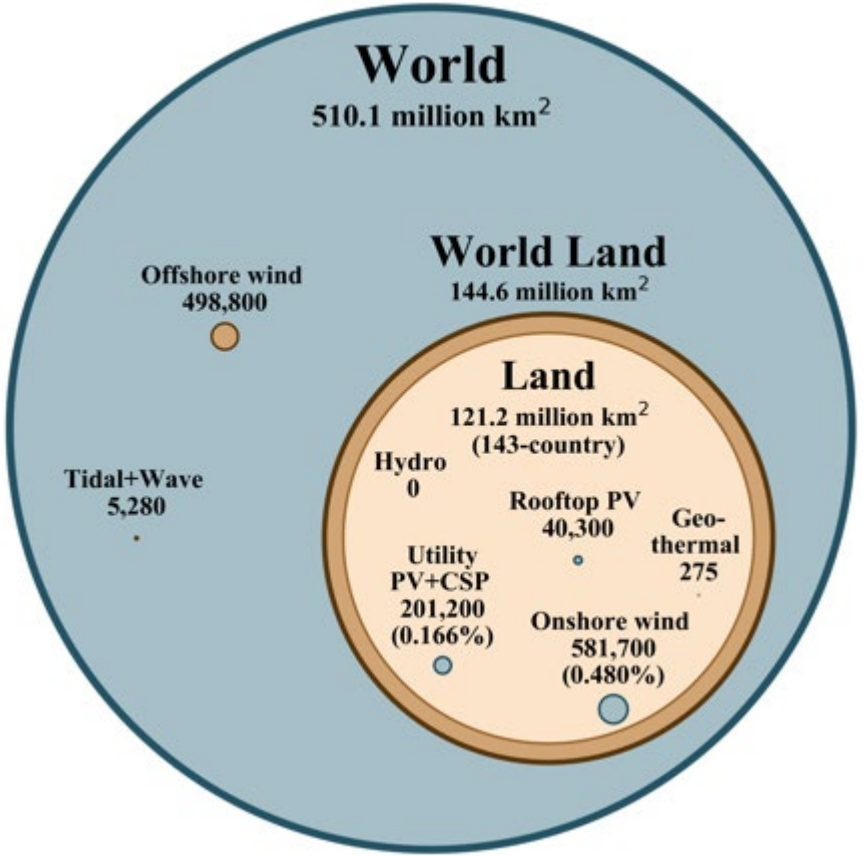
Time-line for a Trans-ition



Percent of 2050 143-Country End-Use Demand Supplied by WWS Devices and Number of New Devices

TECHNOLOGY	PCT SUPPLY 2050 World
5-MW onshore wind turbines	30.5%
5-MW offshore wind turbines	14.5
5-kW Res. roof PV systems	11.1
100-kW com/gov roof PV systems	13.8
50-MW Solar PV plants	19.0
100-MW CSP plants	3.93
100-MW geothermal plants	0.92
1300-MW hydro plants	5.72
1-MW tidal turbines	0.08
0.75-MW wave devices	0.34
	100%

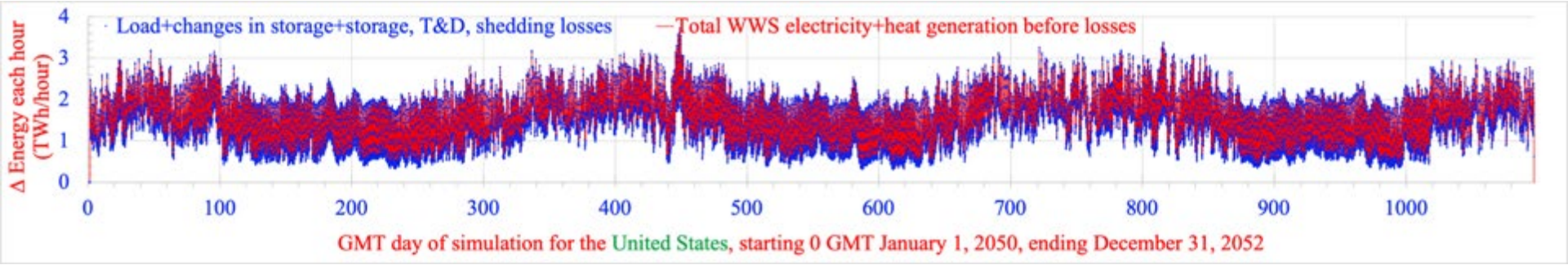
Area Beyond 2018 Installations to Power 143 Countries for all Purposes With 100% WWS in 2050



Percent of 143-Country Land

Onshore wind:	0.48%
Utility PV+CSP:	0.17%
Total	0.65%

Matching U.S. All-Sector Demand Every 30 Sec. With 100% WWS+Storage for 3 Years (2050-2052) and 100 Days



Red = Energy supply

Blue = Energy demand + change in storage + losses + shedding

Interconnecting Countries Reduces Cost

Norway alone:	$10.8 billion/yr
Denmark alone:	$11.0 billion/yr
Total:	$21.8 billion/yr
Norway+Denmark:	$17.3 billion/yr

→Interconnnecting 21% less expensive

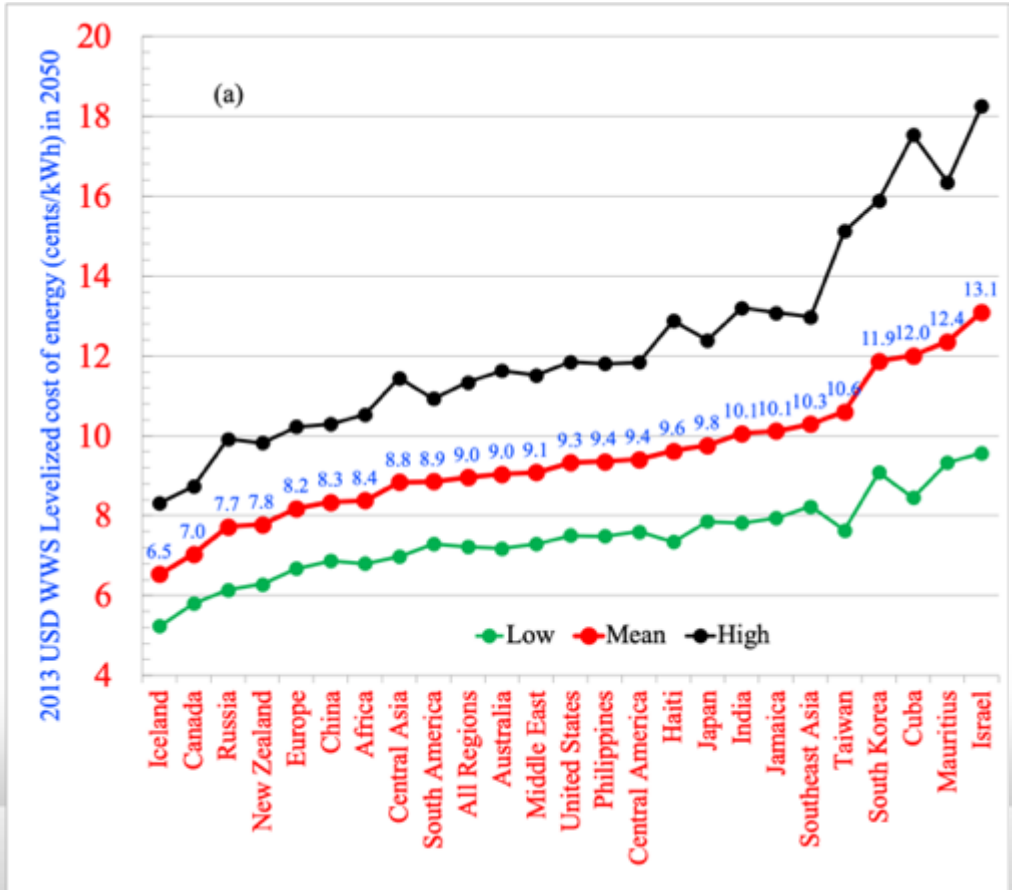
Energy Cost for 143 Countries in 24 Regions Resulting in a Stable Grid Upon Electrification of all Energy With 100% WWS+Storage

World: 9.0 cents/kWh
Capital Cost: $73 trillion

U.S.: 9.3 cents/kWh
Capital cost: $7.8 trillion

China: 8.3 cents/kWh
Capital cost: $16.6 trillion

Europe: 8.2 cents/kWh
Capital cost: $6.2 trillion



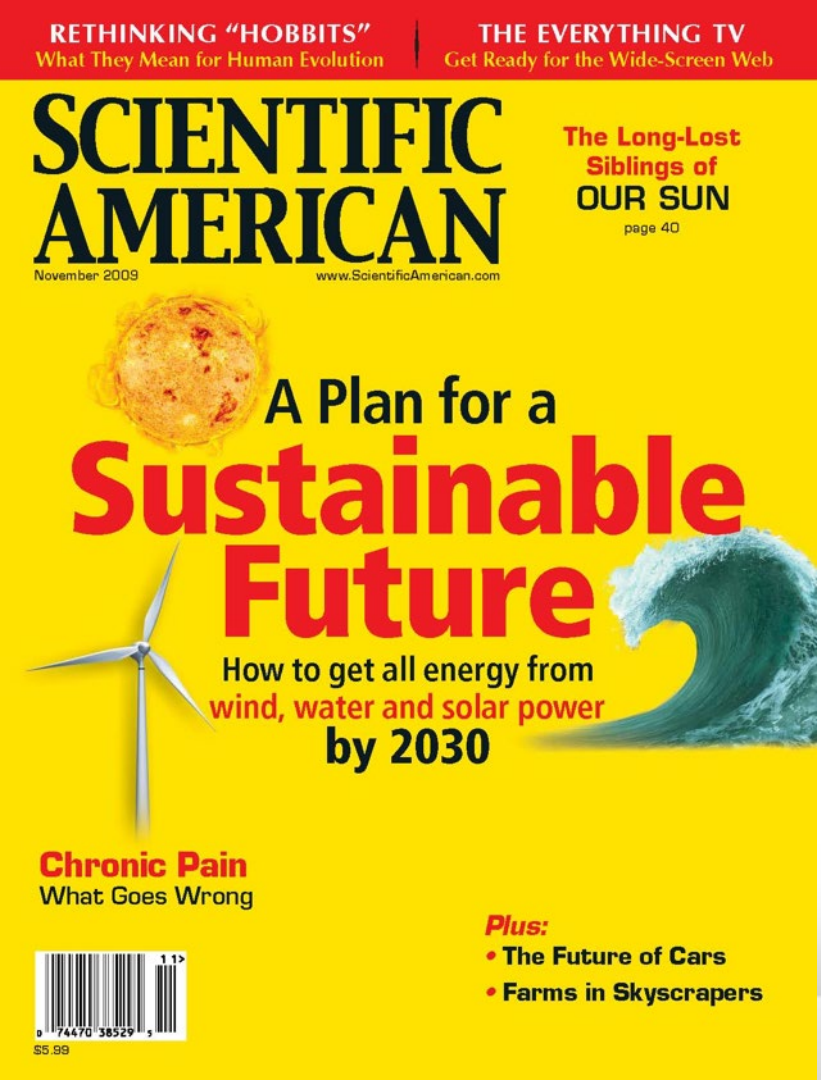
2050 World BAU vs WWS Cost

BAU fuel energy cost	$17.7 trillion/yr
BAU fuel health cost	$30.0 trillion/yr
BAU fuel climate cost	$28.4 trillion/yr
Total conventional fuel electricity sector cost	$76.1 trillion/yr

WWS replacing all BAU energy sectors $6.8 tril/yr

WWS reduces energy cost 61.4% and economic (social) cost 91%

Jacobson et al. (2018)



2009

100% worldwide wind, water, solar (WWS) all-sector energy plan introduced

Basis for *Green New Deal*

Conclusion

While technically and economically possible to transition by 2030, social and political barriers make complete transition more practical by 2050 with most (~80%) by 2030

61 Countries Committed to 100% Renewable Electricity

Afghanistan
Aruba
Bangladesh
Barbados
Bhutan
Burkina Faso
Cabo Verde
Cambodia
Colombia
Comoros
Congo, DR
Cook Islands
Costa Rica
Denmark
Djibouti
Dominica
Dom Rep.
Ethiopia
Fiji
Gambia
Ghana
Grenada
Guatemala
Haiti
Honduras
Kenya
Kirbati
Lebanon
Madagas
Malawi
Maldives
Marsh Is.
Mongolia
Morocco
Nepal
Niger
Niue
Palau
Palestine
Papua N.G.
Philippines
Portugal
Rwanda
Samoa
Senegal
Solom Is.
S. Sudan
Spain
Sri Lanka
St. Lucia
Sudan
Sweden
Tanzania
Timor-Les
Tokelau
Tunisia
Tuvalu
Scotland
Vanuatu
Vietnam
Yemen

11 Countries Near or Above 100% Renewable Electricity in Annual Average and Their Top Two Electricity Sources

Iceland (H,G)
Norway (H, W)
Costa Rica (H, W)
Paraguay (H)
Uruguay (H, W)
Tajikistan (H)
Albania (H)
Scotland (W, H)
Kenya (G, H)
Bhutan (H)
Nepal (H)

H = hydro
G = geothermal
W = wind

U.S. House H.Res.540 (2015), Senate S.Res.632 (2016)

U.S. transition to "100% clean renewable energy by 2050"

U.S. Senate Bill S.987 (2017) and House Bill H.R. 3314 (2017)

"100% clean and renewable energy by 2050"

U.S. House Bills H.R. 3671 (2017), H.R. 330 (2019)

"100% clean, renewable energy by 2035"

"100% renewable electricity by 2035"

U.S. Green New Deal (H.Res. 109; S.Res. 59, 2019)

100% Renewable Energy for the U.S. by 2030

U.S. House Resolution 540 (2015)

Whereas a Stanford University study concludes that the United States energy supply could be based entirely on renewable energy by the year 2050 using current technologies;

…the policies of the United States should support a transition to near zero greenhouse gas emissions, 100 percent clean renewable energy, infrastructure modernization, green jobs,…

14 100% Renewable Electricity State/Territory Laws/Exec Orders Resulting From WWS Roadmaps

100% by 2030

Rhode Island

By 2032

Washington D.C.

By 2040

Connecticut

By 2045

Hawaii, California, New Mexico, Washington State, New York

By 2050

Puerto Rico, Nevada, Maine, Wisconsin, Virginia, New Jersey

Renewables

Atlanta (GA)
Chicago (IL)
Cincinatti (OH)
Cleveland (OH)
Denver (CO)
Kansas City (MO)
Los Angeles (CA)
Madison (WI)
Minneapolis (MN)
Orlando (FL)
Philadelphia (PA)
Portland (OR)
Salt Lake City (UT)
San Diego (CA)
San Francisco (CA)
San Jose (CA)
Spokane (WA)
St. Louis (MO)
St. Paul (MN)
St. Petersburg (FL)
Tallahassee (FL)
Abita Springs (LA)
Sarasota (FL)
Hanover (NH)
Sylva (NC)
Moab (UT)
Boulder (CO)
Burlington (VT)
Rochester (MN)
Fayetteville (AR)
Palo Alto (CA)
Middleton (WI)
Missoula (MT)
Questa (NM)
Fayetteville (AR)
Clarkston (GA)

Some of the 280 Companies Committed to 100% Renewables

IKEA
Google
Microsoft
Apple
Workday
Bloomberg
P&G
GM
Kellogg's
Salesforce

Adobe
H&M
Nestle
S&P
T-Mobile
BMW Group
Ebay
Goldman-Sachs
Lego
Organic Valley

JPMor/Chas
HP
Nike
Starbucks
AB InBev
Burberry
Facebook
HSBC
Mars
Amazon

Coca Cola
Goldman-Sachs
Johnson & Johnson
Walmart
Bank of America
Citi
Estee Lauder
Infosys
Morgan Stanley
Wells Fargo

Some of the 100+ NGOs Committed to 100%

The Solutions Project
100.Org
Sierra Club
350.Org
Greenpeace
theRE100.org
go100percent.org
renewables100.org
Climate Reality
iclei.org
The Center for Working Families
Miami Climate Alliance
Environment America
Toxics Action Center
Renewable Cities
National People's Action
Institute for Self-Reliance
Hip Hop Caucus
Environmental Action
Renewable Energy Long Island
Emerald Cities Collaborative
Community Power
Center for Community Change
Asian Pacific Environmental Network

Public Opinion Survey

26,000 people in 13 countries November 2017
Canada, China, Denmark, France, Germany Netherlands,
Poland, South Korea, Sweden, Taiwan, UK, USA

82% want a world with 100% renewable energy
66% believe climate change is a global challenge
69% say renewables make countries more energy independent
73% say renewables will boost economic growth

https://orsted.com/en/Barometer

Summary – Transitioning to 100% WWS

Creates 28 million more jobs than are lost worldwide

Requires only 0.17% of land for footprint; 0.48% for spacing

Avoids ~7 mil. air pollution deaths per year

Slows then reverses global warming

Grids can stay stable throughout the world with 100%

WWS absolute energy costs are 60% less than of fossils

WWS absolute energy+health+climate costs 90% less than of fossils

Online Course on 100% WWS

http://stanford.io/windwatersolar

Roadmaps

web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html

Infographic maps

www.thesolutionsproject.org/why-clean-energy/

Textbook on 100% WWS

https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html

Twitter: @mzjacobson