Transitioning the U.S., Japan, and the World to 100% Clean, Renewable Energy for All Purposes as Fast as Possible

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What are the Problems? Why act Quickly?

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

Global warming will cost ~30 trillion/year by 2050.

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

Drastic problems require immediate solutions

Wind, Water, Solar (WWS) Solution

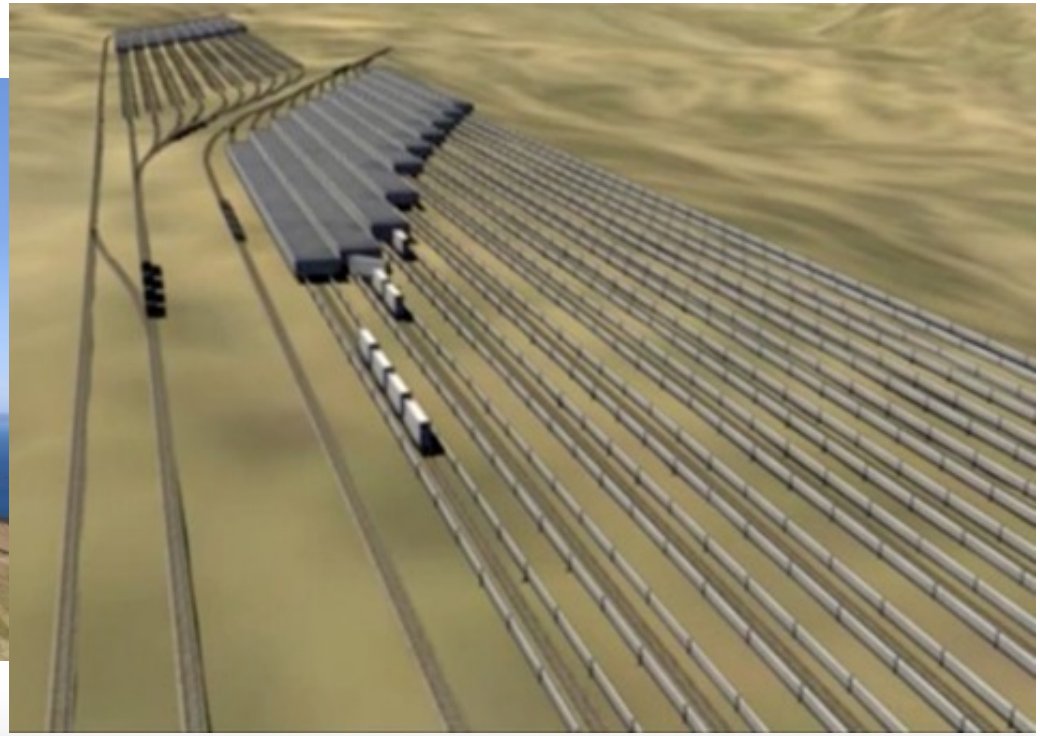
Electrify or Provide Direct Heat For All Sectors and Provide the Electricity and Heat with 100% WWS

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

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



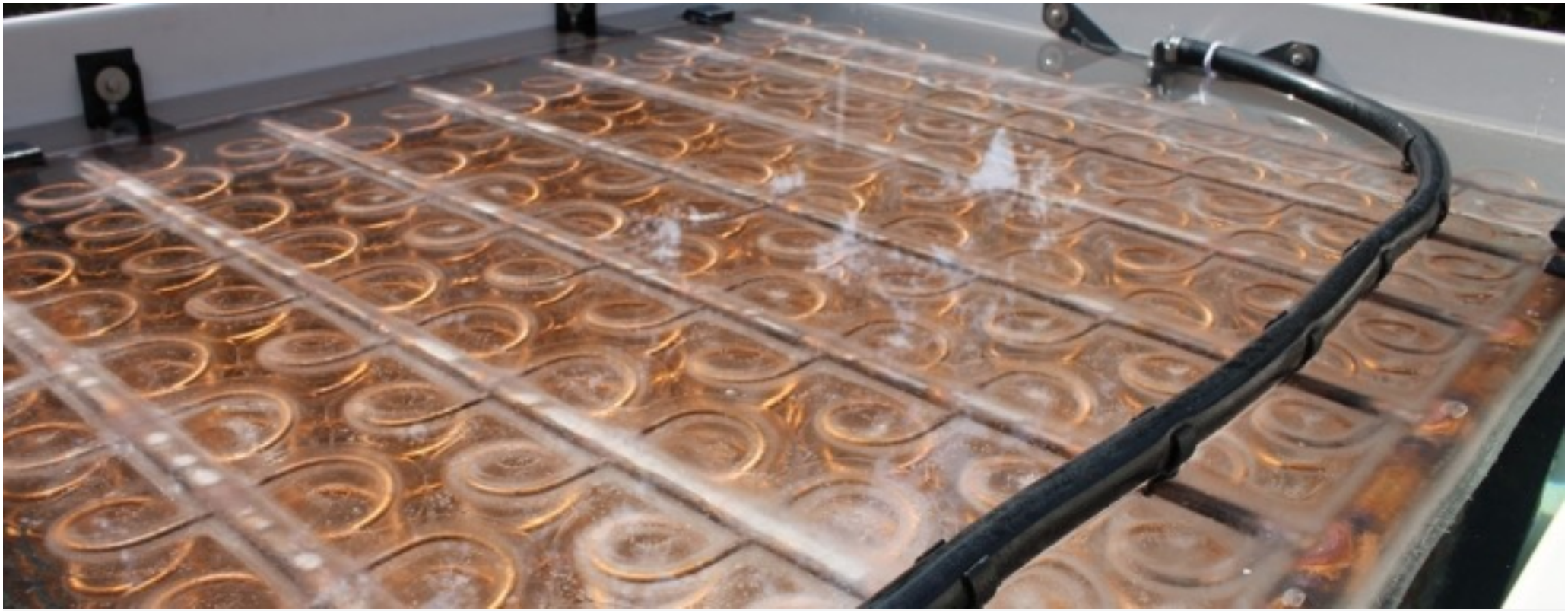
Stanford University 4th Generation District Heating System

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

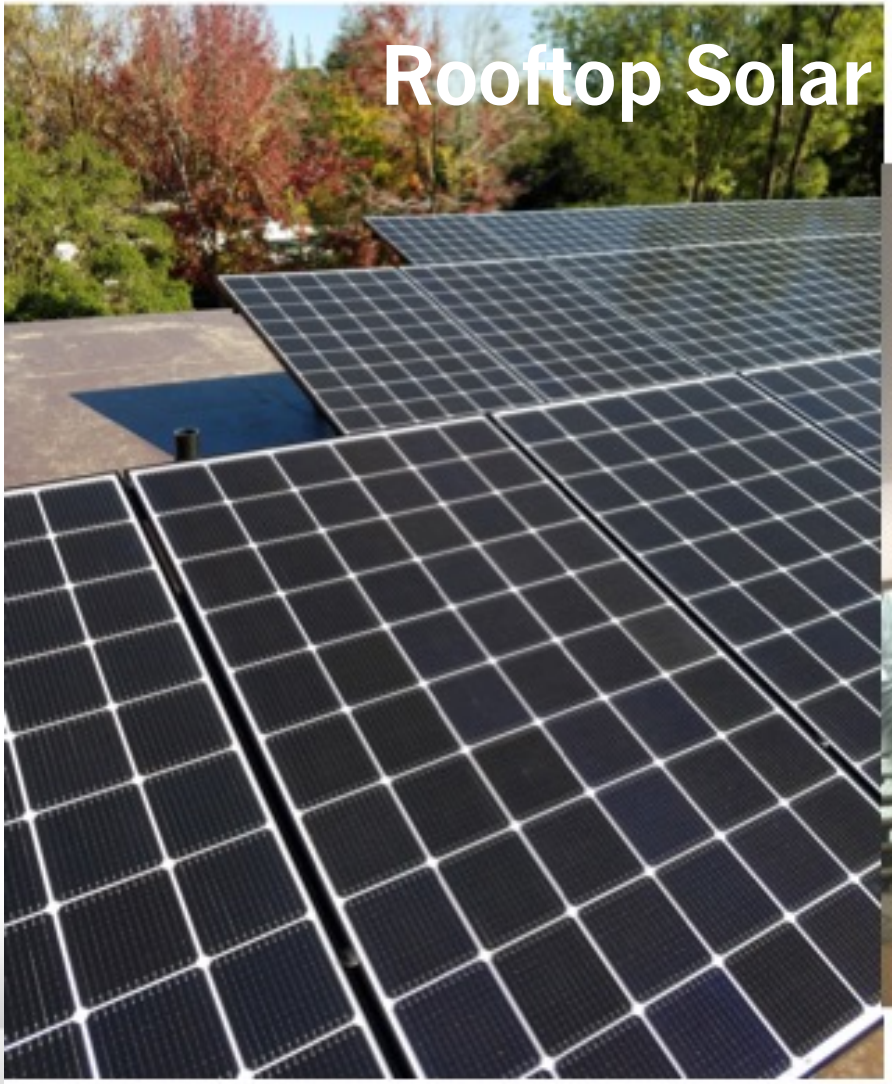


Photo by M.Z. Jacobson

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

Four Years of Energy Use

Generated 120% of all home and vehicle energy

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

Received average $800/yr from CCA for excess electricity to grid

Avoided costs of all-electric home

Gas hookup fee: 3-8 K

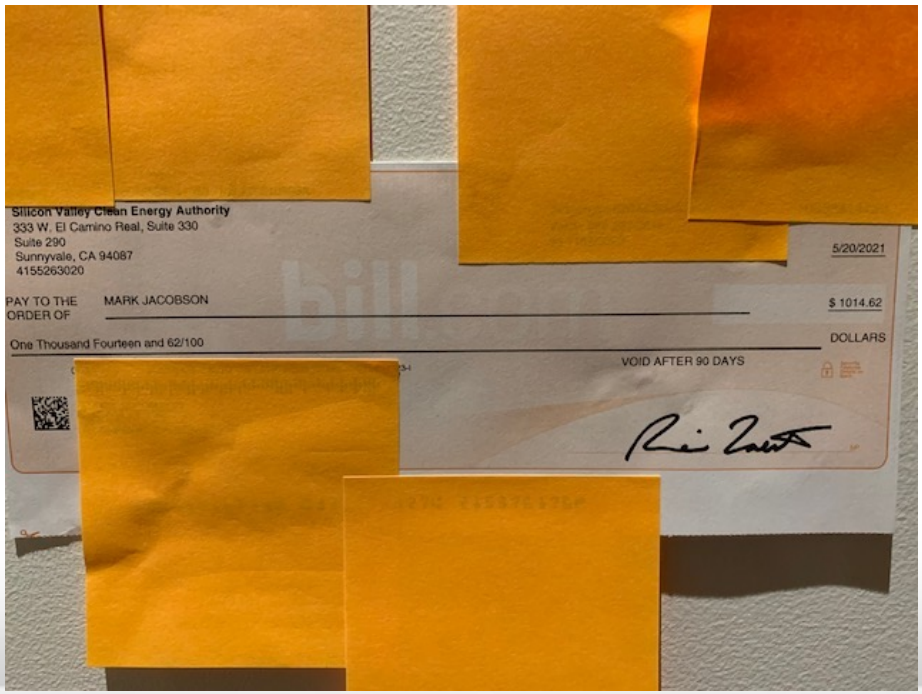
Gas pipes: 2-15 K

Electric bill 1-3 K per year

Natural gas bill 1-3 K per year

Vehicle fuel bill 1-4 K per year

Total: 5-23 K plus 3-10 K per year



5y payback with subsidy; 10y w/o

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No Blackout on Hottest Day of Year

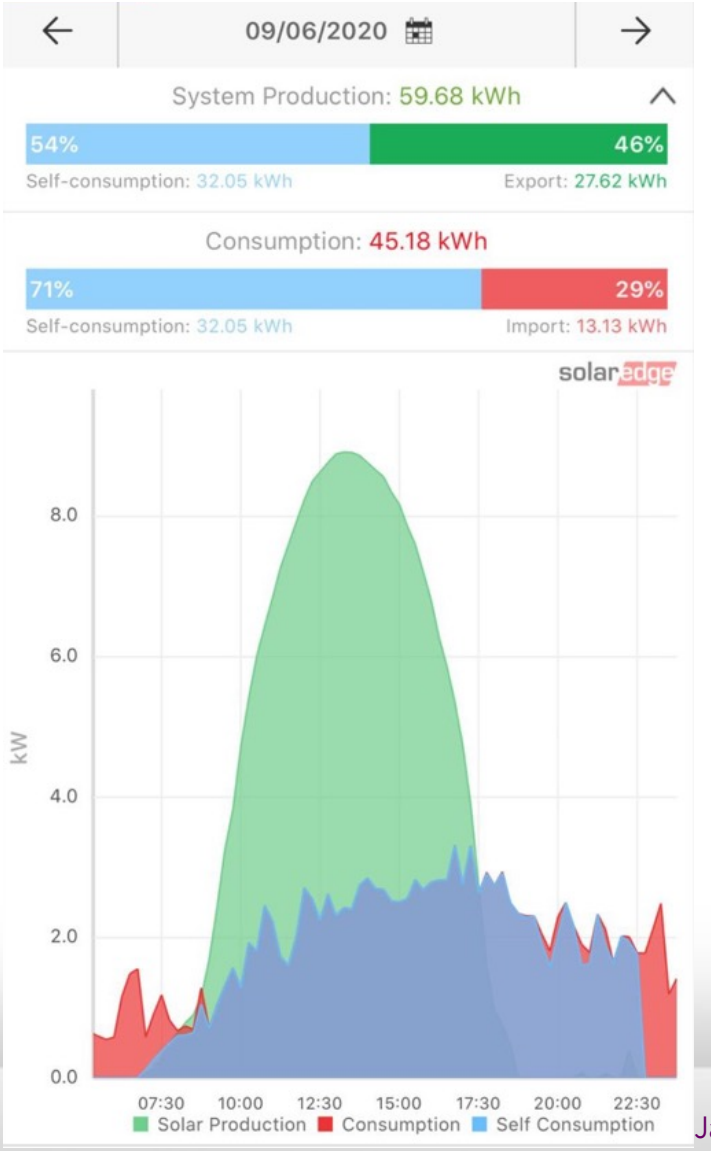
Sept. 6, 2020

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



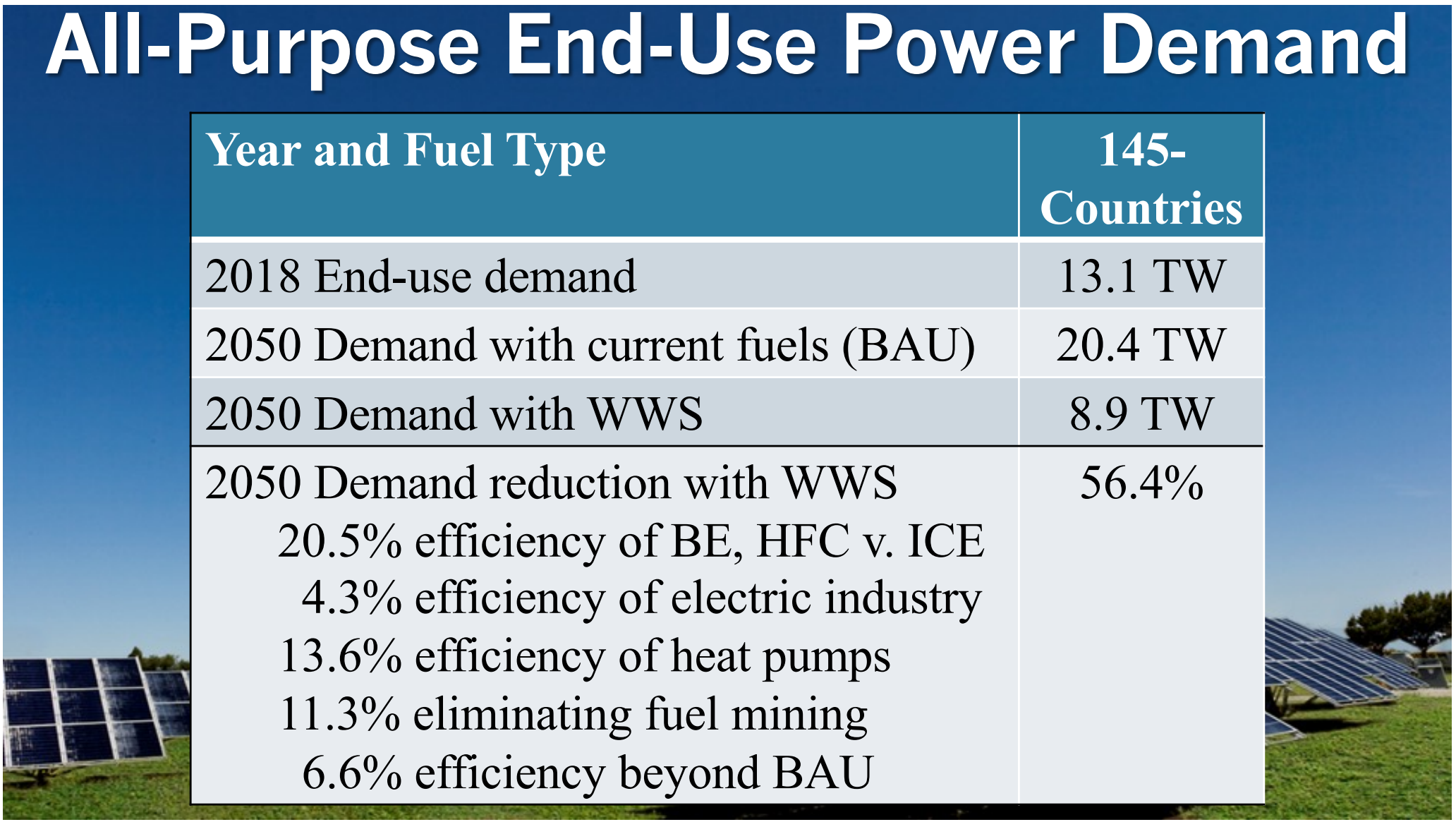
Jacobson

Can the U.S., Japan, and the World Transition to 100%, Clean, Renewable Energy for all Purposes?

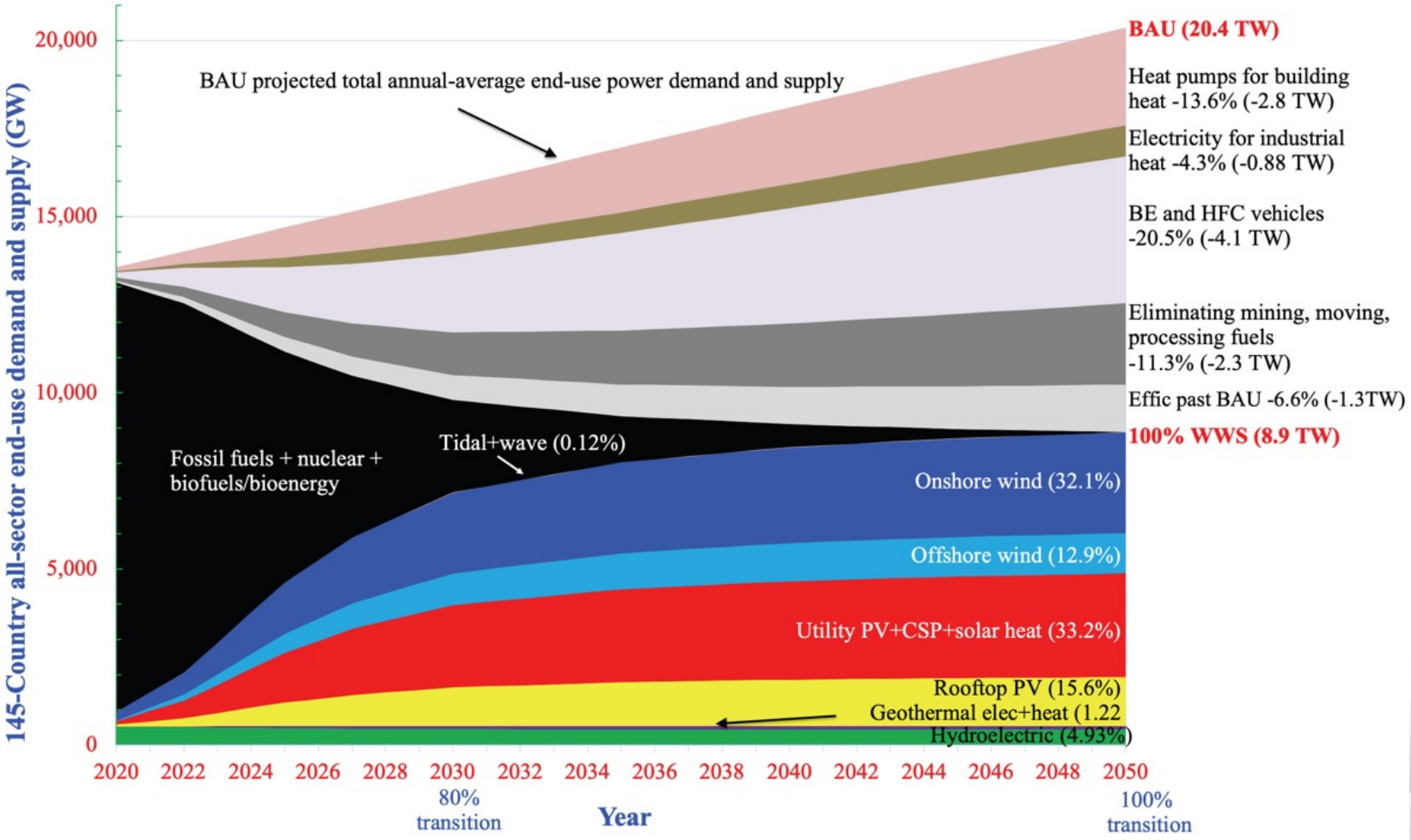
Roadmaps for 145 Countries

All-Purpose End-Use Power Demand

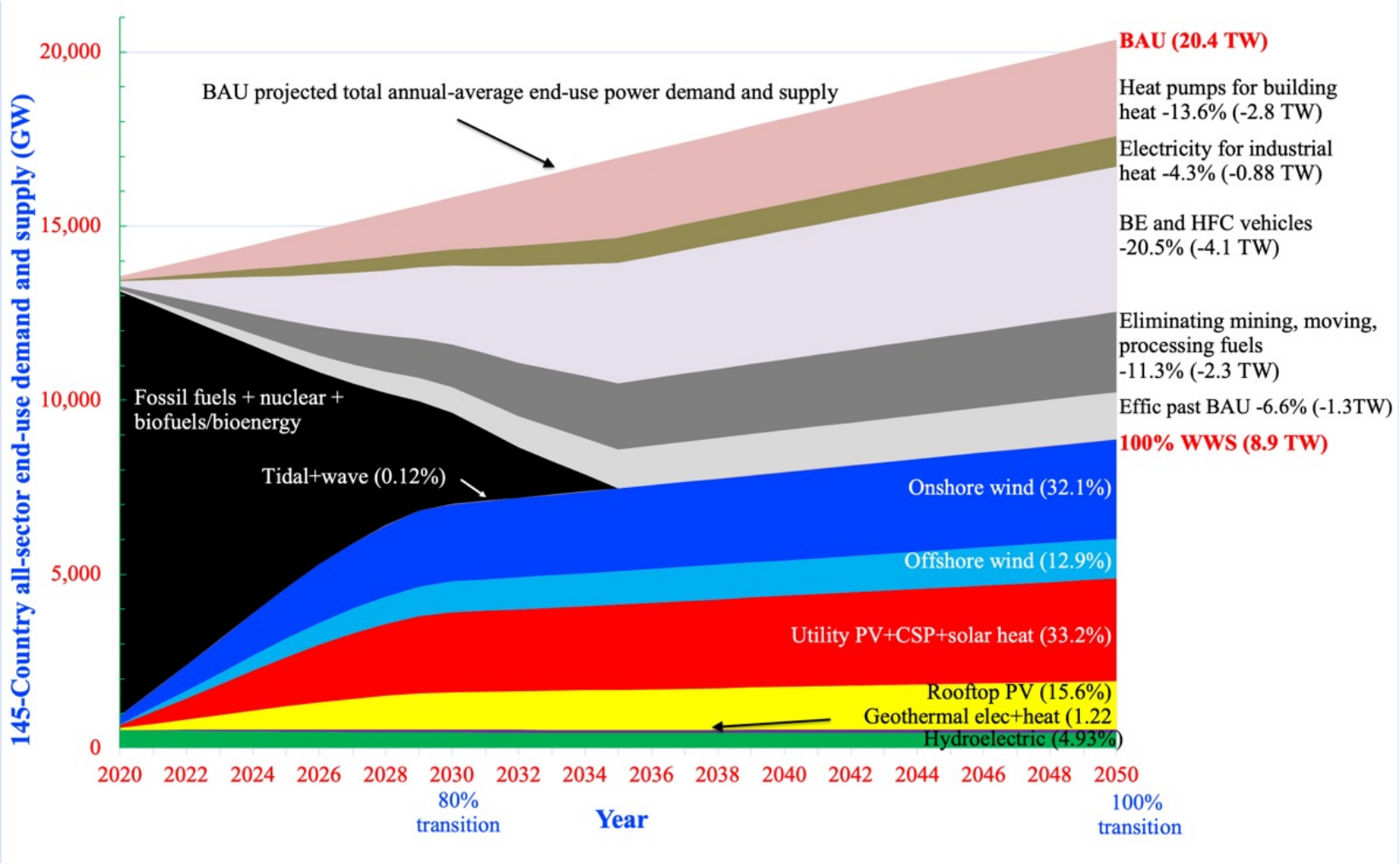
Year and Fuel Type	145-Countries
2018 End-use demand	13.1 TW
2050 Demand with current fuels (BAU)	20.4 TW
2050 Demand with WWS	8.9 TW
2050 Demand reduction with WWS 20.5% efficiency of BE, HFC v. ICE 4.3% efficiency of electric industry 13.6% efficiency of heat pumps 11.3% eliminating fuel mining 6.6% efficiency beyond BAU	56.4%



Timeline for a 145-Country Transition



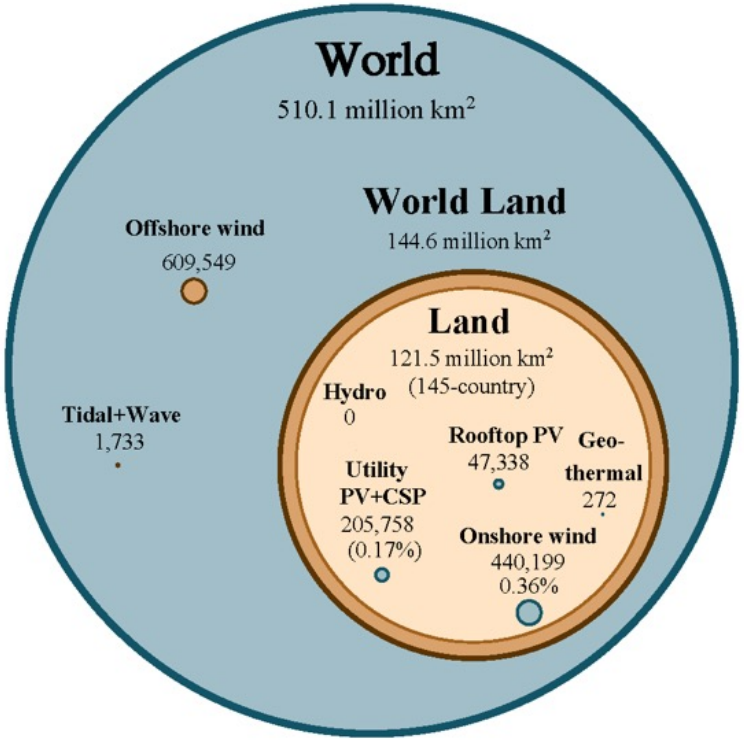
Faster Timeline for a 145-Country Transition



Percent of 2050 145-Country, U.S., and Japan End-Use Demand Supplied by WWS

TECHNOLOGY	World	U.S.	Japan
Onshore wind	32.1%	45.2%	1.77%
Offshore wind	12.9	5.62	52.0
Rooftop Solar PV	15.6	8.50	2.79
Utility PV	30.0	34.4	37.3
CSP	2.73	2.08	0
Geothermal electricity	0.73	0.42	0.56
Hydroelectric	4.93	2.70	4.53
Tidal	0.04	.006	0.23
Wave	0.08	0.15	0.15
Geothermal heat	0.49	0.81	0.59
Solar heat	0.42	0.14	0.11
	100%	**100%**	**100%**

Percent of Land Beyond 2018 Installations to Power 145 Countries, U.S., Japan for all Purposes With 100% WWS in 2050

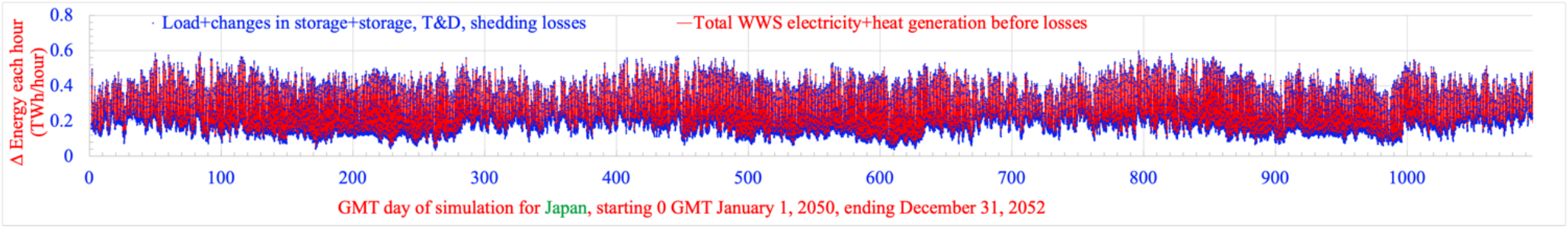


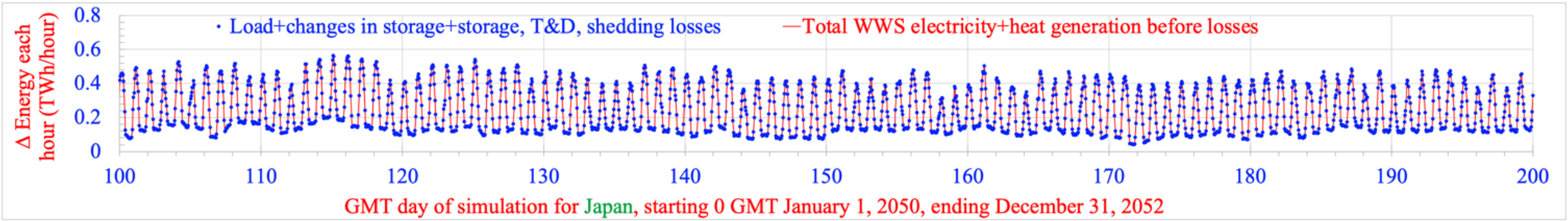
Onshore wind: 0.36%
Utility PV+CSP: 0.17%
Total 145 Countries 0.53%

Onshore wind: 0.84%
Utility PV+CSP: 0.31%
Total U.S. 1.25%

Onshore wind: 0.09%
Utility PV+CSP: 1.34%
Total Japan 1.43%

Matching Japan's All-Sector Demand Every 30 Seconds With 100% WWS+Storage for all of 2050 and for 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 145 Countries in 24 Regions Resulting in a Stable Grid Upon Electrification of all Energy With 100% WWS+Storage

World: 8.5 cents/kWh
Capital Cost: $61.5 trillion

U.S.: 8.7 cents/kWh
Capital cost: $6.7 trillion

China: 7.6 cents/kWh
Capital cost: $13.1 trillion

Japan: 8.9 cents/kWh
Capital cost: $1.15 trillion

2050 World BAU vs WWS Cost

BAU fuel energy cost	$17.8 trillion/yr
BAU fuel health cost	$33.6 trillion/yr
BAU fuel climate cost	$31.8 trillion/yr
BAU total social cost	$83.2 trillion/yr

WWS total social cost $6.6 trillion/yr

WWS reduces energy cost 63% and economic (social) cost 92%

Jacobson et al. (2022)

2050 U.S. BAU vs WWS Cost

BAU fuel energy cost	$2,189 $bil/yr
BAU fuel health cost	$830 $bil/yr
BAU fuel climate cost	$3,382 $bil/yr
BAU total social cost	$6,400 $bil/yr

WWS total social cost	$742 $bil/yr

WWS reduces energy cost 66% and economic (social) cost 88%

Jacobson et al. (2022)

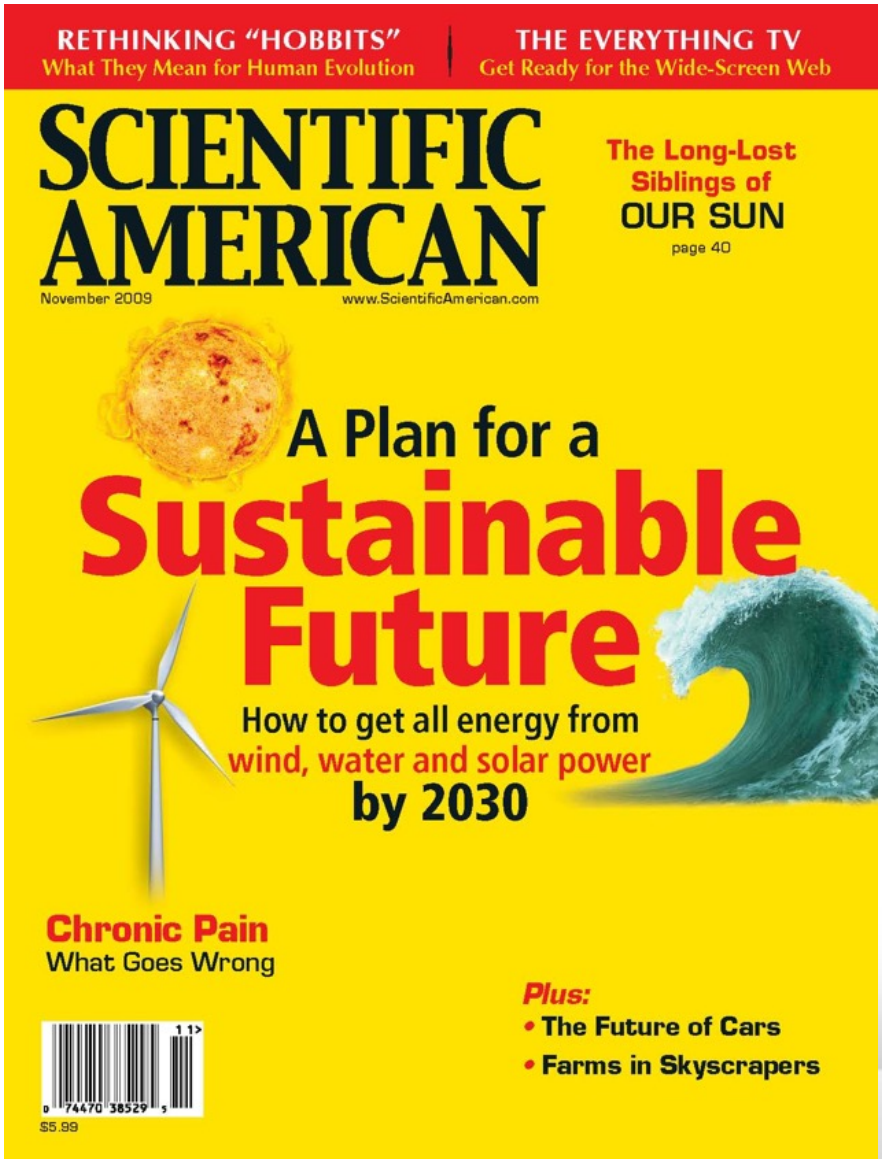
2050 Japan BAU vs WWS Cost

BAU fuel energy cost	$326 $bil/yr
BAU fuel health cost	$262 $bil/yr
BAU fuel climate cost	$678 $bil/yr
BAU total social cost	$1,266 $bil/yr

WWS total social cost $136 $bil/yr

WWS reduces energy cost 58% and economic (social) cost 89%

Jacobson et al. (2022)



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

13 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)
Ethiopia (H, W)
Congo, DR (H)

H = hydro
G = geothermal
W = wind

15 100% Renewable Electricity State/Territory Laws/Exec Orders Resulting From WWS Roadmaps

100% by 2030

Rhode Island

By 2032

Washington D.C.

By 2040

Connecticut, Oregon

By 2045

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

By 2050

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

Some of 180 US Cities/Counties Committed to 100% 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 340+ Companies Committed to 100% Renewables

IKEA	Adobe	JPMor/Chas	Coca Cola
Google	H&M	HP	Goldman-Sachs
Microsoft	Nestle	Nike	Johnson & Johnson
Apple	S&P	Starbucks	Walmart
Workday	T-Mobile	AB InBev	Bank of America
Bloomberg	BMW Group	Burberry	Citi
P&G	Ebay	Facebook	Estee Lauder
GM	Goldman-Sachs	HSBC	Infosys
Kellogg's	Lego	Mars	Morgan Stanley
Salesforce	Organic Valley	Amazon	Wells Fargo

Summary – Transitioning World to 100% WWS

Creates 28 million more jobs than lost worldwide (1.2 mil in S. Korea)

Requires only 0.17% of land for footprint; 0.36% 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 63% less than of fossils

WWS absolute energy+health+climate costs 92% less than of fossils

Book on 100% WWS

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

Roadmaps

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

Online Course on 100% WWS

https://online.stanford.edu/courses/cee176b-100-clean-renewable-energy-and-storage-everything

Infographic maps

https://sites.google.com/stanford.edu/wws-roadmaps/home

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