Transitioning Minnesota and the World to 100% Clean, Renewable Energy and Storage for Everything Without Miracles

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What are the Problems? Why act Quickly?

Fossil-fuel and bioenergy air pollution cause ~7.4 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/HEAT	TRANSPORTATION	BUILDINGS	INDUSTRY
Wind	Battery-electric	Heat pumps	Arc furnaces
Solar PV/CSP	H_2 fuel cell	Induction cooktops	Induction furnaces
Geothermal		LED lights	Resistance furnaces
Hydro		Insulation	Dielectric heaters
Tidal/Wave			Electron beam heaters
Solar/Geo Heat			Heat pumps

Types of Storage for a 100% WWS System

ELECTRICITY STORAGE	HOT/COLD STORAGE	HYDROGEN STORAGE
CSP with storage	Water tank	Non-grid hydrogen
Pumped hydro storage	Ice	
Existing hydroelectric	Underground	
Batteries	Borehole	
Flywheels	Water Pit	
Compressed air	Aquifer	
Gravitational Storage	Building materials	
Grid hydrogen/fuel cells	Firebricks	

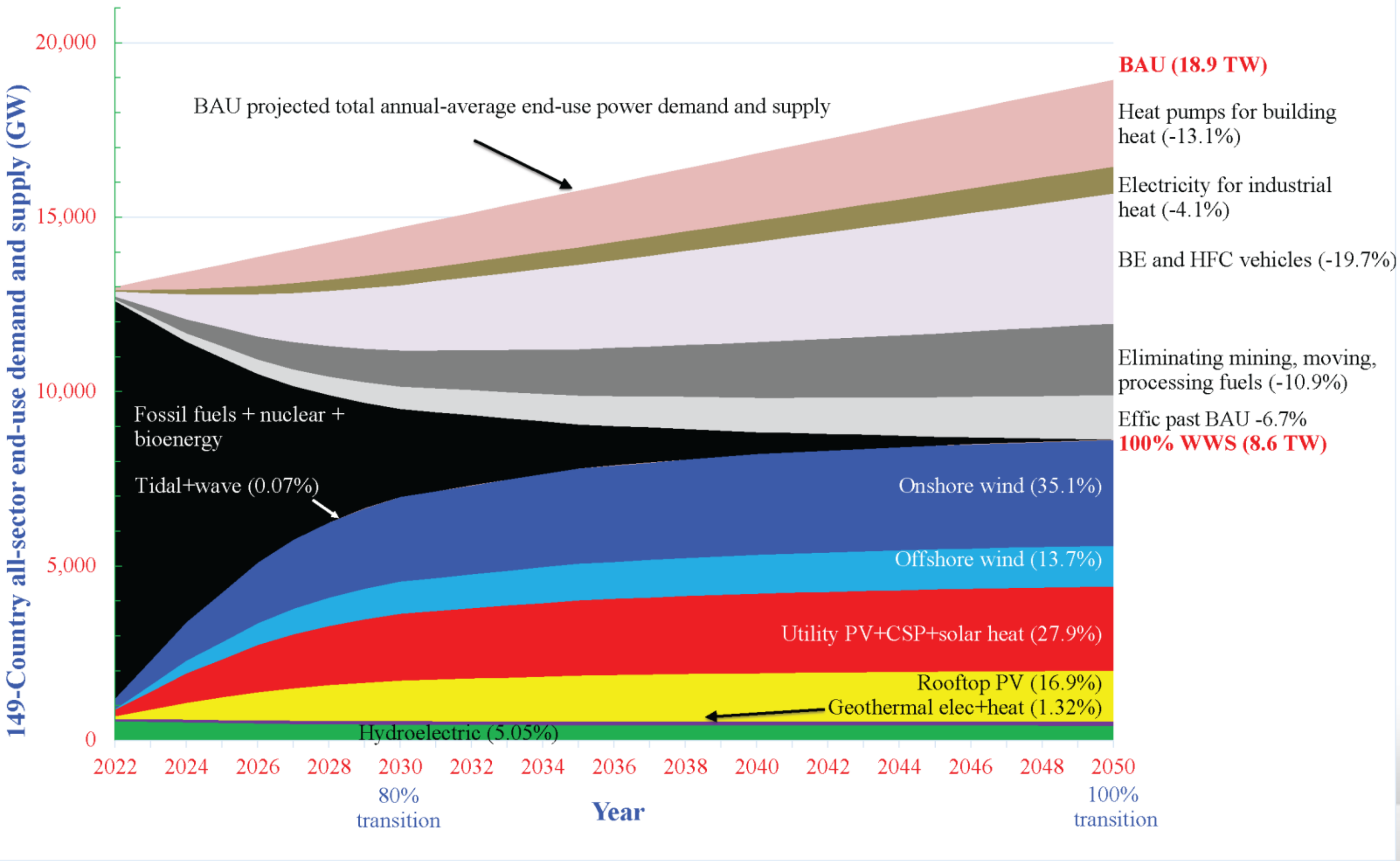
Can the World Transition to 100%, Clean, Renewable Energy for all Purposes?

Roadmaps for 149 Countries

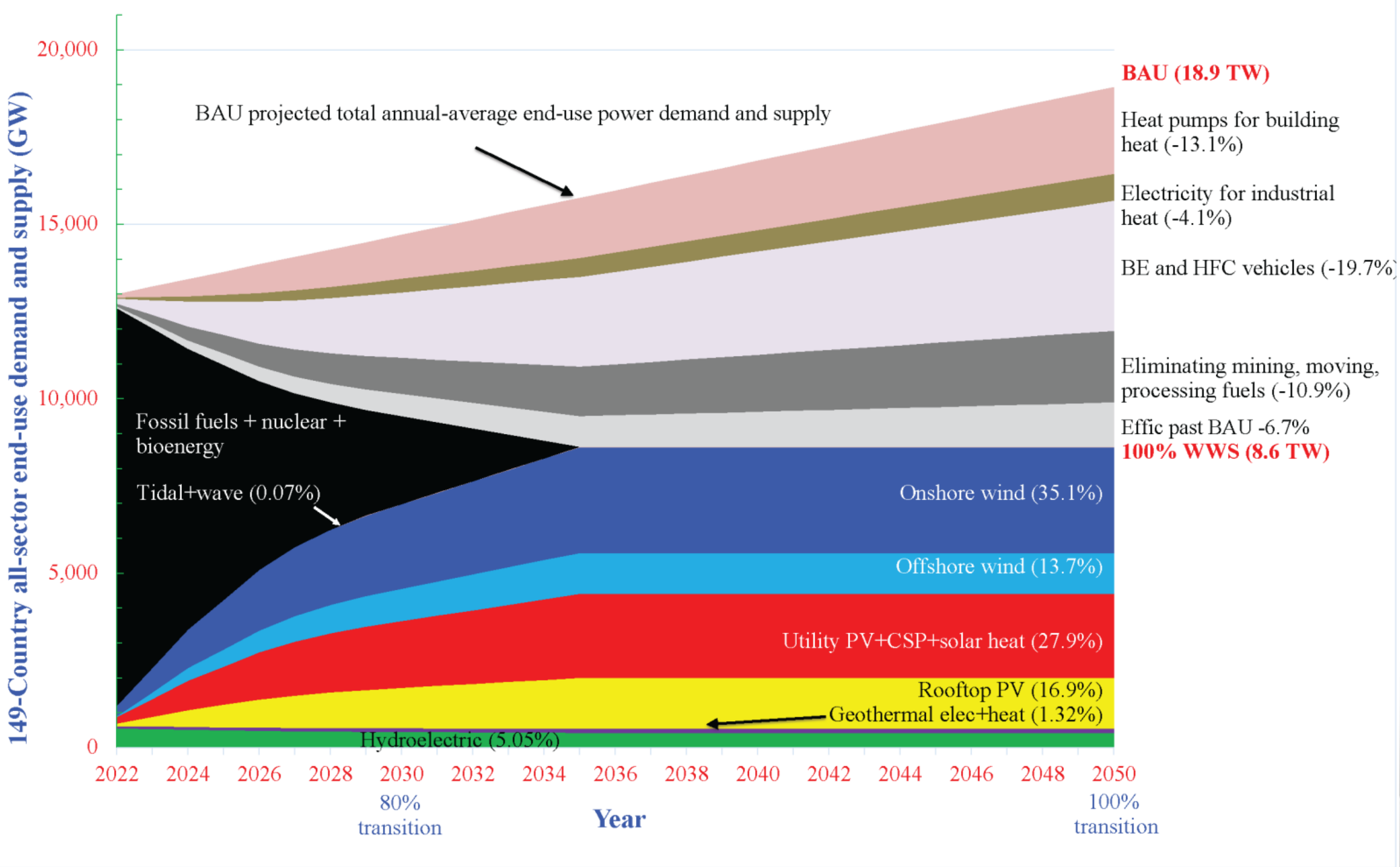
All-Sector End-Use Power Demand BAU v WWS

Year and Fuel Type	149 Countries
2020 End-use demand	12.6 TW
2050 Demand with current fuels (BAU)	18.9 TW
2050 Demand with WWS	8.6 TW
2050 Demand reduction with WWS 19.7% efficiency of BE, HFC v. ICE 4.1% efficiency of electric industry 13.1% efficiency of heat pumps 10.9% eliminating fuel mining 6.6% efficiency beyond BAU	54.4%

Timeline for Transitioning 149 Countries 80% by 2030; 100% by 2050



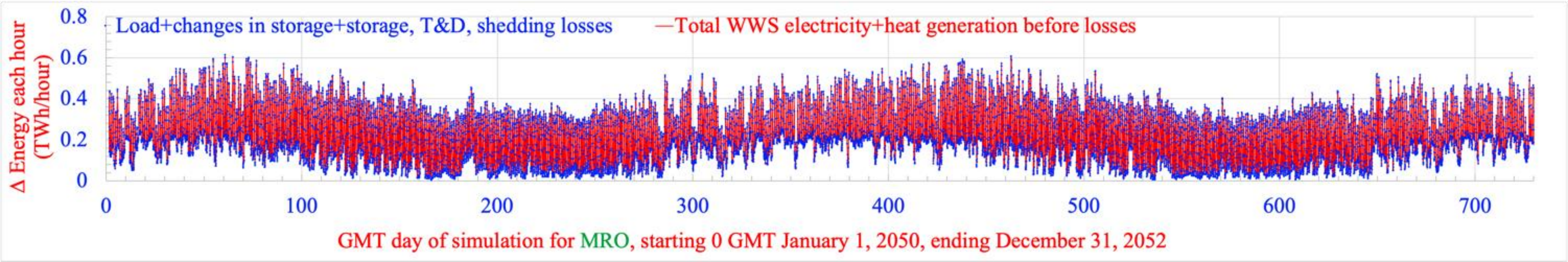
Timeline for Transitioning 149 Countries 80% by 2030; 100% by 2035

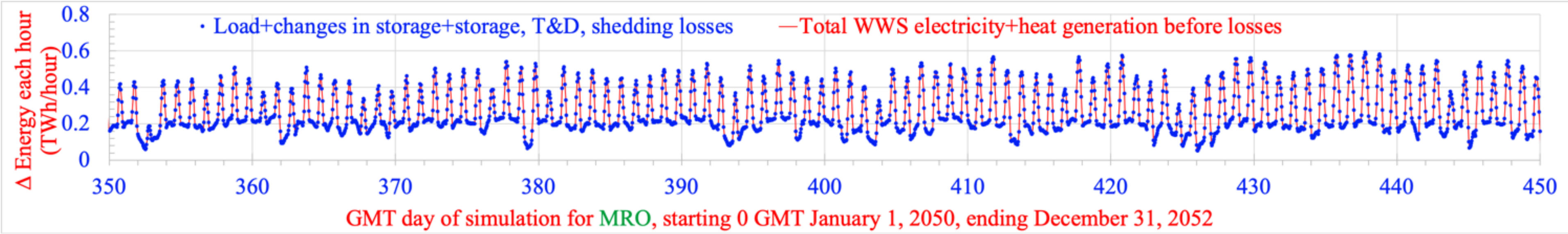


Percent of End-Use Demand Supplied by WWS by 2050

TECHNOLOGY	World	U.S.	MRO
Onshore wind	35.1%	54.1%	46.5
Offshore wind	13.7	8.57	3.56
Rooftop Solar PV	16.9	11.3	17.0
Utility PV	26.4	21.8	31.3
CSP	1.02	0.70	0
Geothermal electricity	0.79	0.47	0
Hydroelectric	5.05	1.87	1.63
Tidal	0.02	0.001	0
Wave	0.05	0.074	0.07
Geothermal heat	0.53	0.90	0
Solar heat	0.49	0.16	0
	100%	**100%**	**100%**

Matching MRO All-Sector Demand Every 30 Sec. With 100% WWS+Storage for 2 Years (2050-2051) and 100 Days





Red = Energy supply

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

Capital Costs Resulting in a Stable Electric Grids Upon Electrification of all Energy With 100% WWS

World (149 Countries): $58.2 trillion

U.S.: $5.7 trillion

China: $14.6 trillion

Europe: $5.06 trillion

Minnesota: $168 billion

2050 149-Country BAU vs WWS Annual Energy Cost

BAU fuel energy cost	\$16.5 trillion/yr
BAU fuel health cost	\$33.8 trillion/yr
BAU fuel climate cost	\$30.9 trillion/yr
BAU total social cost	\$81.2 trillion/yr
WWS total social cost	\$6.7 trillion/yr

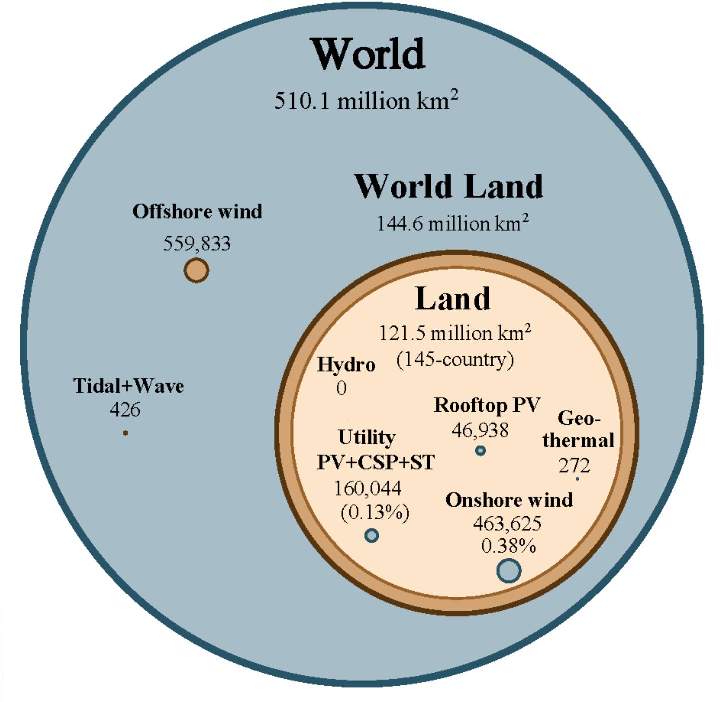
WWS reduces energy cost 60% and economic (social) cost 92%

Jacobson et al. (2024)

World Average Levelized Cost of Electricity in 2023 (IRENA, 2024)

Fossil fuels	$100 / MWh
Utility PV	$44 / MWh (56% lower)
Onshore wind	$33 / MWh (67% lower)
Offshore wind	$75 / MWh (25% lower)
Geothermal	$71 / MWh (29% lower)
Hydro	$57 / MWh (43% lower)

Percent of Land Beyond 2022 Installations to Power 149 Countries for all Purposes With 100% WWS in 2050



Onshore wind:	0.38%
Utility PV+CSP:	0.13%
Total 149 Countries	0.51%
Onshore wind:	0.16%
Utility PV+CSP:	0.90%
Total U.S.	1.06%
Onshore wind:	0.71%
Utility PV+CSP:	0.14%
Total Minnesota	0.85%

Vs. 1.24% of U.S. land for corn ethanol and 1.3% of U.S. land for the fossil industry

Plan to Electrify Minnesota and Provide all Electricity With Wind-Water-Solar (WWS) (Which Includes Storage)

Reduces energy requirements 57% versus business-as-usual in 2050

Reduces annual energy costs by 64% ($29.6 bil/y) (from $46.4 to $16.8 bil/y)

Reduces annual health costs by $8 bil/y (610 lives saved/y)

Reduces annual climate costs to world by $61 bil/y

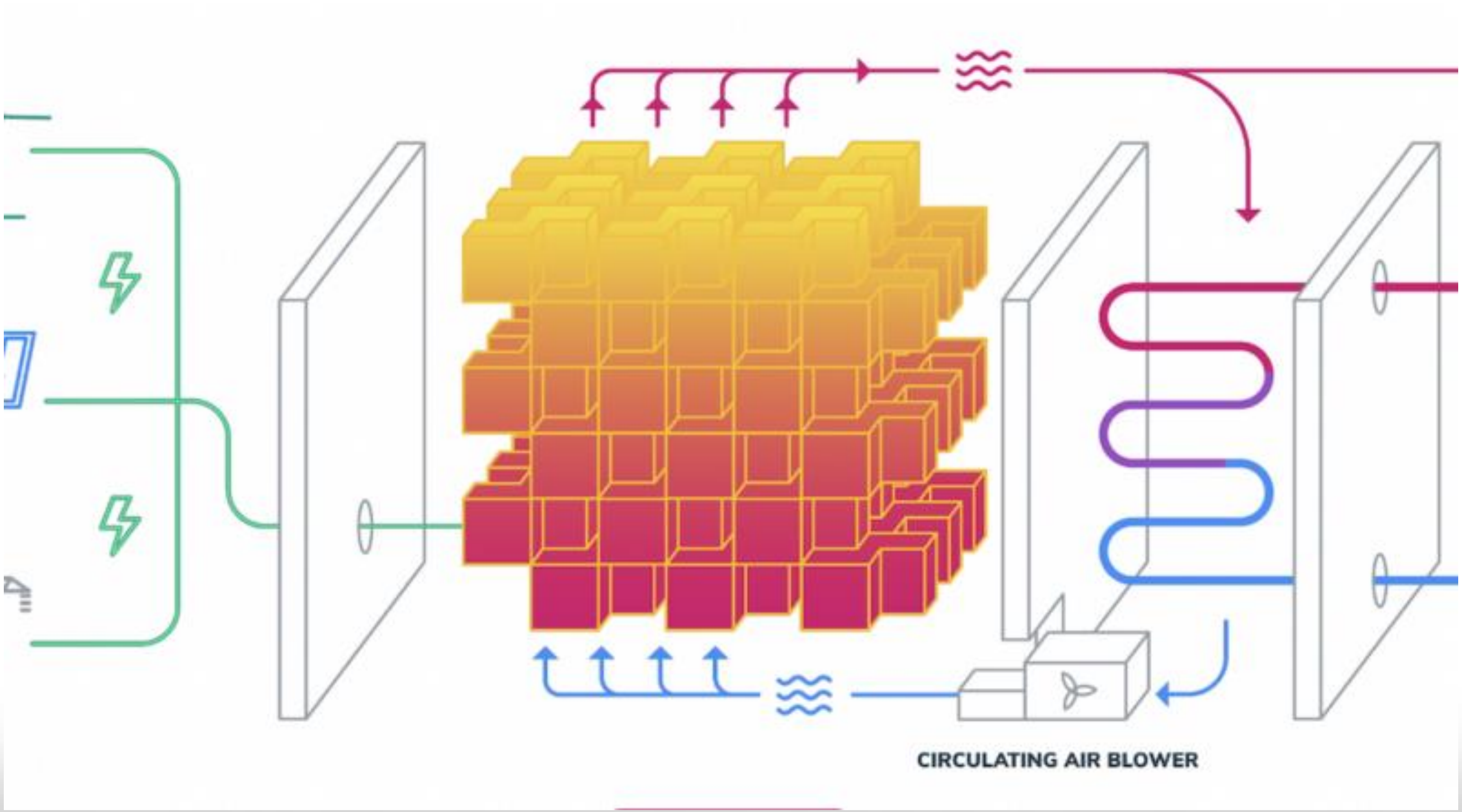
Capital cost $168 bil, but $29.6 bil/y savings -> energy cost payback time: 5.7 y

Creates 103,000 more long-term, full-time jobs than lost in Minnesota

Requires only 0.14% of Minnesota's land for utility PV and 0.71% for wind (vs 1.3% of U.S. land used by fossil industry & 1.24% for corn ethanol)

https://web.stanford.edu/group/efmh/jacobson/Articles/I/21-USStates-PDFs/21-WWS-Minnesota.pdf

Firebricks



Bricks that store heat up to 2,000 Celsius for 90% of industry

Impacts of Firebricks on Cost of WWS System

Bricks that store low- to high-temperature heat for 90% of industry

Heat (resistive) from 100% renewable wind-water-solar (WWS) electricity

Air blown through channels in the bricks allows industry to run 24/7 on WWS

One tenth the cost per kWh-storage as batteries & eliminates need for furnaces

Tests across 149 countries with firebricks replacing other heating: Reduces world capital cost to transition by $1.27 tril. (from $58.24 to $56.97 tril.) and LCOE by1.8%.

Seven Problems With Nuclear Electricity

1. Long planning-to-operation times
2. High costs
3. Nuclear weapons proliferation risks
4. Core meltdown risks
5. Waste storage issues and risks
6. Carbon dioxide, water vapor, and heat emissions
7. Underground uranium mining lung cancer risks

Small Modular Reactors, which do not exist commercially, have similar risks

https://web.stanford.edu/group/efmh/jacobson/WWSStillNMN/SNMN-WhyNotNuclear.pdf

Nuclear Planning-to-Operation Times

	Construction Time (Years)	Plan-to-Operation Time (Years)	Cost $/W
Olkiluoto 3 (Finland)	18	23	8
Hinkley Point (UK)	11-13	21-23	19
Vogtle 3 and 4 (US)	10-11	17-18	16
Flamanville (France)	17	20	16
Haiyang 1 and 2 (China)	9	13-14	
Taishan 1 and 2 (China)	10-11	12-13	
Shidao Bay (China)	10	17	
Barakah 1-4 (UAE)	9	12-15	

Issues With New Nuclear Reactors

Take 12-23 y between plan & operation v 0.5-5 y for new solar/wind

Capital costs 10-20 x and cost per unit energy 3-8 x those of wind/solar

Produce 9-37 times more CO_2e and pollution per unit energy than wind

IPCC 2014: P. 517. "Robust evidence, high agreement" that increased use of nuclear leads to more

(a) Weapons proliferation risk
(b) Meltdown risk
(c) Waste risk for 200,000+ years
(d) Underground uranium mining lung cancer risk from radon

WWS vs. CC & DAC: 4 Cases Across 149 Countries

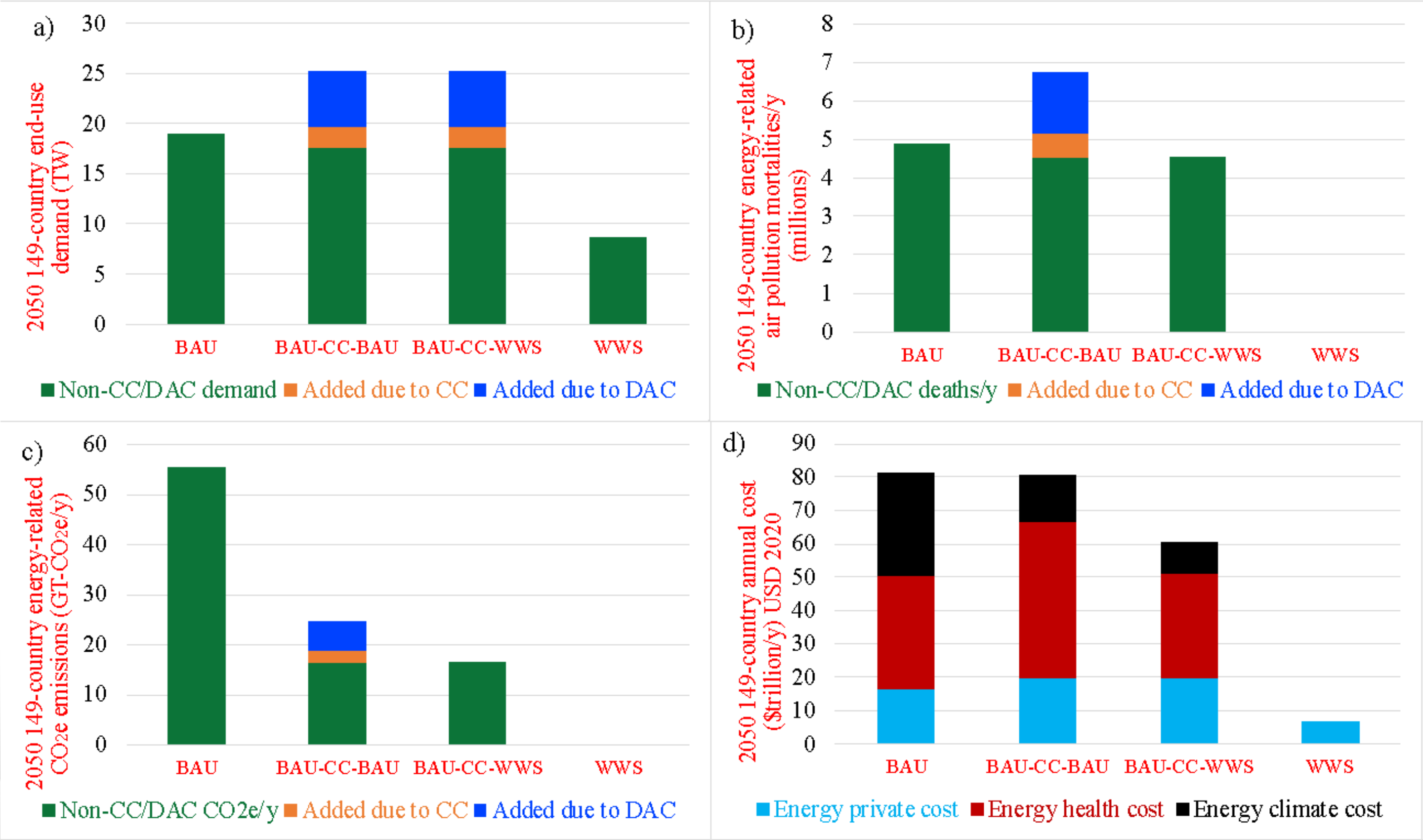
BAU: Business-As-Usual

BAU-CC-BAU: CC attached to fossil and bioenergy stationary sources; SDACC offsetting mobile and distributed CO_2 sources, and using BAU sources to supply the electricity for CC and SDACC

BAU-CC-WWS: Same as BAU-CC-BAU, but using WWS sources to supply the electricity for CC and SDACC

WWS: Replace all non-WWS BAU energy with WWS

a) Energy Demand; b) Air Pollution Deaths/y; c) CO_2e/y; d) Social Cost Across 149 Countries in Four Cases



Problems With Carbon Capture/Direct Air Capture

Policies promoting CC and DAC increase air pollution, CO_2e emissions, energy needs, private energy costs, and social energy costs 9.1-12.1 times those of policies promoting 100% Wind-Water-Solar (WWS)

The conclusions apply to any level of carbon removal above zero.

CC and DAC may, in the limit, cause millions of unnecessary air pollution deaths each year worldwide and substantial climate damage in the short and long term.

As such, policies promoting CC and DAC should be abandoned.

New paper: ES&T doi:10.1021/acs.est.4c10686, 2025
https://web.stanford.edu/group/efmh/jacobson/Articles/I/149Country/149-Countries.pdf

Left: 14 Countries With Elec. Generation 95-100% WWS 2023
Right: 12 States With Consumption 47-110% WWS 2023-4

Albania 100% (H,S)
Bhutan 100% (H)
Central African Republic 100% (H)
Lesotho 100% (H)
Nepal 100% (H,S,W)
Iceland 100% (H,G,W)
S. Georgia/SW 100% (H,W)
Ethiopia 99.95% (H,W,S,G)
Congo, DR 99.81% (H,S)
Paraguay 99.46% (H)
Costa Rica 99.40% (H,G,W,S)
Norway 98.38% (H,W,G)
Namibia 97.88% (H,S,W)
Sierra Leone 95.24 (H,S)

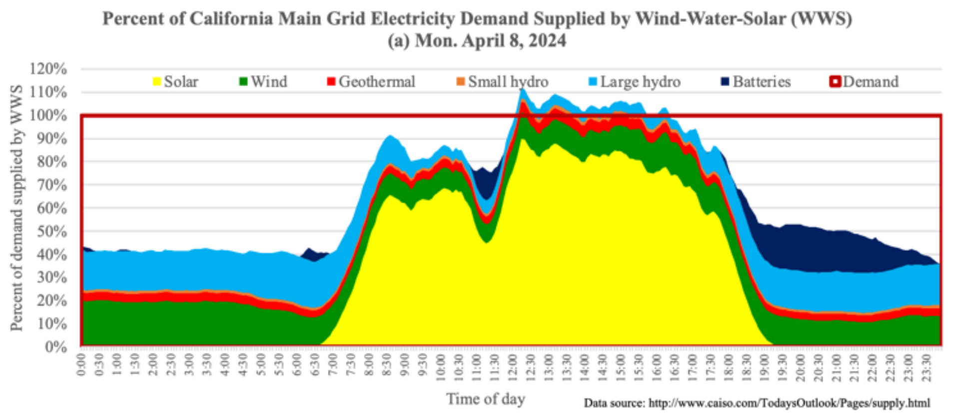
S. Dakota 109.8% (W,H,S)
Montana 86.5% (H,W,S)
Iowa 79.4 (W,S,H)
Washington State 72.6% (H,W,S)
Kansas 70.2 (W,S,H)
Oregon 64.2% (H,W,S,G)
Maine 62.1% (H,W,S)
New Mexico 59.7% (W,S,G)
Wyoming 56.1% (W,H,S)
N. Dakota 55.1% (W,H)
Oklahoma 53.7% (W,H,S)
California 47.3% (S,H,W,G)

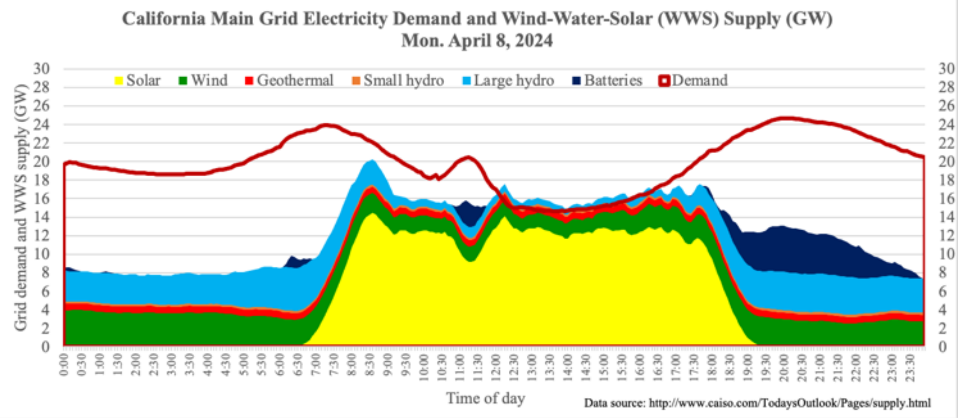
H = hydro; G = geothermal
W = wind; S = Solar

Progress in California Toward 100% WWS in the Electric Power Sector

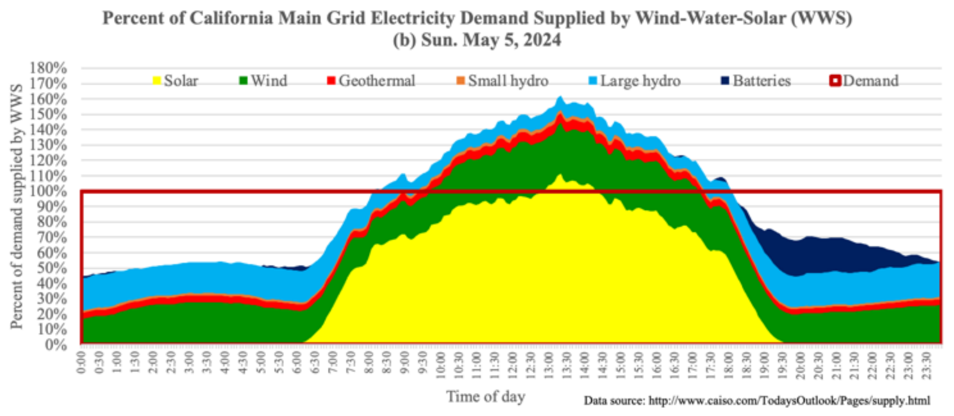
Examples With the CAISO Grid

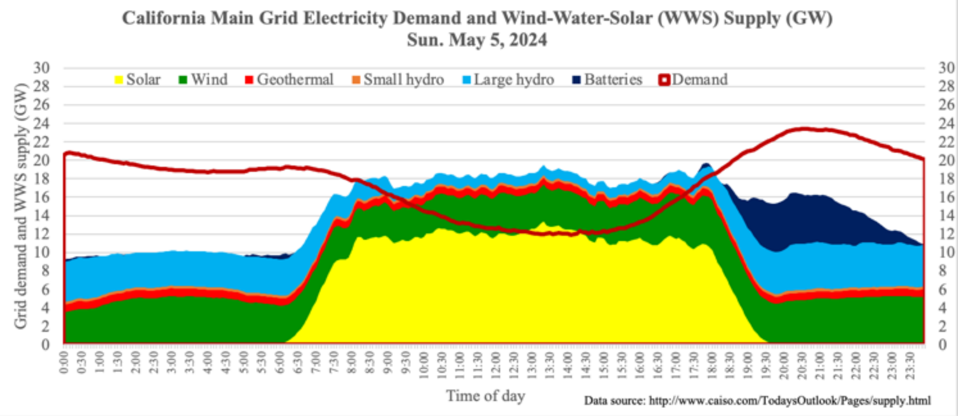
Monday, April 8, 2024, a Solar Eclipse Occurred Reducing WWS Supply and Increasing Grid Demand for Electricity - Batteries Filled in the Gap in California



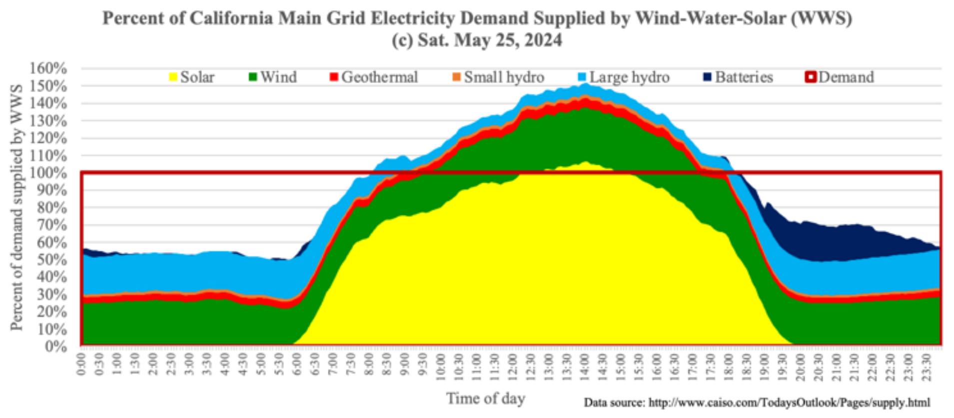


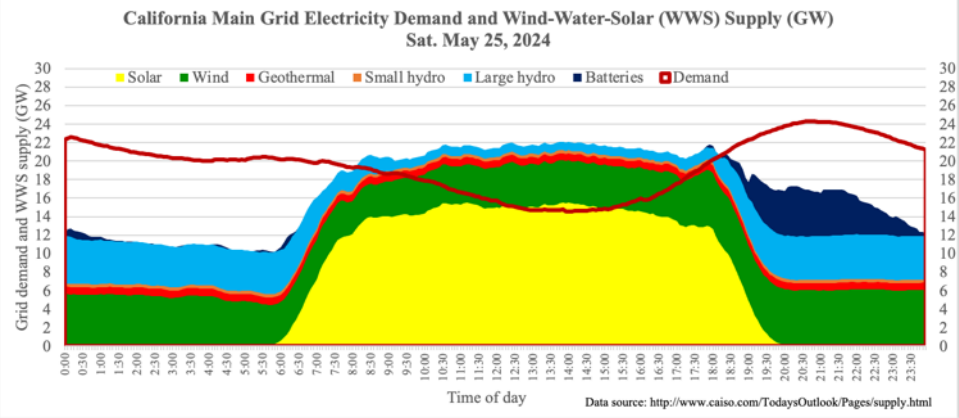
Sunday, May 5, 2024, WWS Supply Met 162.3% of Demand for 5 Minutes and Exceeded Demand for 9.9 Hours



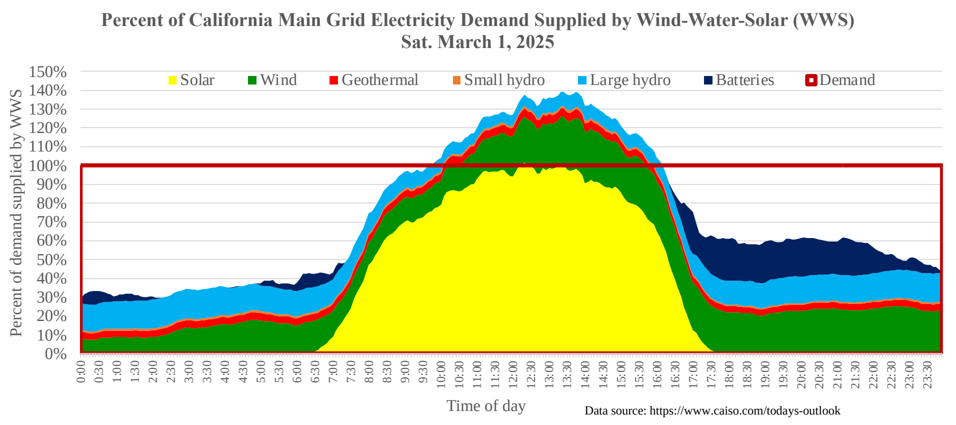


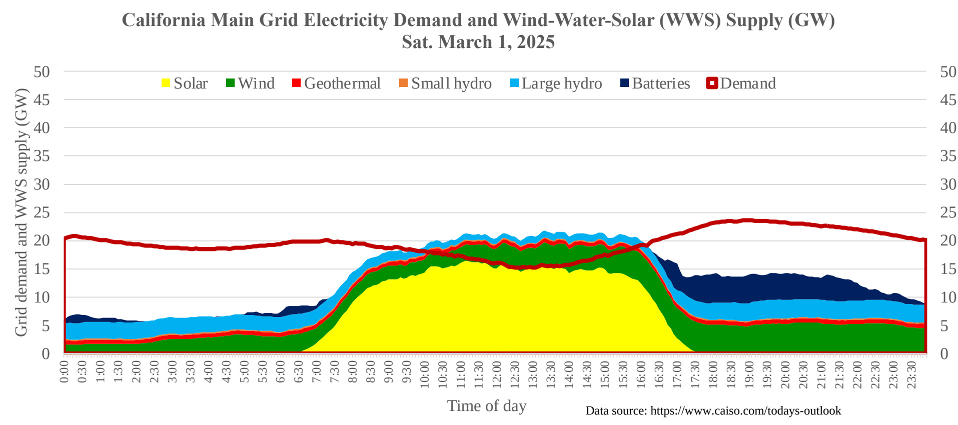
Saturday, May 25, 2024, WWS Supply Met 82.3% of Demand in the 24-Hour Average



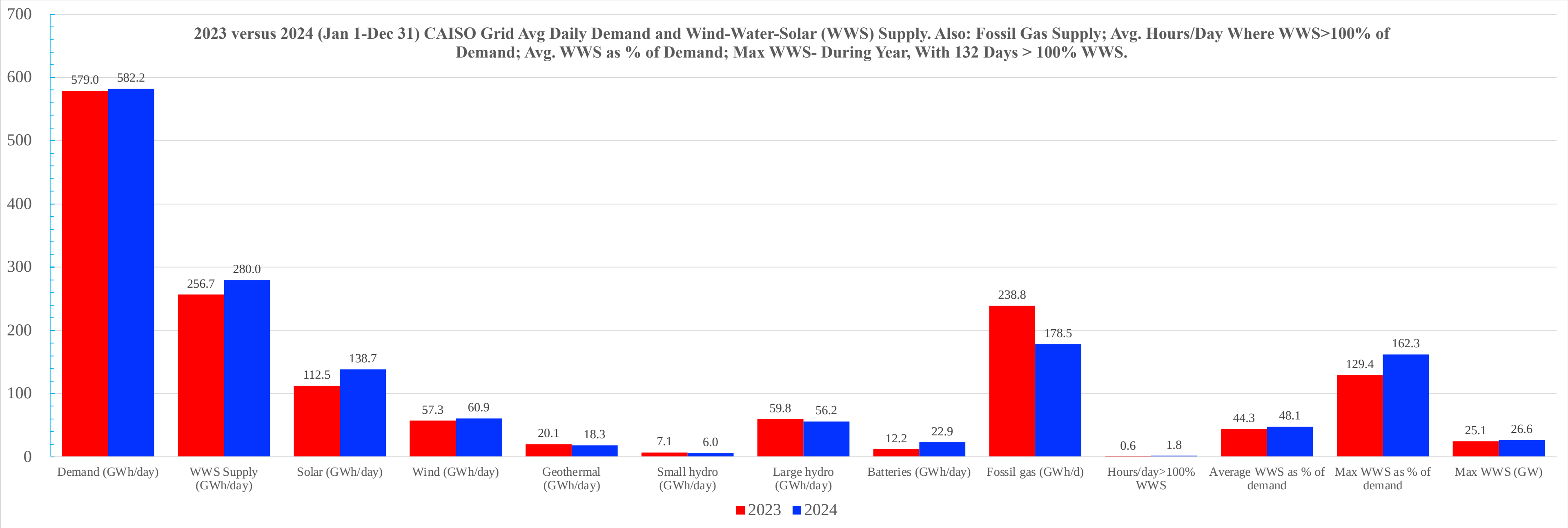


Sunday, Mar. 1, 2025, WWS Supply Met 63% of 24-Hour Demand and a Peak of 139% of Demand

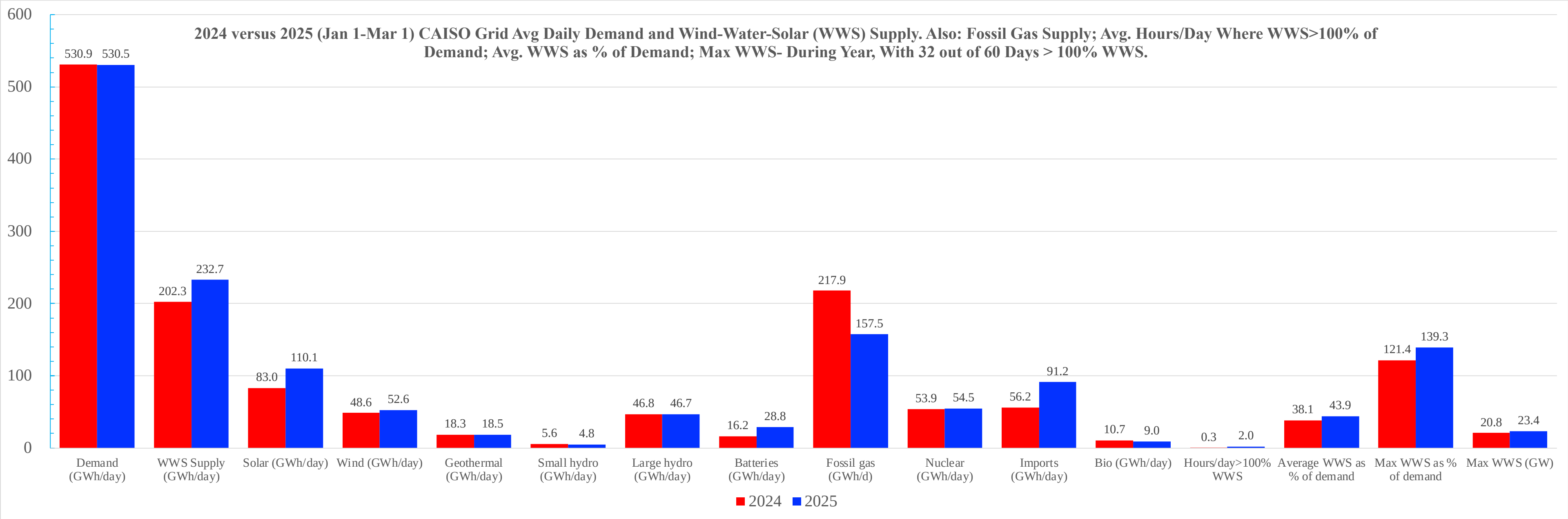




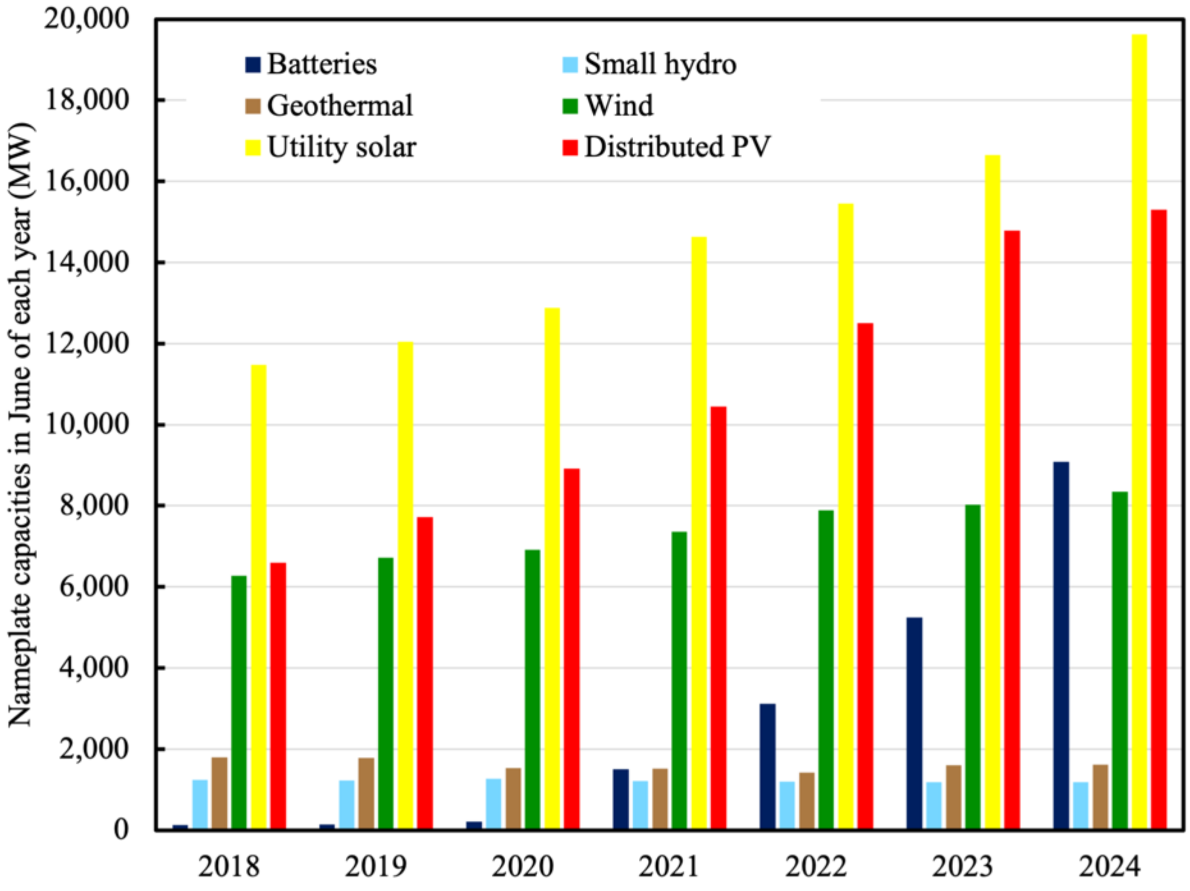
California (CAISO) Grid Stats Jan. 1–Dec. 31, 2024, Versus 2023



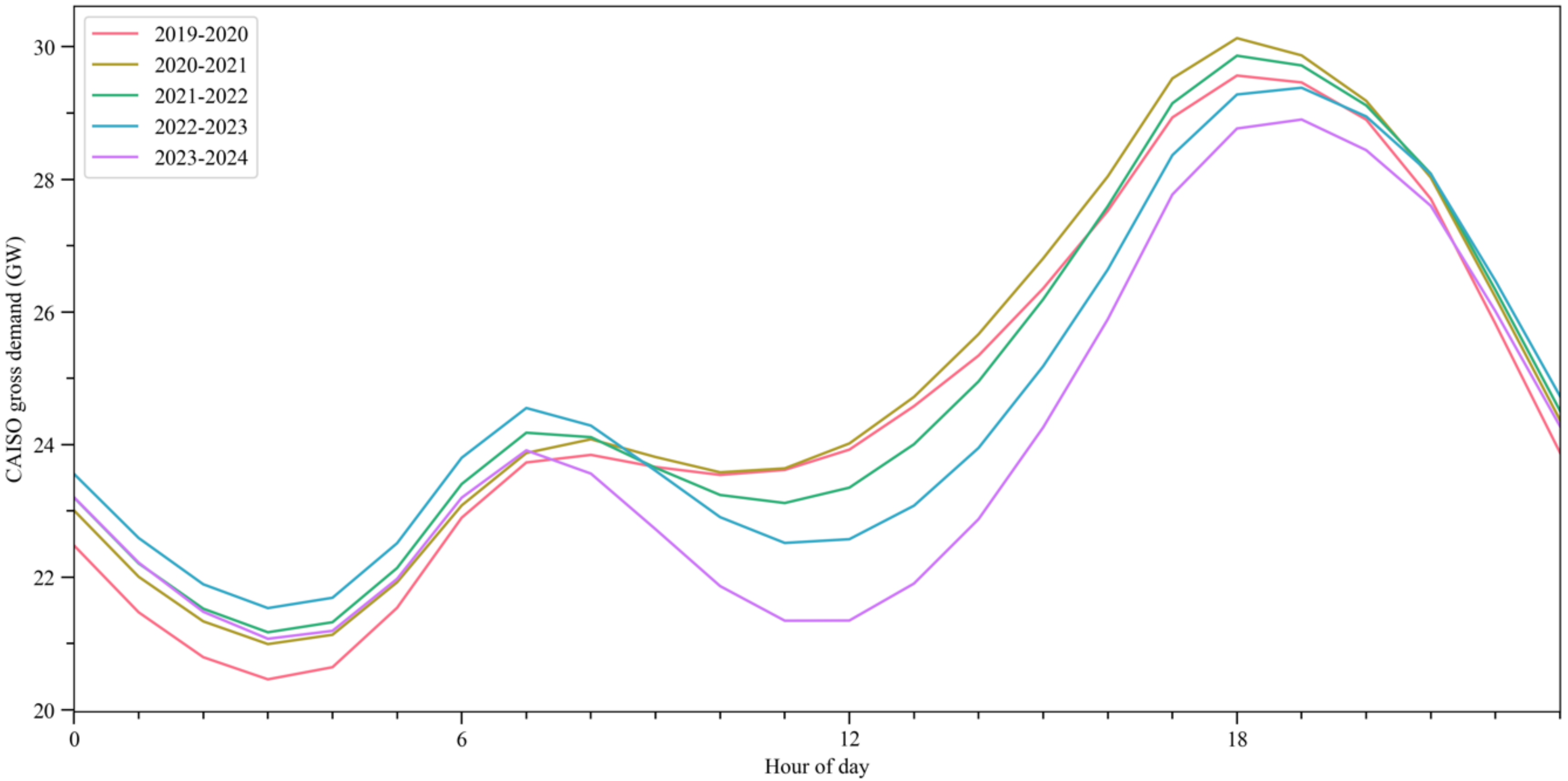
California (CAISO) Grid Stats Jan 1–Mar 1, 2025, Versus 2024



Nameplate Capacities of WWS Generators and Batteries on CAISO Grid 2018-2024



CAISO Grid Demand by Hour of Day for Different Years



What Can be Done to Obtain 100% WWS Every Hour?

More utility PV+batteries

More rooftop PV+batteries, heat pumps, & energy-effic buildings

Offshore wind

Enhanced geothermal

Shift more hydro to night

Use demand response more effectively

Summary – Transitioning World to 100% WWS

Creates 23 million more jobs than lost worldwide

Requires only 0.13% of land for footprint; 0.38% 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 annual energy costs are 60% less than of fossils

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

Book on 100% WWS ("No Miracles Needed")

https://web.stanford.edu/group/efmh/jacobson/WWSNoMN/NoMiracles.html

100% WWS Plans for Countries, States, Cities

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

Online Course on 100% WWS

https://stanford.io/windwatersolar

Infographic maps

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

Twitter: @mzjacobson

Minnesota 100% Wind-Water-Solar Plan
https://web.stanford.edu/group/efmh/jacobson/Articles/I/21-USStates-PDFs/21-WWS-Minnesota.pdf

Evaluation of Nuclear
https://web.stanford.edu/group/efmh/jacobson/WWSStillNMN/SNMN-WhyNotNuclear.pdf

Evaluation of Carbon Capture/Direct Air Capture
https://web.stanford.edu/group/efmh/jacobson/WWSStillNMN/SNMN-WhyNotCCorDAC.pdf

New Paper on Carbon Capture/Direct Air Capture
https://web.stanford.edu/group/efmh/jacobson/Articles/Others/25-CaliforniaWWS.pdf

Book on all these issues "No Miracles Needed"
https://web.stanford.edu/group/efmh/jacobson/WWSNoMN/NoMiracles.html

Paper on Proposed Ethanol With Carbon Capture Project in Upper Midwest
https://web.stanford.edu/group/efmh/jacobson/Articles/Others/23-E85vBEVs.pdf

Paper on Transitioning Land, Air, and Sea Vehicles to Battery/Hydrogen Fuel Cell Vehicles
https://web.stanford.edu/group/efmh/jacobson/Articles/Others/22-BEH2Vehicles.pdf