Grid Reliability and the Diablo Canyon Power Plant

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San Luis Obispo, California
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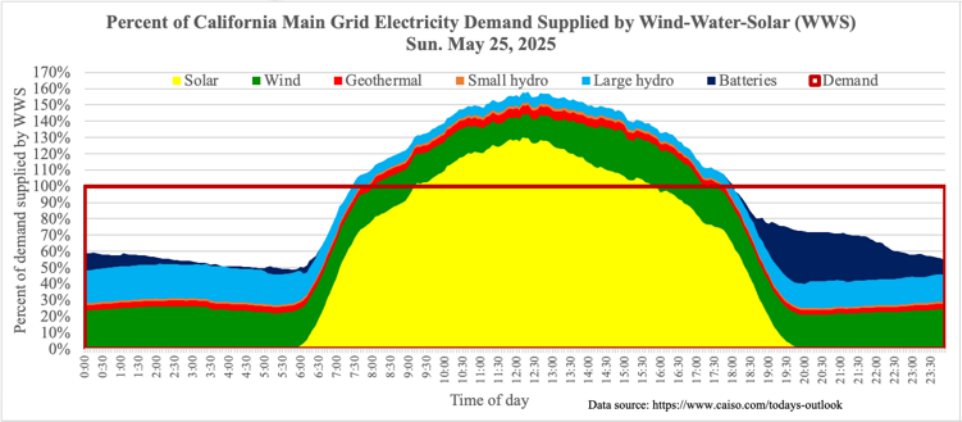
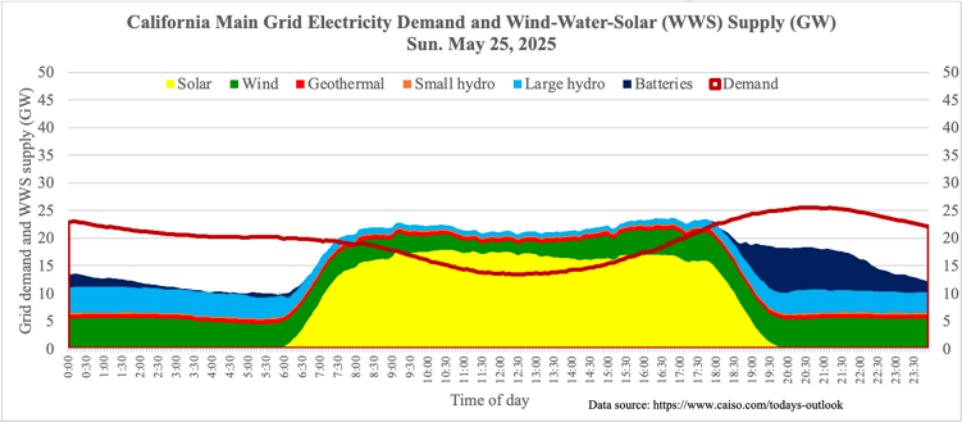
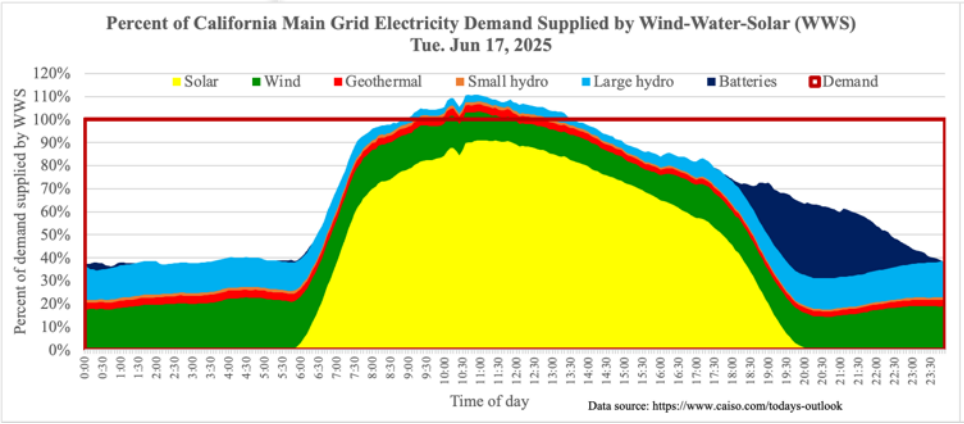
Progress in California in Moving to 100% Clean, Renewable Energy

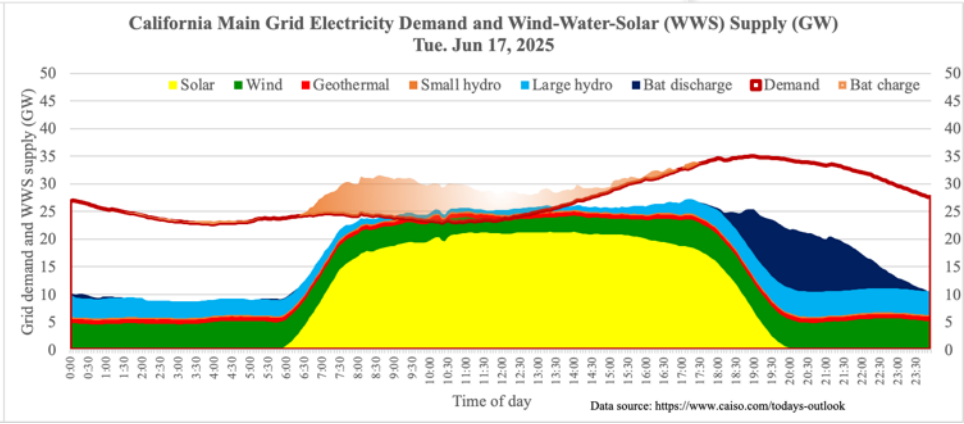
Sunday, May 25, 2025
10.5 h > 100% WWS
82% of 24-h demand met by WWS
WWS met a peak of 158.3% of demand



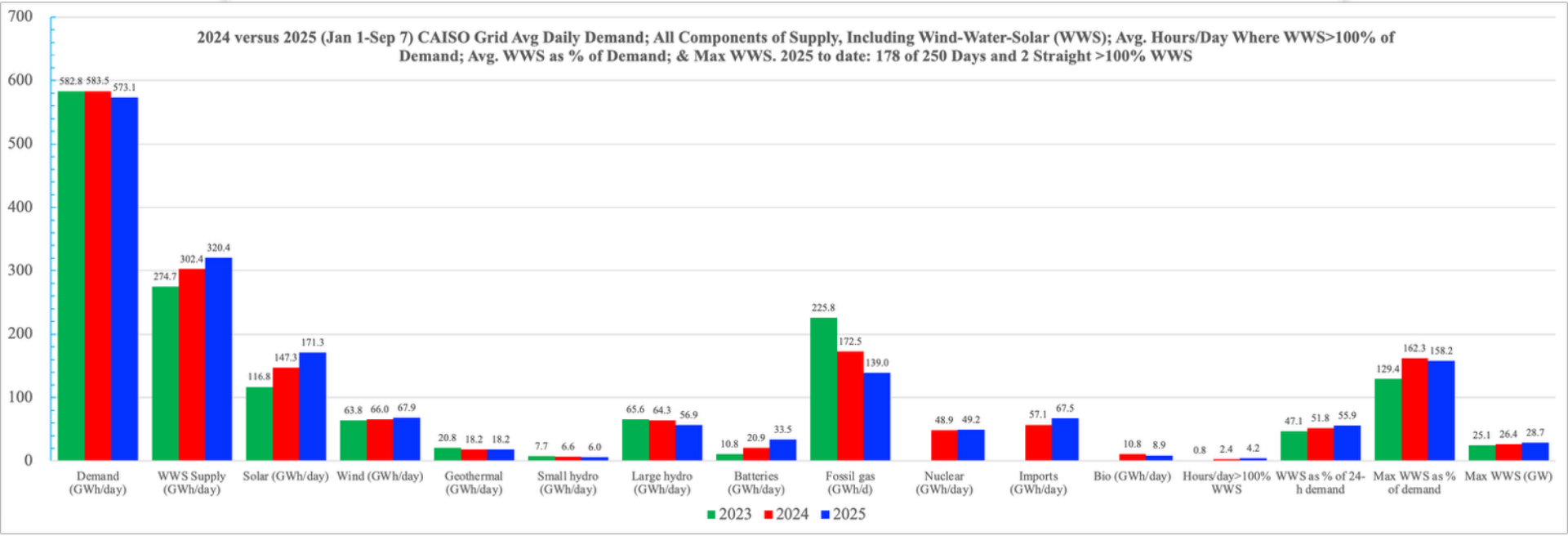


Tuesday, June 17, 2025
Record battery discharge rate: 10.895 GW at 7:55 PM





California (CAISO) Grid Stats Jan 1–Sept. 7, 2025, Versus 2024
178 of 250 (71%) Days in 2025 With >100% WWS



Demand down in 2025 1.8% versus 2024 and 1.6% versus 2023.

WWS up 6%; Solar up 16%; Wind up 3%; Hydro down 11%; Batteries up 60% (and up 211% versus 2023)

Fossil gas down 19.4% (and down 38.4% versus 2023); Imports up 18%

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

Seven Issues With Nuclear Electricity

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

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

https://nationalinterest.org/blog/energy-world/why-new-large-and-small-nuclear-reactors-are-not-green

Issues With Nuclear Electricity

Takes 12-23 y between plan & operation v 0.5-3 y for new solar/wind

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

Produces 9-37 times more CO_2e & 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

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	

Total CO_2e Emissions of an Energy Technology

- Lifecycle emissions
- Opportunity cost emissions
- Anthropogenic heat emissions
- Anthropogenic water vapor emissions
- Emissions from CCS leakage
- Loss of CO_2 from soil/vegetation by covering ground

Nuclear Versus Wind CO_2e Emissions

	Nuclear (g-CO_2e/kWh)	Onshore Wind (g-CO_2e/kWh)
Lifecycle	9-70	7-10.8
Opportunity cost	64-102	0
Anthropogenic heat	1.6	-1.7 to -0.7
Anthropogenic water vapor	2.8	-0.5 to -1.5
Weapons proliferation risk	0-1.4	0
Covering land	0.17-0.28	0.0003
Total	**78-178**	**4.8-8.6**

Ratio of nuclear to wind: 9-37:1

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

Roadmaps for 150 Countries

All-Sector End-Use Power Demand BAU v WWS

Year and Fuel Type	150 Countries
2022 End-use demand	13.3 TW
2050 Demand with current fuels (BAU)	19.6 TW
2050 Demand with WWS	9.0 TW
2050 Demand reduction with WWS 19.8% efficiency of BE, HFC v. ICE 4.1% efficiency of electric industry 13.1% efficiency of heat pumps 10.6% eliminating fuel mining 6.6% efficiency beyond BAU	54.2%

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

World (150 Countries): $60.0 trillion

U.S.: $6.5 trillion

China: $15.5 trillion

Europe: $5.4 trillion

California: $517 billion

2050 150-Country BAU vs WWS Annual Energy Cost

BAU fuel energy cost	$17.2 trillion/yr
BAU fuel health cost	$36.9 trillion/yr
BAU fuel climate cost	$32.5 trillion/yr
BAU total social cost	$86.6 trillion/yr
WWS total social cost	$6.8 trillion/yr

WWS reduces energy cost 61% and economic (social) cost 92%

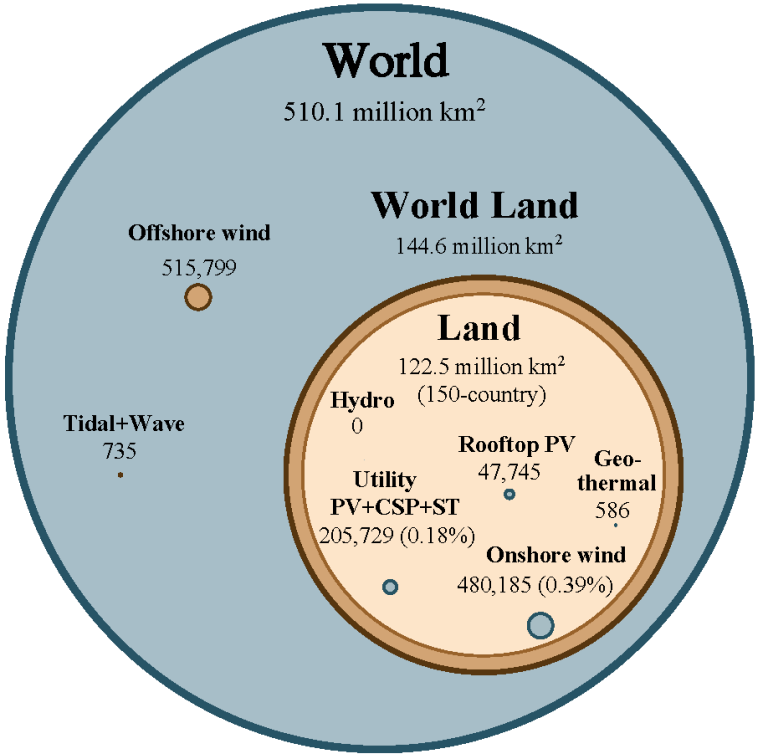
→ Energy-cost-savings payback time = 6 yr; social cost payback = 1 yr

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 150 Countries for all Purposes With 100% WWS in 2050



Onshore wind:	0.39%
Utility PV+CSP:	0.18%
Total 150 Countries	0.57%
Onshore wind:	0.36%
Utility PV+CSP:	0.69%
Total U.S.	1.05%
Onshore wind:	0.47%
Utility PV+CSP:	0.33%
Total California	0.80%

Vs. 1.24% of U.S. land for corn ethanol and 1.16% of U.S. land for the fossil industry

Left: 14 Countries With Elec. Generation 95-100% WWS 2023

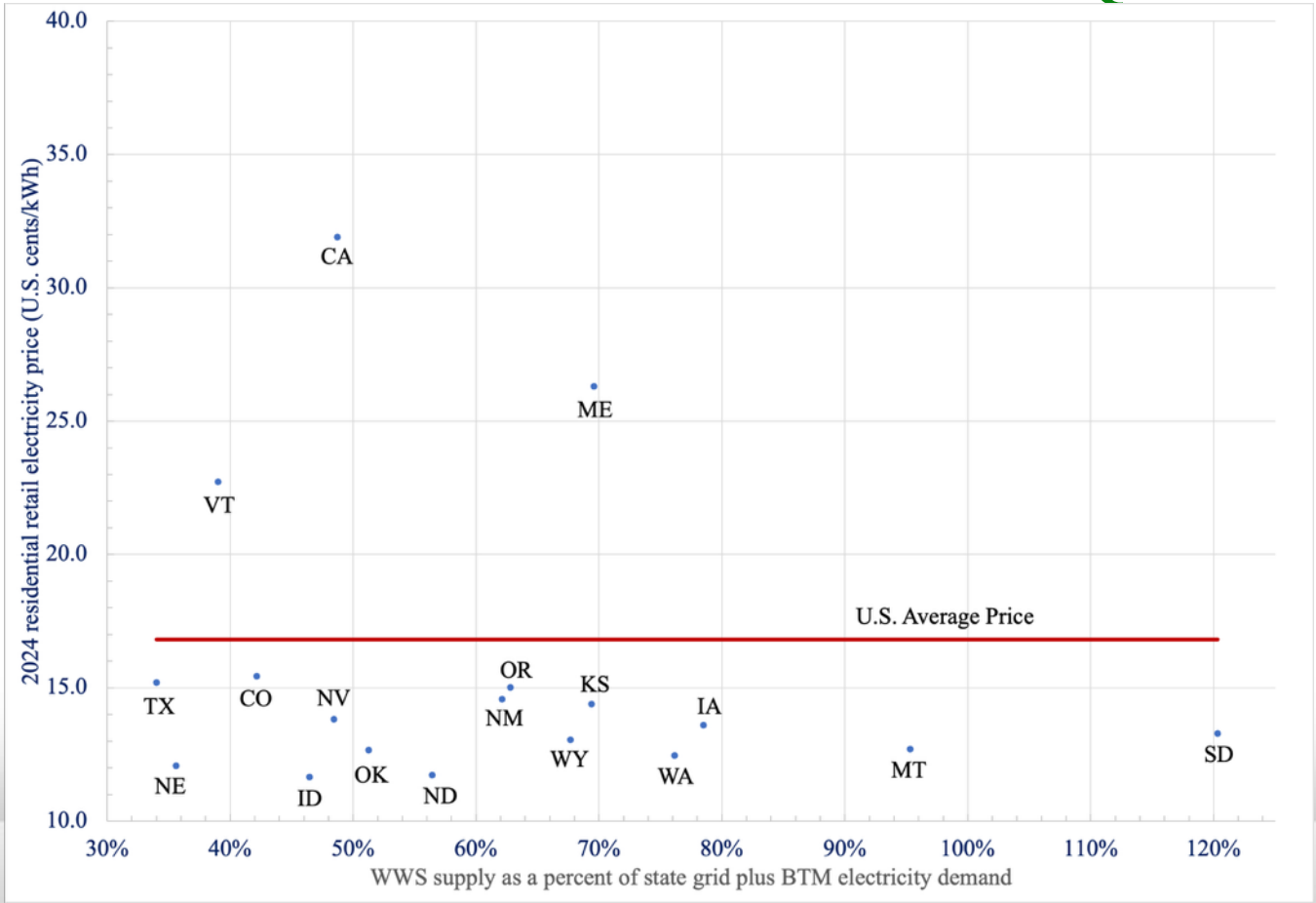
Right: 12 States With Consumption 49-120% WWS Q324-Q225

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 120% (W,H,S)
Montana 95.3% (H,W,S)
Iowa 78.5 (W,S,H)
Washington State 76.2% (H,W,S)
Maine 69.6% (H,W,S)
Kansas 69.4 (W,S,H)
Wyoming 67.7% (W,H,S)
Oregon 62.8% (H,W,S,G)
New Mexico 62.1% (W,S,G)
N. Dakota 56.4% (W,H)
Oklahoma 51.3% (W,H,S)
California 48.7% (S,H,W,G)

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

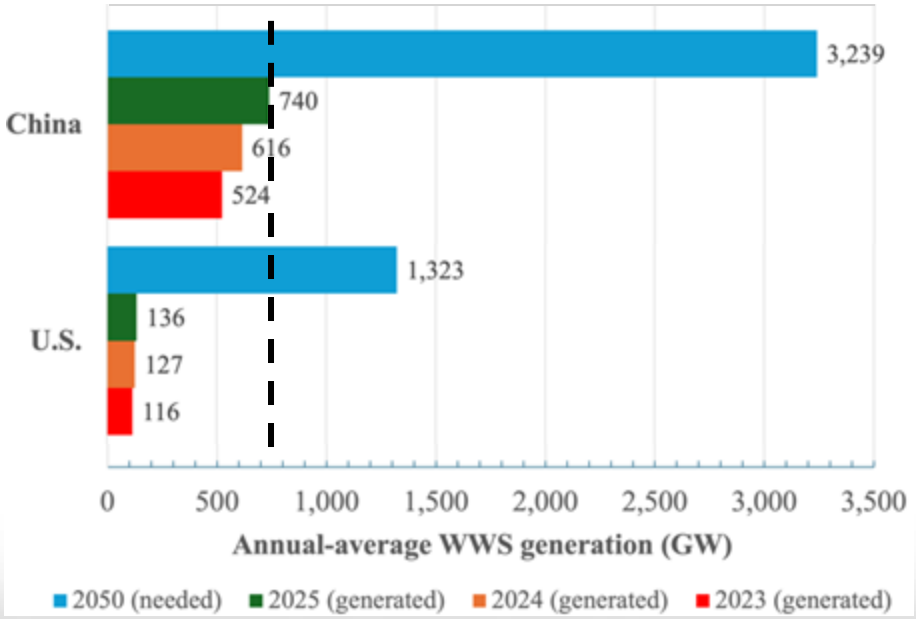
U.S. State Residential Retail Electricity Price vs WWS Supply as a Percent of Grid Plus Behind-The-Meter Demand Q3 2024-Q2 2025.



Dates by Which Countries Will Reach 100% WWS if They Electrify All Energy Sectors and Provide Electricity With WWS

Laos	2025	Sweden	2060	Slovenia	2085
Estonia	2035	Finland	2061	Bos-Herz	2087
Lithuania	2036	Netherlands	2062	Albania	2088
Greece	2041	Chile	2064	France	2094
Norway	2043	Australia	2065	World avg	2095
China	2045	Hungary	2067	Brazil	2096
Switzerland	2047	Romania	2067	Bulgaria	2096
Portugal	2048	Uzbekistan	2070	Tanzania	2109
Macedonia	2052	Italy	2070	Ethiopia	2111
Germany	2053	Poland	2074	Croatia	2116
Spain	2055	New Zealand	2075	Belgium	2122
Turkiye	2057	Ireland	2078	Latvia	2127
Austria	2058	Nepal	2082	India	2144
Denmark	2059	Cyprus	2083	U.S.	2155

WWS Power Generation Needed to Meet 100% of All-Sector End-Use Demand in 2050 v. WWS Generation in 2023, 2024, 2025



If all energy sectors are electrified and electricity is provided with WWS …

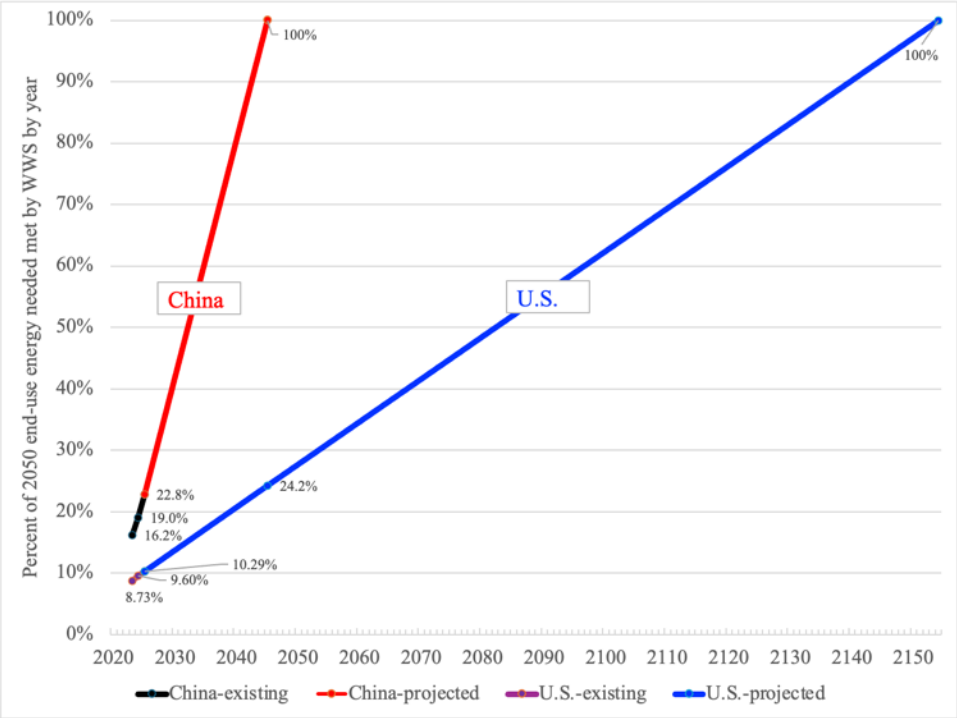
China trajectory for 100% WWS is by **2045**

U.S. trajectory for 100% WWS is by **2155**

The 2050 estimates are from Jacobson et al. (ES&T 59, 3034-3045, 2025), which start with 2022 IEA data. The 2023, 2024, and 2025 estimates are based on actual nameplate capacities and estimated capacity factors from Jacobson et al. (2025).

China is Projected to Reach 100% WWS by 2045, 110 Years Before the U.S. (2155)

Percent of energy needs met by WWS



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Summary – Transitioning World to 100% WWS

Creates 28 million more jobs than lost worldwide

Requires only 0.18% of land for footprint; 0.39% 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 61% less than of fossils

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

Book on 100% WWS (“Still 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