Transitioning Buildings, Cities, States, and Countries to 100% Clean, Renewable Energy For All Purposes

Mark Z. Jacobson
Stanford University

SES4DH Conference
Aalborg University, Denmark
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What's the Problem? Why act Quickly?

Fossil-fuel + biofuel air pollution cause 4-7 mil. premature air pollution deaths per year worldwide costing ~$20-25 trillion/year

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

Fossil fuels are limited resources, and their continued use must increase energy prices and economic, political, and social instability

Drastic problems require immediate solutions.

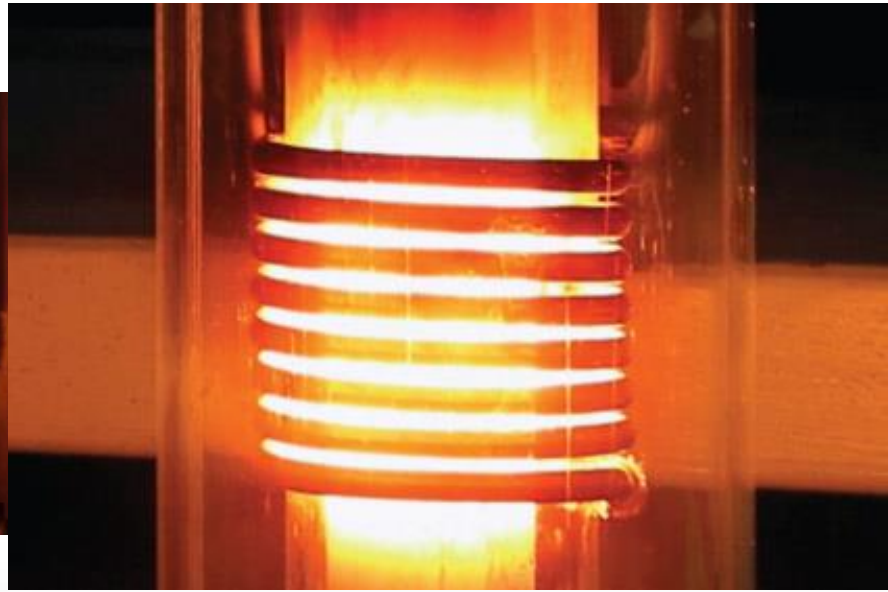
Wind, Water, Solar (WWS) Solution

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	HFC-BE hybrids	Solar water preheat	Induction furnaces
Geothermal			Dielectric heating
Hydro			
Tidal/Wave			

Industrial Heat: Replace Fossils With Electricity

Electric Arc Furnace



Electric Induction Furnace

Electric & Hydrogen Fuel Cell Trucks and Buses

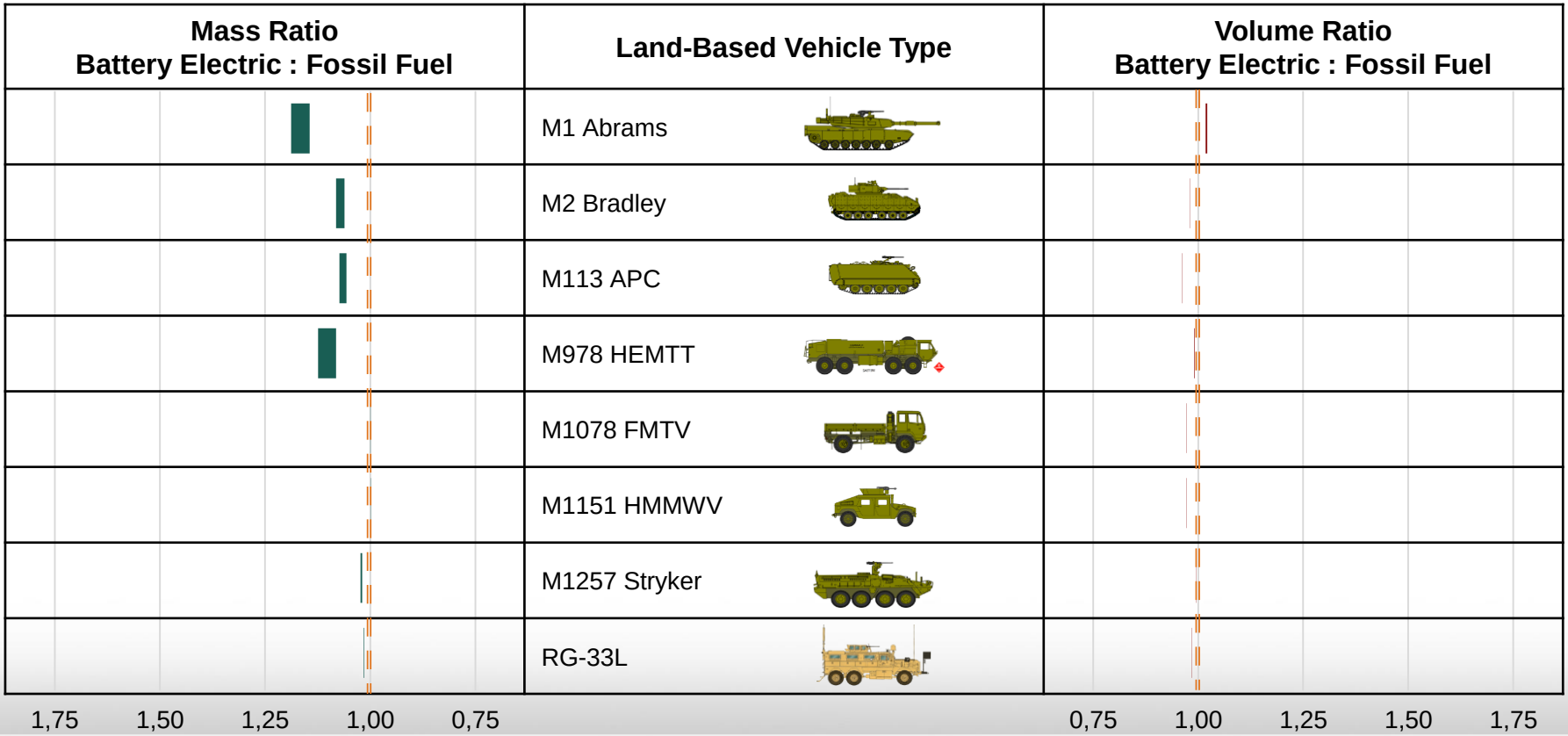
Tesla semi electric

Nikola One semi hydrogen fuel cell

Protera electric bus

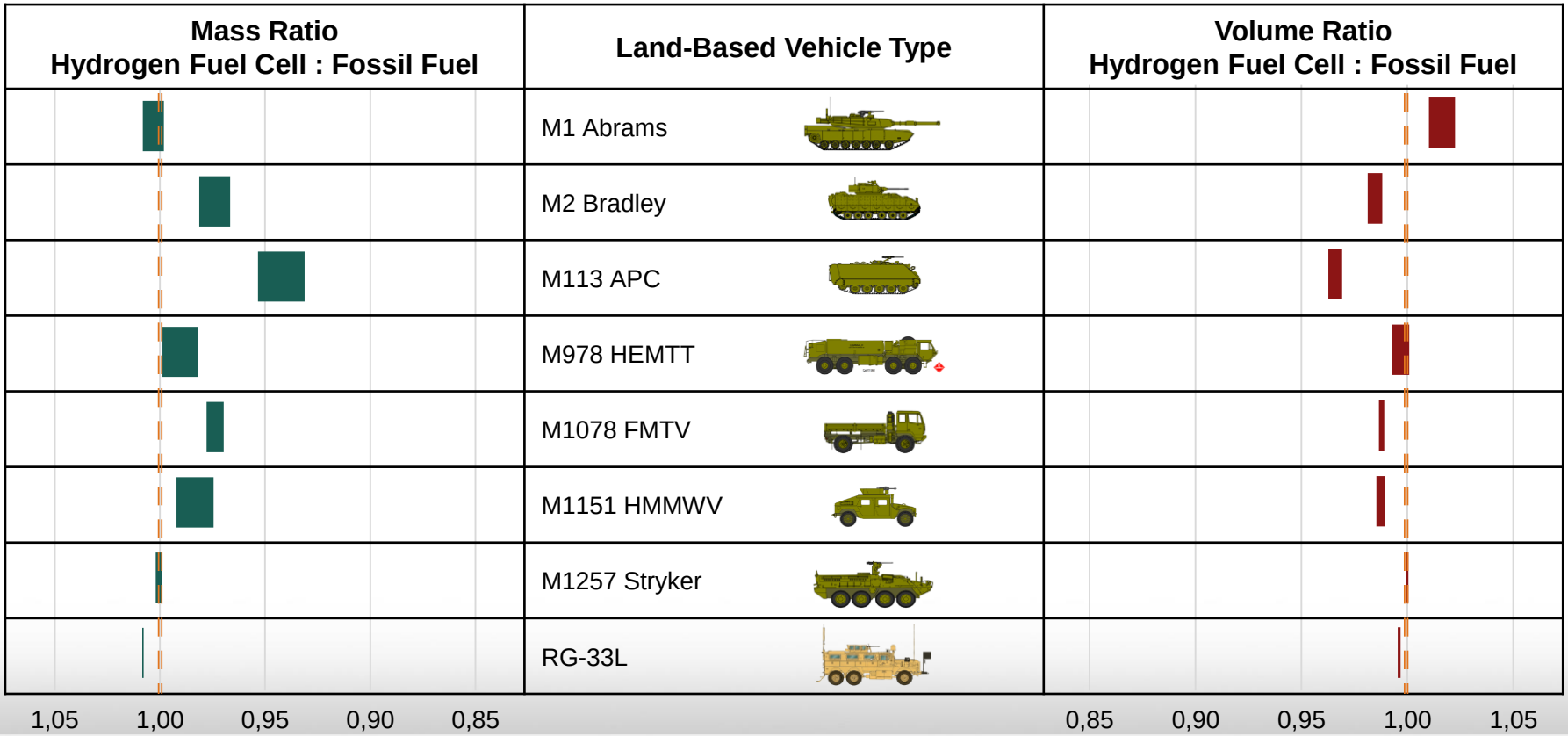
Hydrogen fuel cell–electric hybrid bus

What if we Converted the Army's Land-Based Vehicle Fleet to Battery Electric Vehicles Using 2020 Target Technology?



* Bars show difference in equivalency calculations to gross vs. curb vehicle weight of FF variant (i.e. delta could be used to improve the ratio but would decrease payload capacity of new variant)

What if we Converted the Army's Land-Based Vehicle Fleet to Hydrogen Fuel Cell Vehicles Using 2020 Target Technology?



* Bars show difference in equivalency calculations to gross vs. curb vehicle weight of FF variant (i.e. delta could be used to improve the ratio but would decrease payload capacity of new variant)

Planes: Replace Jet Fuel With Batteries & Hydrogen Fuel Cells

Battery electric aircraft

Cryogenic hydrogen aircraft

Hydrogen fuel cell aircraft

Electric Appliances

Electric lift

Electric lawn mower

Electric leaf blower

Provide More Electricity With Floating Offshore Wind and PV

Types of Storage for a 100% WWS System

ELECTRICITY	HEATING/COOLING	OTHER
CSP with storage	Water	Hydrogen for transport
Pumped hydro	Ice	Demand-response
Existing hydroelectric	Rocks in soil	
Batteries		

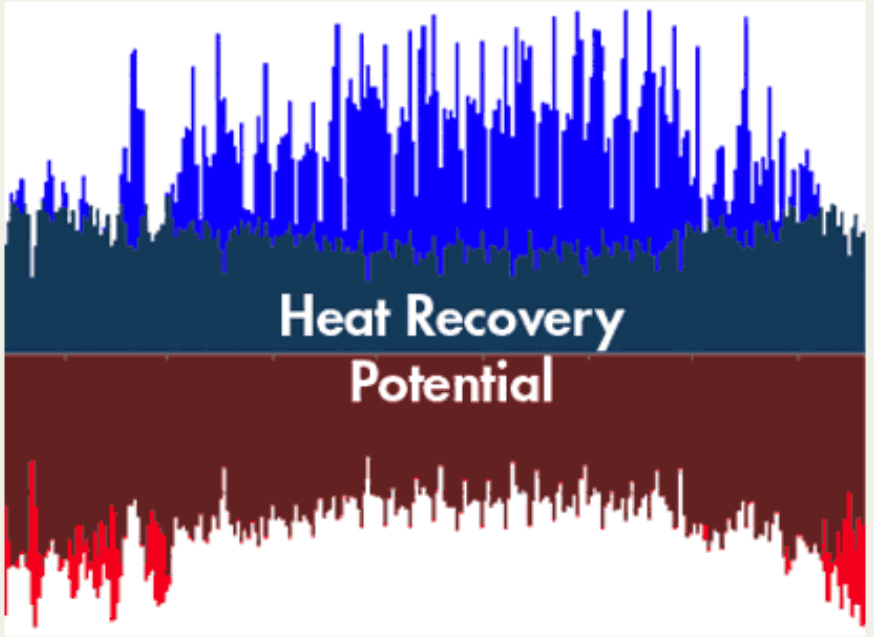
Nighttime Storage in Ice for Daytime Air Cooling

https://www.torontohydro.com/sites/electricsystem/electricityconservation/businessconservation/Pages/IceBearEnergyStoragePilot.aspx

Seasonal Heat Storage in Underground Rocks
Okotoks, Canada

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

Stanford Boilers/Chillers & Heat/Cold Demand For 1 Year



https://sustainable.stanford.edu/sites/default/files/SESI_Condensed_factsheet_0.pdf

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

80% Recycled, Prefabricated Steel Structure (from Bone Structure) -> No Wood Waste for Structure

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

Electric Heat Pump Water Heater

Photo by M.Z. Jacobson

Electric Induction Cooktop

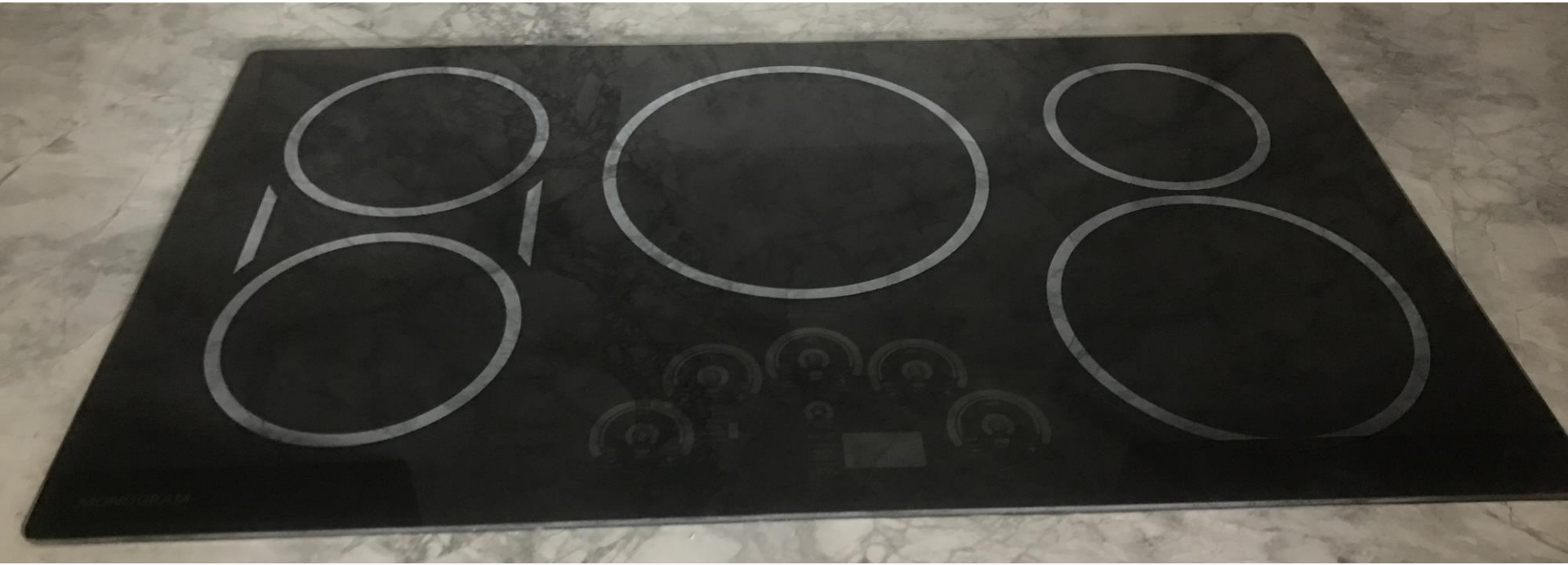


Photo by M.Z. Jacobson

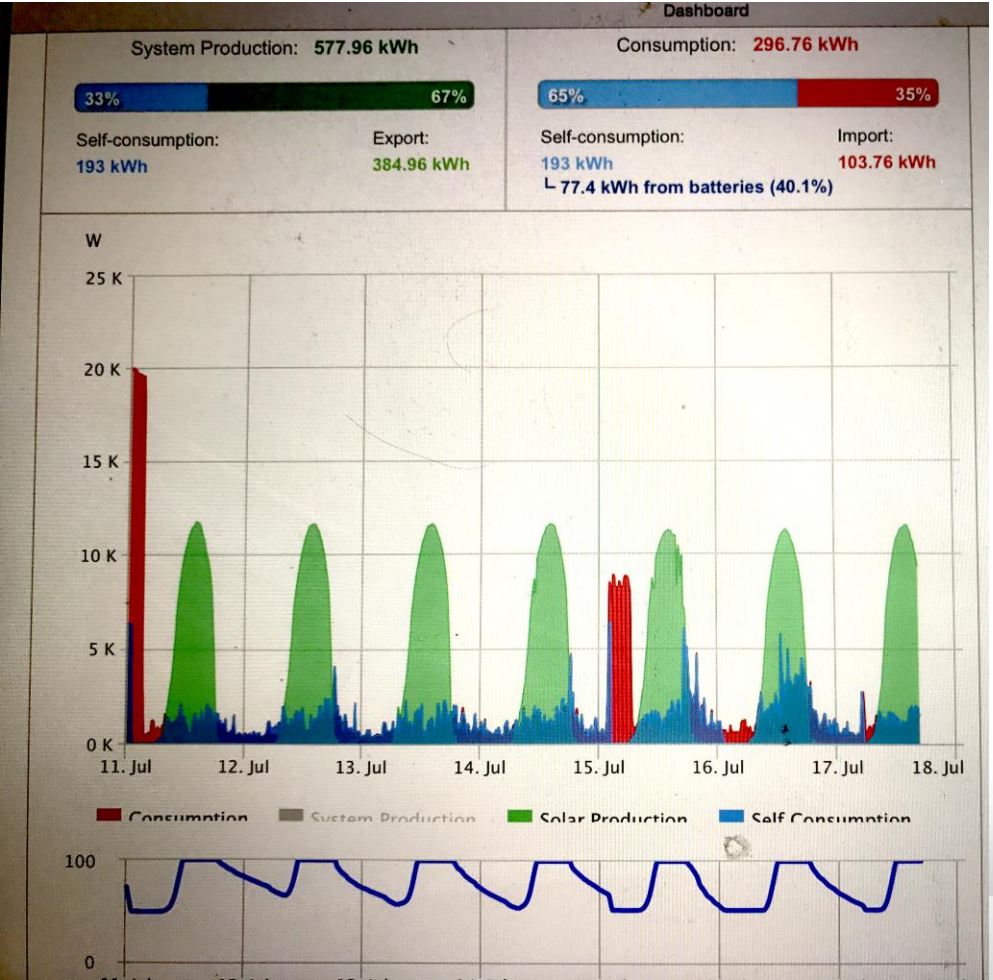
Rooftop Solar Plus Battery Storage

Photo by M.Z. Jacobson

Electric Cars + Batteries

Photo by M.Z. Jacobson

7 Days of Home Energy Use



Green: PV supply

Light Blue: Use from PV

Dark Blue: Use from batteries

Red: Use from grid

Line = battery charging/discharging

M.Z. Jacobson

One Year of Energy Use

Generated 120% of all home and vehicle energy

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

Instead, received $530 from CCA for excess electricity to grid

Avoided costs of all-electric home with solar PV+batteries

Gas hookup fee: 3-8 K

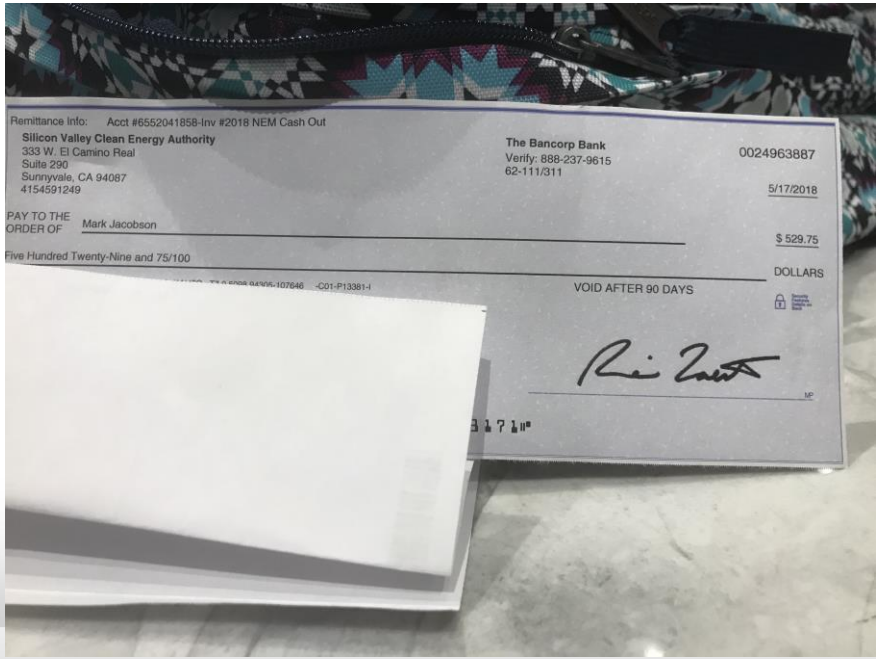
Gas pipes: 1-7 K

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



M.Z. Jacobson

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

Roadmaps for 139 Countries

All-Purpose End-Use Power Demand

Year and Fuel Type	139-Countries
2012 Demand	12.1 TW
2050 Demand with current fuels (BAU)	20.6 TW
2050 Demand with WWS, no heat pumps 2050 Demand with WWS, w/heat pumps	11.8 TW 8.6 TW
2050 Demand reduction w/ WWS 23.0% electrification 12.6% energy self use 15.8% efficiency of heat pumps 6.9% efficiency beyond BAU	58.3%

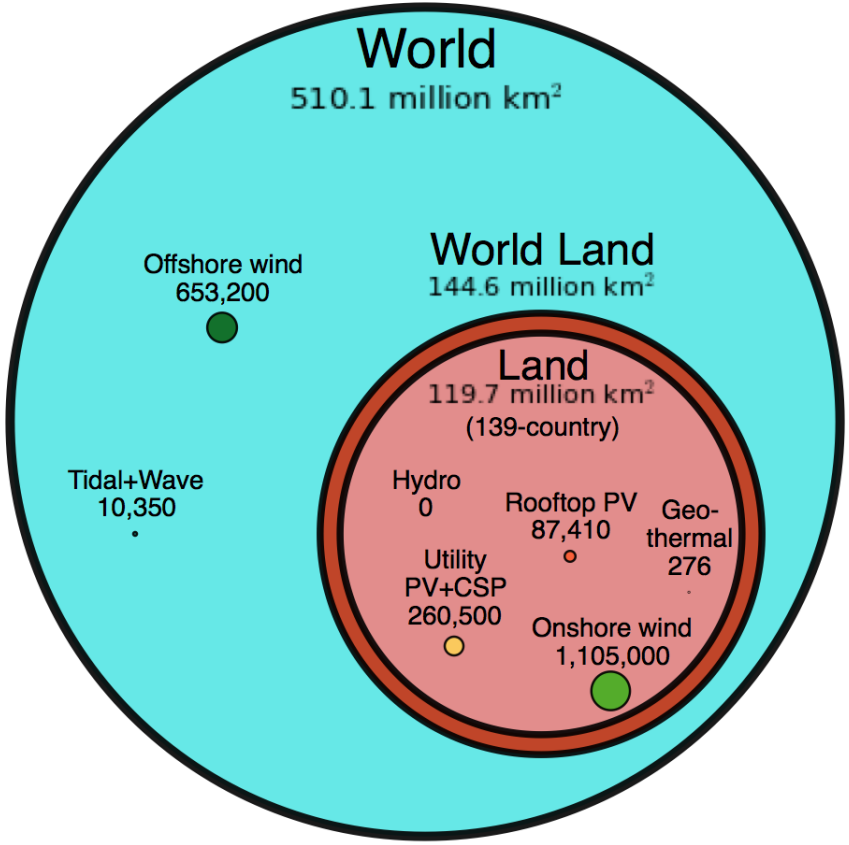
Percent of 2050 Denmark End-Use Demand Supplied by WWS Devices and Number of New Devices

TECHNOLOGY	PCT SUPPLY 2050	NUMBER
5-MW onshore wind turbines	26.5%	1,500
5-MW offshore wind turbines	37.3	2,700
5-kW Res. roof PV systems	3.7	694,000
100-kW com/gov roof PV systems	1.9	22,000
50-MW Solar PV plants	29.4	550
100-MW CSP plants	0	0
100-MW geothermal plants	0	0
1300-MW hydro plants	0	0
1-MW tidal turbines	0.1	72
0.75-MW wave devices	1.1	1,900
	100%	

Percent of 2050 139-Country End-Use Demand Supplied by WWS Devices and Number of New Devices

TECHNOLOGY	PCT SUPPLY 2050	NUMBER
5-MW onshore wind turbines	23.5%	1,582,000
5-MW offshore wind turbines	13.6	935,000
5-kW Res. roof PV systems	16.0	1.96 billion
100-kW com/gov roof PV systems	12.2	78.6 million
50-MW Solar PV plants	19.7	233,000
100-MW CSP plants	9.7	21,500
100-MW geothermal plants	0.67	839
1300-MW hydro plants	4.0	0
1-MW tidal turbines	0.06	30,000
0.75-MW wave devices	0.58	410,000
	100%	

Area Beyond 2015 Installations to Power 139 Countries for all Purposes With 100% WWS in 2050



Percent of 139-Country Land

Onshore wind:	**0.92%**
Utility PV+CSP:	**0.22%**
Total	**1.14%**

Land Areas Required For Fossil Fuels

	California	United States
Active oil and gas wells	105,000	1.2 million
Abandoned oil wells	225,000	2.6 million
Abandoned gas wells	48,000	550,000
Coal mines	0	1,520
Oil refineries	17	135
Miles of gas pipeline	112,000	1.6 million
Miles of oil pipeline	3,000	161,000
Power plants	39	3,364
Gas stations	10,200	114,500
Gas storage facilities	10	394
% of California or US land	1.7	1.3

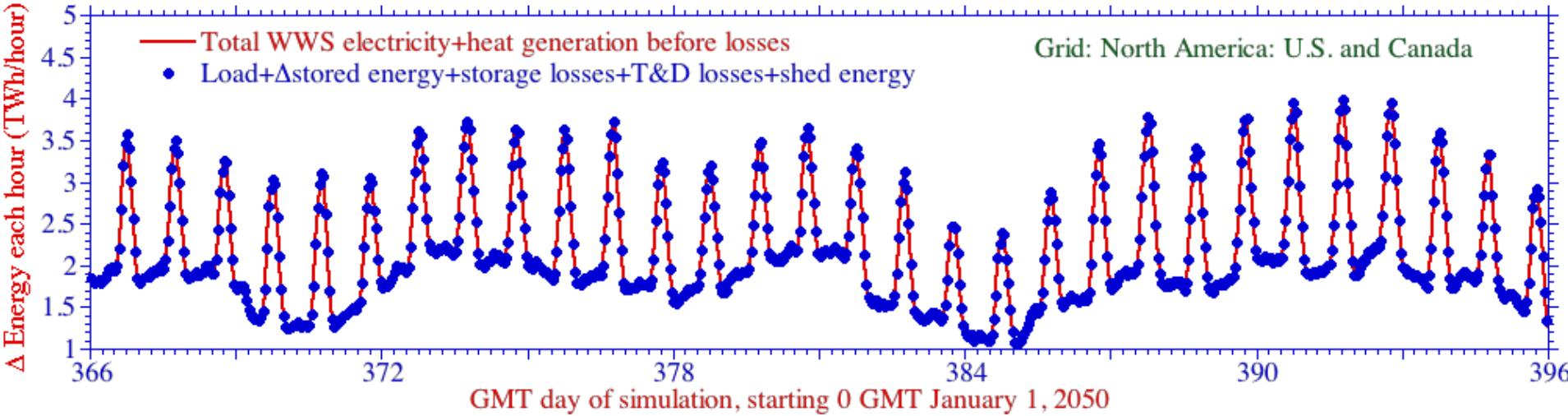
Grid Stability Studies for 20 World Regions

3 Storage Scenarios for 100% WWS in 2050

CASE	A	B	C
Batteries	Yes	No	Yes
CSP storage	Yes	Yes	Yes
Heat/cold storage	Yes	Yes	No
Heat pumps	No	No	Yes
Added hydropower turbines	No	Yes	No
Pumped hydropower storage	Yes	Yes	Yes
Hydrogen for transportation	Yes	Yes	Yes
Mean World Cost (¢/kWh)	10.6	10.7	10.6
Demand reduction vs. BAU (%)	42.5	42.5	58.3

One Month of Results From a 2050-2054 Study on Matching 2050-54 U.S.+Canada All-Sector Demand With 100% WWS

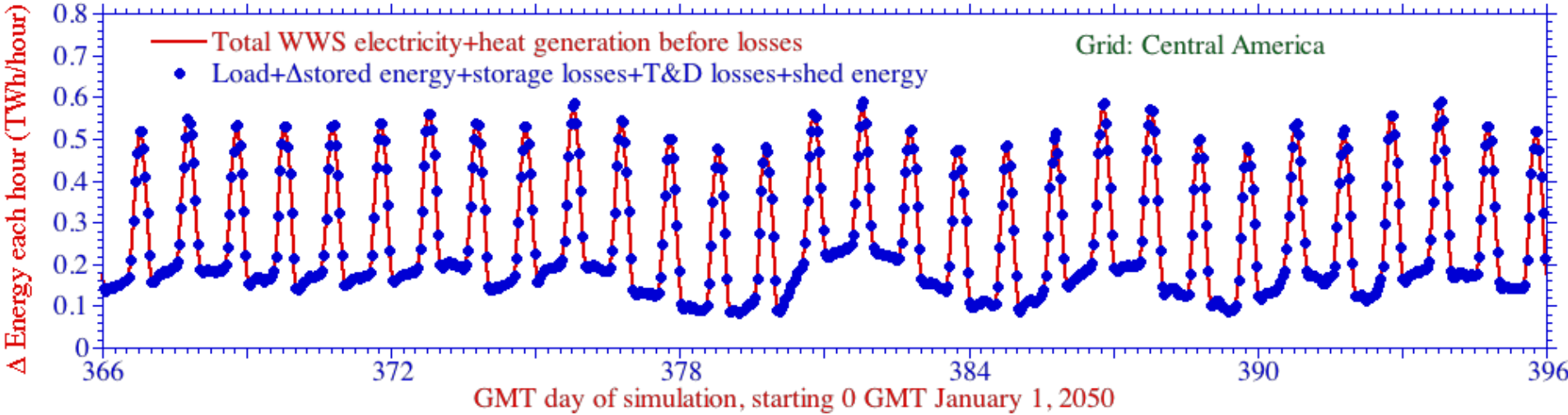
With Zero Added Hydropower Turbines or Heat Pumps (Case A)



Red = Energy supply

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

Matching 2050-54 Central America (7 Countries) All-Sector Load With 100% WWS



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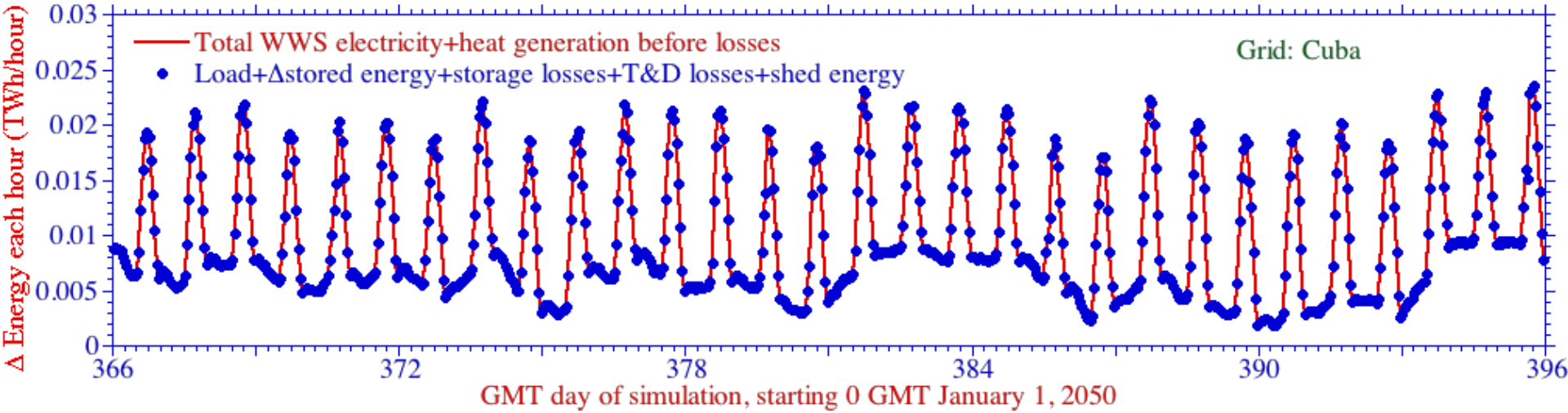
Matching 2050-54 Cuba All-Sector Load With 100% WWS



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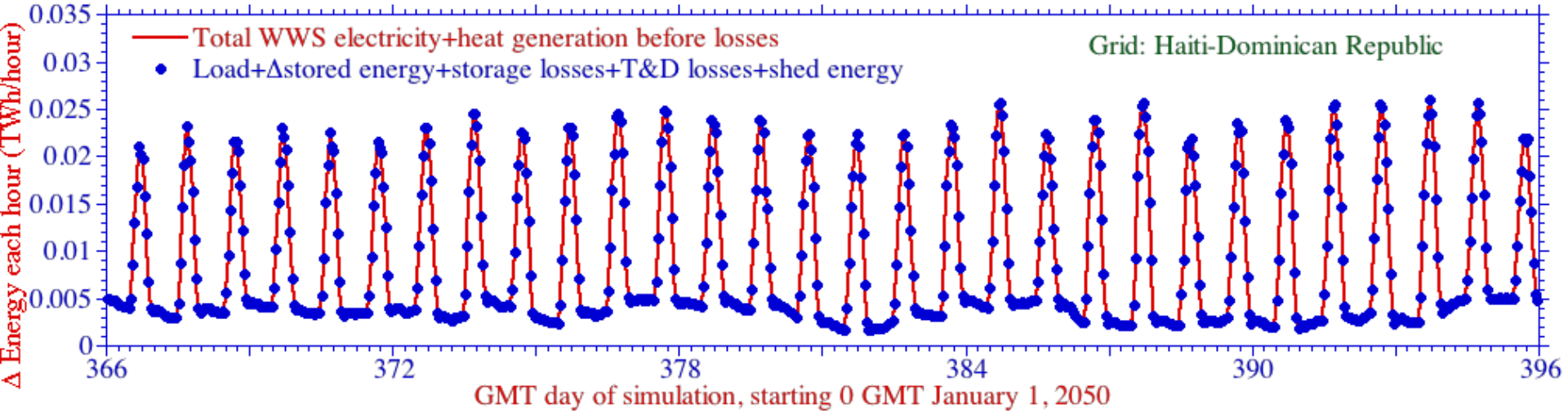
Matching 2050-54 Haiti-Dominican Republic All-Sector Load With 100% WWS



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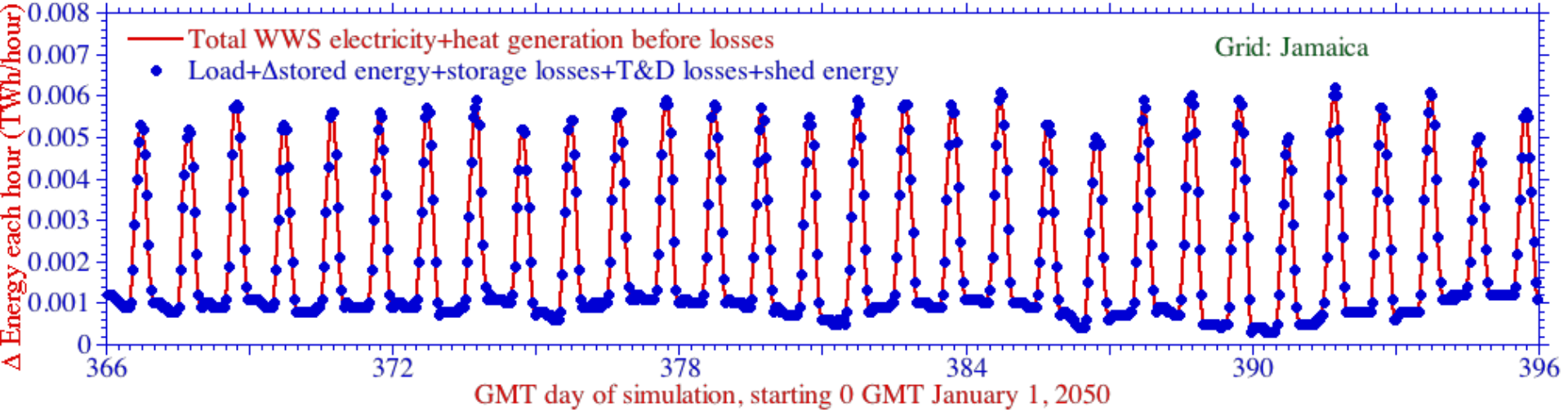
Matching 2050-54 Jamaica All-Sector Load With 100% WWS



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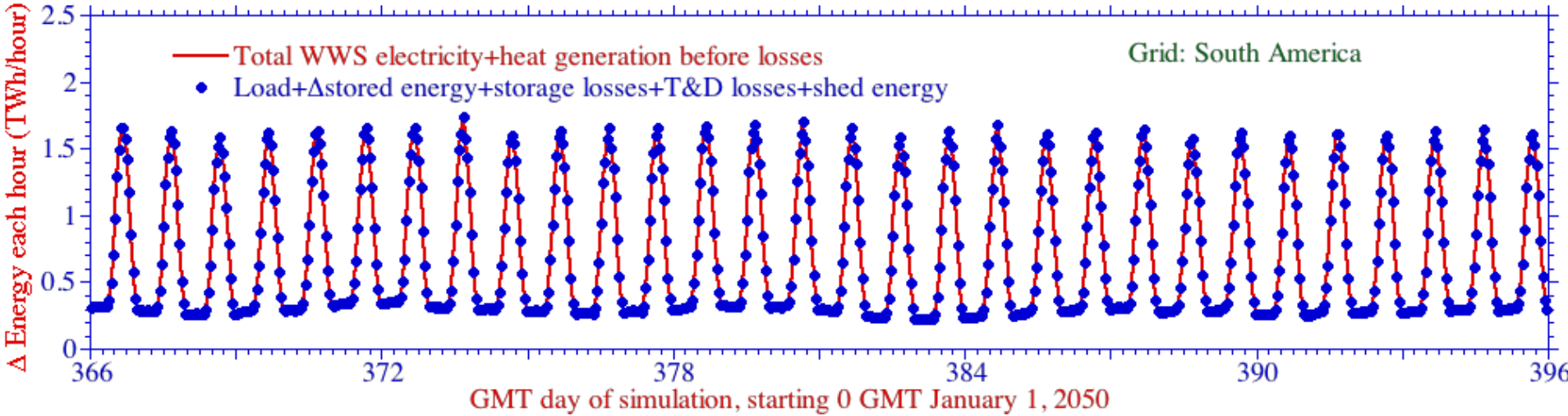
Matching 2050-54 South America (12 Countries) All-Sector Load With 100% WWS



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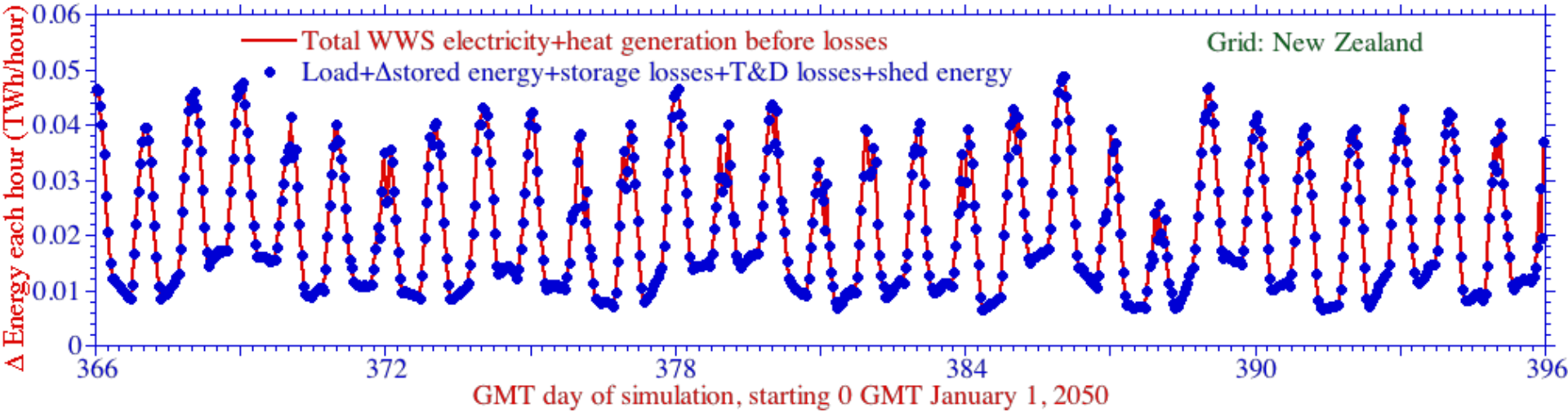
Matching 2050-54 New Zealand All-Sector Load w/100% WWS



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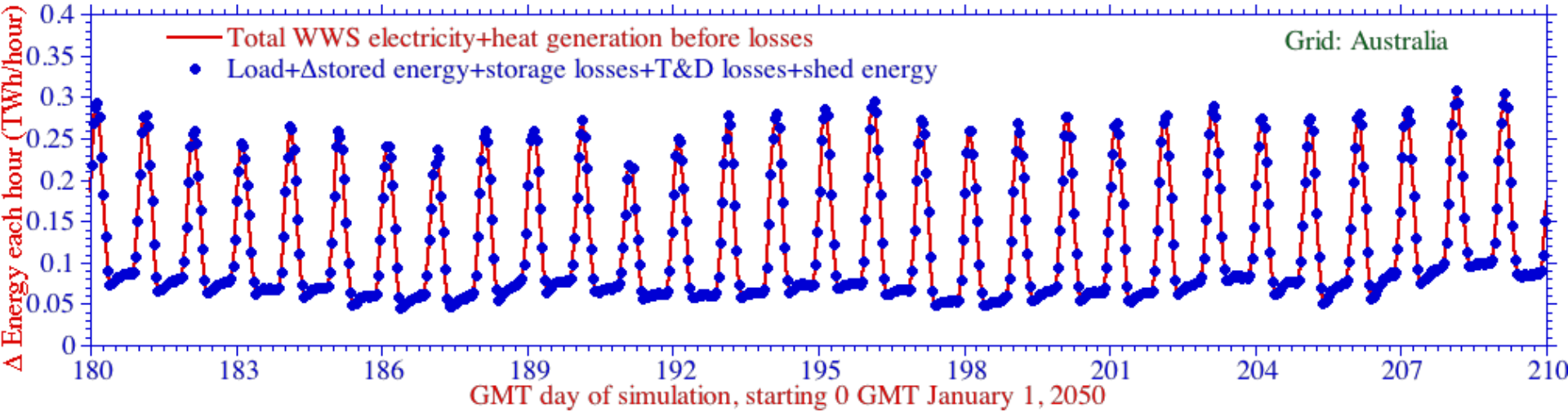
Matching 2050-54 Australia All-Sector Load With 100% WWS



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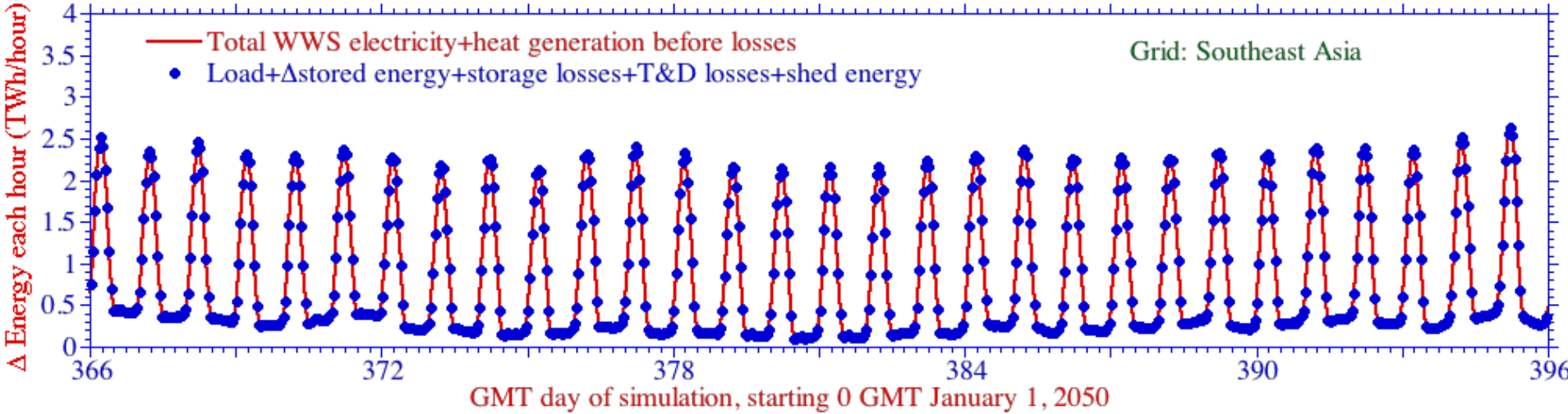
Matching 2050-54 Southeast Asia (9 Countries) All-Sector Load With 100% WWS



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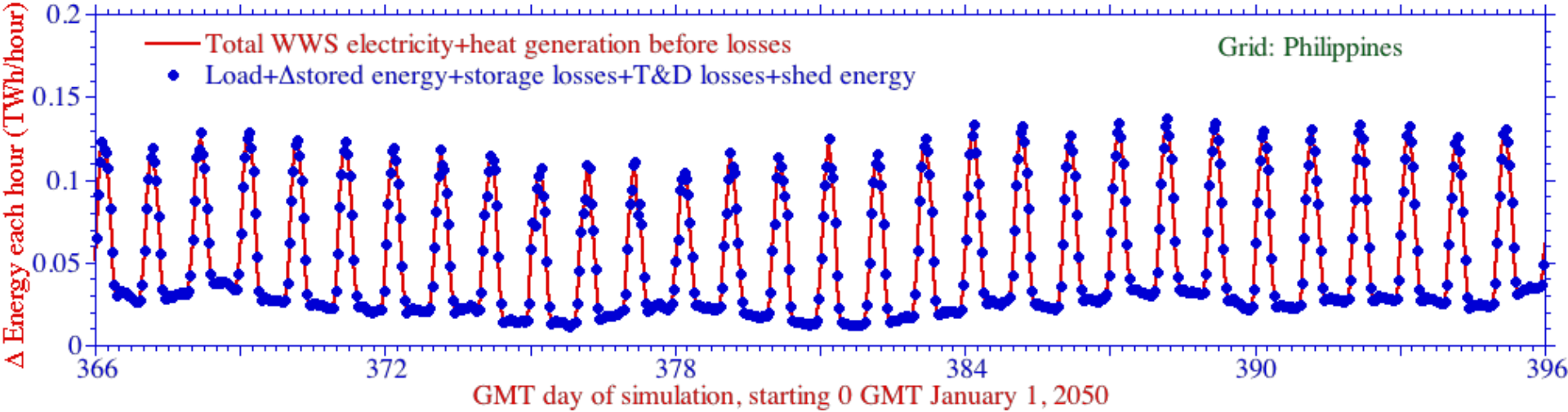
Matching 2050-54 Philippines All-Sector Load With 100% WWS



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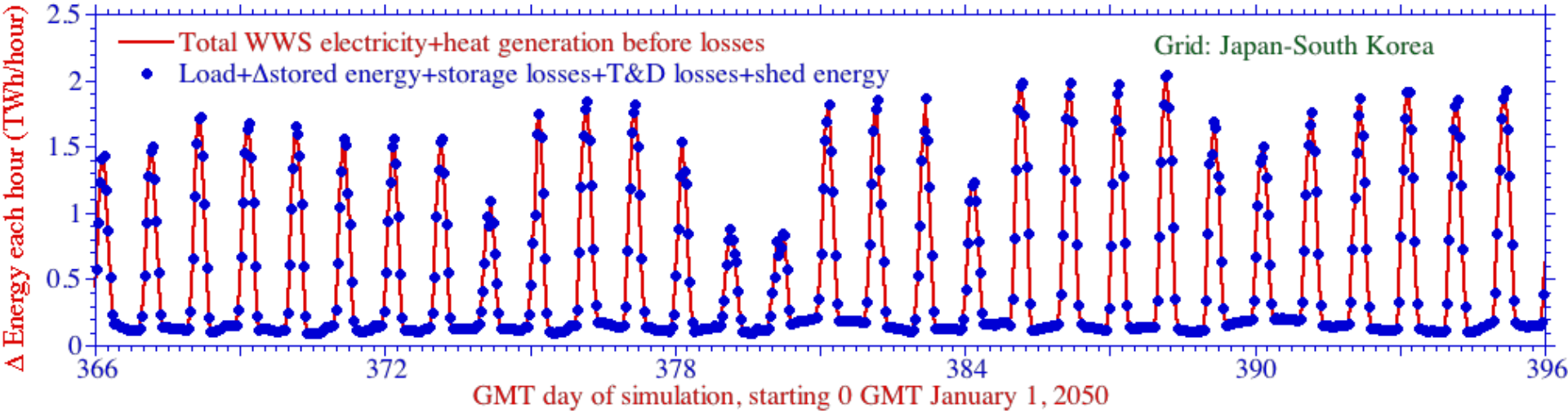
Matching 2050-54 Japan-South Korea All-Sector Load With 100% WWS



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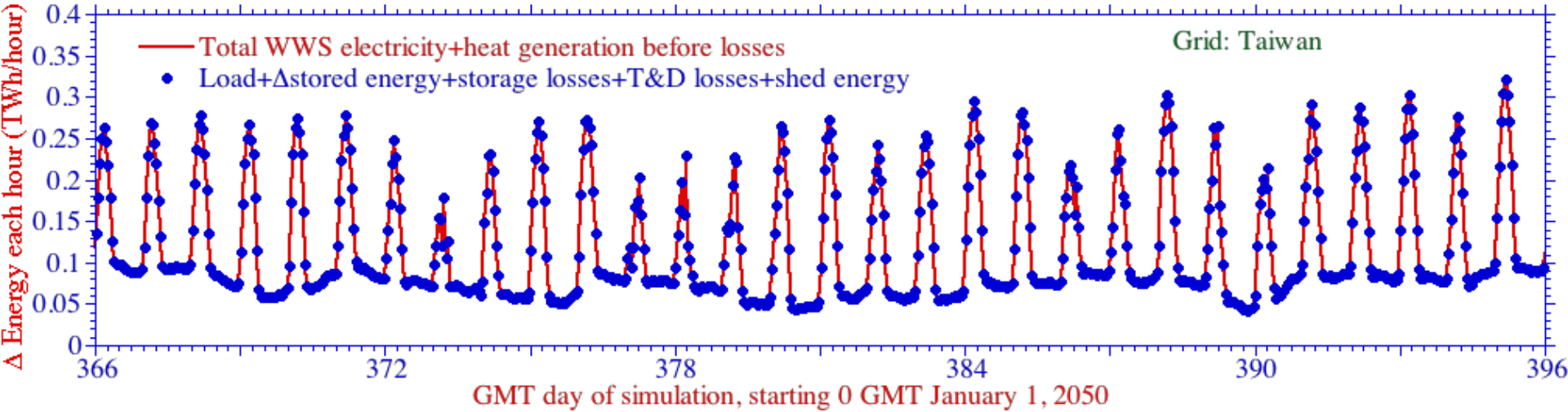
Matching 2050-54 Taiwan All-Sector Load With 100% WWS



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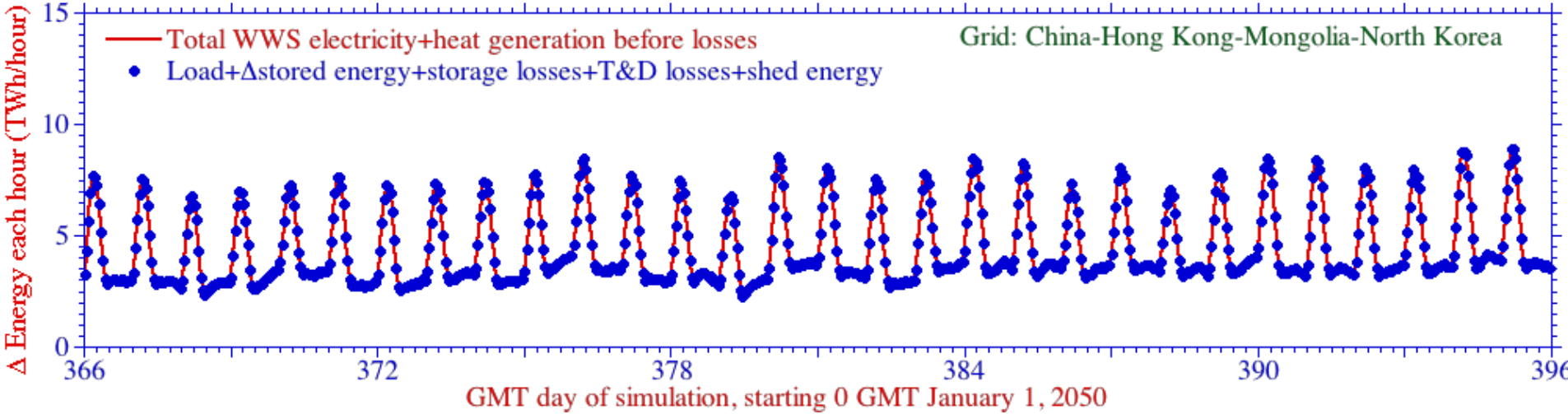
Matching 2050-54 China-Hong Kong-Mongolia-North Korea All-Sector Load With 100% WWS



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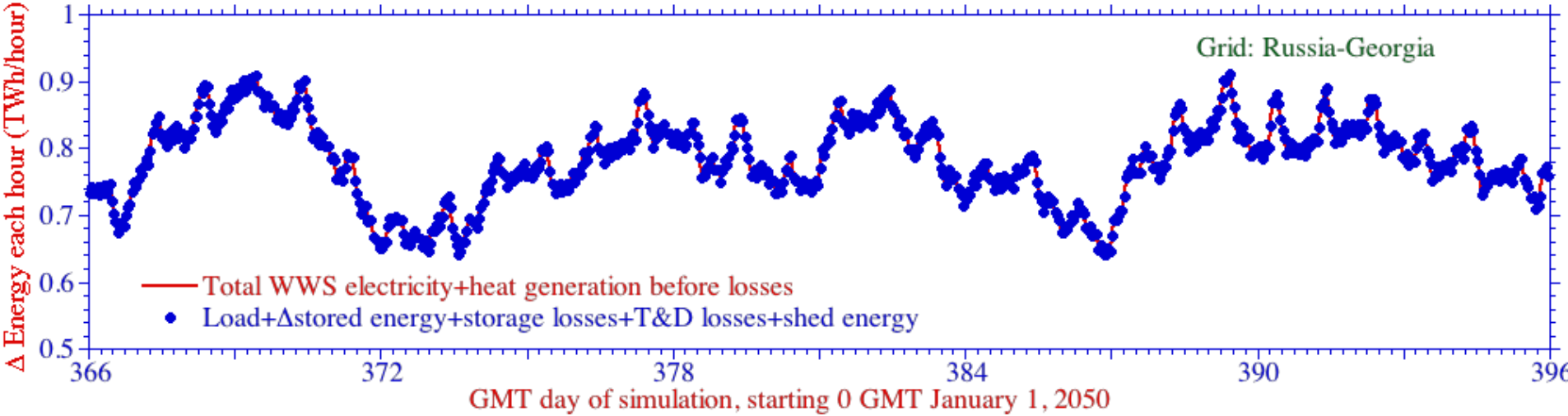
Matching 2050-54 Russia-Georgia All-Sector Load With 100% WWS



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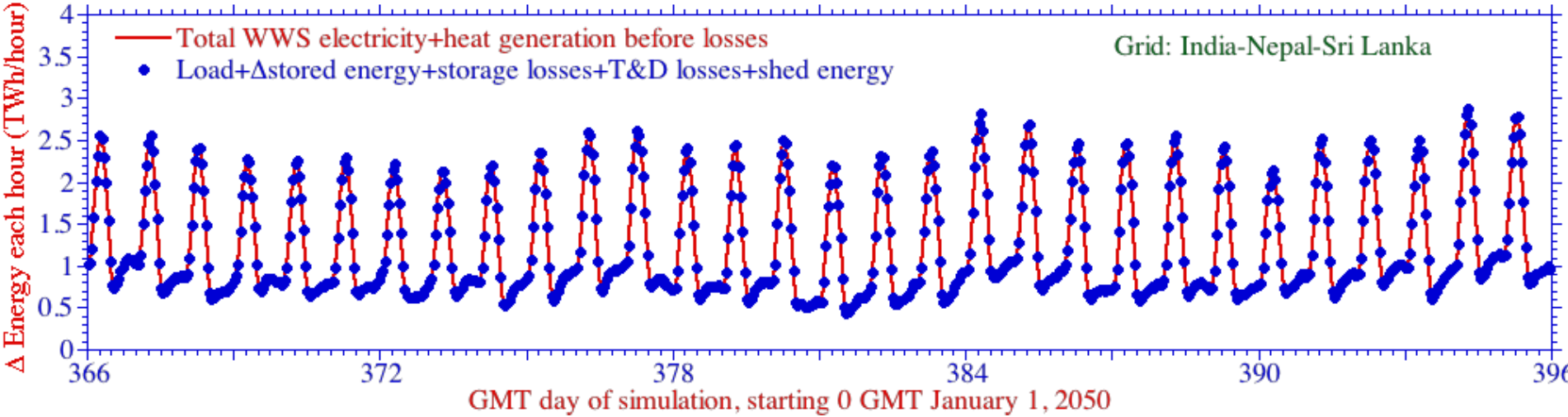
Matching 2050-54 India-Nepal-Sri Lanka All-Sector Load With 100% WWS



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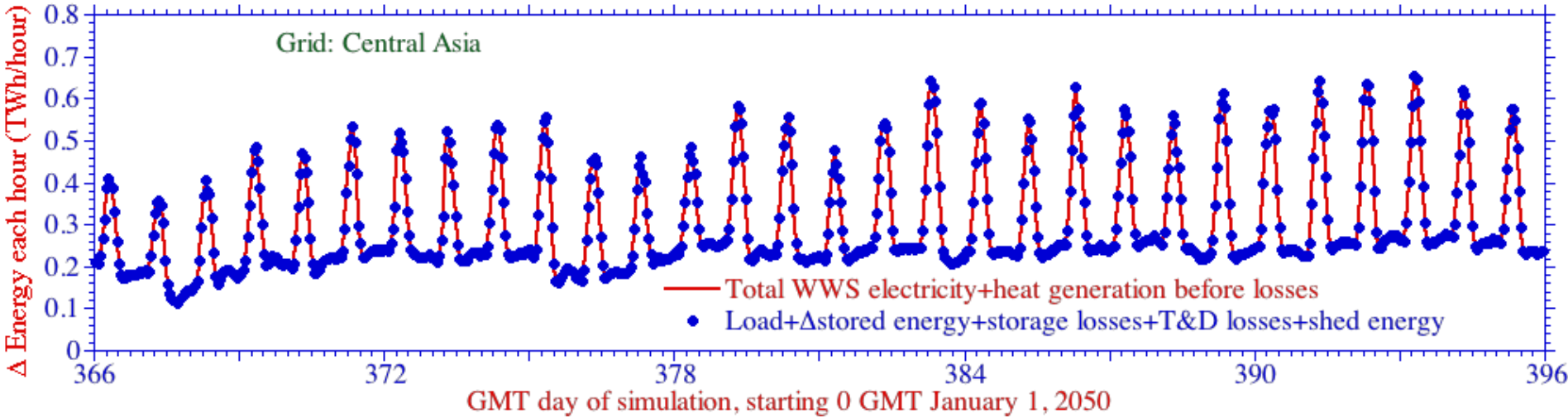
Matching 2050-54 Central Asia (6 Countries) All-Sector Load With 100% WWS



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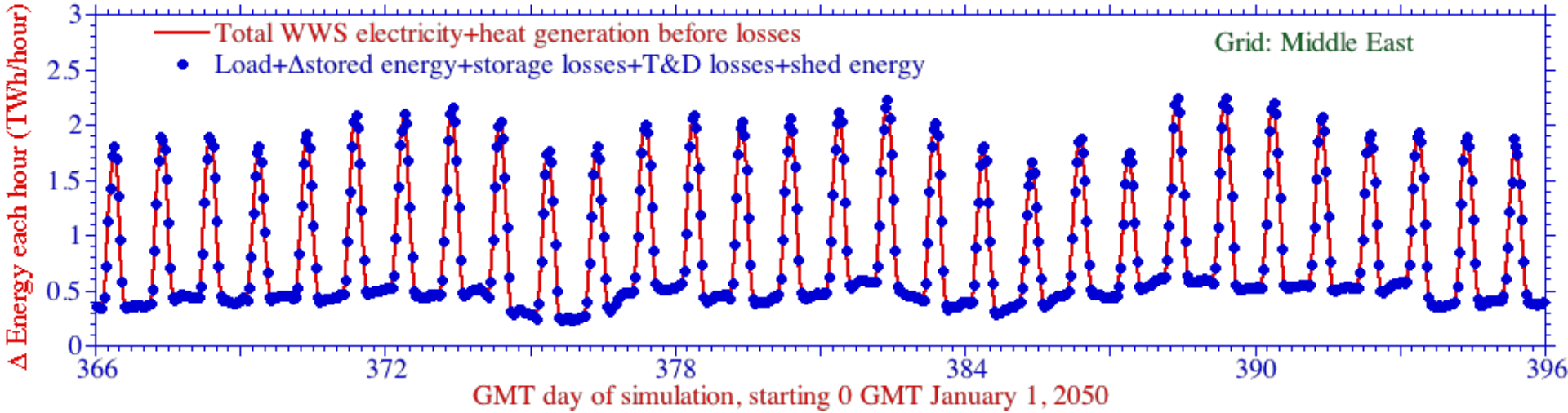
Matching 2050-54 Middle East (16 Countries) All-Sector Load With 100% WWS



Red = Energy supply

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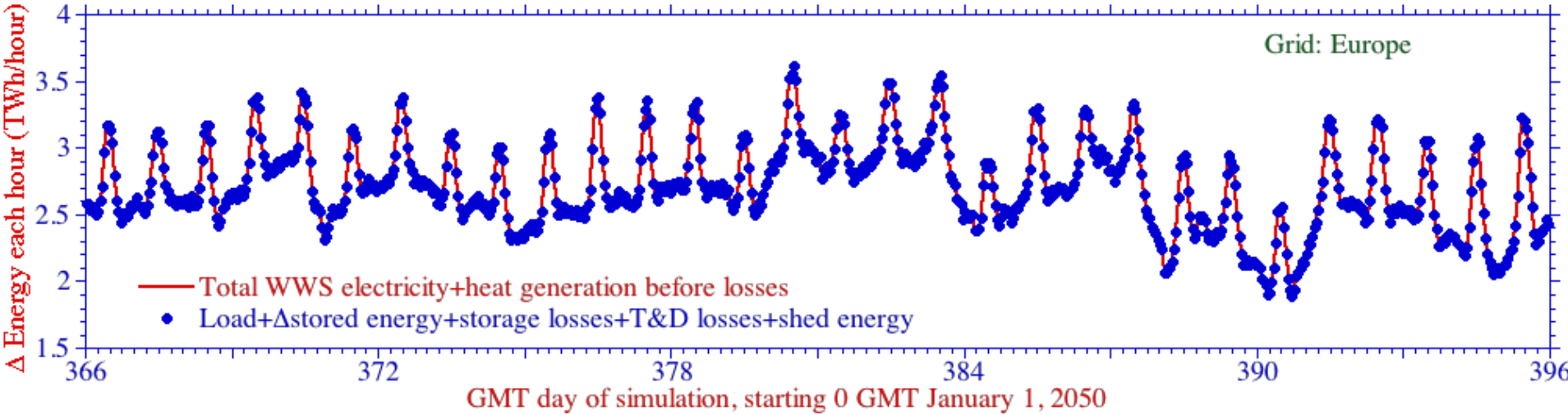
Matching 2050-54 Europe (40 Countries) All-Sector Load With 100% WWS



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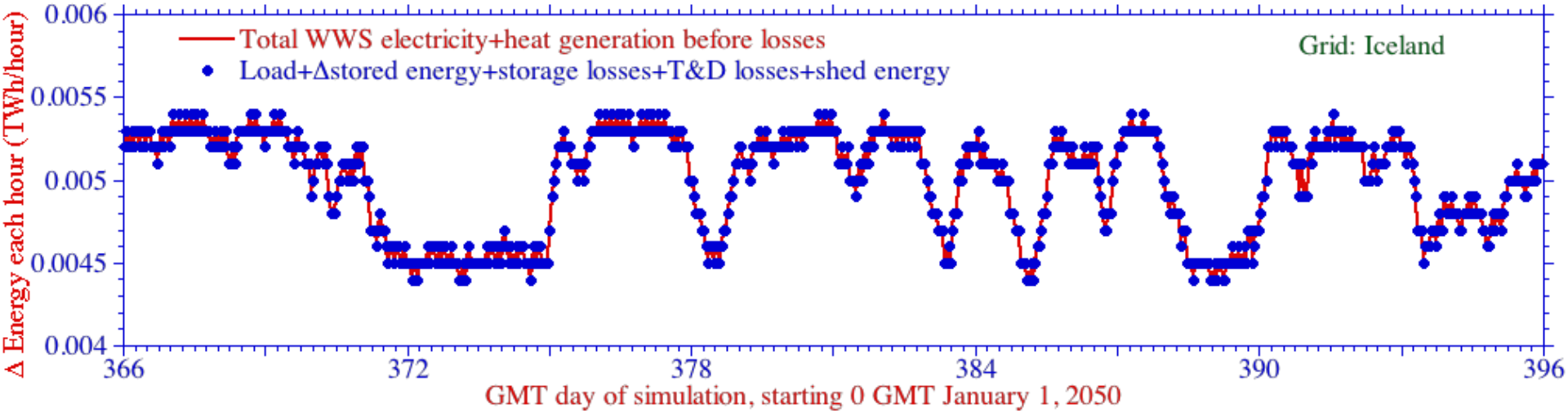
Matching 2050-54 Iceland All-Sector Load With 100% WWS



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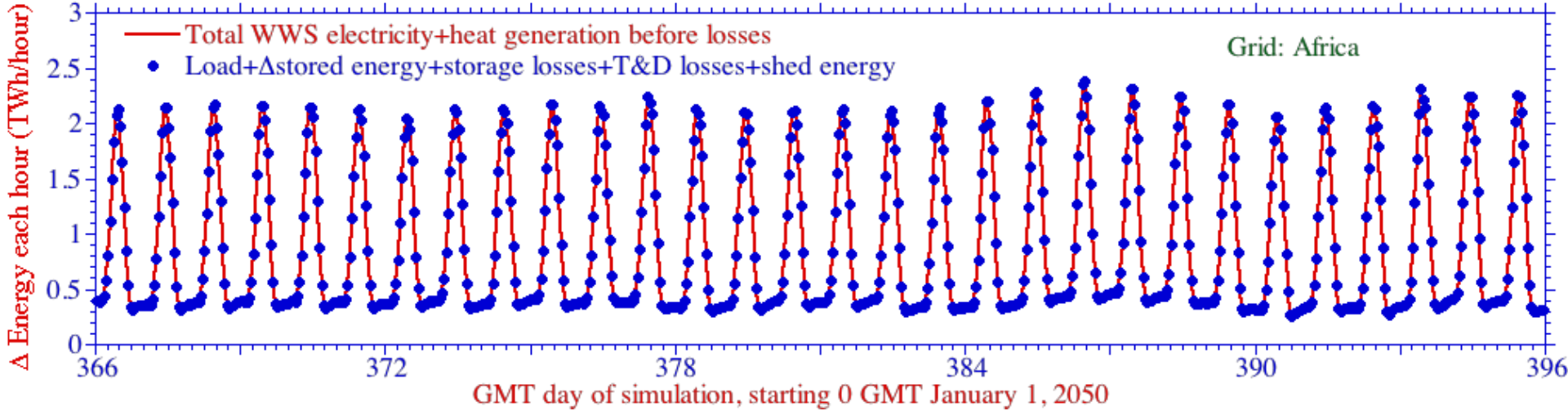
Matching 2050-54 Africa (27 Countries) All-Sector Load With 100% WWS



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2050 139-Country WWS vs. BAU Cost

BAU electricity sector cost (includes T&D+storage)	9.8 ¢/kWh
BAU fuel health cost	12.7
BAU fuel climate cost	15.8
Total conventional fuel electricity sector cost	38.3 ¢/kWh

WWS replacing BAU electricity sector only (includes T&D+storage)	9.7 ¢/kWh
WWS replacing all BAU energy sectors	10.6 ¢/kWh

Similar cost per kWh but WWS uses 43-58% fewer kWh

Jacobson et al. (2018)

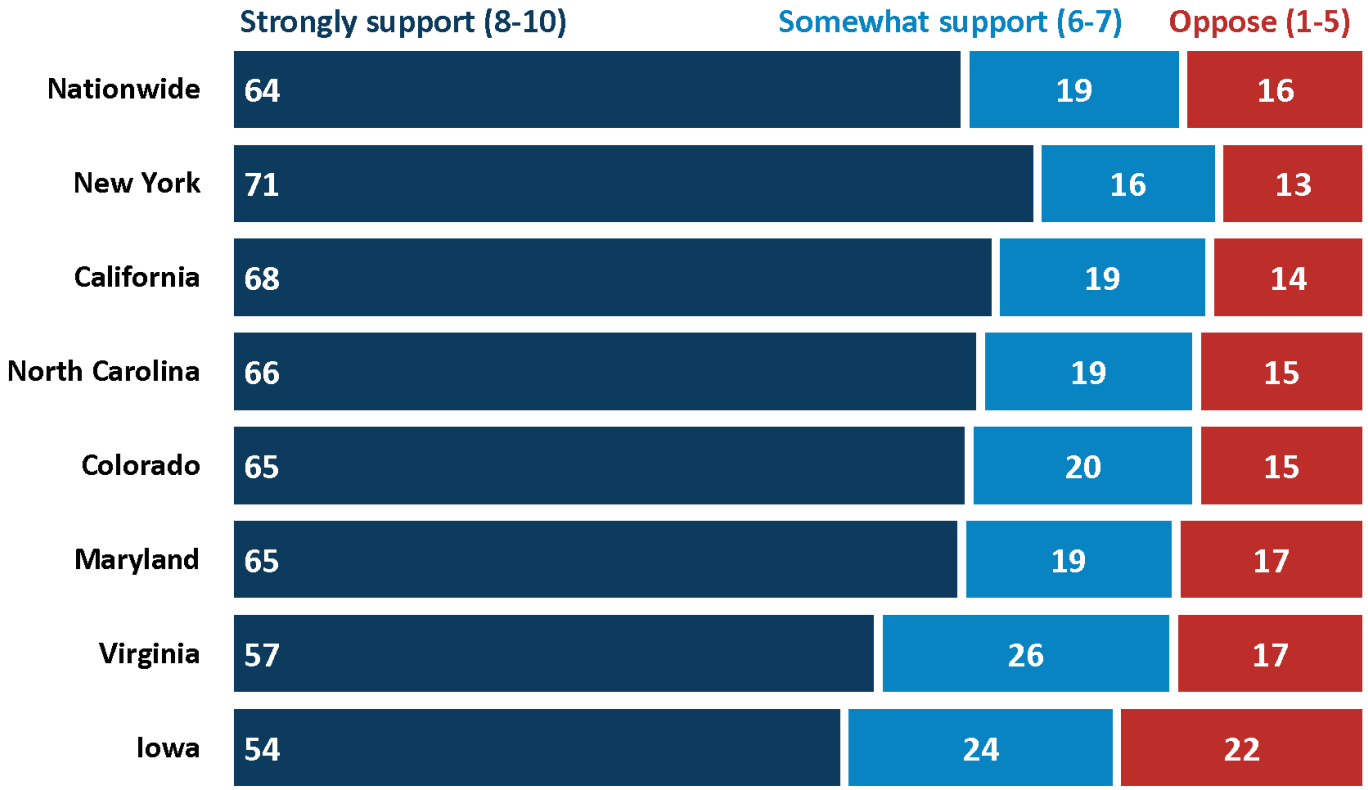
Public Opinion Survey

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

Do you support or oppose powering all energy in the U.S. entirely by clean and renewable sources like wind, solar, and hydroelectric by 2050? That means homes, businesses, cars, trucks.



House Resolution H.Res.540 (60 co-sponsors)

"…United States should support a transition to…100 percent clean renewable energy,…"

Senate Resolution S.Res.632 (8 co-sponsors)

"A resolution supporting a transition to 100% clean, renewable energy…"

Senate Bill S.987 (5 co-sponsors)

"A bill to transition away from fossil fuel sources to 100 percent clean and renewable energy by 2050"

U.S. House Bill H.R.3314 (36 co-sp) and 3671 (44 co-sp)

"…toward 100% clean and renewable energy by 2050"

"…to 100% clean (WWS) energy and efficiency by 2035"

WWS?Contributory Impacts of 100% WWS Roadmaps

Law: Hawaii

100% renewable electricity by 2045

Law: California

100% renewable electricity by 2045, 60% by 2030

Law: Vermont

75% renewable electricity by 2032

Law: New York

50% renewable electricity by 2030

Proposed: Washington State

SB 6253 100% carbon-free electricity by 2045

Energy 73 (2014) 875–889

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Energy

journal homepage: www.elsevier.com/locate/energy

A roadmap for repowering California for all purposes with wind, water, and sunlight

Mark Z. Jacobson [a, *], Mark A. Delucchi [b], Anthony R. Ingraffea [c, d], Robert W. Howarth [e], Guillaume Bazouin [a], Brett Bridgeland [a], Karl Burkart [f], Martin Chang [a], Navid Chowdhury [a], Roy Cook [a], Giulia Escher [a], Mike Galka [a], Liyang Han [a], Christa Heavey [a], Angelica Hernandez [a], Daniel F. Jacobson [g], Dionna S. Jacobson [g], Brian Miranda [a], Gavin Novotny [a], Marie Pellat [a], Patrick Quach [a], Andrea Romano [a], Daniel Stewart [a], Laura Vogel [a], Sherry Wang [a], Hara Wang [a], Lindsay Willman [a], Tim Yeskoo [a]

[a] Atmosphere/Energy Program, Department of Civil and Environmental Engineering, Stanford University, 473 Via Ortega, Stanford, CA 94305, USA

Some of 110+ Cities/Counties Committed to 100% Renewables

Burlington (VT)
Greensburg (KS)
Aspen (CO)
Vancouver (BC)
San Diego (CA)
Honolulu (HI)
Columbia (SC)
Palo Alto (CA)
San Francisco (CA)
Georgetown (TX)
Madison (WI)
Santa Barbara (CA)
Oxford County (ON)
Grand Rapids (MI)
Lancaster (CA)
Park City (UT)
San Jose (CA)
Santa Fe (NM)
Santa Monica (CA)
Pueblo (CO)
Boone (NC)
Moab (UT)
Abita Springs (LA)
Portland (OR)
Salt Lake City (UT)
Fayetteville (AR)
Sylva (NC)
Atlanta (GA)
Orlando (FL),
East Hampton (NY)
Rochester (MN)
WestChester (PA)
S. Lake Tahoe (CA)
Nelson (BC)
St. Petersburg (FL)
St. Louis (MO)
Sarasota (FL)
Nevada City (NV)
Boulder (CO)

Some of the 154+ Companies Committed to 100% Renewables

IKEA	Adobe	Autodesk	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
Clif Bar	Ebay	Facebook	Estee Lauder
GM	Goldman-Sachs	HSBC	Infosys
Kellogg’s	Lego	Mars	Morgan Stanley
Salesforce	Organic Valley	VM Ware	Wells Fargo

Some of the 70+ 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

Summary – Transitioning to 100% WWS

Creates ~24 million more jobs than are lost worldwide

Requires only 0.22% of land for footprint; 0.92% for spacing

Avoids ~4-7 mil. air pollution deaths per year

Slows then reverses global warming

Grids can stay stable throughout the world with 100%

WWS energy cost per kWh slightly less than that of fossils

WWS energy+health+climate costs per kWh are 1/4th that of fossils

Absolute WWS energy+health+climate costs are 1/8th that of fossils

Summary – Transitioning to 100% WWS

Transitioning to 100% WWS in all energy sectors is technically and economically possible

The main barriers are social and political

The solution requires collective willpower and immediate deployment

Slides for this talk

web.stanford.edu/group/efmh/jacobson/Articles/I/1811-Aalborg.pptx

Roadmaps

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

Grid Studies

www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html

Infographic maps

www.thesolutionsproject.org 100.org

Twitter: @mzjacobson