



# Getting to 100% Clean, Renewable Energy: A Roadmap to Transition Homes, Cities, Countries, and the World

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



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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

Wind  
Solar PV/CSP  
Geothermal  
Hydro  
Tidal/Wave

## TRANSPORTATION

Battery-electric  
HFC-BE hybrids

## HEATING/COOLING

Electric heat pumps  
Solar water preheat

## INDUSTRY

Electric arc furnaces  
Induction furnaces  
Dielectric heating

# 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

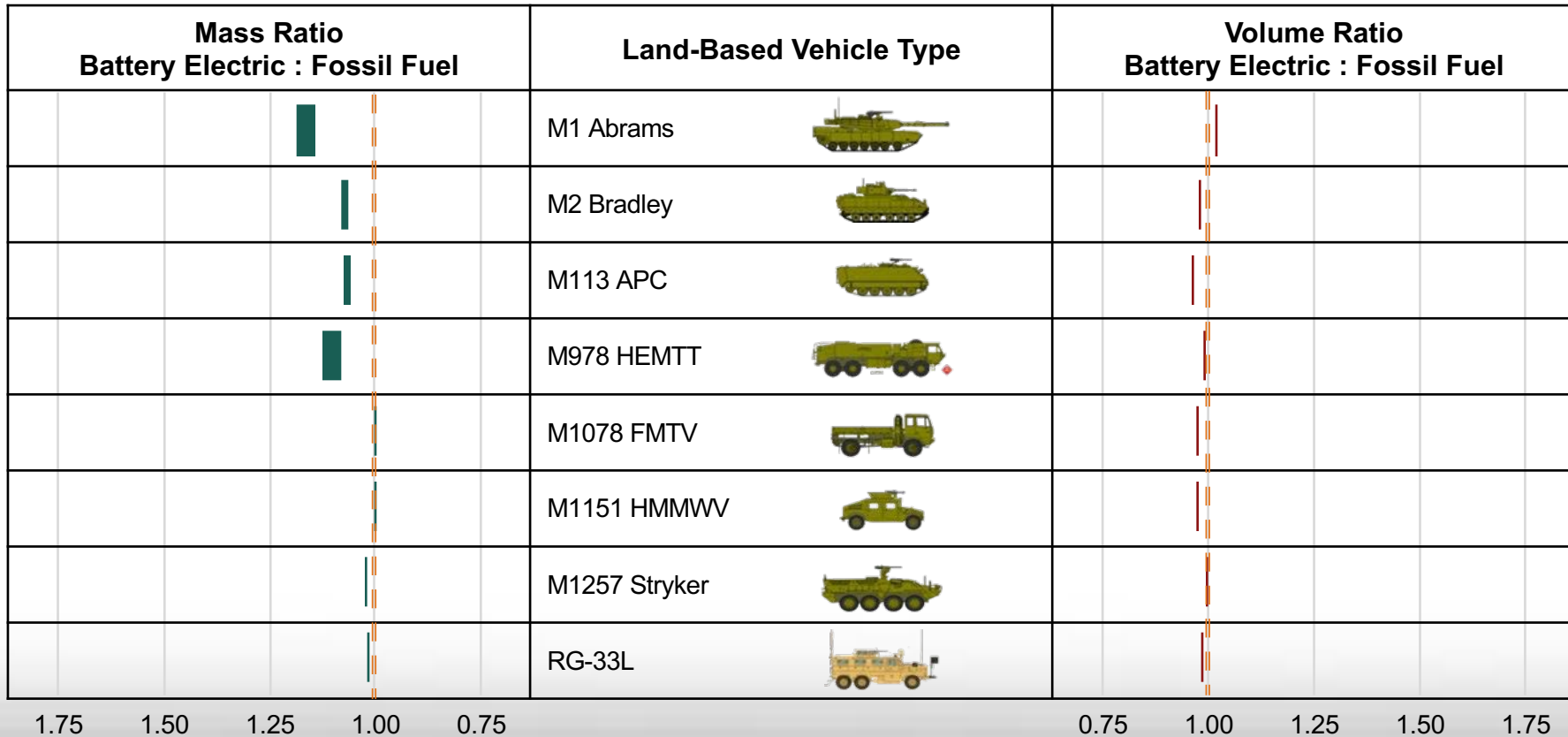


Proterra electric bus



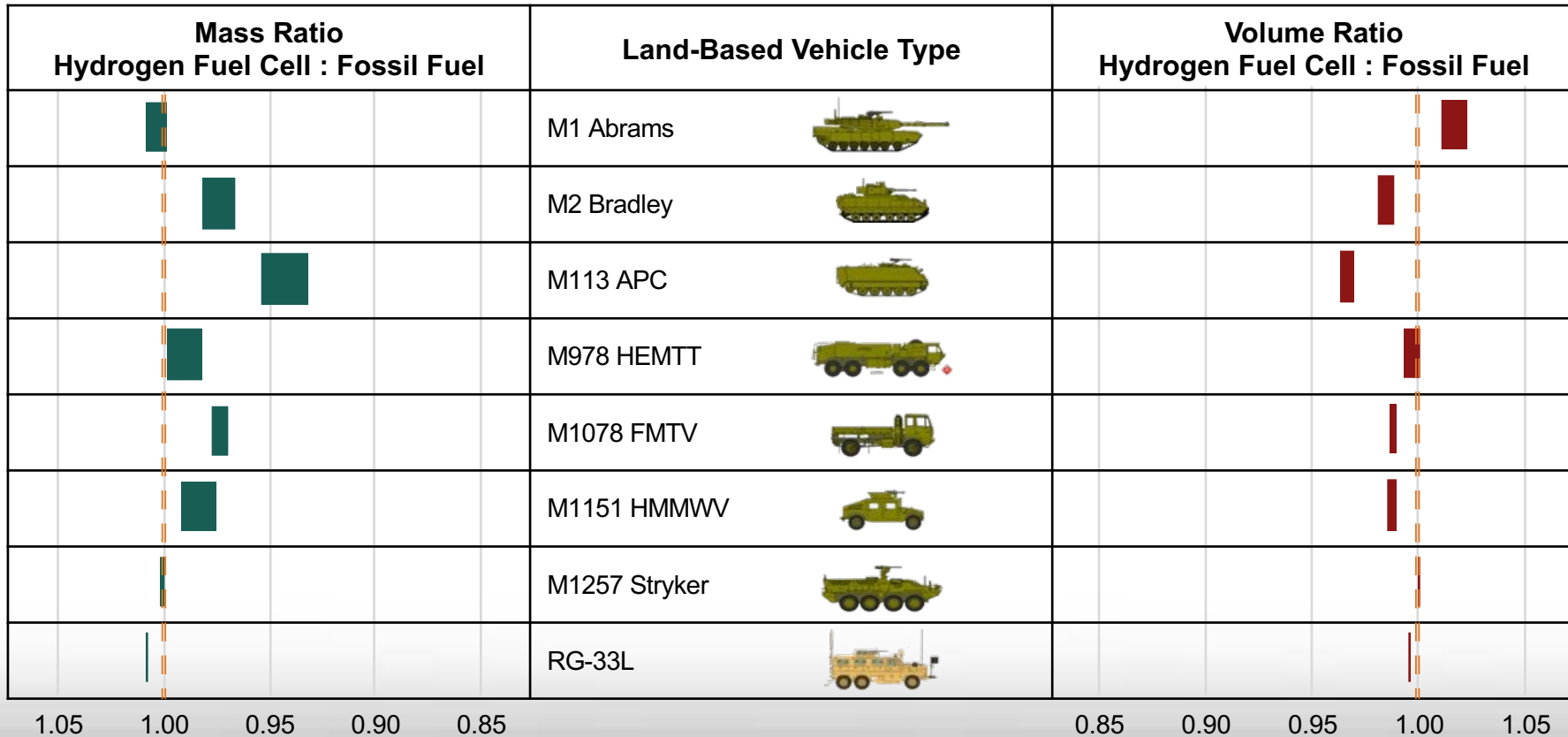
Hydrogen fuel cell-electric hybrid bus

# 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

# Replace Helicopters With Vertical Take-Off and Landing Aircraft



Pipistrel VTOL 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

CSP with storage  
Pumped hydro  
Existing hydroelectric  
Batteries

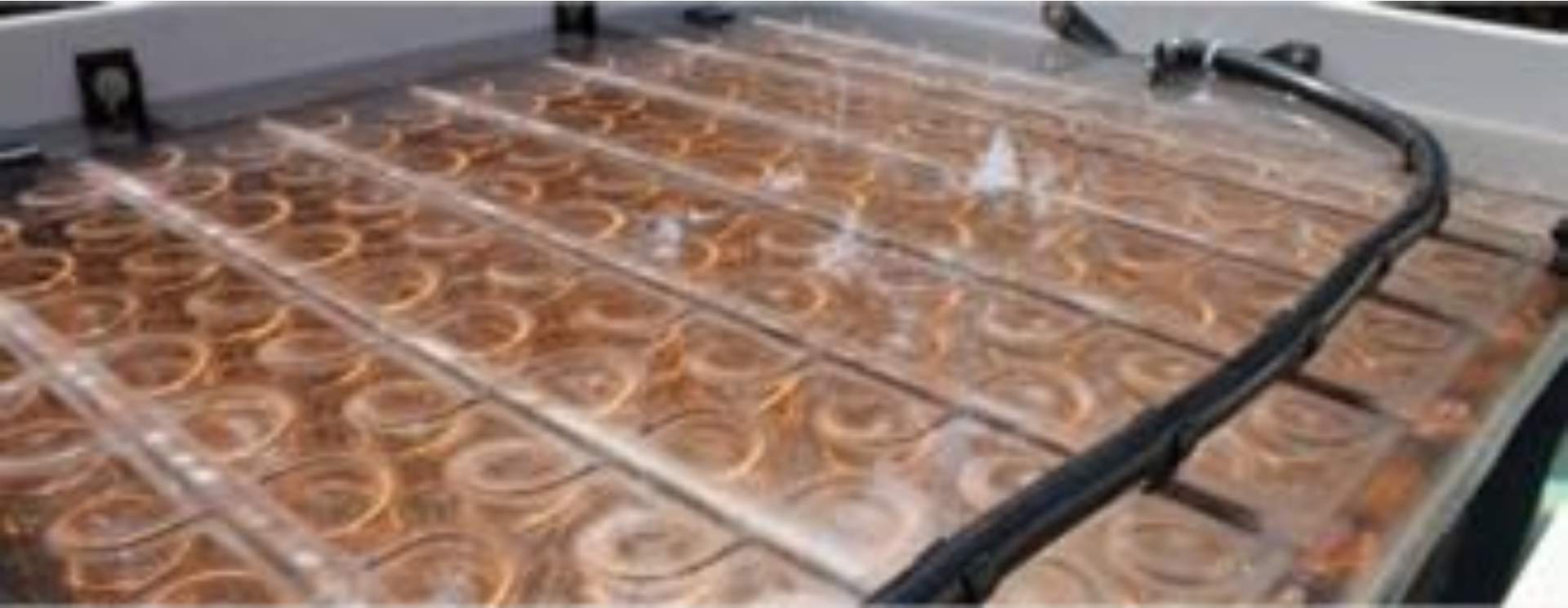
## HEATING/COOLING

Water  
Ice  
Rocks in soil

## OTHER

Hydrogen for transport  
Demand-response

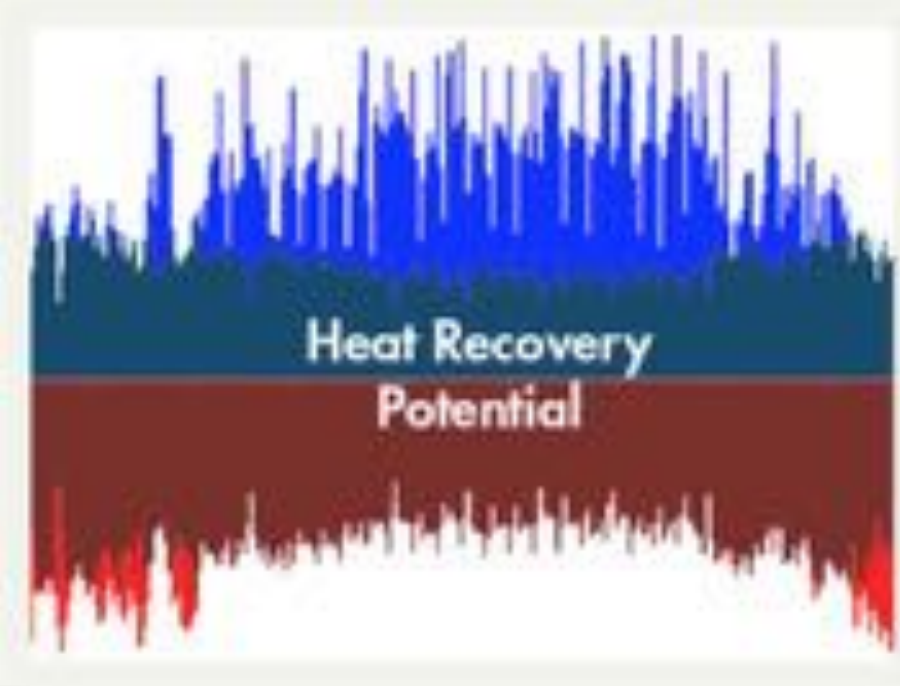
# Nighttime Storage in Ice for Daytime Air Cooling



# Seasonal Heat Storage in Underground Rocks Okotoks, Canada



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





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

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



# Electric Heat Pump Water Heater



# Electric Induction Cooktop



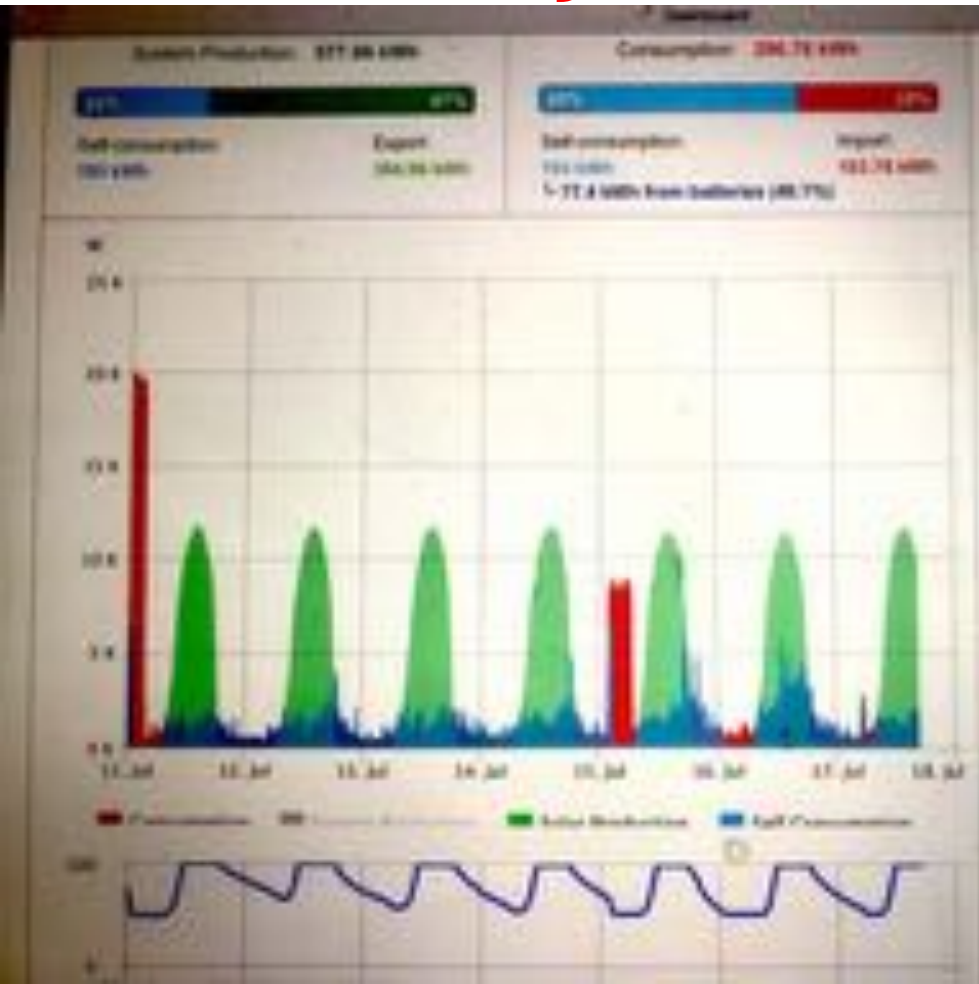
# Rooftop Solar Plus Battery Storage



# Electric Cars + Batteries



# 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**

# 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**





# **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	11.8 TW
2050 Demand with WWS, w/heat pumps	8.6 TW
2050 Demand reduction w/ WWS	58.3%
23.0% electrification	
12.6% energy self use	
15.8% efficiency of heat pumps	
6.9% efficiency beyond BAU	

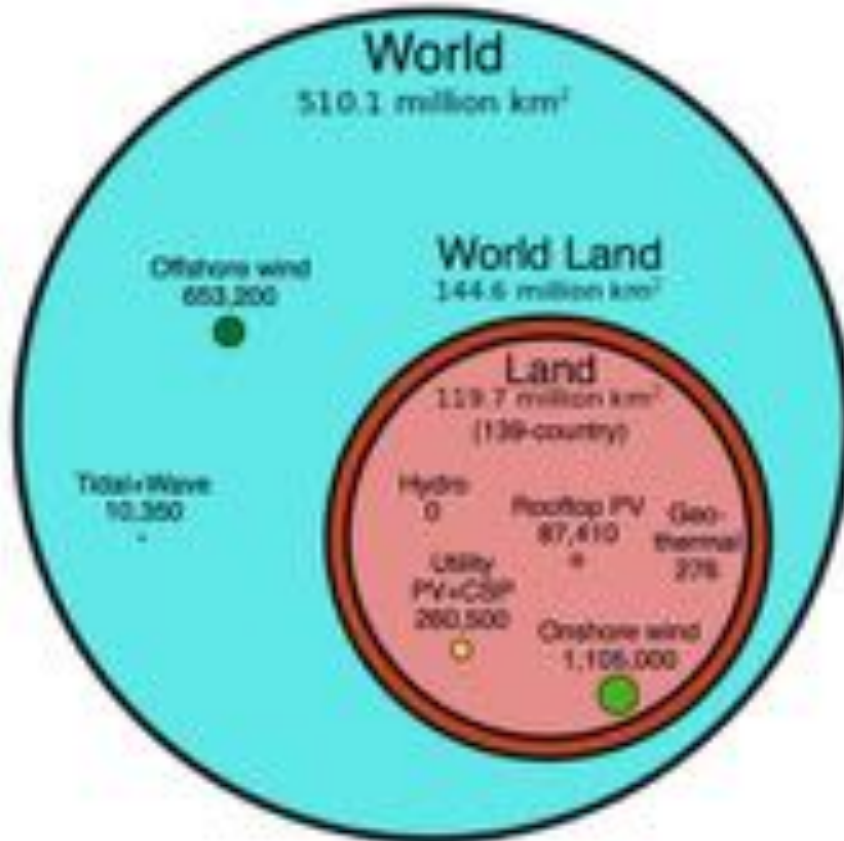
# Percent of 2050 Canadian End-Use Demand Supplied by WWS Devices and Number of New Devices

TECHNOLOGY	PCT SUPPLY 2050	NUMBER
5-MW onshore wind turbines	27.5%	32,800
5-MW offshore wind turbines	22.9	27,200
5-kW Res. roof PV systems	5.3	12.9 million
100-kW com/gov roof PV systems	9.1	1.4 million
50-MW Solar PV plants	6.9	1,660
100-MW CSP plants	9.8	459
100-MW geothermal plants	1.7	50
1300-MW hydro plants	14.5	0
1-MW tidal turbines	0.2	1,980
0.75-MW wave devices	2.2	26,200
	<b>100%</b>	

# 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
	<b>100%</b>	

# 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

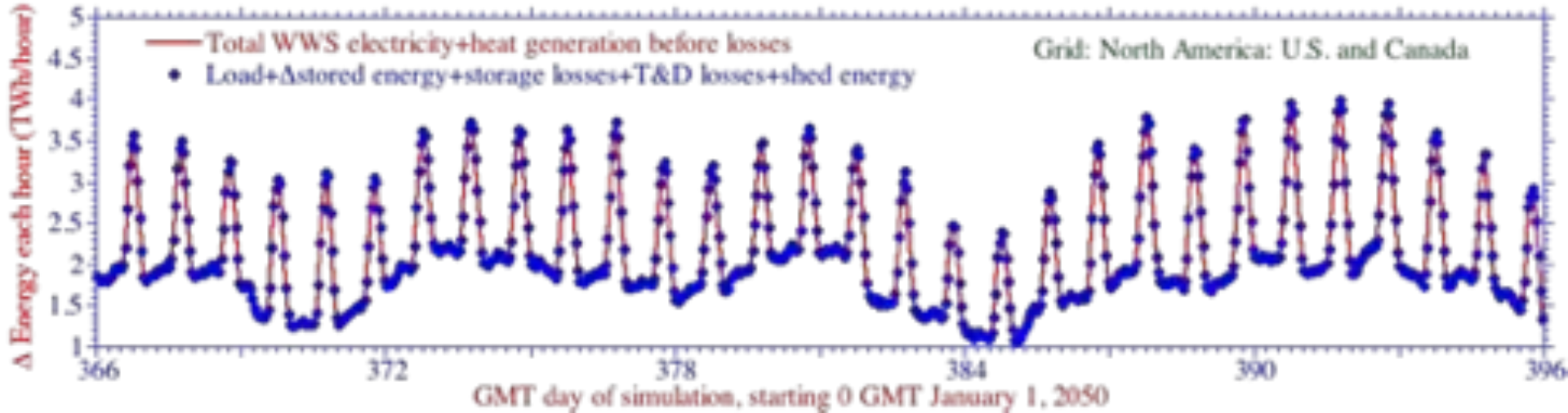
	California	United States
Active oil and gas wells	105,000	1.2 million
Abandoned oil wells	225,000	2.6 million
Abandoned gas wells	48,000	550,000
Coal mines	0	1,520
Oil refineries	17	135
Miles of gas pipeline	112,000	1.6 million
Miles of oil pipeline	3,000	161,000
Power plants	39	3,364
Gas stations	10,200	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

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

# 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)

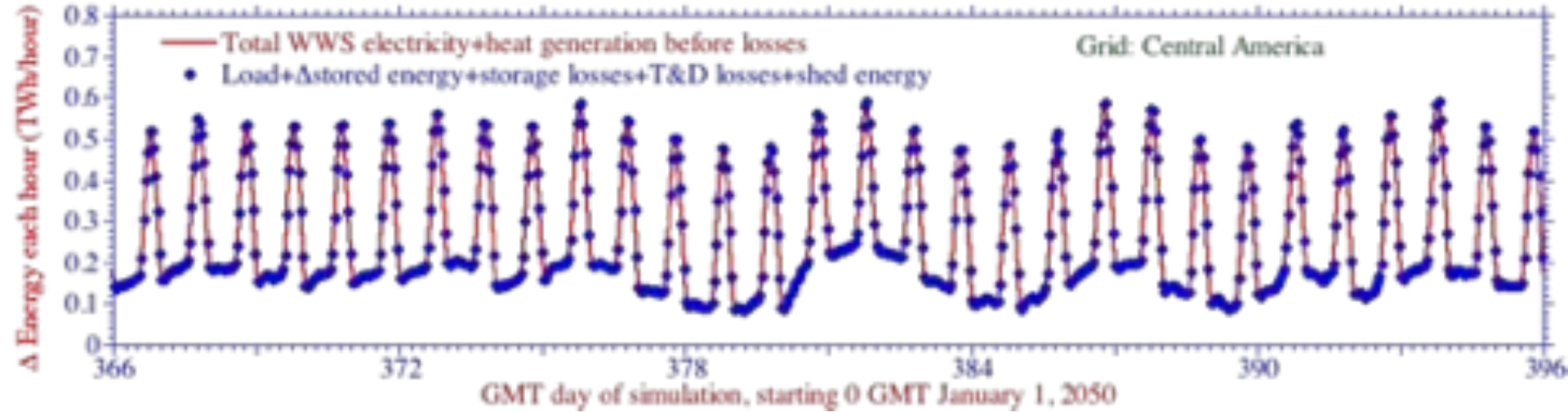


**Red = Energy supply**

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



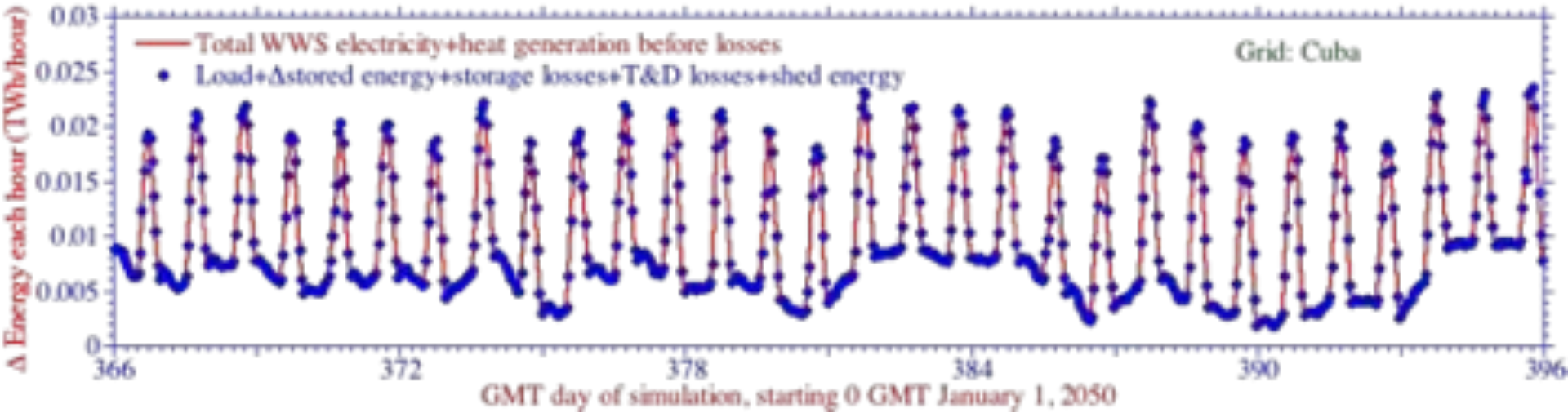
# Matching 2050-54 Central America (7 Countries) All-Sector Load With 100% WWS



**Red = Energy supply**

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

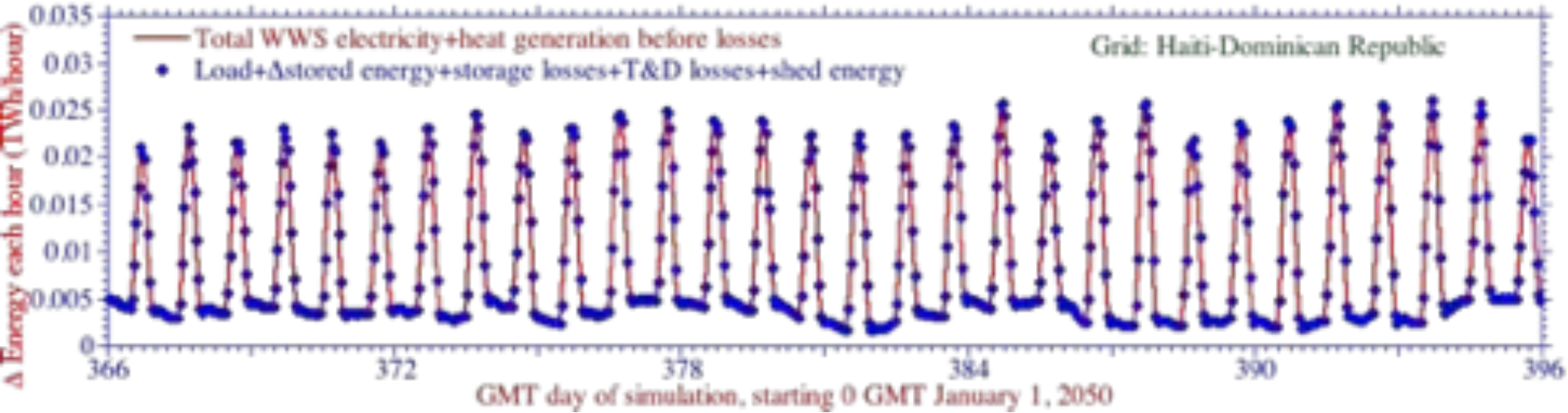
# Matching 2050-54 Cuba All-Sector Load With 100% WWS



**Red = Energy supply**

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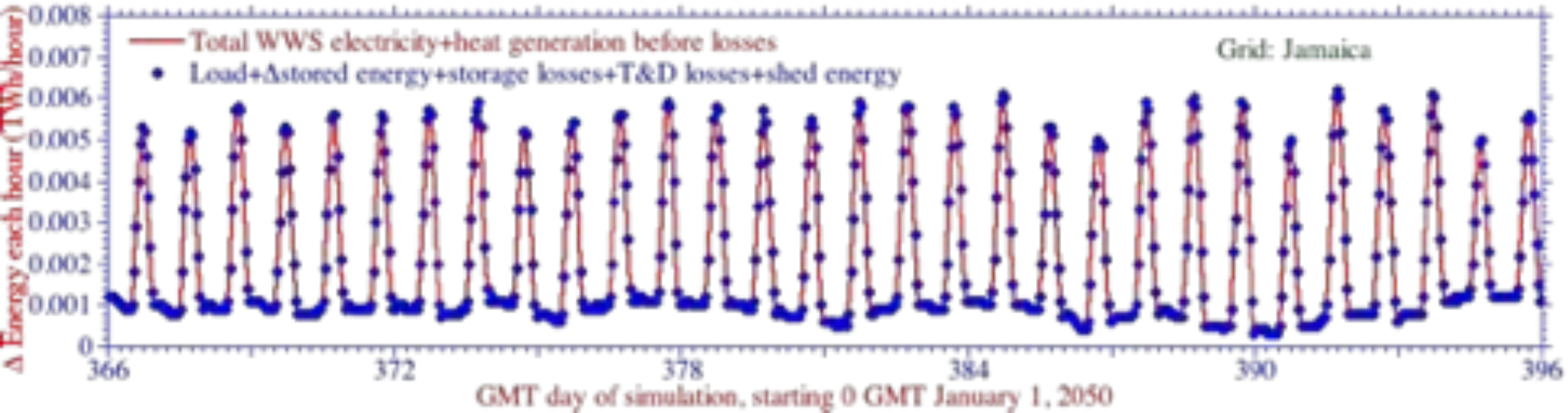
# Matching 2050-54 Haiti-Dominican Republic All-Sector Load With 100% WWS



**Red = Energy supply**

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

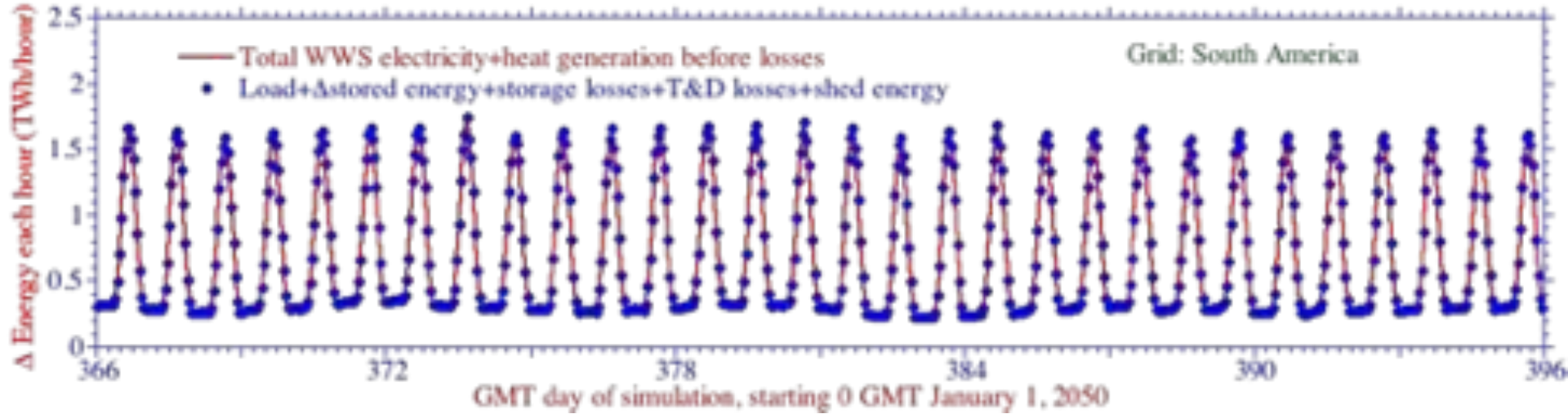
# Matching 2050-54 Jamaica All-Sector Load With 100% WWS



**Red = Energy supply**

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

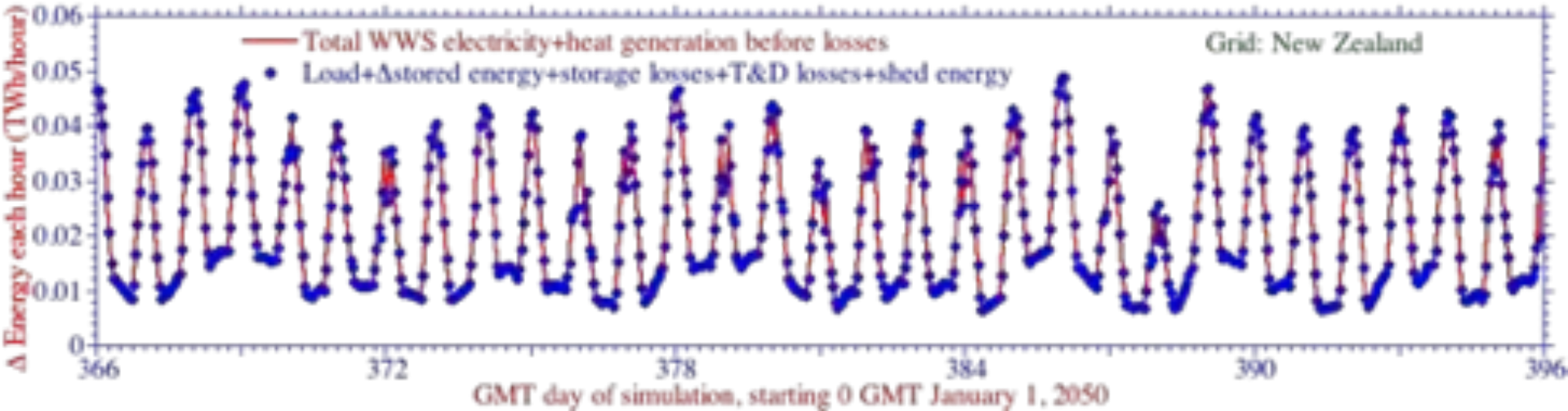
# Matching 2050-54 South America (12 Countries) All-Sector Load With 100% WWS



**Red = Energy supply**

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

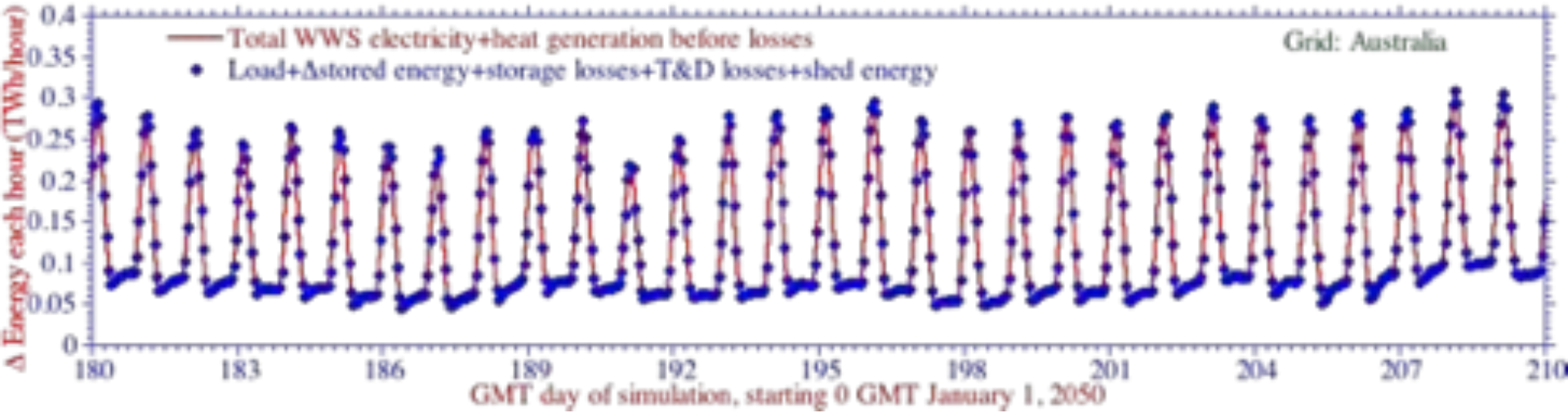
# Matching 2050-54 New Zealand All-Sector Load w/100% WWS



**Red = Energy supply**

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

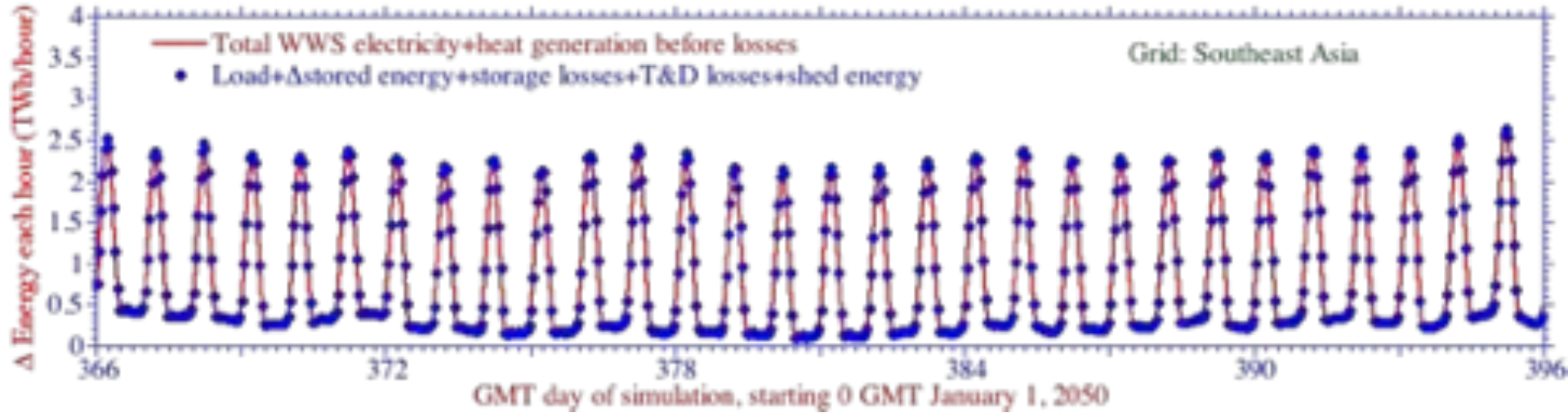
# Matching 2050-54 Australia All-Sector Load With 100% WWS



**Red = Energy supply**

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

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

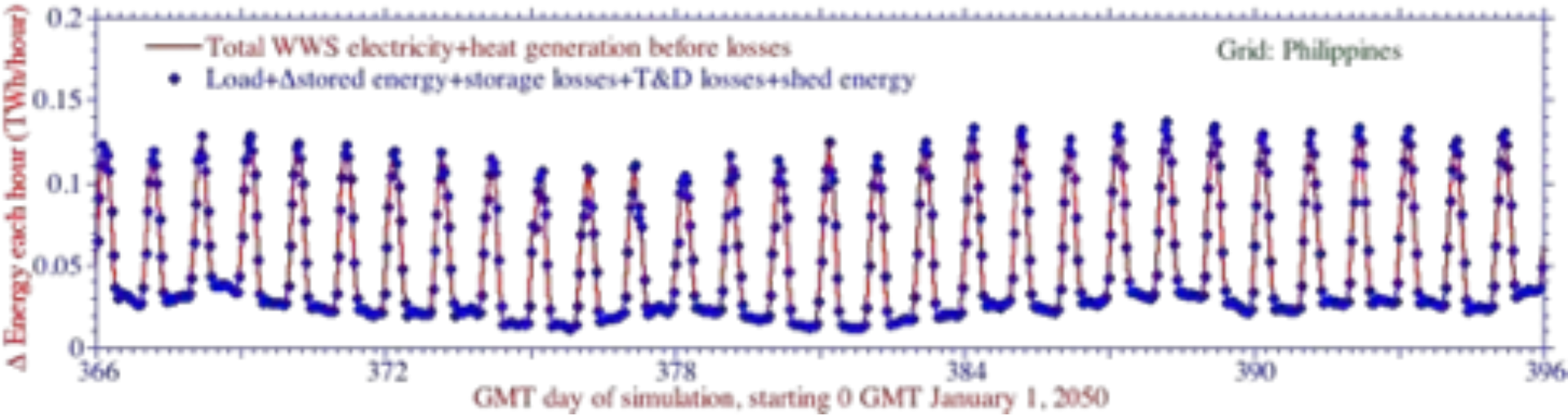


**Red = Energy supply**

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



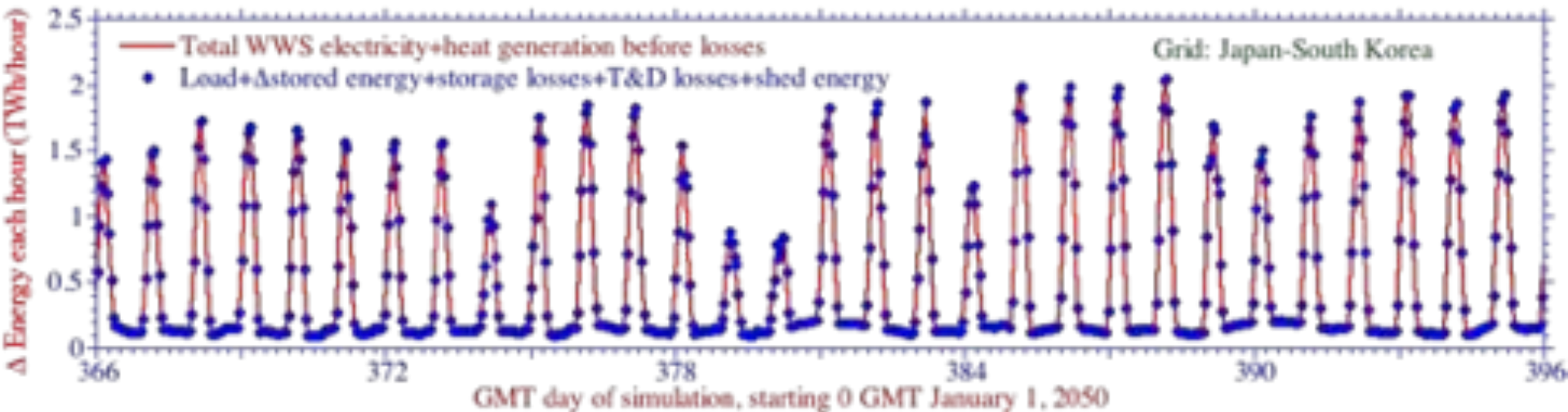
# Matching 2050-54 Philippines All-Sector Load With 100% WWS



**Red = Energy supply**

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

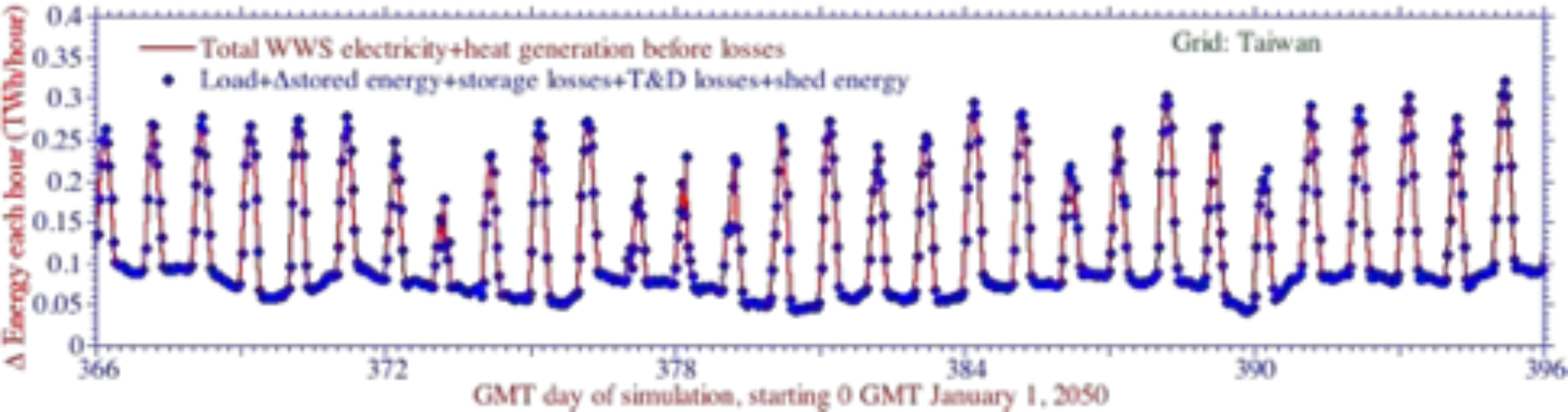
# Matching 2050-54 Japan-South Korea All-Sector Load With 100% WWS



**Red = Energy supply**

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

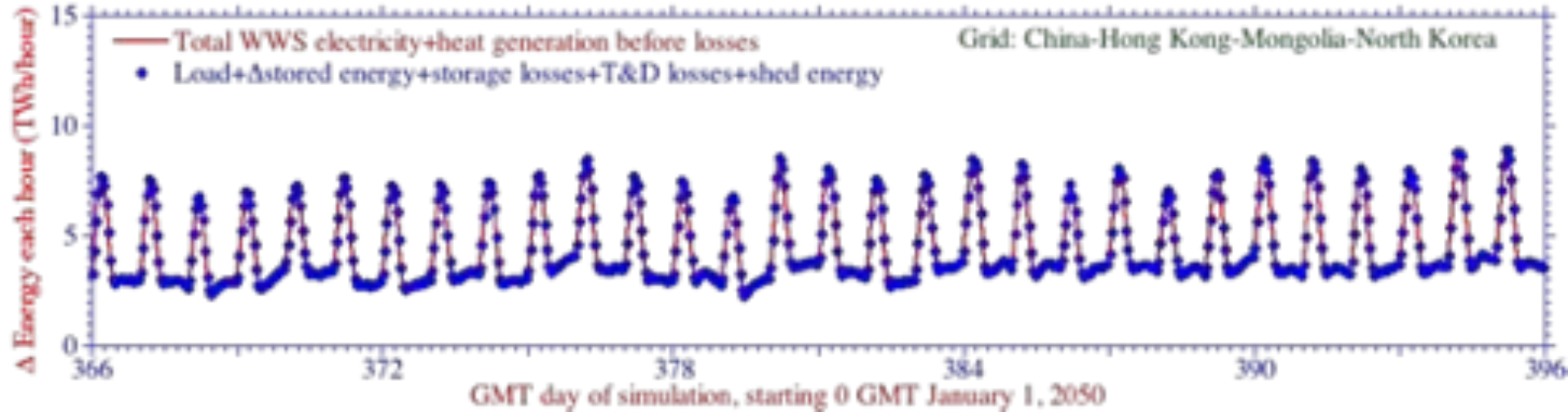
# Matching 2050-54 Taiwan All-Sector Load With 100% WWS



**Red = Energy supply**

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

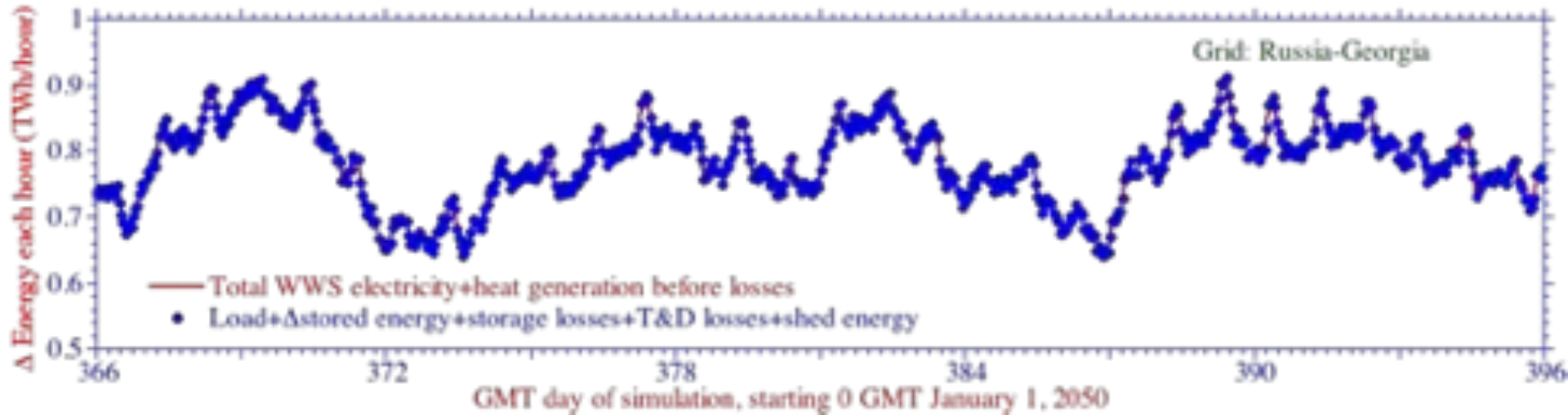
# Matching 2050-54 China-Hong Kong-Mongolia-North Korea All-Sector Load With 100% WWS



**Red = Energy supply**

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

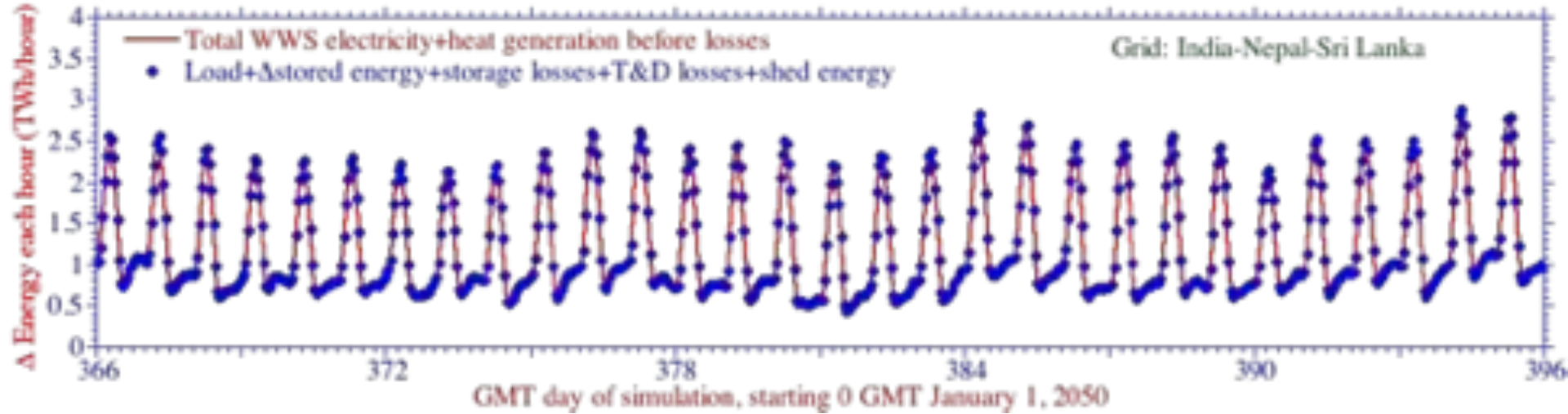
# Matching 2050-54 Russia-Georgia All-Sector Load With 100% WWS



**Red = Energy supply**

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

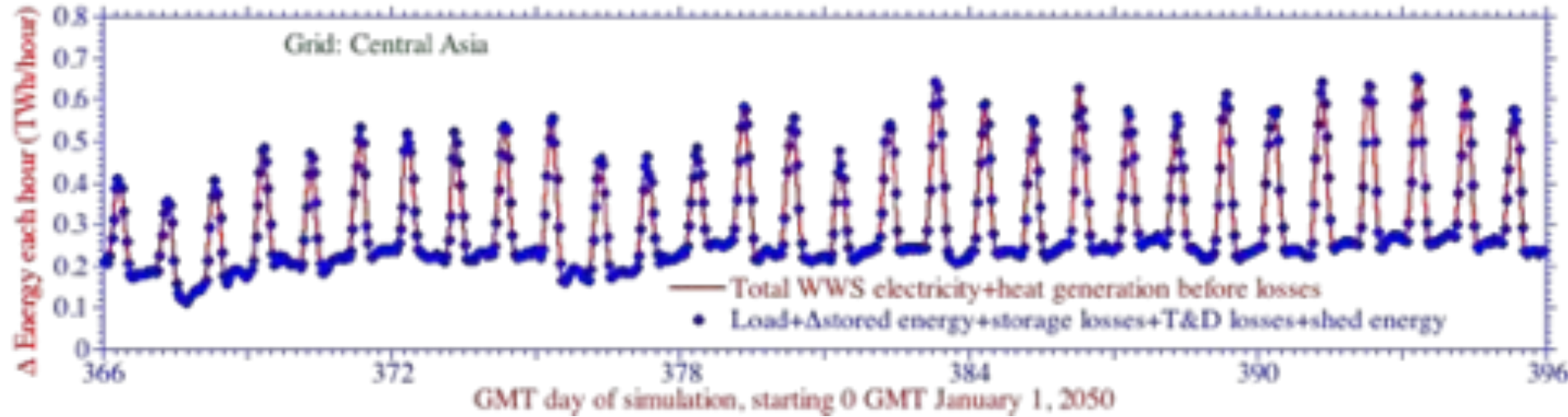
# Matching 2050-54 India-Nepal-Sri Lanka All-Sector Load With 100% WWS



**Red = Energy supply**

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

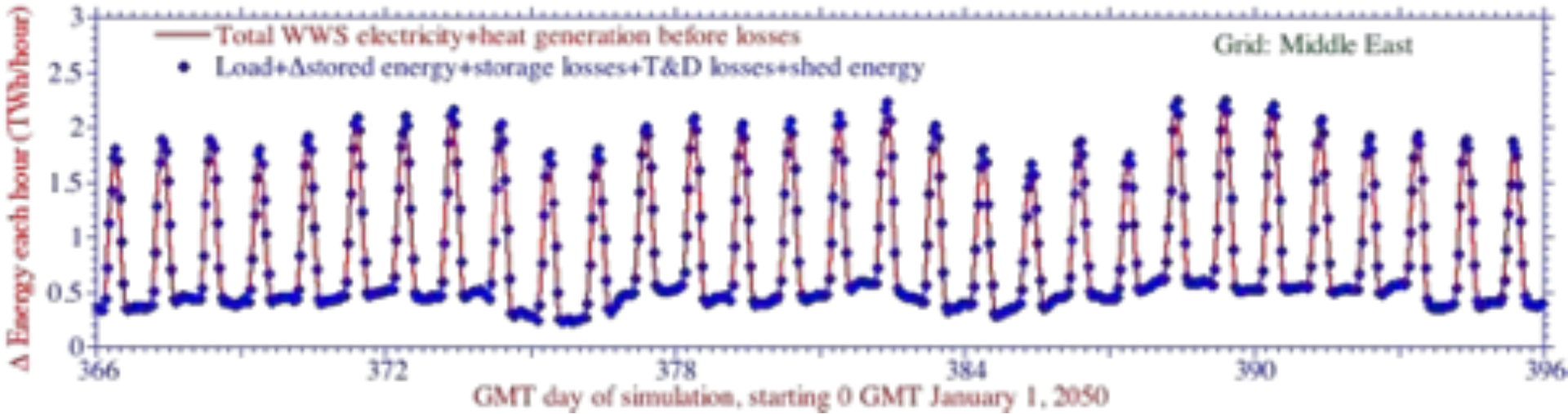
# Matching 2050-54 Central Asia (6 Countries) All-Sector Load With 100% WWS



**Red = Energy supply**

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

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

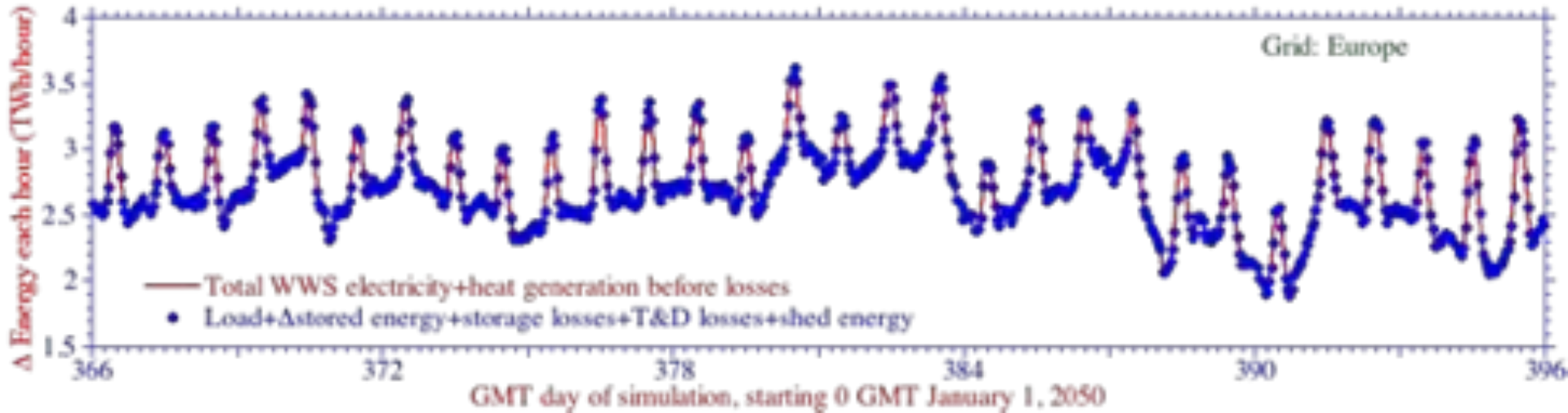


**Red = Energy supply**

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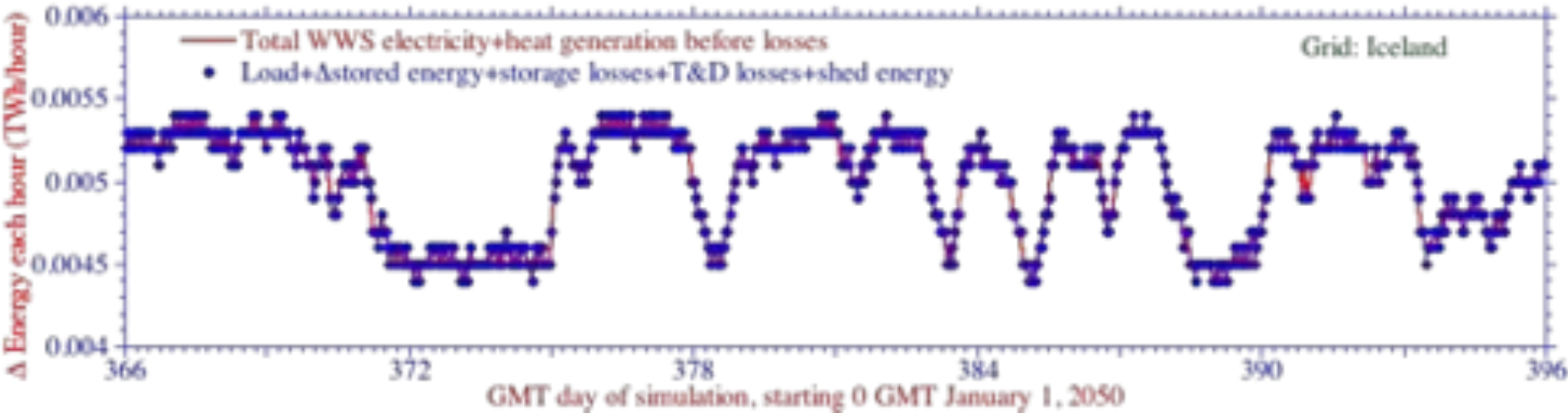
# Matching 2050-54 Europe (40 Countries) All-Sector Load With 100% WWS



**Red = Energy supply**

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

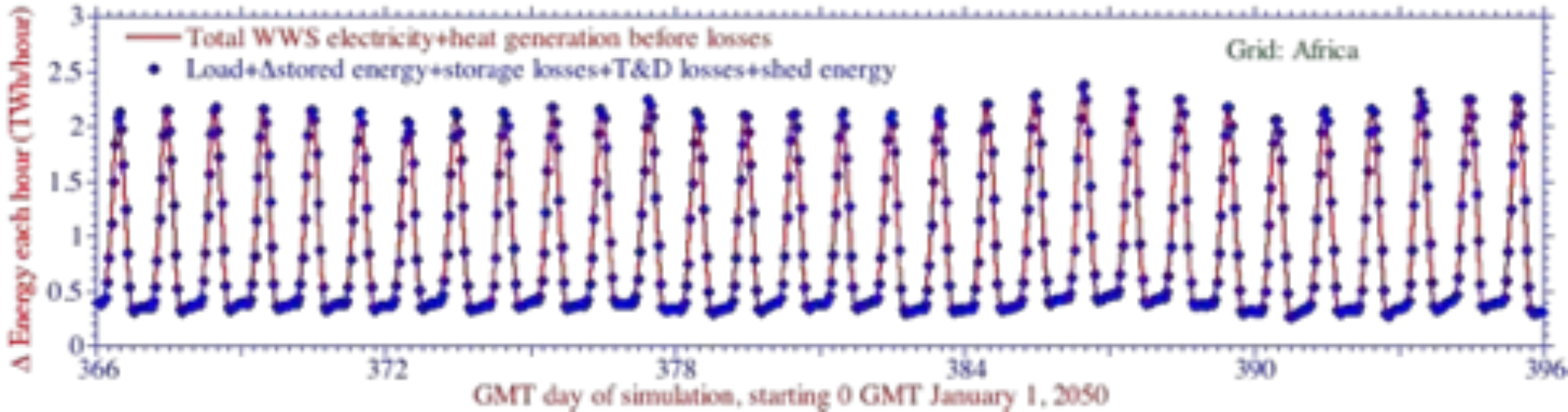
# Matching 2050-54 Iceland All-Sector Load With 100% WWS



**Red = Energy supply**

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

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



**Red = Energy supply**

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

# 2050 139-Country WWS vs. BAU Cost

BAU electricity sector cost (includes T&D+storage)	9.8 ¢/kWh
BAU fuel health cost	12.7
<u>BAU fuel climate cost</u>	<u>15.8</u>
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**

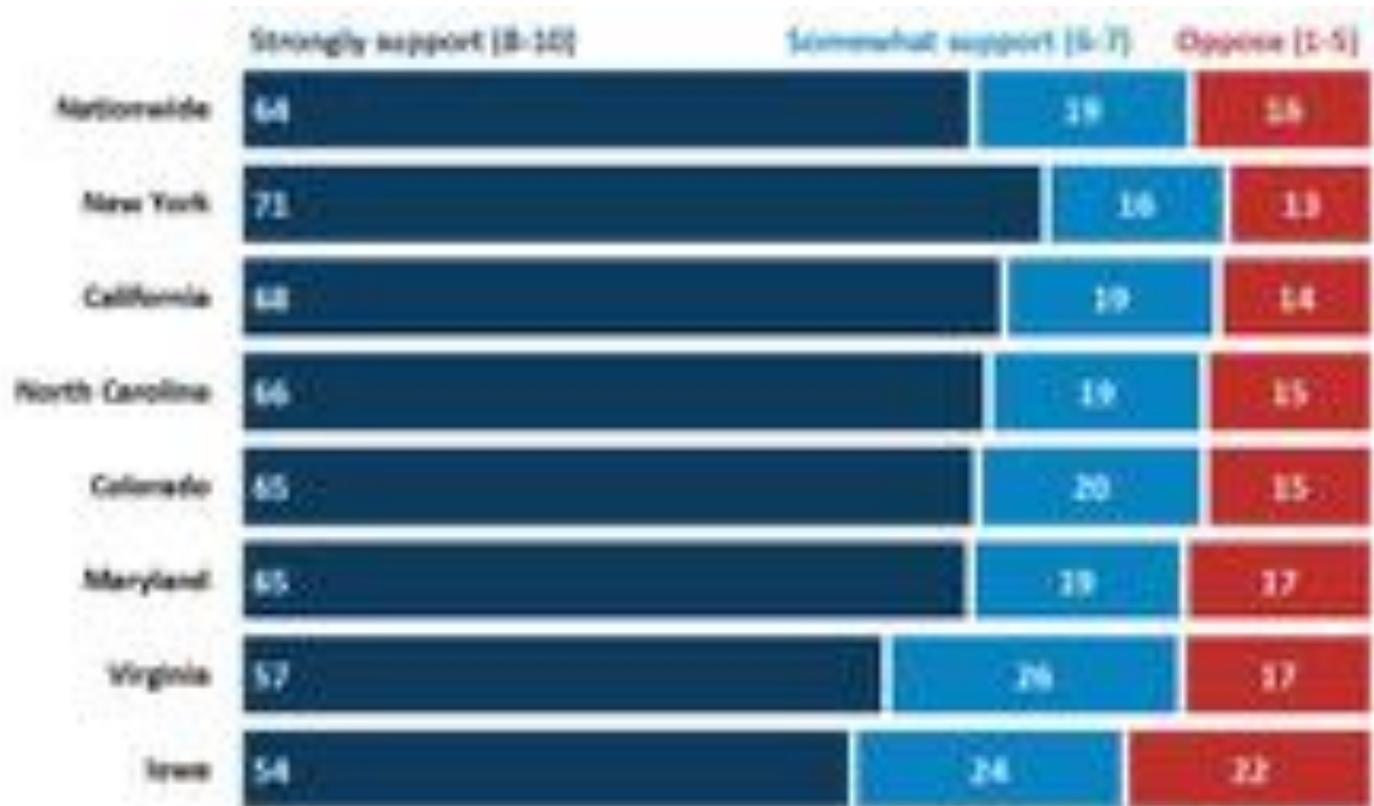
**66% believe climate change is a global challenge**

**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**



## Some of the 85+ Cities Committed to 100% Renewables

**Burlington (VT)**

**Grand Rapids (MI) Sylva (NC)**

**Greensburg (KS)**

**Lancaster (CA)**

**Atlanta (GA)**

**Aspen (CO)**

**Park City (UT)**

**Orlando (FL),**

**Vancouver (BC)**

**San Jose (CA)**

**East Hampton (NY)**

**San Diego (CA)**

**Santa Fe (NM)**

**Rochester (MN)**

**Honolulu (HI)**

**Santa Monica (CA)**

**WestChester (PA)**

**Columbia (SC)**

**Pueblo (CO)**

**S. Lake Tahoe (CA)**

**Palo Alto (CA)**

**Boone (NC)**

**Nelson (BC)**

**San Francisco (CA)**

**Moab (UT)**

**St. Petersburg (FL)**

**Georgetown (TX)**

**Abita Springs (LA)**

**St. Louis (MO)**

**Madison (WI)**

**Portland (OR)**

**Sarasota (FL)**

**Santa Barbara (CA)**

**Salt Lake City (UT)**

**Nevada City (NV)**

**Oxford County (ON)**

**Fayetteville (AR)**

**Boulder (CO)**

## Some of the 144+ Companies Committed to 100% Renewables

<b>IKEA</b>	<b>Adobe</b>	<b>Autodesk</b>	<b>Coca Cola</b>
<b>Google</b>	<b>H&amp;M</b>	<b>HP</b>	<b>Goldman-Sachs</b>
<b>Microsoft</b>	<b>Nestle</b>	<b>Nike</b>	<b>Johnson &amp; Johnson</b>
<b>Apple</b>	<b>S&amp;P</b>	<b>Starbucks</b>	<b>Walmart</b>
<b>Workday</b>	<b>T-Mobile</b>	<b>AB InBev</b>	<b>Bank of America</b>
<b>Bloomberg</b>	<b>BMW Group</b>	<b>Burberry</b>	<b>Citi</b>
<b>Clif Bar</b>	<b>Ebay</b>	<b>Facebook</b>	<b>Estee Lauder</b>
<b>GM</b>	<b>Goldman-Sachs</b>	<b>HSBC</b>	<b>Infosys</b>
<b>Kellogg's</b>	<b>Lego</b>	<b>Mars</b>	<b>Morgan Stanley</b>
<b>Salesforce</b>	<b>Organic Valley</b>	<b>VM Ware</b>	<b>Wells Fargo</b>

# 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 1/4<sup>th</sup> that of fossils

Absolute WWS energy+health+climate costs are 1/8<sup>th</sup> 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/1810-Vancouver.pptx](http://web.stanford.edu/group/efmh/jacobson/Articles/I/1810-Vancouver.pptx)

## Roadmaps

[web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html](http://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](http://www.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/combining.html)

## Infographic maps

[www.thesolutionsproject.org](http://www.thesolutionsproject.org)      [100.org](http://100.org)

Twitter: [@mzjacobson](https://twitter.com/mzjacobson)