



How to go to 100% Wind, Water, Solar with a Stable Grid at Low Cost 100% of the Time with no Coal, Oil, Gas, or Nuclear

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J. G. Swanepoel/Dreamstime.com

Wind farm near Middelgrunden, Denmark

Wind, Water, Solar (WWS) All-Sector Solutions to Energy and Job Security, Air Pollution, Global Warming

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			Electric resistance
Tidal/Wave			

Types of Storage for 100% WWS System

ELECTRICITY

CSP with storage
Pumped hydro
Existing hydroelectric
Batteries

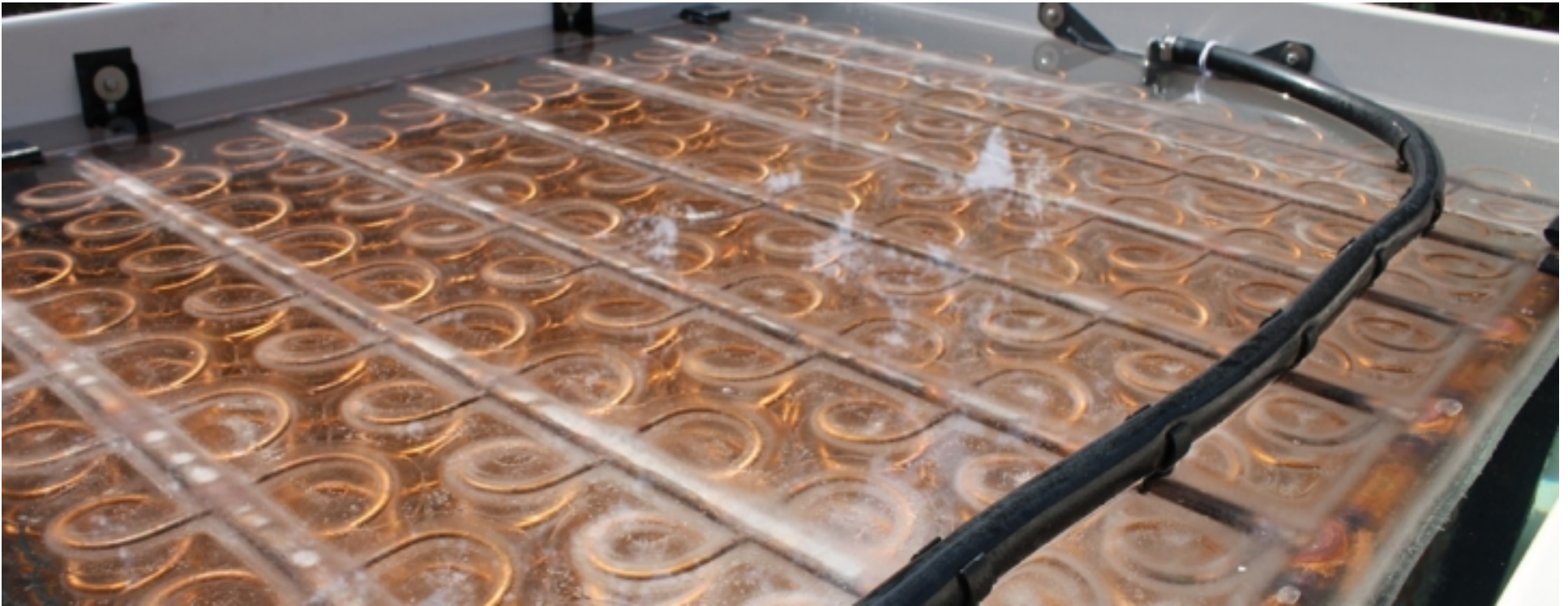
HEATING/COOLING

Water
Ice
Rocks in soil

OTHER

Hydrogen
Demand-response

Nighttime Storage in Ice for Daytime Air Cooling



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

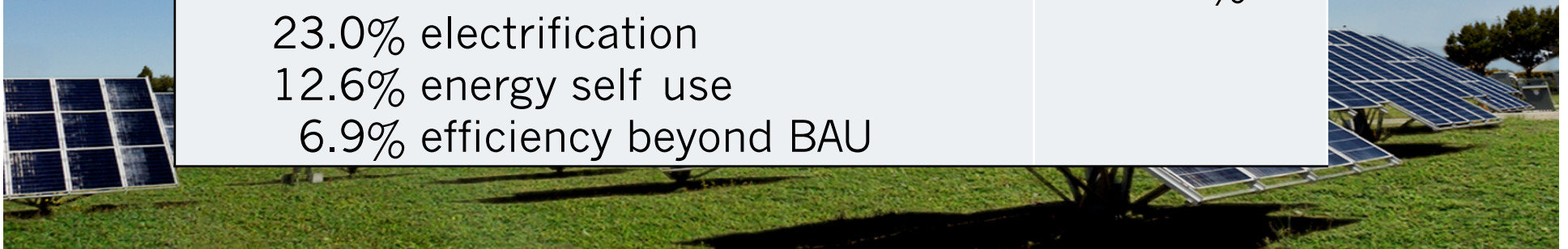
Seasonal Heat Storage in Underground Rocks, Okotoks, Canada



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

End-Use Power Demand For All Energy Purposes

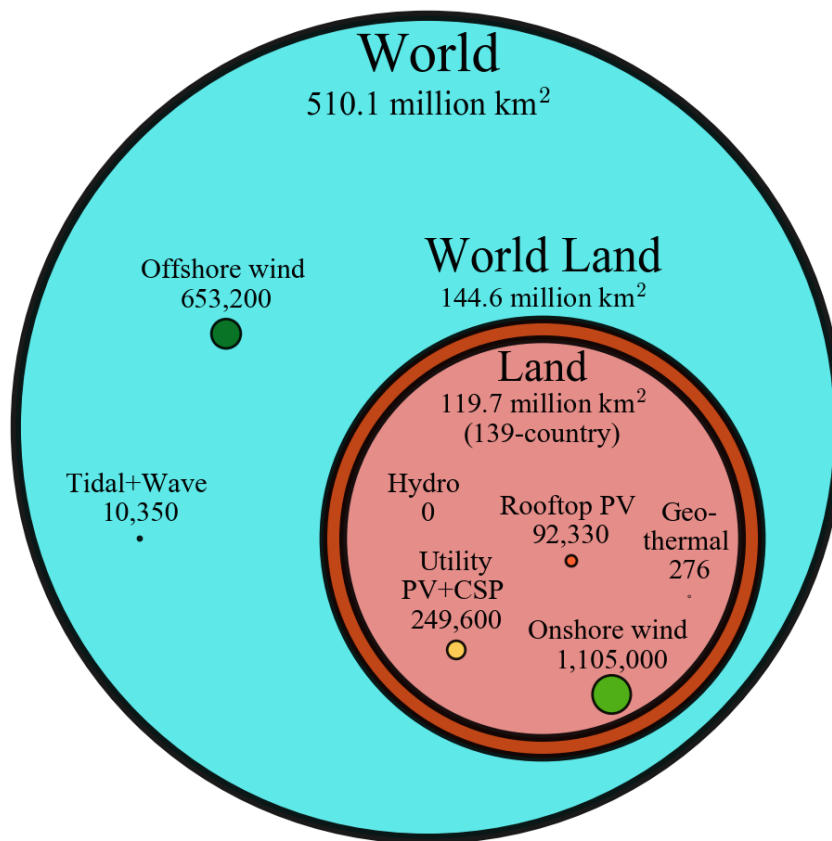
Year and Fuel Type	139-Countries
2012 Demand	12.1 TW
2050 Demand with current fuels (BAU)	20.6 TW
2050 Demand with WWS	11.8 TW
2050 Demand reduction w/ WWS 23.0% electrification 12.6% energy self use 6.9% efficiency beyond BAU	42.5%



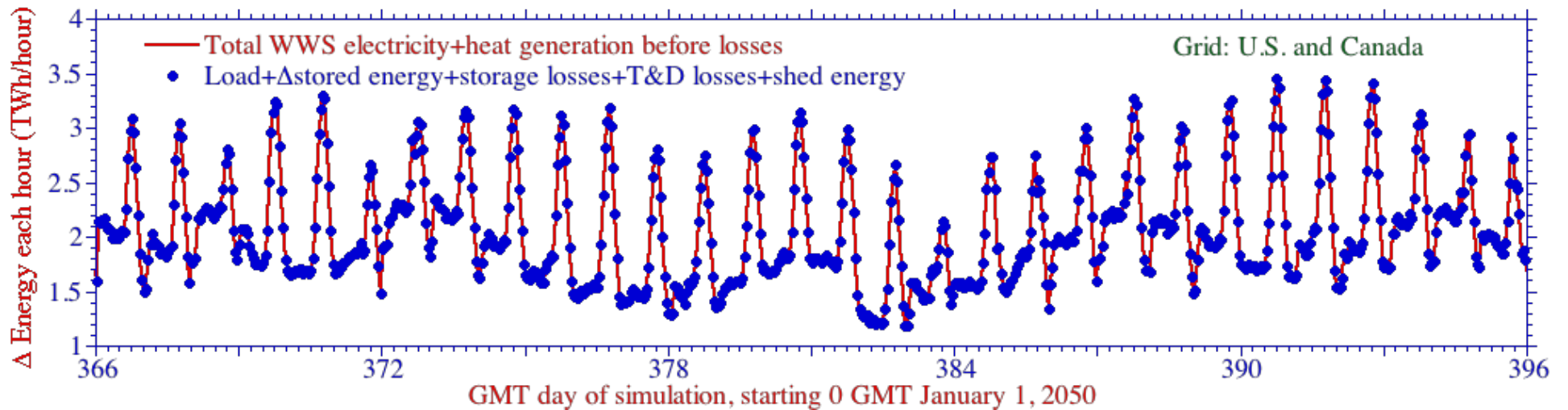
Number of New Plants to Power 139 Countries All Purposes

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 (km²) Beyond 2015 Installations to Power 100% of 139 Countries for all Purposes w/ WWS in 2050



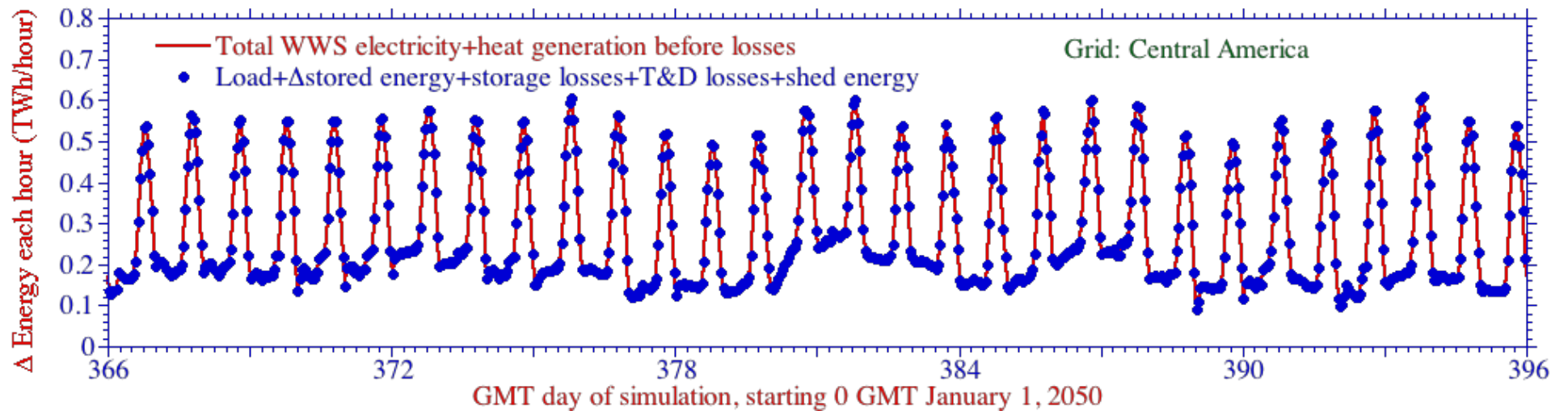
Matching 100% 2050-51 U.S. & Canada All-Sector Load w/WWS



Red = Energy supply

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

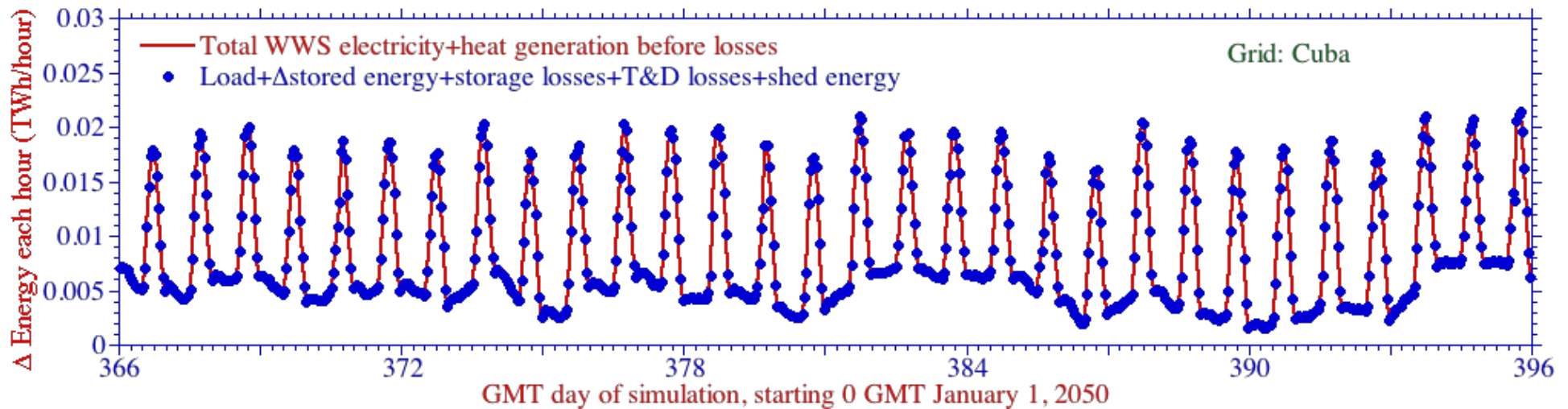
Matching 100% 2050-51 Central America (7 Countries) All-Sector Load w/WWS



Red = Energy supply

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

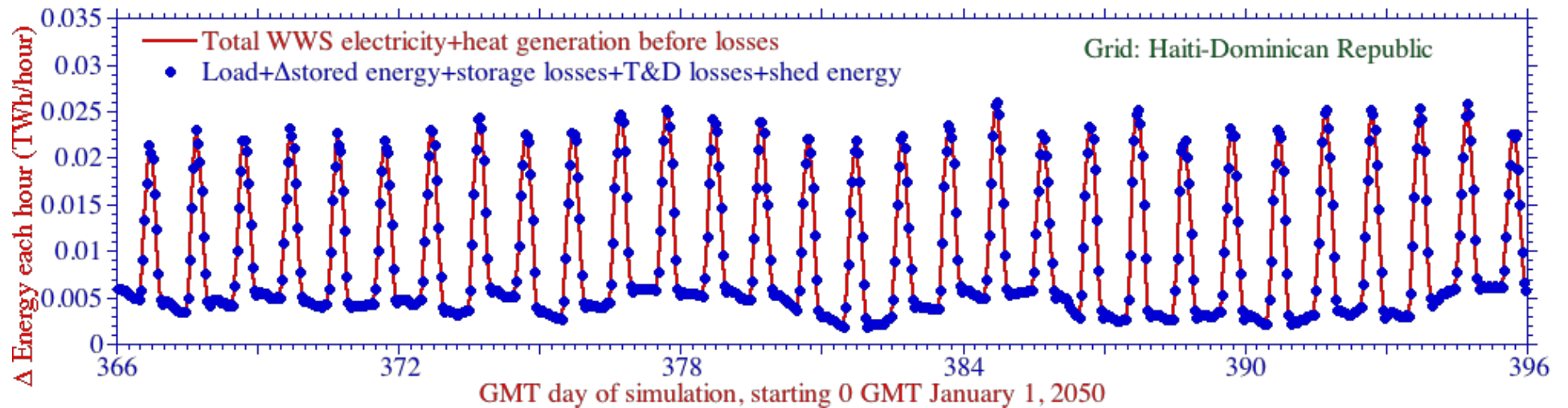
Matching 100% 2050-51 Cuba All-Sector Load With WWS



Red = Energy supply

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

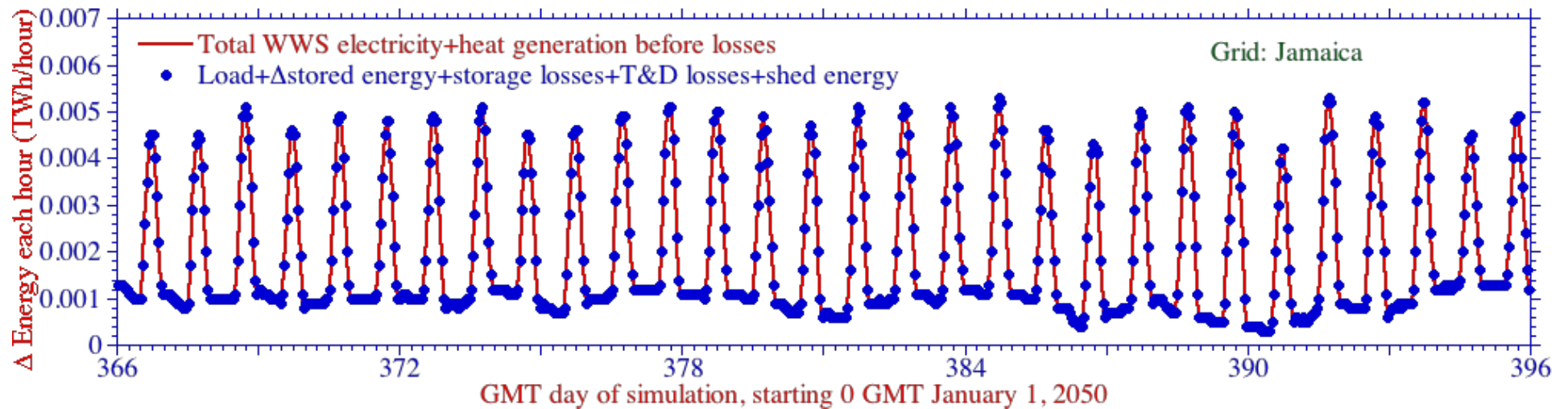
Matching 100% 2050-51 Haiti-Dominican Republic All-Sector Load With WWS



Red = Energy supply

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

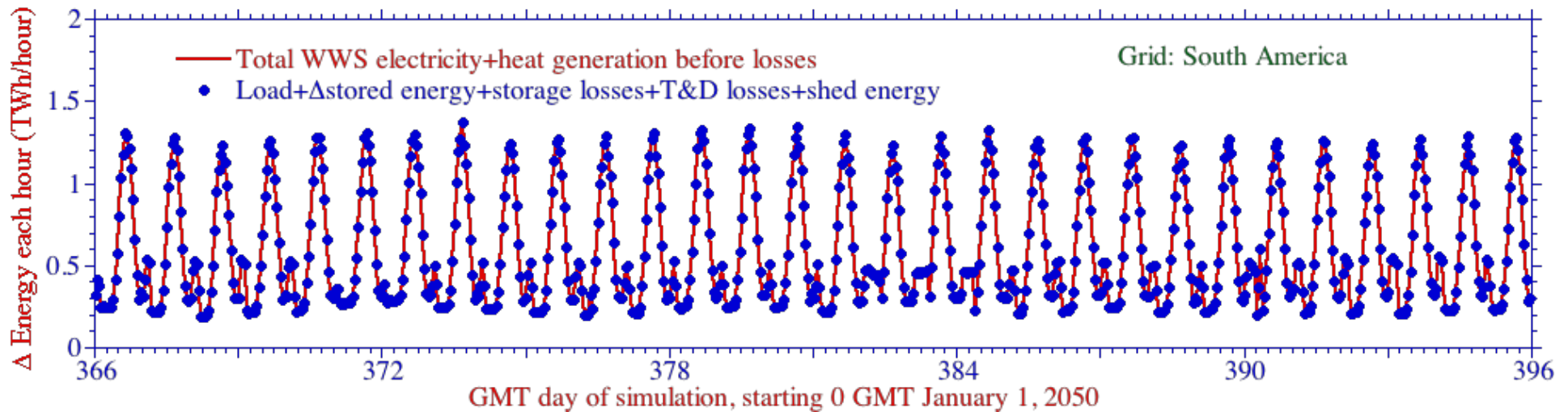
Matching 100% 2050-51 Jamaica All-Sector Load With WWS



Red = Energy supply

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

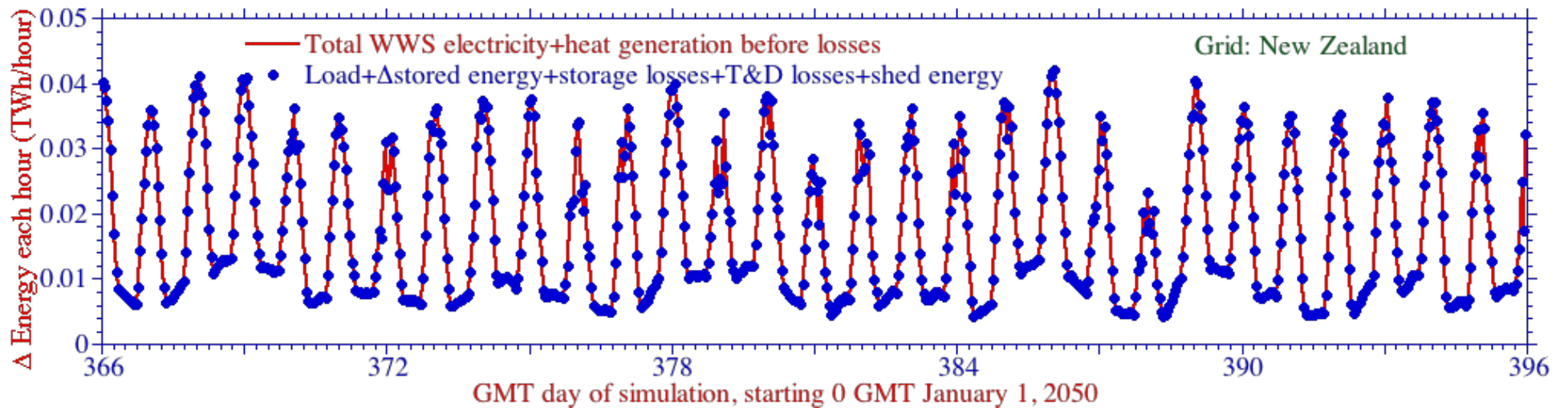
Matching 100% 2050-51 South America (12 Countries) All-Sector Load w/WWS



Red = Energy supply

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

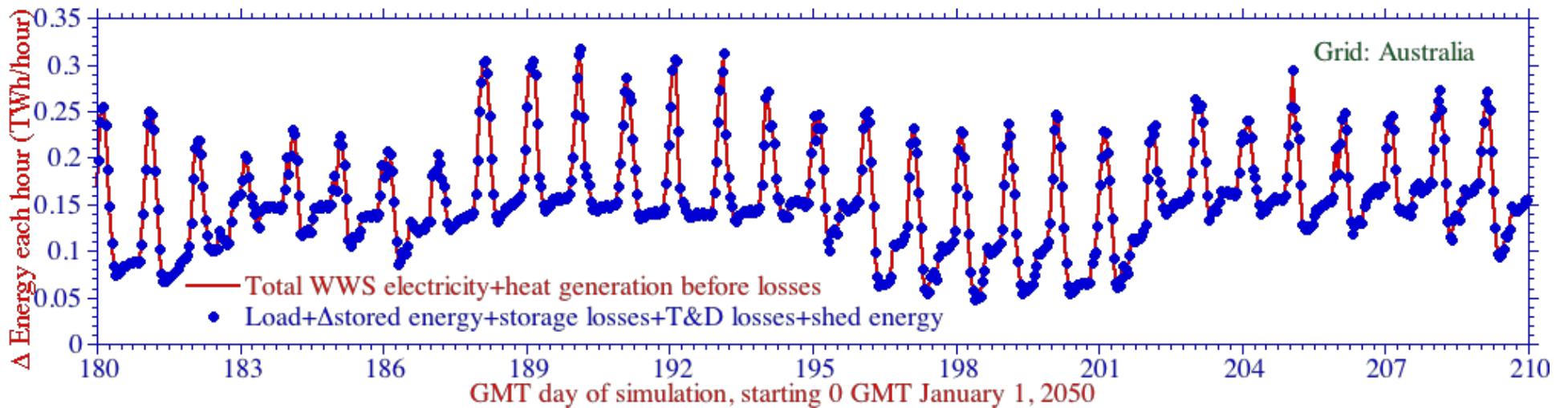
Matching 100% 2050-51 New Zealand All-Sector Load w/WWS



Red = Energy supply

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

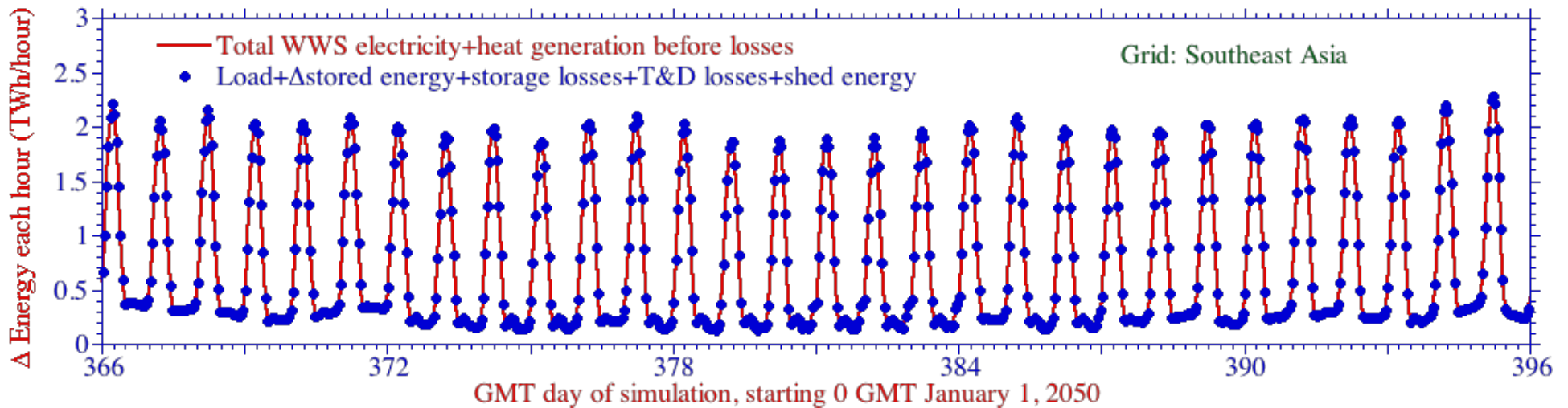
Matching 100% 2050-51 Australia All-Sector Load With WWS



Red = Energy supply

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

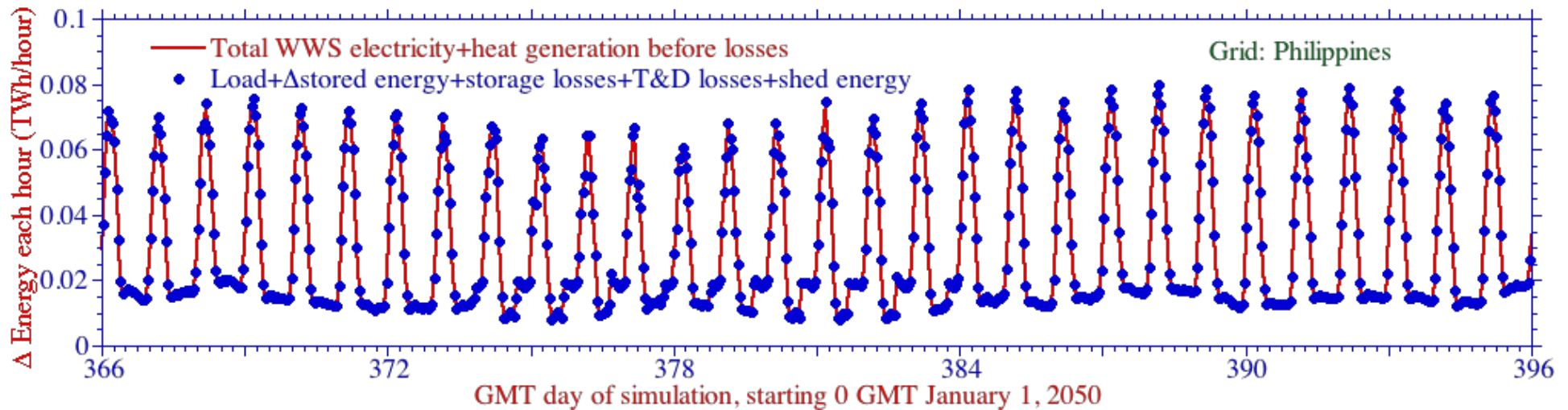
Matching 100% 2050-51 Southeast Asia (9 Countries) All-Sector Load w/ WWS



Red = Energy supply

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

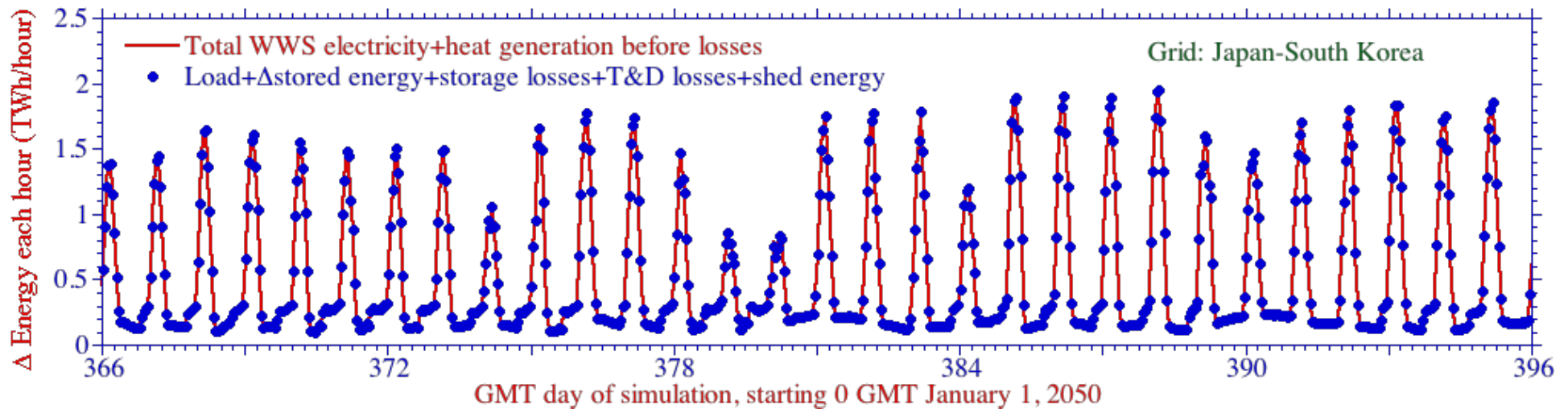
Matching 100% 2050-51 Philippines All-Sector Load With WWS



Red = Energy supply

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

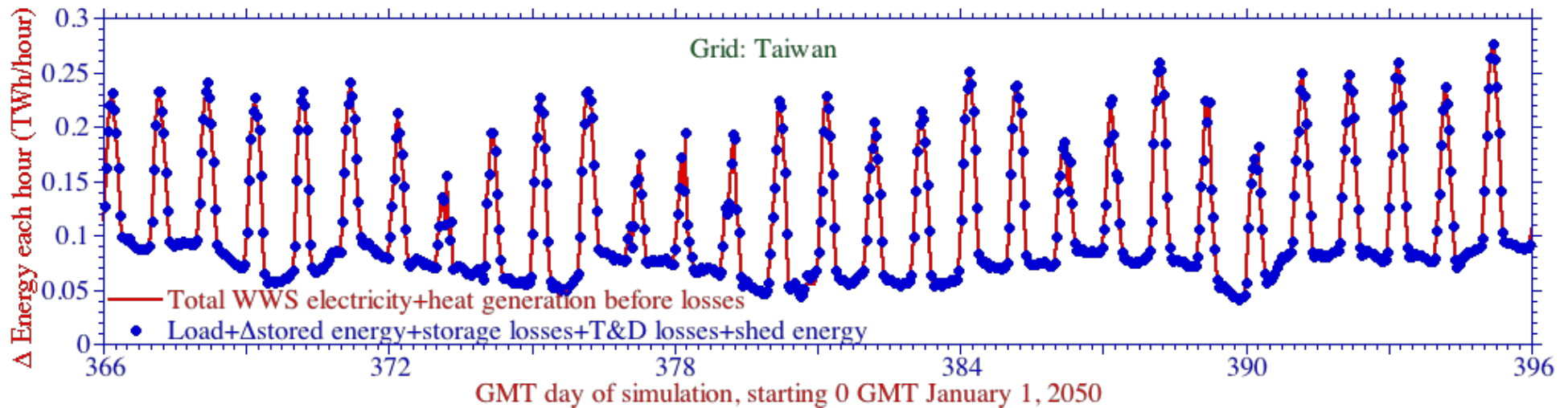
Matching 100% 2050-51 Japan-South Korea All-Sector Load With WWS



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

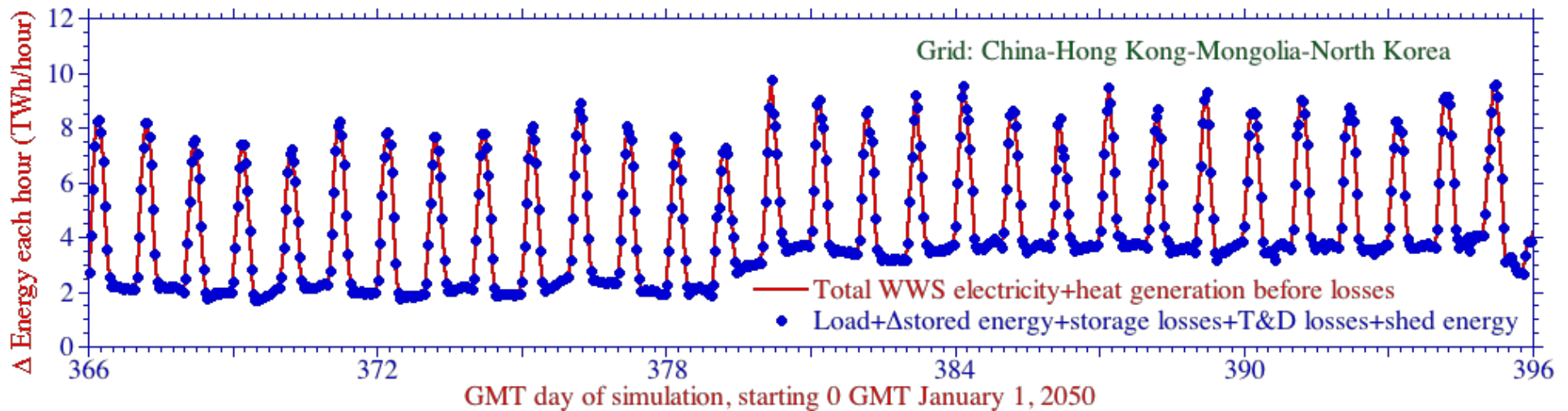
Matching 100% 2050-51 Taiwan All-Sector Load With WWS



Red = Energy supply

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

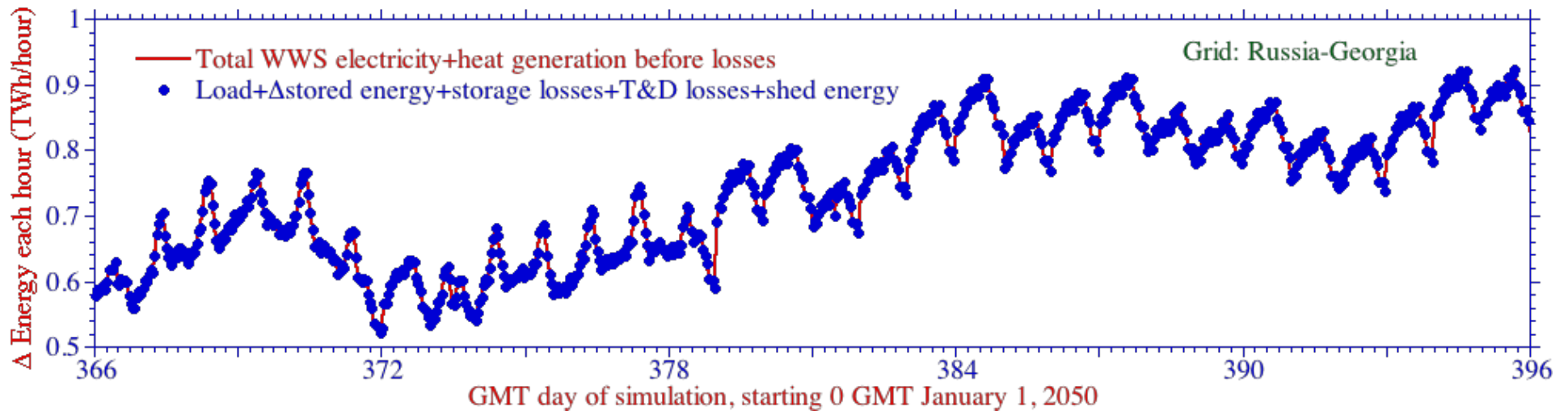
Matching 100% 2050-51 China-Hong Kong-Mongolia-North Korea All-Sector Load With WWS



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

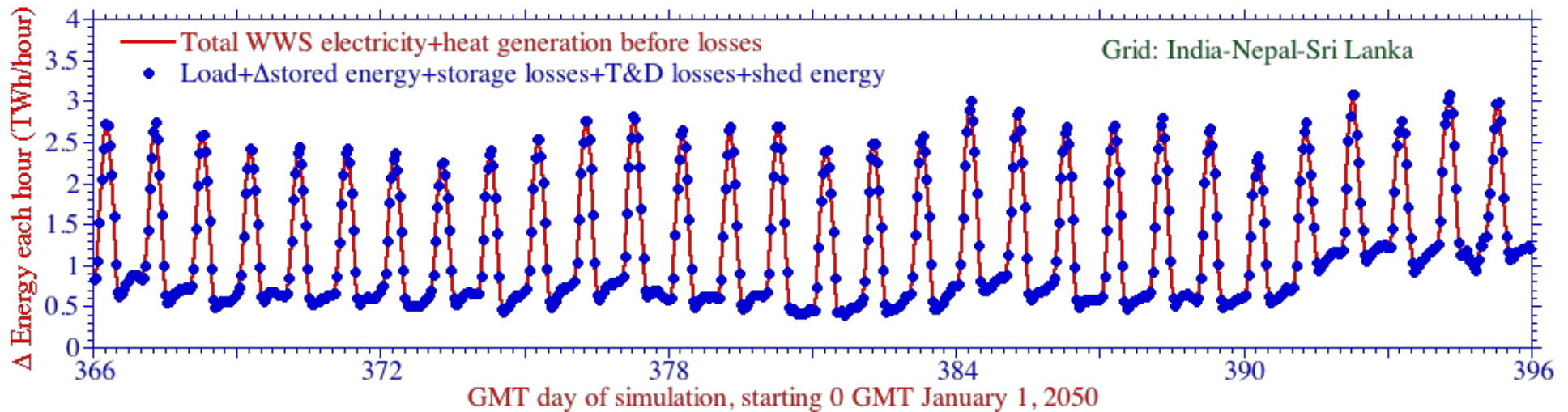
Matching 100% 2050-51 Russia-Georgia All-Sector Load With WWS



Red = Energy supply

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

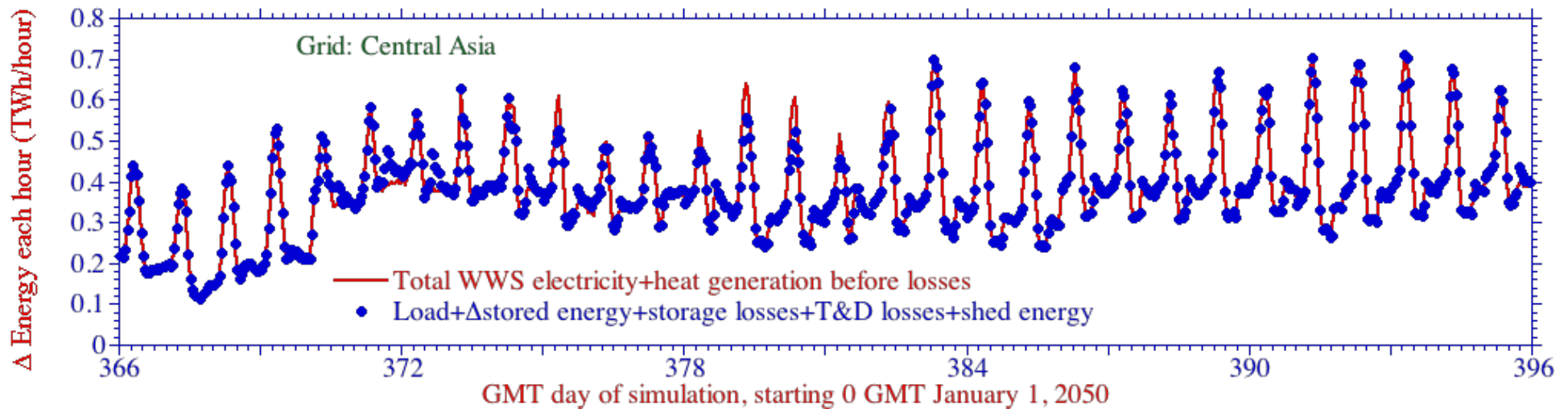
Matching 100% 2050-51 India-Nepal-Sri Lanka All-Sector Load With WWS



Red = Energy supply

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

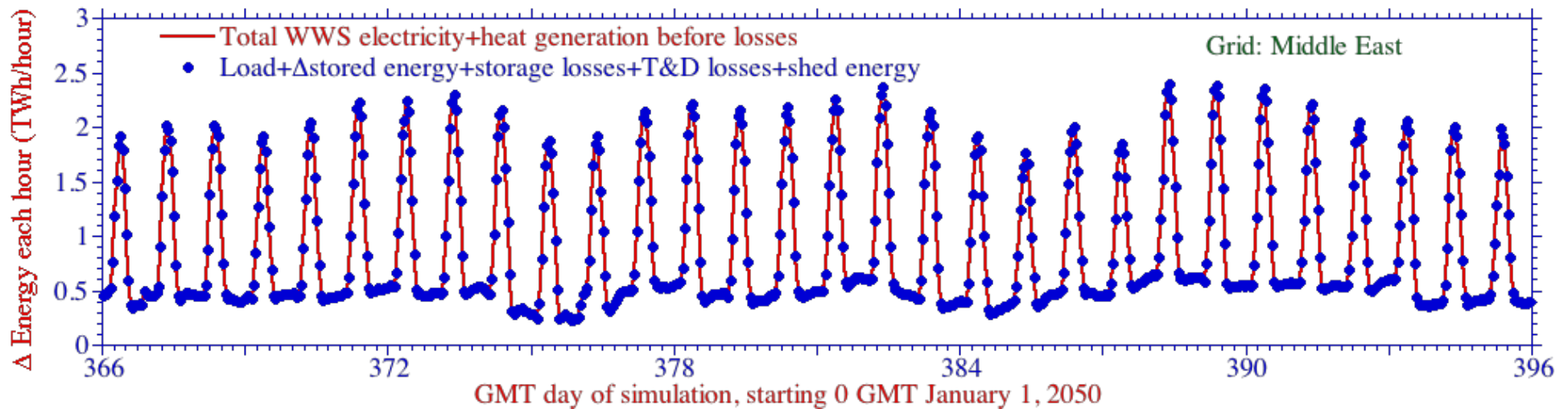
Matching 100% 2050-51 Central Asia (6 Countries) All-Sector Load With WWS



Red = Energy supply

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

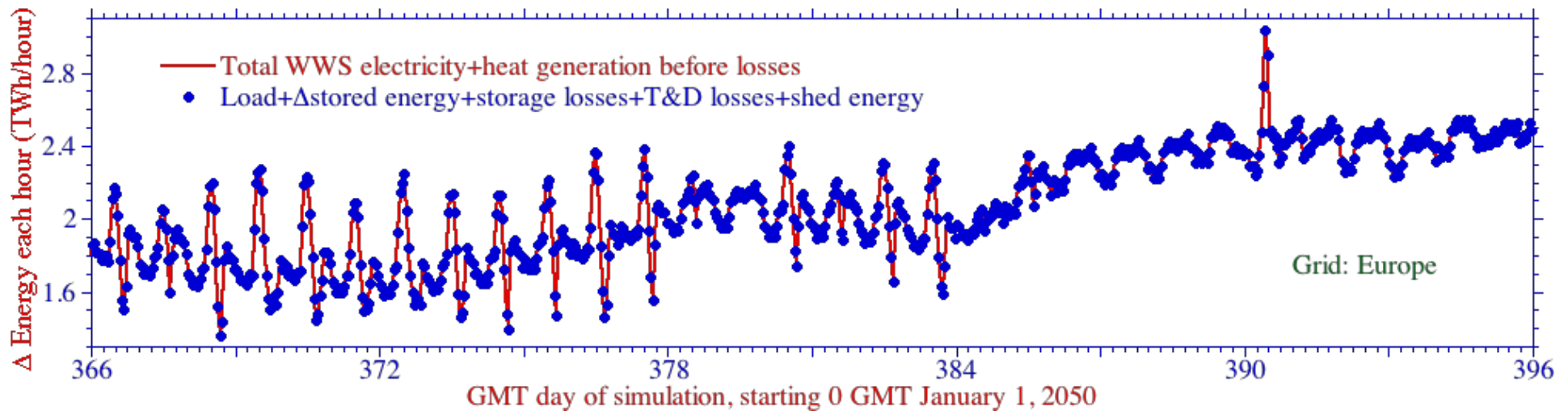
Matching 100% 2050-51 Middle East (16 Countries) All-Sector Load With WWS



Red = Energy supply

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

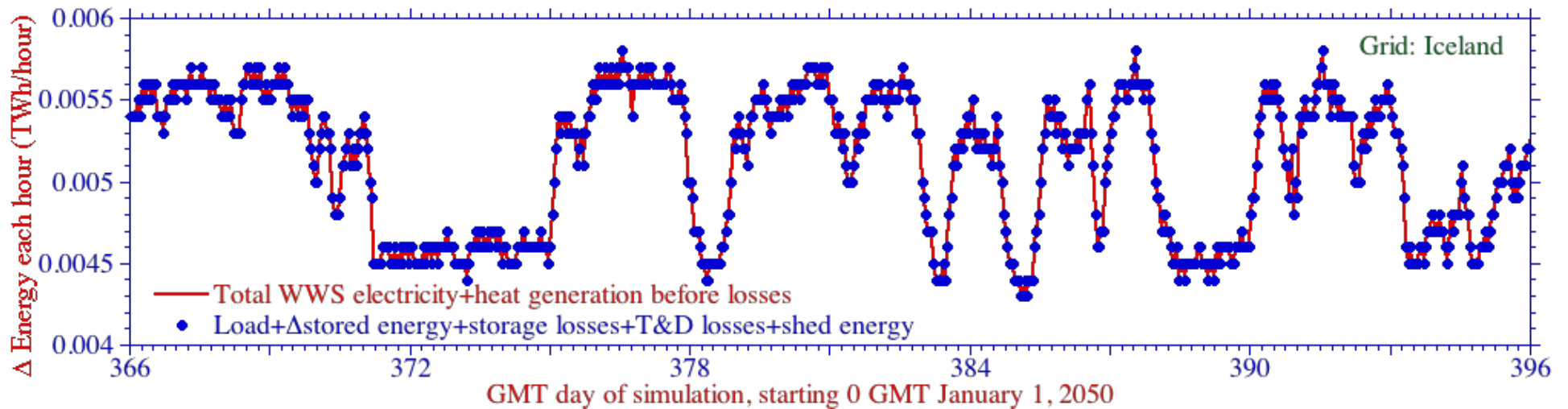
Matching 100% 2050-51 Europe (40 Countries) All-Sector Load With WWS



Red = Energy supply

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

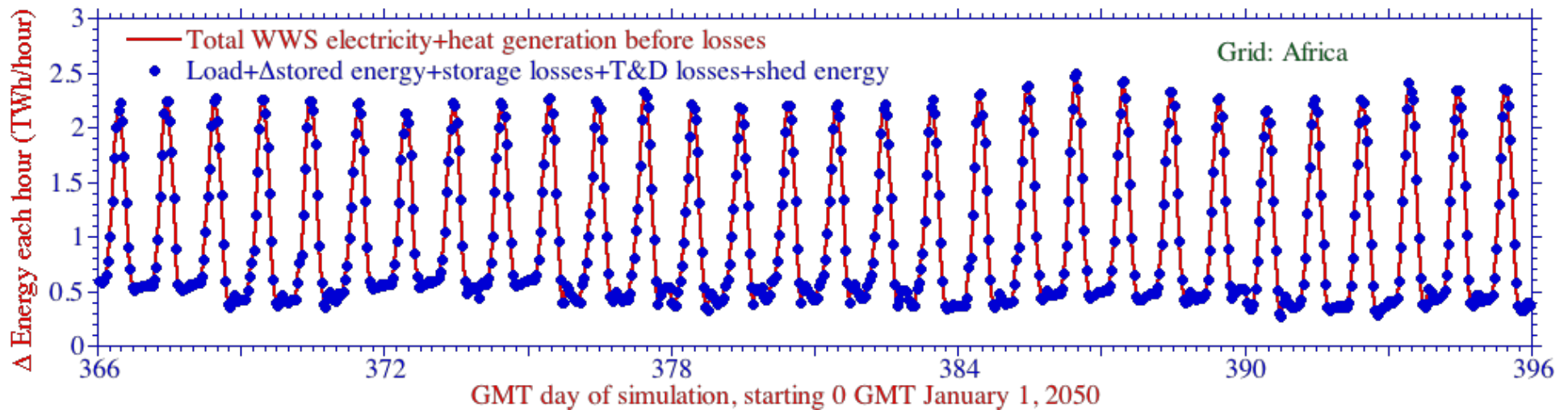
Matching 100% 2050-51 Iceland All-Sector Load With WWS



Red = Energy supply

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

Matching 100% 2050-51 Africa (27 Countries) All-Sector Load With WWS



Red = Energy supply

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

2050 139 Country WWS vs. Conventional Fuel Cost (¢/kWh)

WWS electricity for electricity sector total cost (Includes short+long T&D, elect+heat storage; stable grids)	9.8
Conventional electricity sector total cost	38.3
Conventional fuel for elec sector (incl T&D+storage)	9.8
Conventional fuel health cost	12.7
Conventional fuel climate cost	15.8
WWS electricity for all sectors (elec, transport, heating/cooling, indus, ag/for/fish)	10.7

Why Not Nuclear?

- 1) 6-24 times more CO₂ & air pollution per kWh than wind
- 2) Takes 10-19 yrs between planning & operation vs 2-5 yrs for wind/solar
- 3) Costs 2.5-4 x that of new onshore wind/utility PV
- 4) → Takes 2-10 times longer to obtain 25%-40% the CO₂ savings per dollar than wind/solar.
- 5) 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
 - (d) Mining risk



Can WWS or Nuclear Avoid 1.5 C Warming?

- 1) We can allow 350-575 GT-CO₂ emissions after 2015 to stay below 1.5 °C warming
- 2) Converting to 80% WWS by 2030 & 100% by 2050 emits ~415 GT CO₂, limiting warming to 1.5 °C.
- 3) New nuclear plants proposed today require 10-19 yrs until operation. Wind/solar require 2-5 years
- 4) → Impossible for nuclear to avoid 1.5 °C warming; possible for WWS.

Summary–Grid Reliability With 100% WWS

- It is possible to convert world's energy infrastructure to 100% WWS for all sectors and keep the grid stable 100% of the time at low cost
- We obtained 100% stable grids w/100% WWS in 20 world regions among 139 countries.
- Energy+storage+T&D costs in the 20 regions 10.7 (7.3-13) ¢/kWh
- Nuclear, CCS, and natural gas were not needed

Articles and data

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

Infographic maps

www.thesolutionsproject.org/100.org

Twitter: @mzjacobson