

GE Energy Infrastructure

# Wind and Solar Integration Studies

October 7, 2009

*Utility Scale PV Variability Workshop*

Cedar Rapids

**Nicholas W. Miller**



imagination at work



# Large Scale Solar Integration Studies

## Overview

- Experience
- Objectives
- Data (as available)
- Methods and results
- Data (what we want in the future)

**“oh yeah, and we do Wind, too.”**

# Large scale renewable studies by GE

These studies were commissioned by the Energy Commissions and ISOs of each region... .

- Examining the Feasibility of 100+ GW of new wind and other renewable resource additions
- Considering Operability, Costs, Emissions, Transmission Constraints, Forecasting

2004 New York:

3 GW Wind  
10% of Peak Load  
4% of Energy

2005 Ontario:

15 GW Wind  
50% Peak Load  
~30% Energy

2006 California:

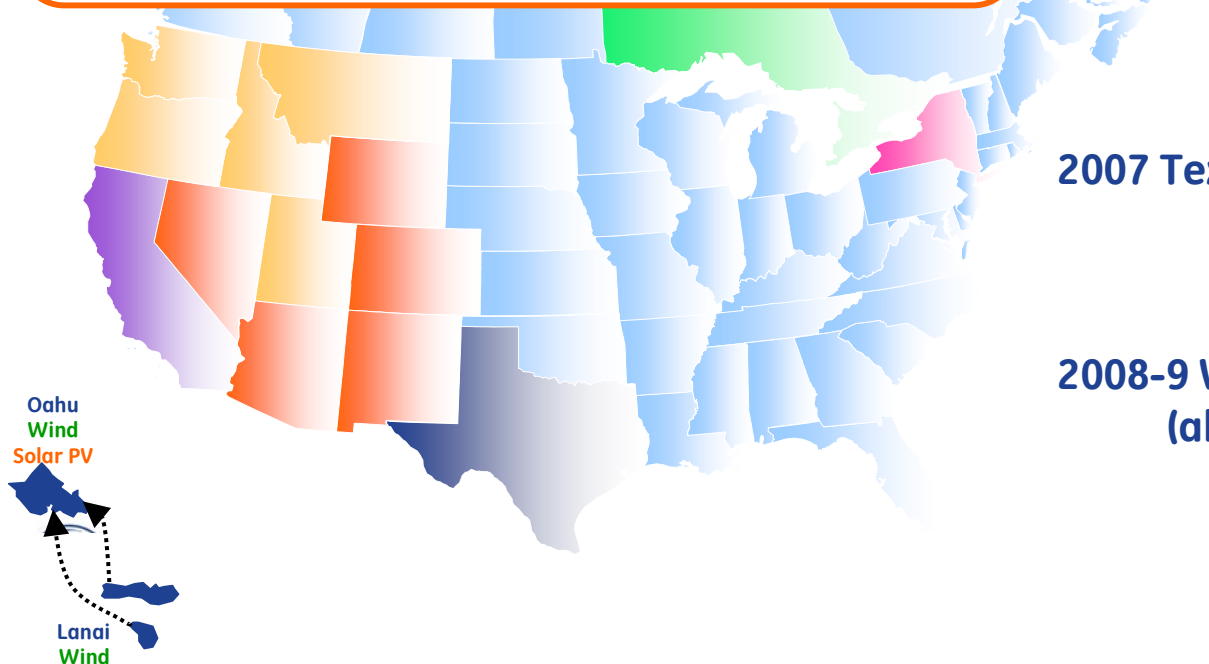
13 GW Wind  
**3 GW Solar**  
5 GW Bio & Geo  
26% Peak Load  
15% Energy (33% Total)

2007 Texas:

15 GW Wind  
25 % Peak Load  
17% Energy

2008-9 Western Wind & Solar:  
(all of Western US)

72 GW Wind  
**15 GW Solar**  
50% Peak Load  
27% Energy



# Variable Generation

## Wind

- Variations cover many timescales
- Season, day, hour, minute

## Solar

- Variations are dominated by day/night cycle and sky conditions (clouds)

Biomass and geothermal generation are not intermittent

# Objectives (typical large scale study)

Evaluate grid operation with increasing levels of variable generation

- Target levels of wind and solar penetration

Identify and quantify system performance and operation problems

- Load following, regulation, minimum load, etc.

Identify and evaluate possible mitigation methods

**A mix of examples from the California and Western Wind and Solar Integration studies follows...**

# California Study: 4 Scenarios Analyzed

2006 Base Case – Existing transmission system with existing mix of generation resources

- Includes 2,100 MW wind and **330 MW solar**

2010T Tehachapi Case – 20% Renewable Energy

- 7,500 MW wind and **1,900 MW solar** in California
- Includes 4,200 MW of wind in Tehachapi region and new 500 kV transmission to support it

2010X Accelerated Case – 33% Renewable Energy

- 12,500 MW wind and **2,600 MW solar** in California

2020 Case – 33% Renewable Energy

- 12,700 MW wind and **6,000 MW solar** in California

# Wind and Solar Generation in California

	2006	2010T	2010X	2020
<b>Concentrating Solar (CS)</b>				
Number of Sites	7	12	42	43
Total CS MW	330	1200	2100	3100
<b>Photovoltaic (PV)</b>				
Number of Sites	0 *	136	128	228
Total PV MW	0 *	630	530	2900
<b>Wind Plants</b>				
Total Sites in CA	57	98	142	147
<b>Sites in Tehachapi</b>	<b>16</b>	<b>40</b>	<b>54</b>	<b>54</b>
Total Wind MW	2100	7500	12500	12700

\* Existing PV aggregated with load

# Types of Analysis

## Statistical Analysis

- Multiple time periods (Hourly, 5-minute, 1-minute)

## Production Cost Simulation with MAPS

- Hour-by-hour simulation of grid operations for an entire year (3 years of different wind, solar and load profiles)

## Quasi-Steady-State Simulation with PSLF

- Minute-by-minute time-sequenced power flows for entire WECC grid for several hours

# Data

Power flow data from Davis Power Consultants

- Scenarios 2006, 2010T, 2010X, 2020

Load data from CAISO, 2002-2004

- Hourly load MW, forecast and actual
- 4-sec load MW for about 400 days
- Load data scaled up to peak for 2006, 2010, 2020

Wind data from AWS Truewind, 2002-2004

- Hourly wind MW, forecast and actual
- 1-minute wind MW for 51 selected periods
- Separate wind profile data for each wind farm

Production simulation data for California and WECC from Rumla, Inc.



# Data

## Solar data from multiple sources

- Hourly and 1-min MW for Sungen and Luz for 2002-2004 (CAISO and UC-Davis)
- Hourly Stirling solar MW for Mojave and Imperial for 2002-2004 (NREL and SES)
- Hourly and 15-min Photovoltaic MW for one year, aggregated by zip code (CPUC - SGIP)
- 1-min or 3-min solar insolation data at two sites, for January and July 2002 (NREL, ARSC SUNY Albany)

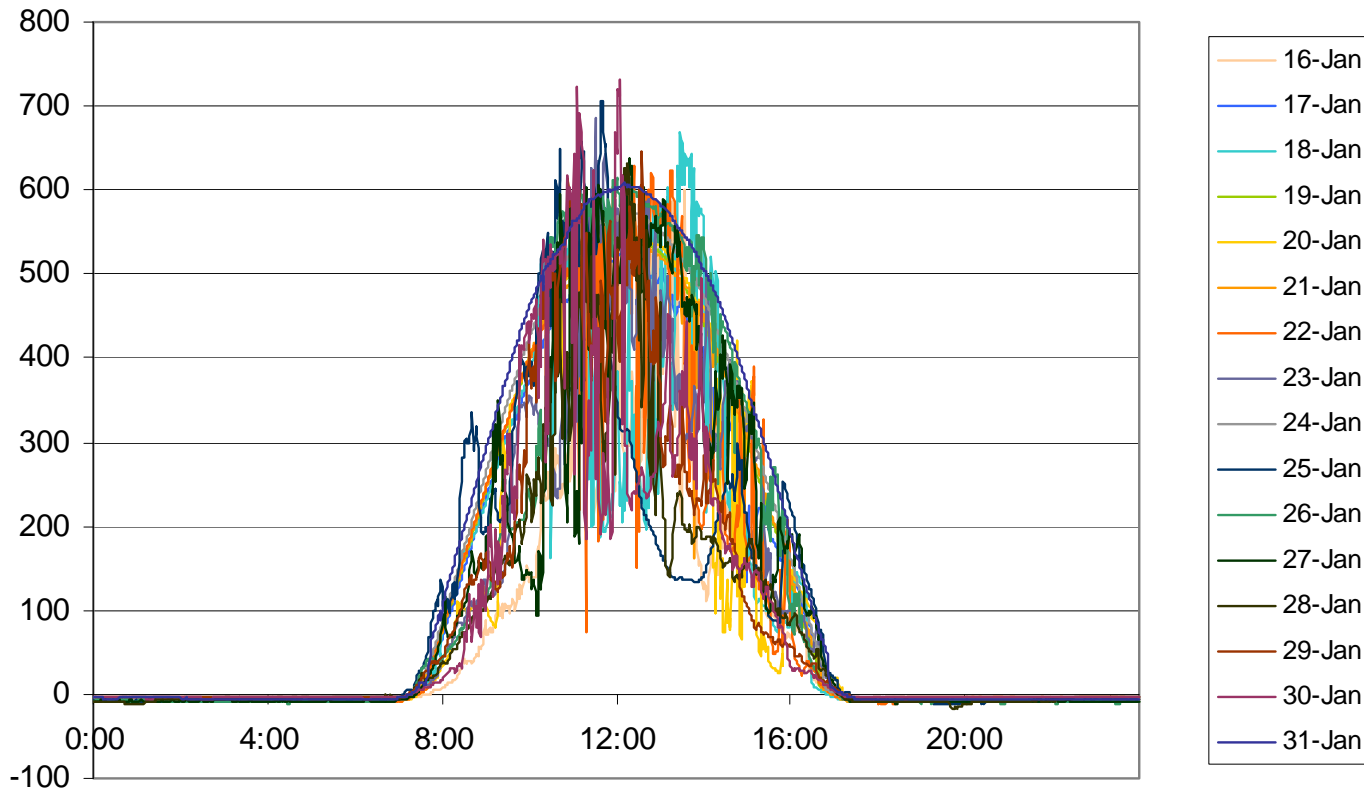
Based on this data, GE compiled solar profiles for multiple sites across California

# Compiling and Extrapolating

Tricks we used to extend the data

- Extraction of 1-min or 3-min variability – essentially high pass filter
- Retain temporal and spatial diversity for slower variations (1 hour and 15 minute samples)
- Overlay ‘fast variability’
- Random draw of variability from a limited sample
- Assumes NO correlation for high frequency variability

Best available...but is it good enough?



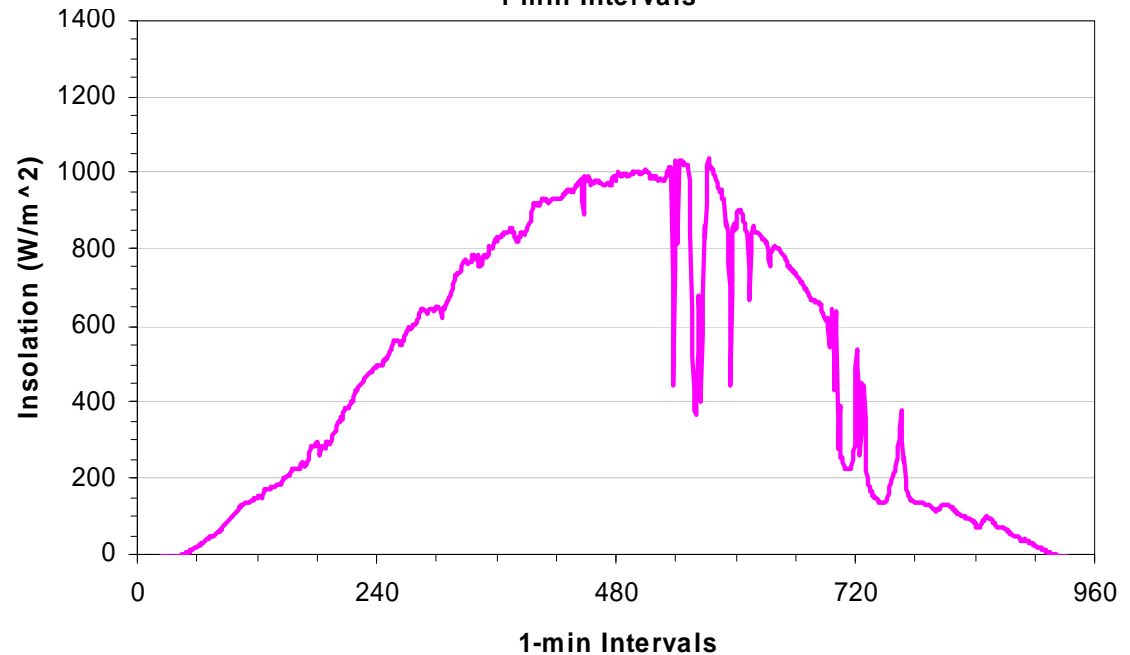
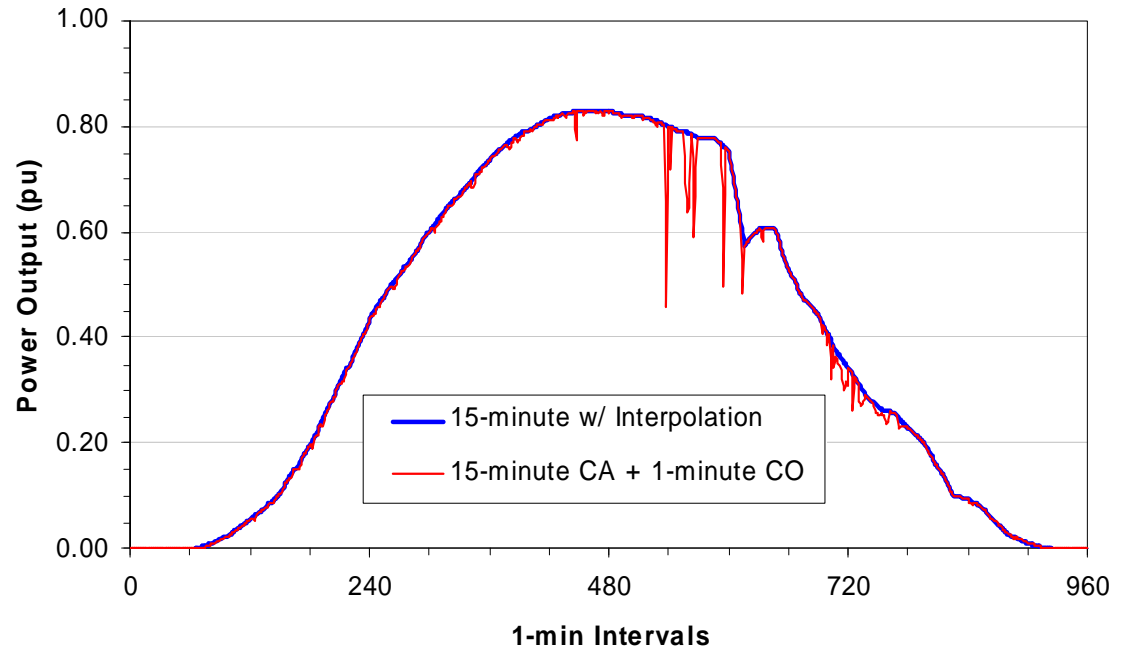
1 minute resolution; single site insolation ( $\text{w/m}^2$ ) in CO.  
Jan 2002



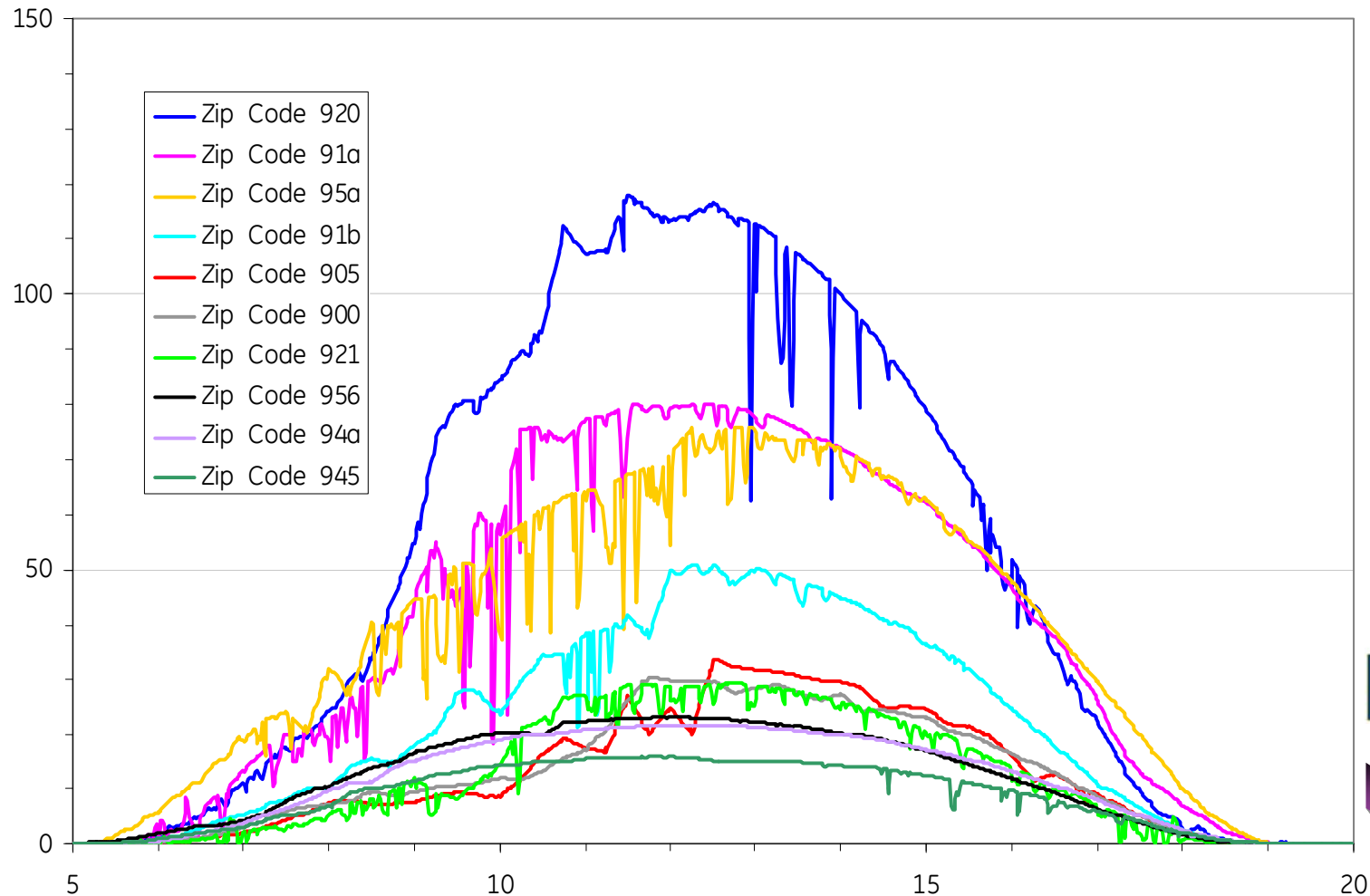
# PV fast variability overlay

Comparison of Original 15-minute Data and Final Profile with 1-minute Variability.

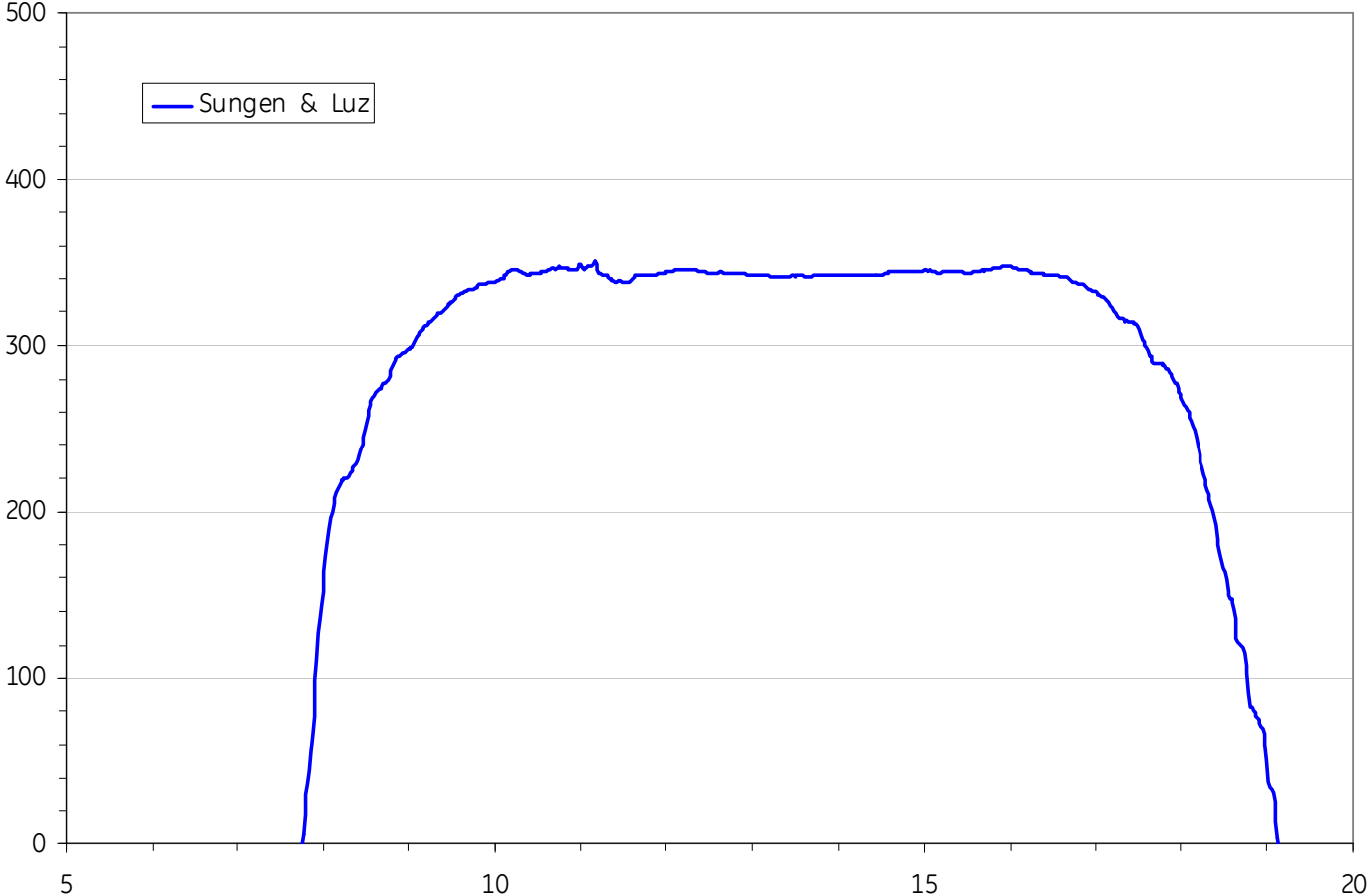
Irradiation Data used as Source of 1-minute Variability in Example.



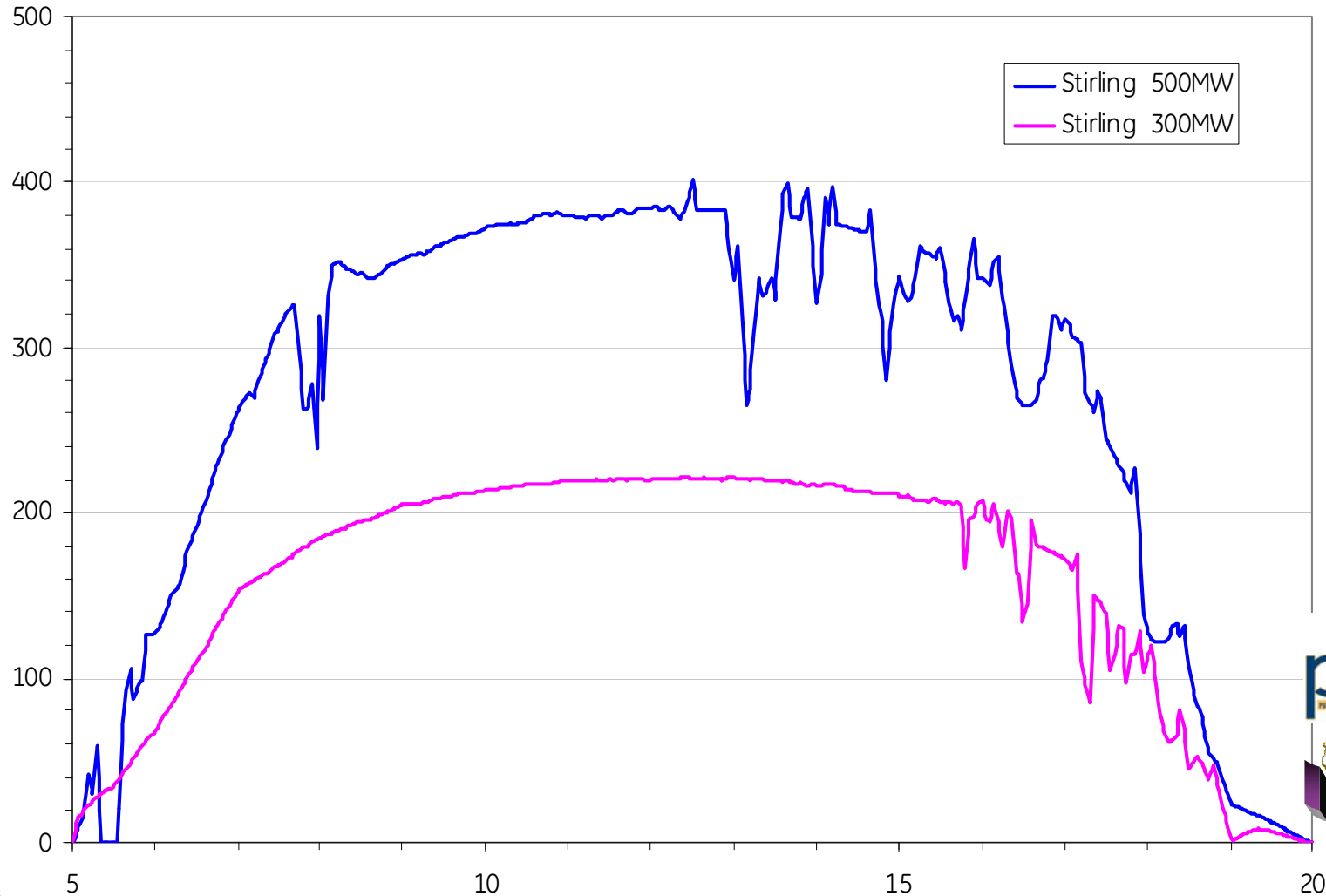
# Example PV Solar Zip Code Profile for a July Morning



# Example Concentrating Solar Project Profile for a May Day



# Example Stirling Solar Project Profile for a May Day

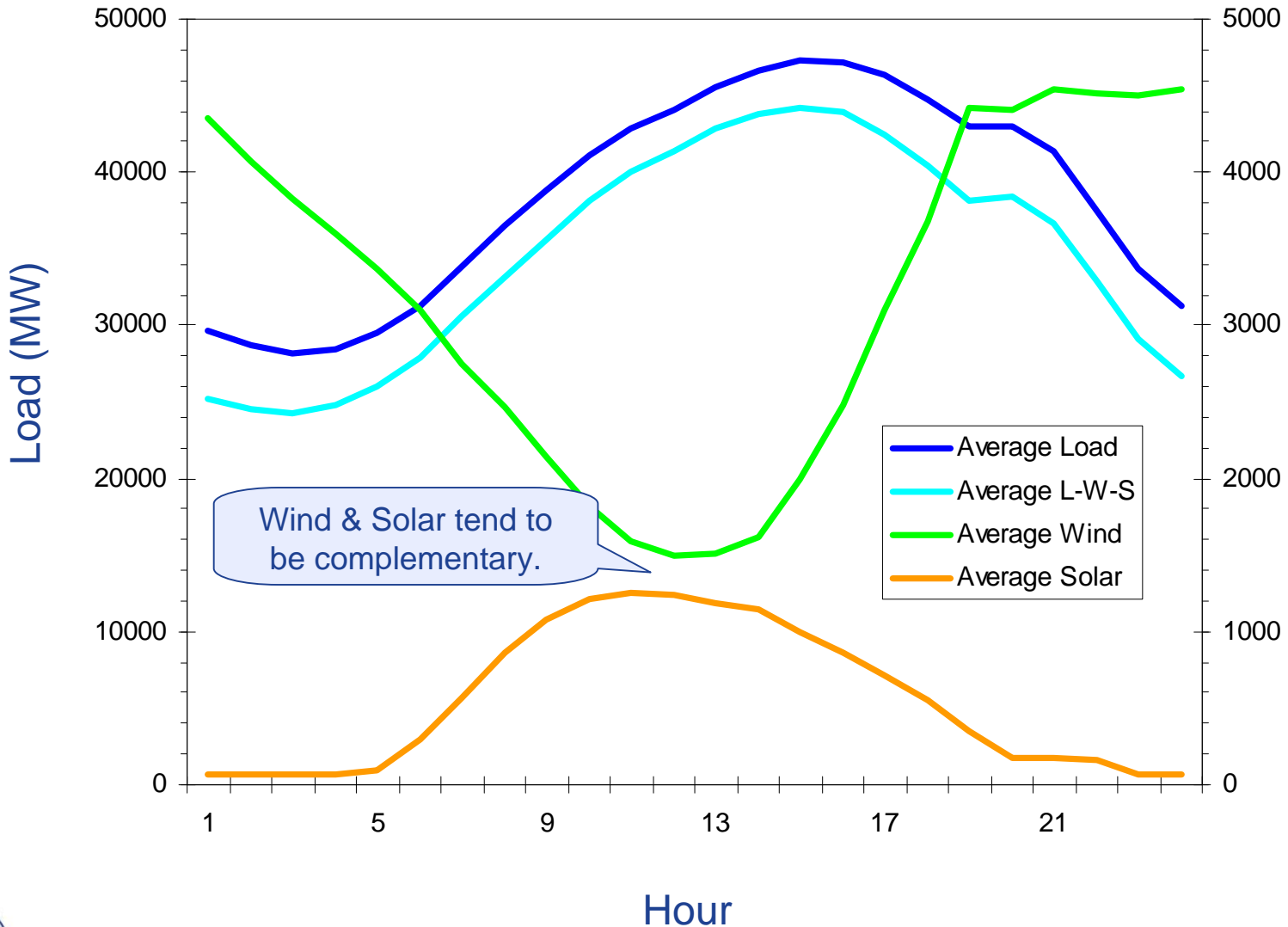


# Some of the things we observed and learned



imagination at work

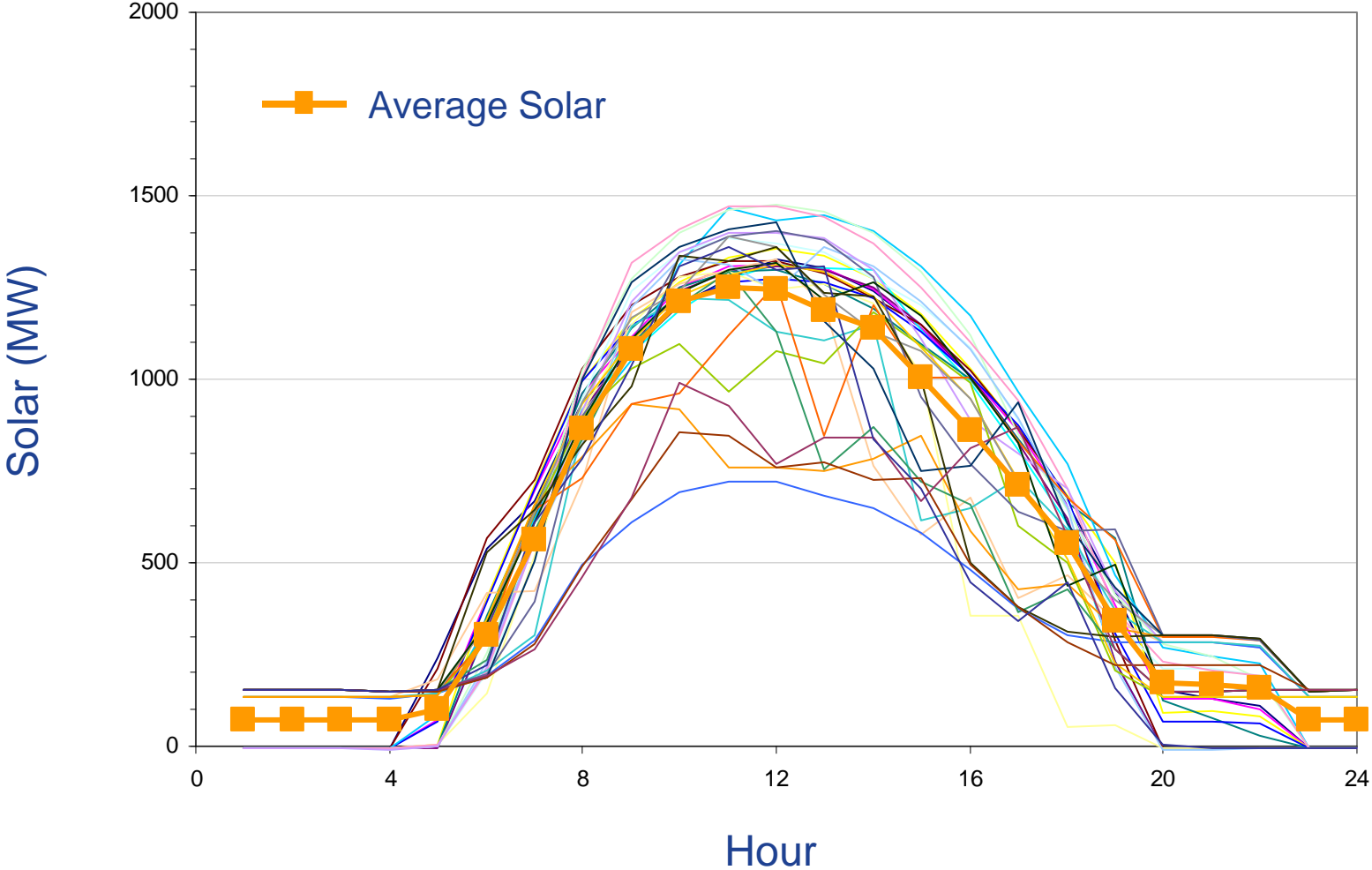
# Temporal Pattern: July 2003 Average Day



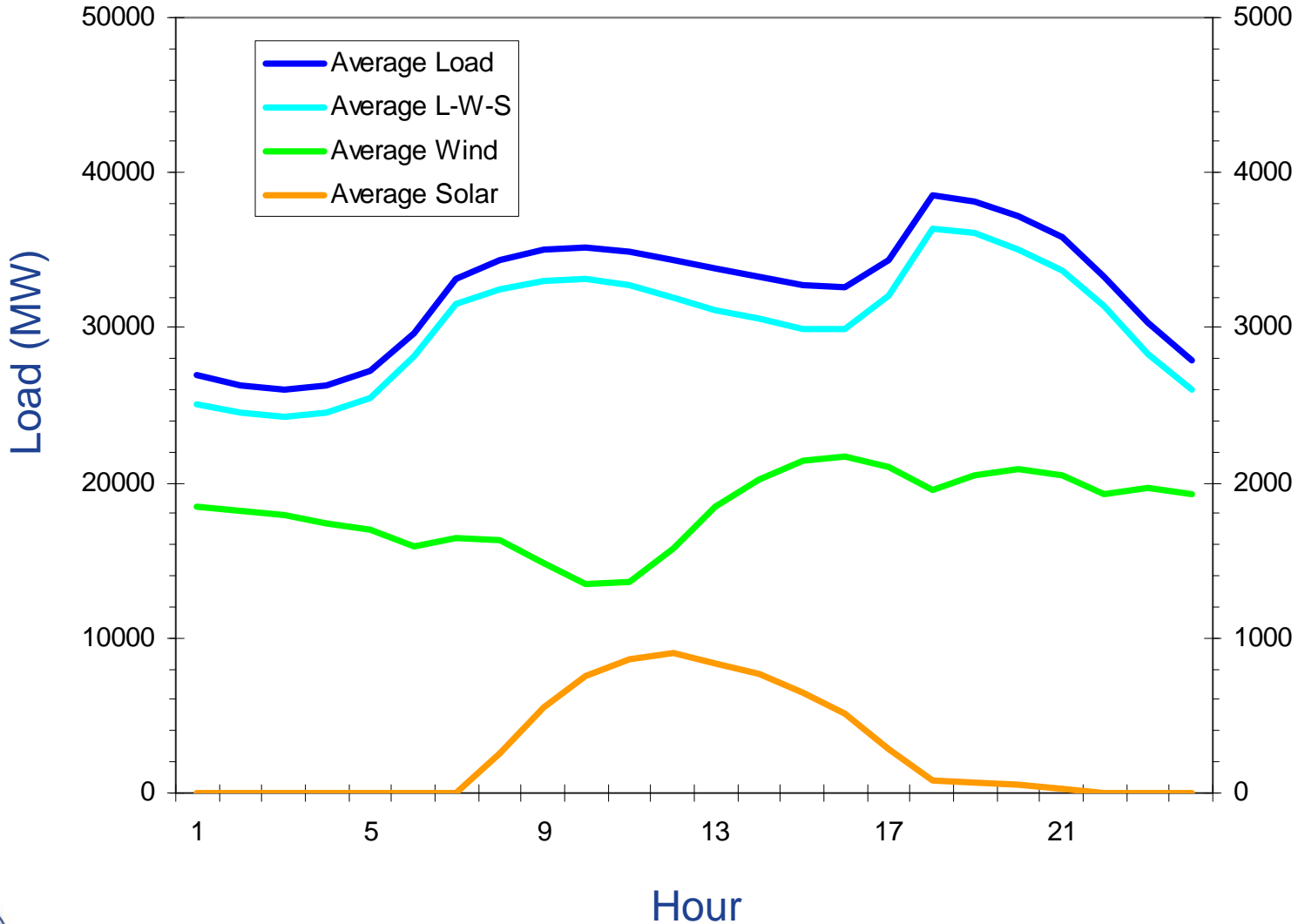
Wind & Solar (MW)



# Temporal Pattern: All Days of July 2003

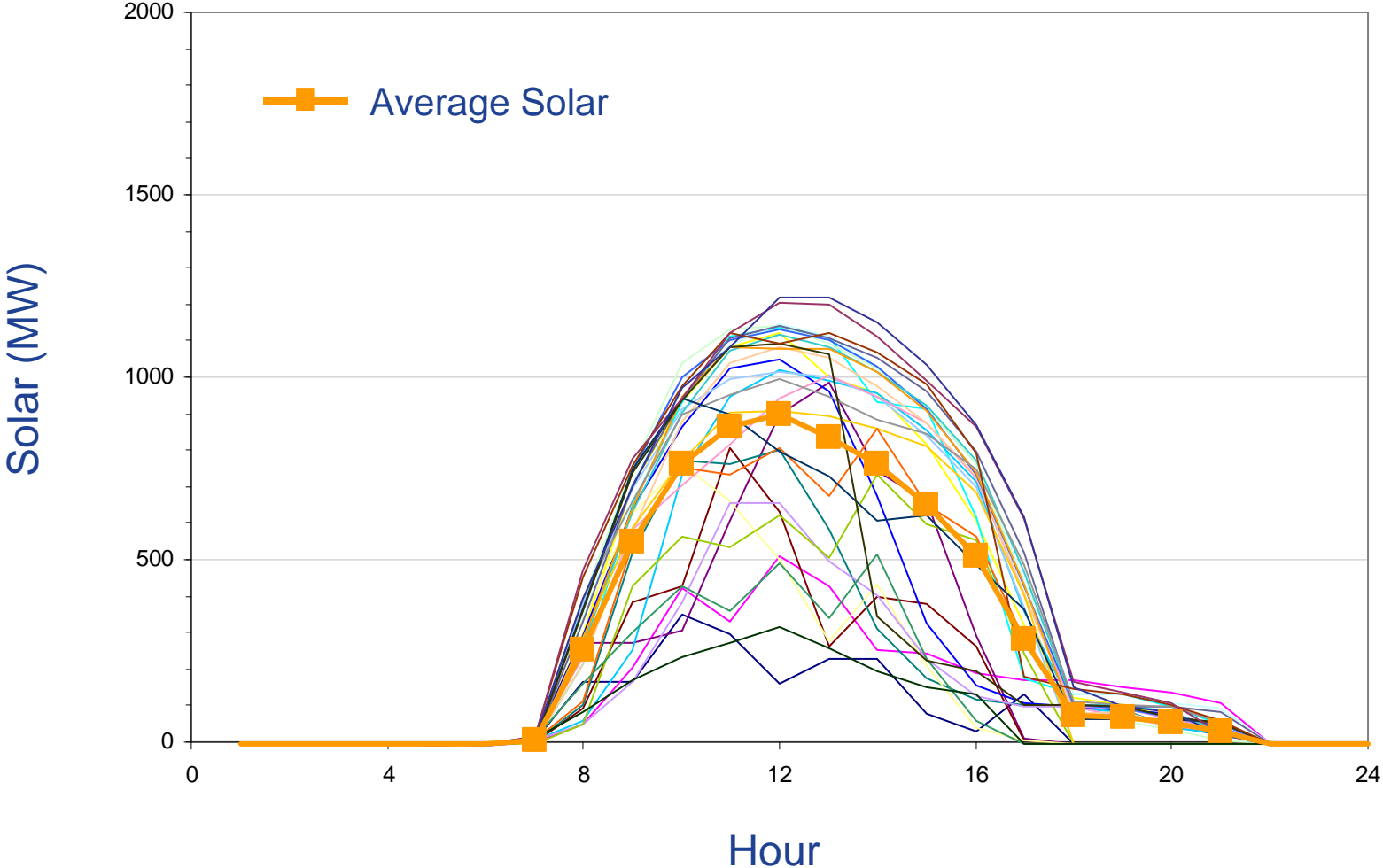


# Temporal Pattern: January 2002 Average Day



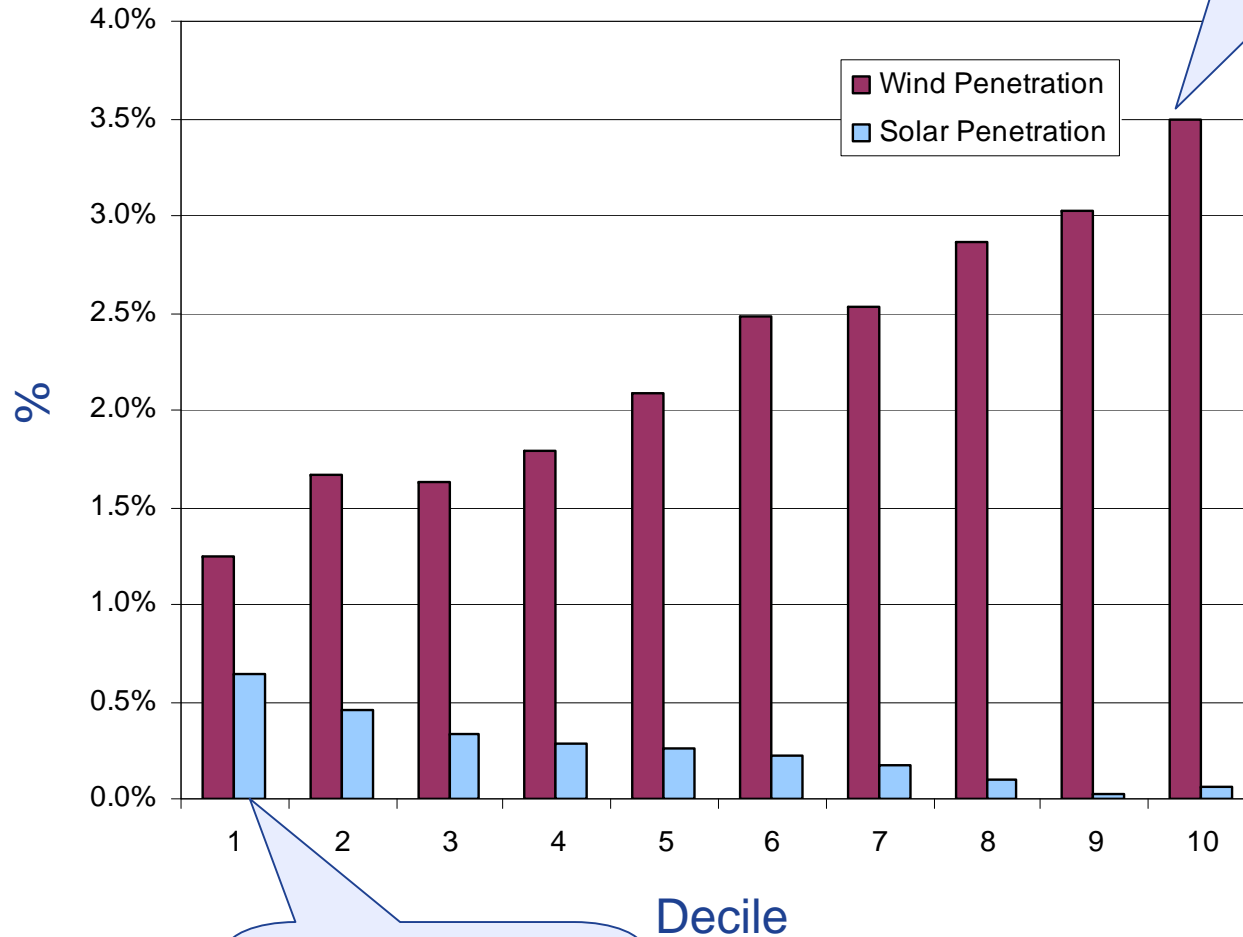
Wind & Solar (MW)

# Temporal Pattern: All Days of January 2003



# 2006 Hourly Wind & Solar Penetration

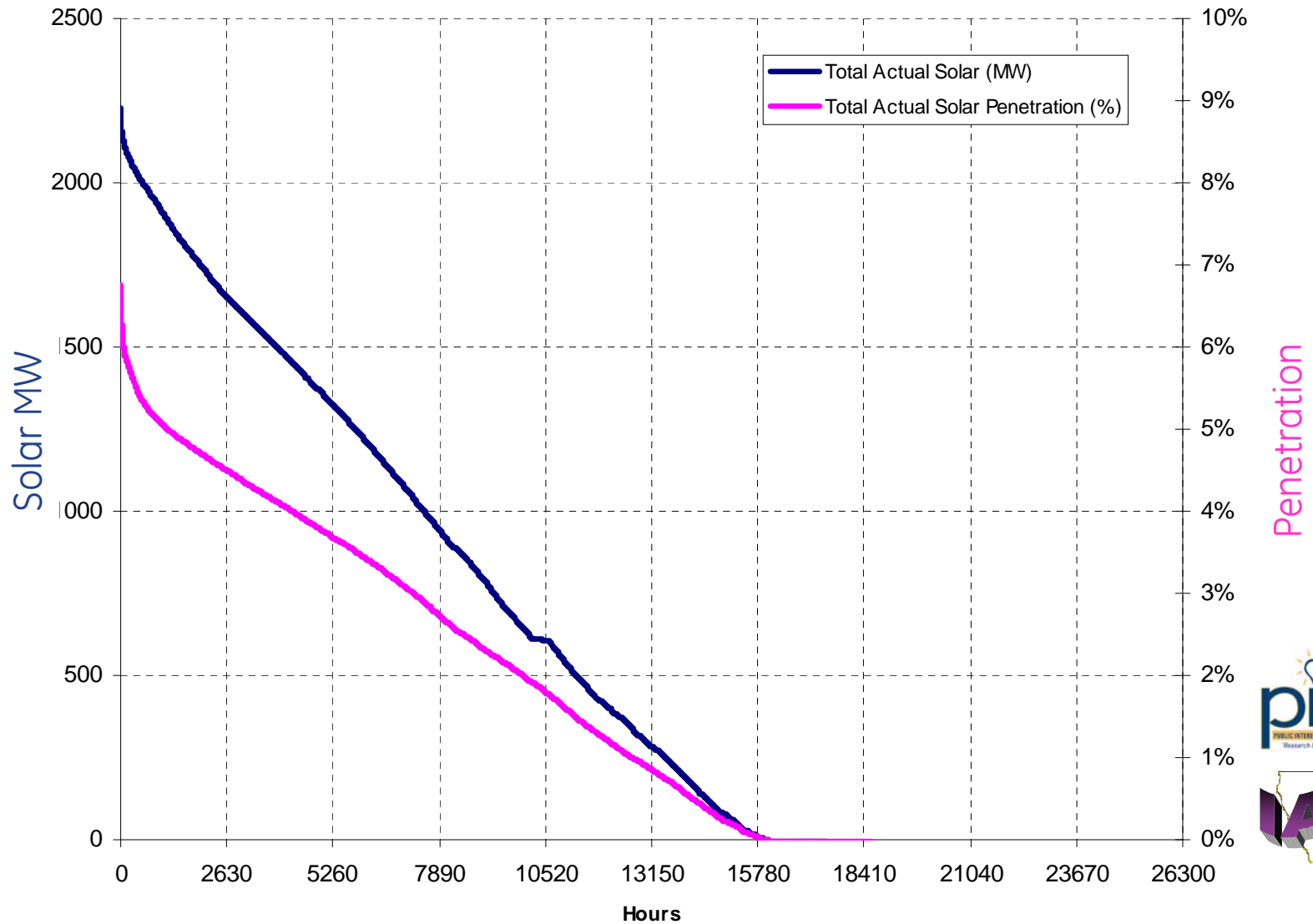
Wind Penetration = Average Wind MW / Average Load MW  
Solar Penetration = Average Solar MW / Average Load MW



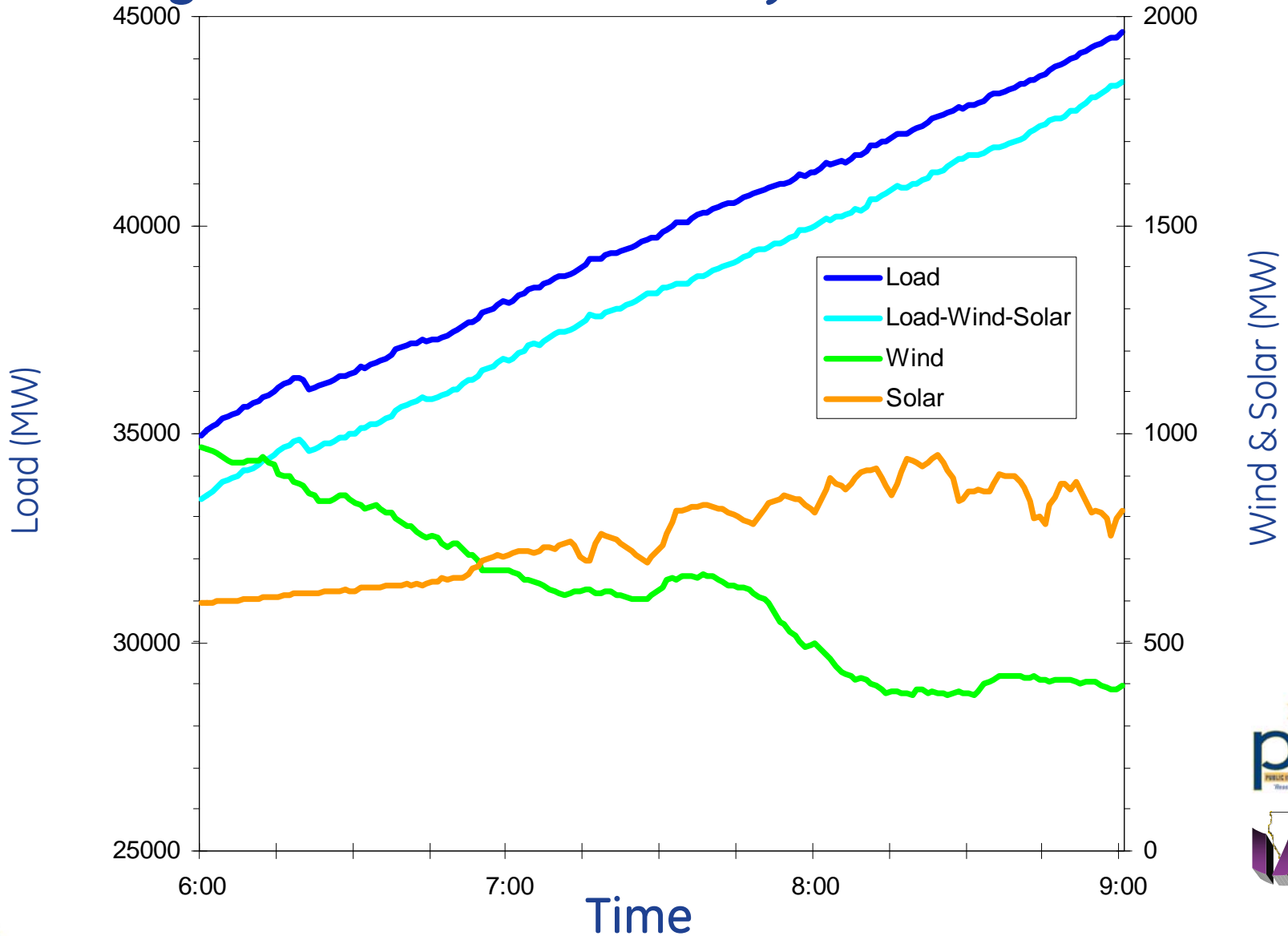
Wind penetration has inverse correlation with load.

Solar penetration has positive correlation with load.

# Solar Generation and Penetration Duration Curves – 2010X

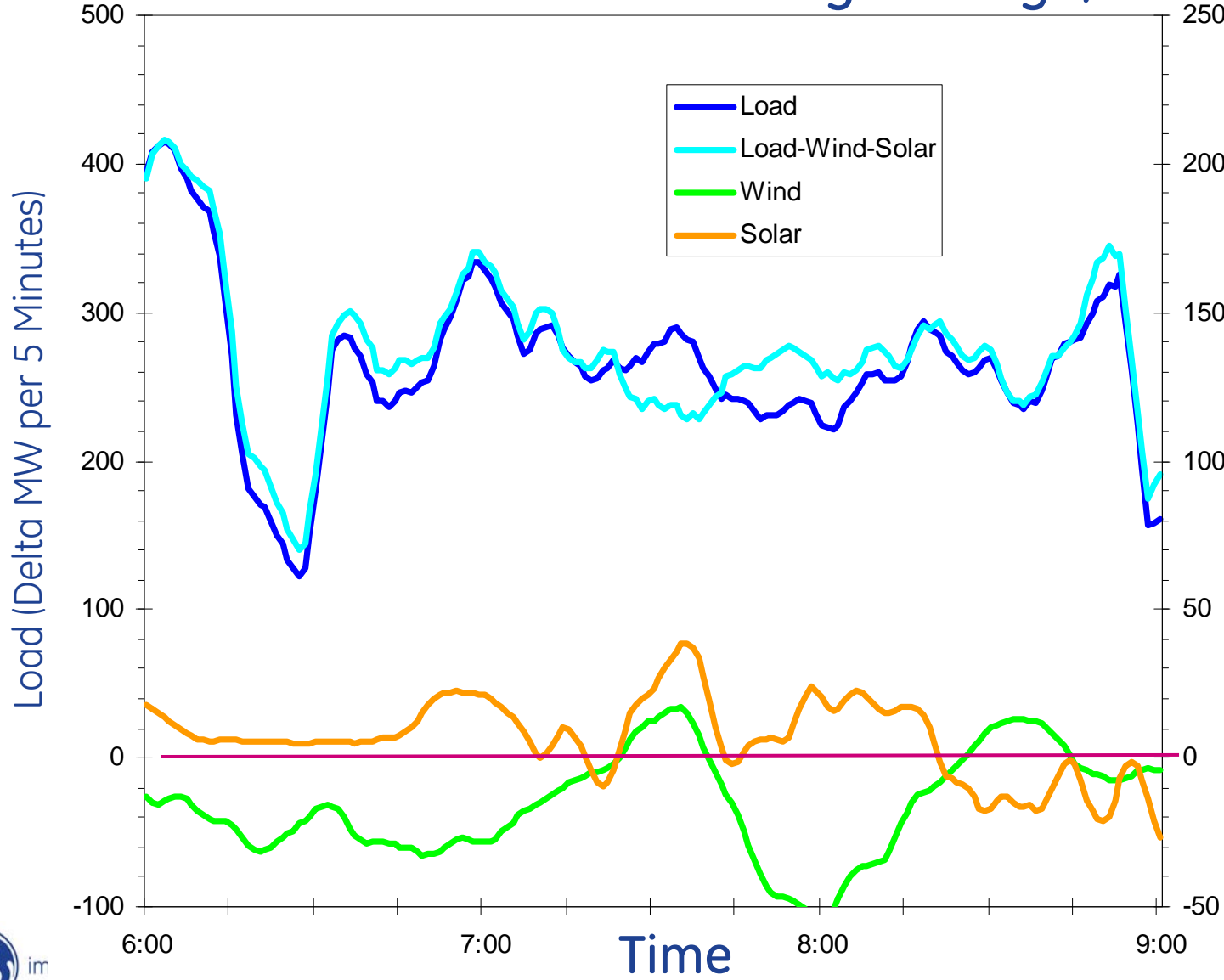


# Morning Load Rise Detail: July 21, 2003



# Load Following Requirement: July 21, 2003 (5 Minute Deltas on 15 Minute Rolling Average)

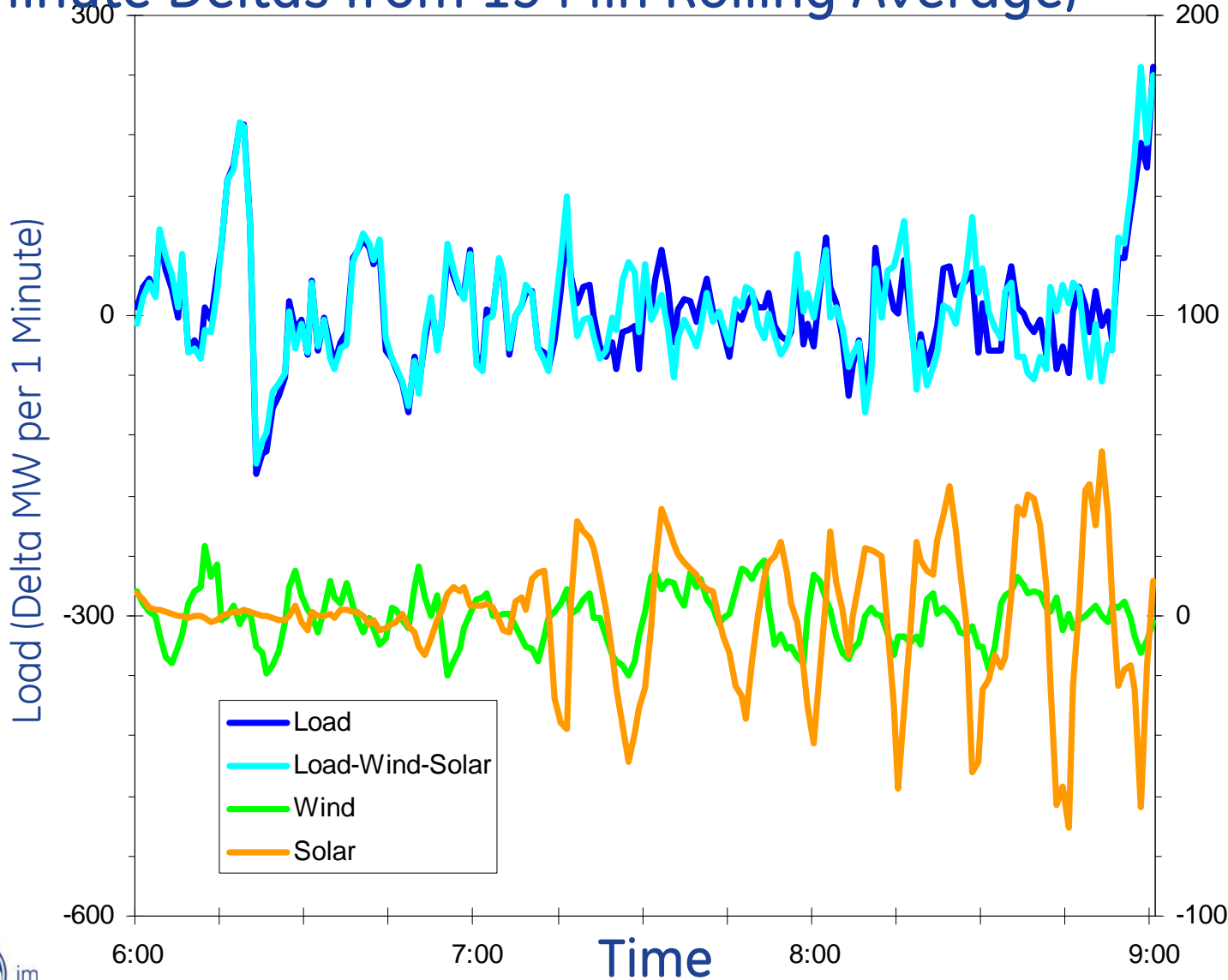
	Mean	$\sigma$
Load	265	54
L-W-S	275	52
Wind	-16	18
Solar	7	13



Wind & Solar (Delta MW per 5 Minutes)



# Regulation Requirement : July 21, 2003 (1 Minute Deltas from 15 Min Rolling Average)

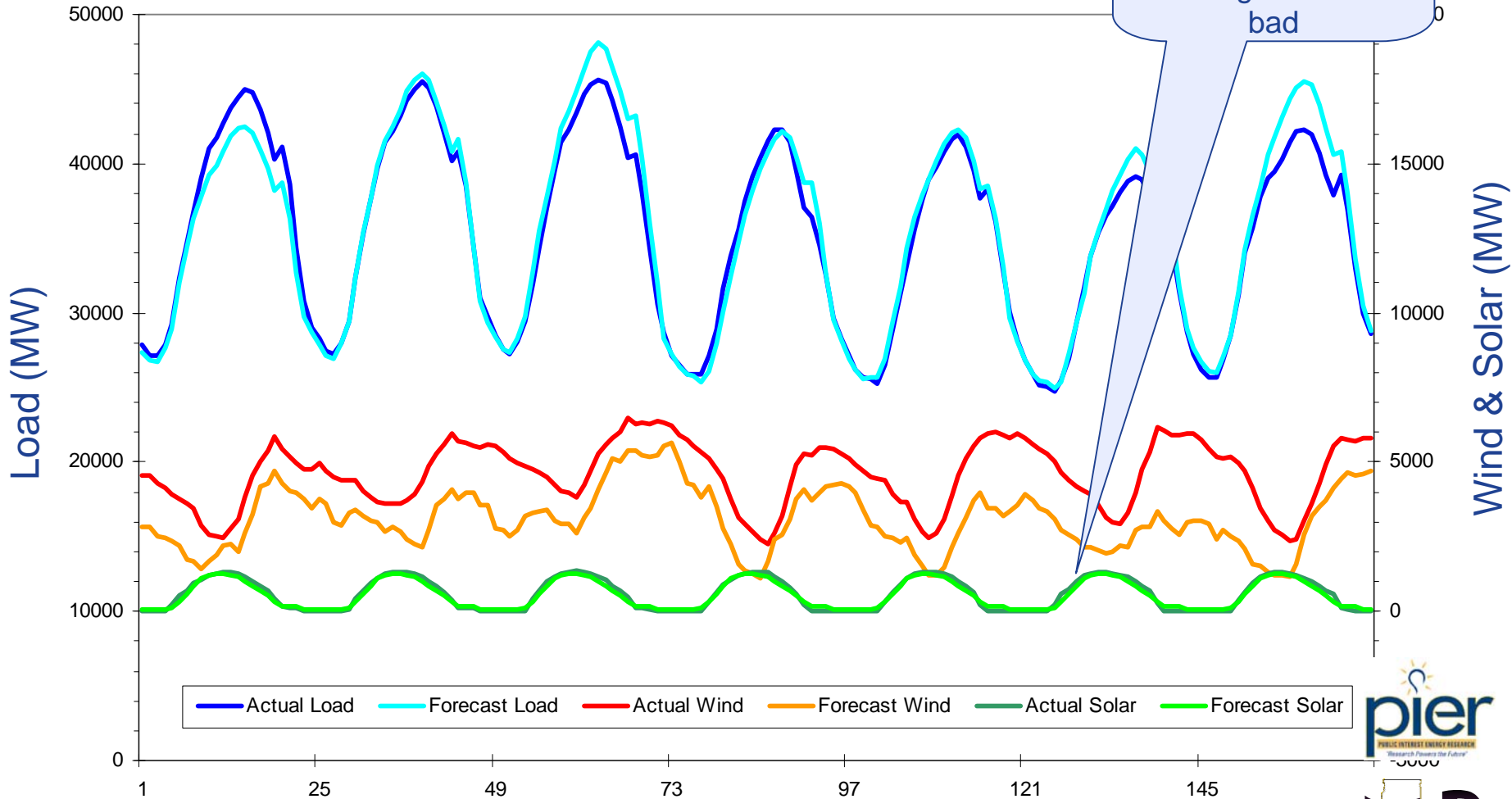


	Mean	$\sigma$
Load	6.5	56
L-W-S	6.8	61
Wind	-0.3	9
Solar	0.0	22

Load & Solar (Delta MW per 1 Minute)

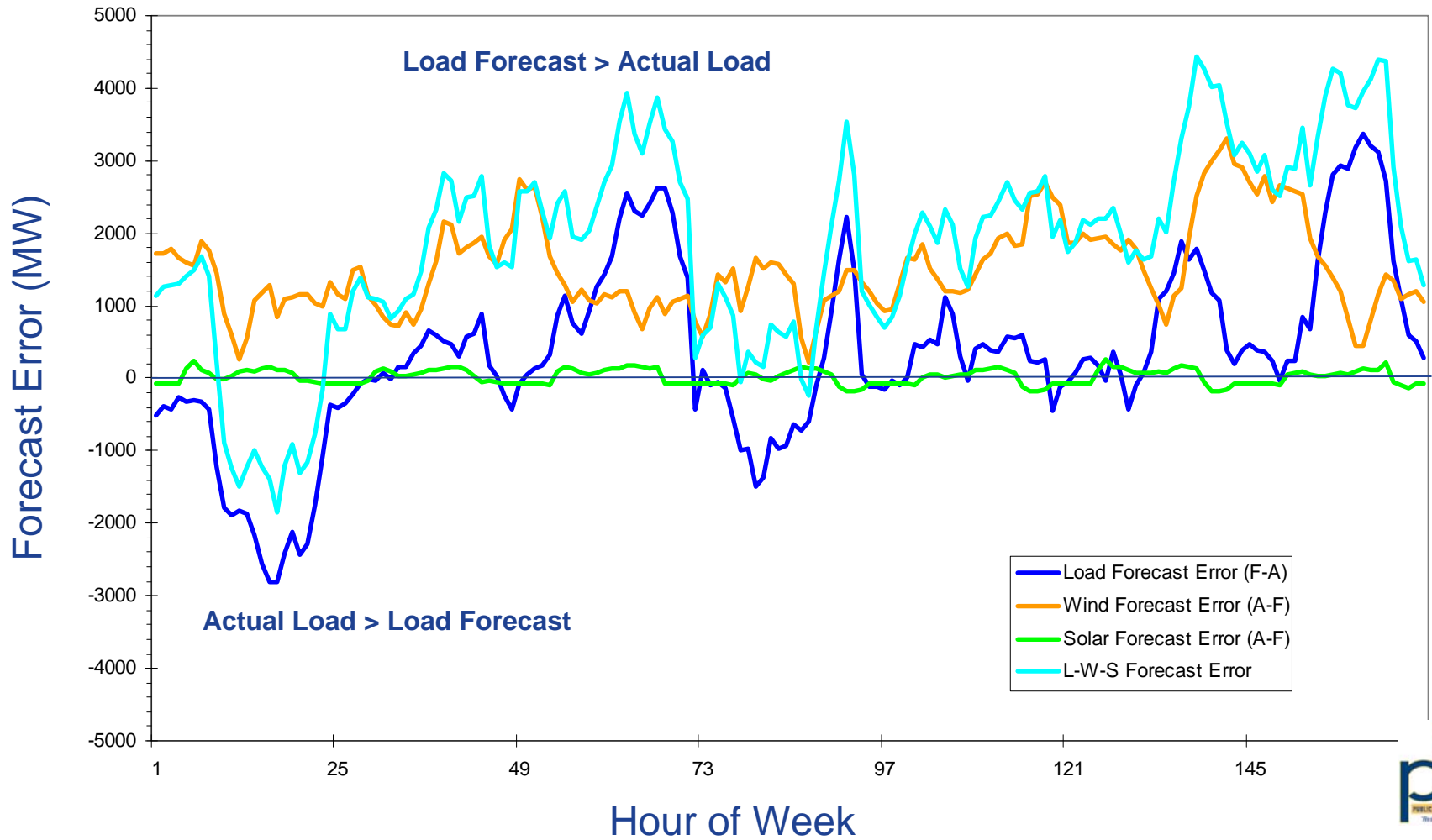


# 2010 Forecast vs. Actual, July Week



**daily average by month forecast seems OK for low penetrations, but won't work forever...**

# 2010 Forecast Errors, July Week



# 2006 Hourly Statistics: Example from One Decile

Each Bin (Load)	1
P_Load (Max)	48113.5
P_Load (Min)	36778.9
<b>Sigma (Delta L)</b>	12000
Delta L (Max)	4529.3
Delta L (Min)	-4334.4
Delta L (Avg)	225.2
Load (Avg.)	40162.9
<b>Load F-A (Avg)</b>	156.9
Load F-A (Sigma)	1317.8
Load F-A (Max)	5824.7
Load F-A (Min)	-6281.2

Standard Deviation,  $\sigma$  :  
 68.3% of Values within  $1\sigma$  of Mean  
 99.7% of Values within  $3\sigma$  of Mean

Forecast Error is F-A = Forecast minus Actual

Each Bin (L-W-S)	1
P_L-W-S (Max)	47736.2
P_L-W-S (Min)	35988.1
Sigma (Delta L-W-S)	1294.4
Delta L-W-S (Max)	4924.3
Delta L-W-S (Min)	-4294.7
Delta L-W-S (Avg)	241.6
Load_L-W-S (Avg.)	39397.6
Wind (Avg.)	492.0
Solar (Avg.)	252.9
<b>Wind Penetration</b>	0.012
Solar Penetration	0.006
L-W-S F-A (Avg)	231.5
L-W-S F-A (Sigma)	1339.4
L-W-S F-A (Max)	6402.1
L-W-S F-A (Min)	-6442.8
Wind F-A (Avg)	-78.7
Wind F-A (Sigma)	196.5
Wind F-A (Max)	536.5
Wind F-A (Min)	-1104.4
Solar F-A (Avg)	-14.1
Solar F-A (Sigma)	60.0
Solar F-A (Max)	305.8
Solar F-A (Min)	-174.8

Wind Penetration = Average Wind/ Average Load  
 (The average is over all hours in a decile)

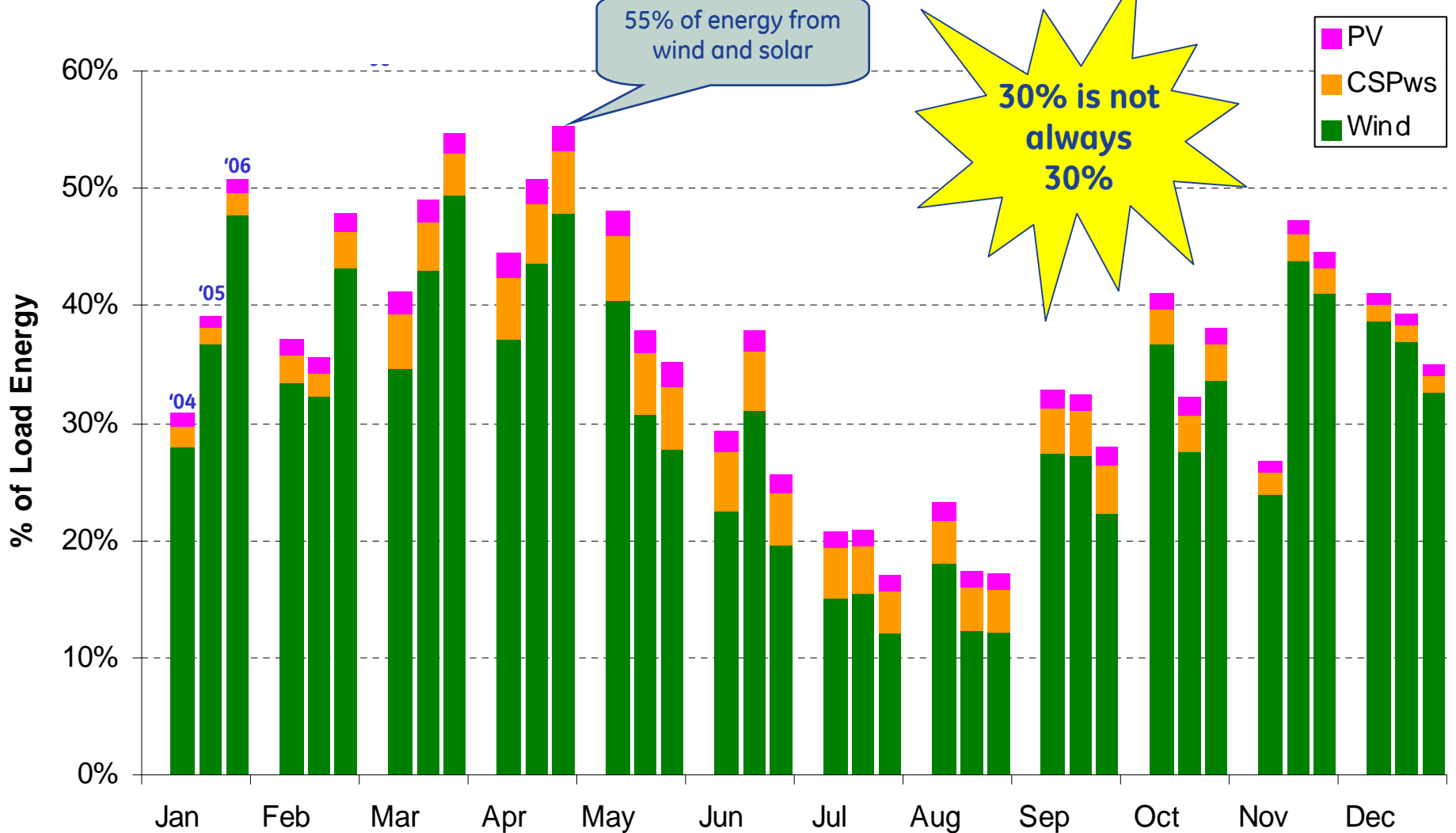
# 2006 Hourly Statistics

Each Bin (Load)	1	2	3	4	5	6	7	8	9	10	All year
P_Load (Max)	48113.5	36776.3	33502.6	31858.7	30654.6	29429.7	27776.0	26093.2	24615.4	23073.6	48113.5
P_Load (Min)	36778.9	33504.8	31859.9	30655.7	29429.8	27776.7	26093.2	24616.4	23073.8	19443.1	19443.1
Sigma (Delta L)	1253.5	1555.3	1470.9	1363.1	1555.2	1816.4	1663.3	1435.9	1075.3	668.9	1436.3
Delta L (Max)	4529.3	4854.2	4775.9	4374.8	6123.0	6070.9	3823.8	3245.1	2862.1	1706.5	6123.0
Delta L (Min)	-4334.4	-4445.8	-4382.4	-4371.6	-5122.3	-4017.0	-3535.5	-3199.9	-2868.1	-2567.1	-5122.3
Delta L (Avg)	225.2	317.3	209.3	129.9	116.6	-19.4	-178.1	-261.5	-309.3	-228.6	0.2
Load (Avg.)	40162.9	34994.6	32598.0	31240.2	30062.7	28656.8	26910.6	25352.7	23839.9	22058.5	29587.2
Load F-A (Avg)	156.9	313.4	140.8	178.4	147.4	93.5	35.6	-1.9	-24.1	59.2	109.9
Load F-A (Sigma)	1317.8	1023.1	745.7	704.3	639.7	672.0	622.7	557.9	589.4	520.2	781.1
Load F-A (Max)	5824.7	6533.2	4761.5	4813.4	3790.9	3585.2	4172.8	2531.2	3840.6	2208.4	6533.2
Load F-A (Min)	-6281.2	-3896.0	-3063.2	-3400.1	-3422.8	-3588.7	-2759.4	-2777.6	-1940.3	-1674.5	-6281.2

Each Bin (L-W-S)	1	2	3	4	5	6	7	8	9	10	All year
P_L-W-S (Max)	47736.2	35985.0	32800.0	31197.2	29993.8	28722.4	27068.3	25376.5	23849.1	22406.8	47736.2
P_L-W-S (Min)	35988.1	32800.7	31197.3	29994.3	28722.4	27068.7	25376.6	23850.7	22407.2	18567.2	18567.2
Sigma (Delta L-W-S)	1294.4	1546.6	1456.4	1398.8	1587.0	1828.5	1699.9	1446.4	1048.9	698.9	1451.0
Delta L-W-S (Max)	4924.3	4728.7	4857.2	4580.7	6090.8	5981.0	3946.6	3240.9	2914.2	2447.8	6090.8
Delta L-W-S (Min)	-4294.7	-4533.4	-4450.4	-4592.1	-5155.4	-4173.7	-3956.1	-3451.9	-2814.0	-2613.0	-5155.4
Delta L-W-S (Avg)	241.6	320.0	183.1	149.5	128.5	-52.7	-146.0	-265.4	-307.1	-250.3	0.1
Load_L-W-S (Avg.)	39397.6	34243.5	31937.5	30590.7	29386.4	27927.0	26188.3	24619.5	23135.7	21373.8	28879.5
Wind (Avg.)	492.0	571.3	520.8	549.3	611.3	692.6	662.6	704.5	698.6	745.7	624.9
Solar (Avg.)	252.9	156.4	104.8	88.2	77.1	61.1	44.2	24.5	5.6	13.3	82.8
Wind Penetration	0.012	0.017	0.016	0.018	0.021	0.025	0.025	0.029	0.030	0.035	0.022
Solar Penetration	0.006	0.005	0.003	0.003	0.003	0.002	0.002	0.001	0.000	0.001	0.003
L-W-S F-A (Avg)	231.5	447.6	247.0	300.8	275.9	261.4	201.6	184.5	141.6	269.0	256.1
L-W-S F-A (Sigma)	1339.4	1059.7	803.2	749.1	713.8	738.8	684.4	660.6	635.9	570.5	829.0
L-W-S F-A (Max)	6402.1	6554.7	4462.6	4518.7	3958.8	3396.6	4686.7	4973.7	3978.8	2321.2	6554.7
L-W-S F-A (Min)	-6442.8	-3954.0	-3035.8	-3205.0	-3343.1	-3555.5	-2667.8	-1773.2	-1742.9	-1700.6	-6442.8
Wind F-A (Avg)	-78.7	-127.9	-111.5	-125.8	-133.9	-169.9	-159.1	-176.8	-171.1	-202.7	-145.7
Wind F-A (Sigma)	196.5	227.3	229.6	240.0	246.1	254.3	260.0	261.4	273.4	284.7	250.9
Wind F-A (Max)	536.5	629.8	645.6	706.9	617.9	697.9	719.9	701.2	611.9	712.5	719.9
Wind F-A (Min)	-1104.4	-1134.2	-992.4	-1083.1	-1058.8	-1078.5	-1072.7	-1079.3	-1135.5	-1136.6	-1136.6
Solar F-A (Avg)	-14.1	-4.1	-1.1	2.6	5.5	4.6	4.1	0.8	0.4	-3.0	-0.4
Solar F-A (Sigma)	60.0	60.5	52.9	55.0	53.9	51.4	48.6	39.2	25.0	37.5	49.8
Solar F-A (Max)	305.8	285.6	205.1	237.1	278.2	225.2	210.1	222.9	174.9	130.9	305.8
Solar F-A (Min)	-174.8	-245.8	-240.7	-658.7	-717.0	-724.4	-656.1	-670.8	-342.7	-547.9	-724.4

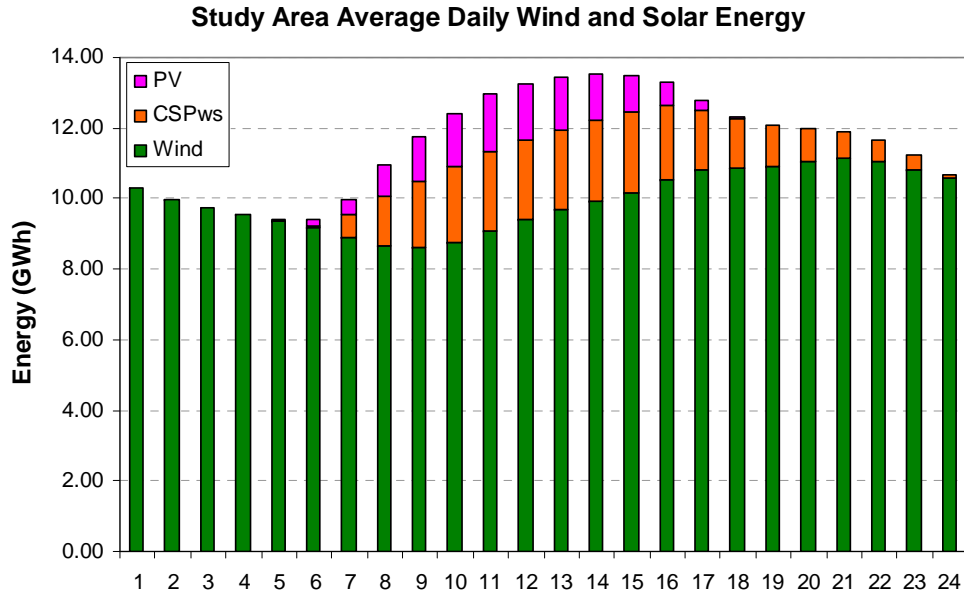
# Footprint % Monthly Energy from Wind and Solar for 2004 – 2006 (30% Wind Energy - In Area Scenario\*)



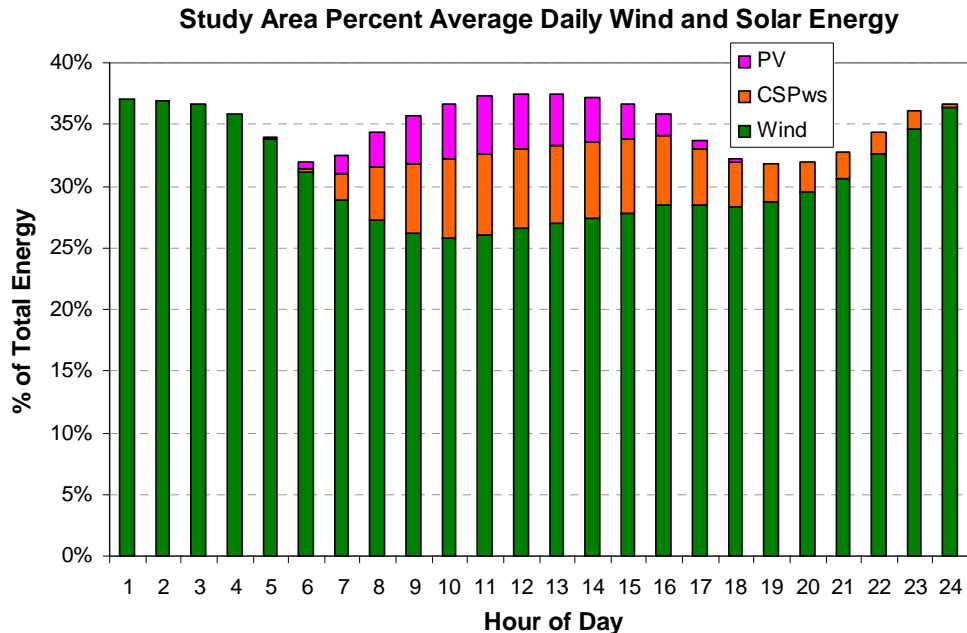
**2006 % monthly energy ranges from 18% (Jul) to 55% (Apr) in study footprint**

Source: NREL Western Wind & Solar Integration Study

# Average Hourly Energy from Wind and Solar Over Entire Year (30% In Area Scenario)

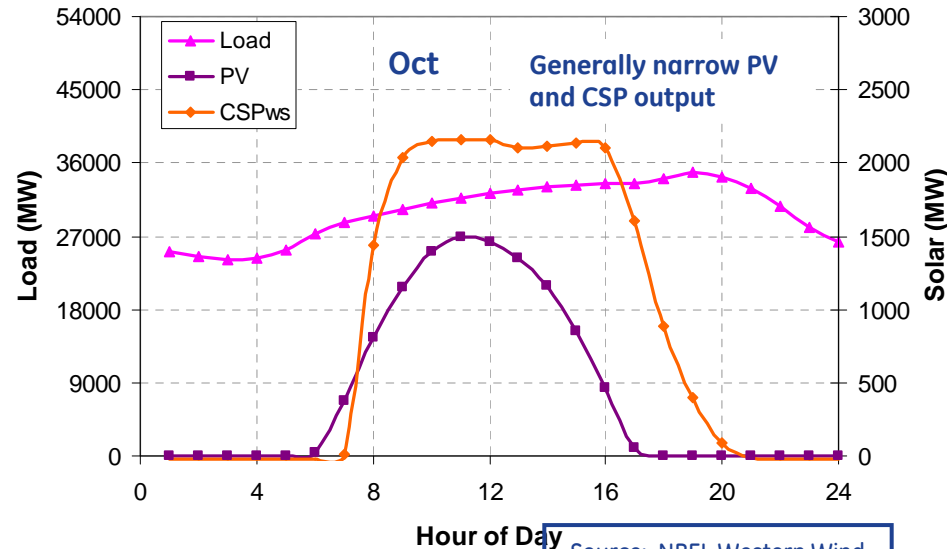
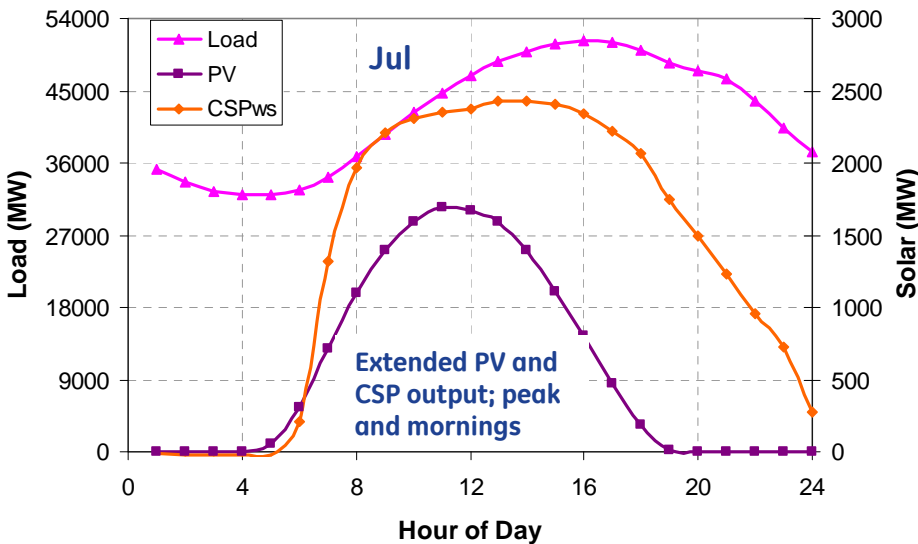
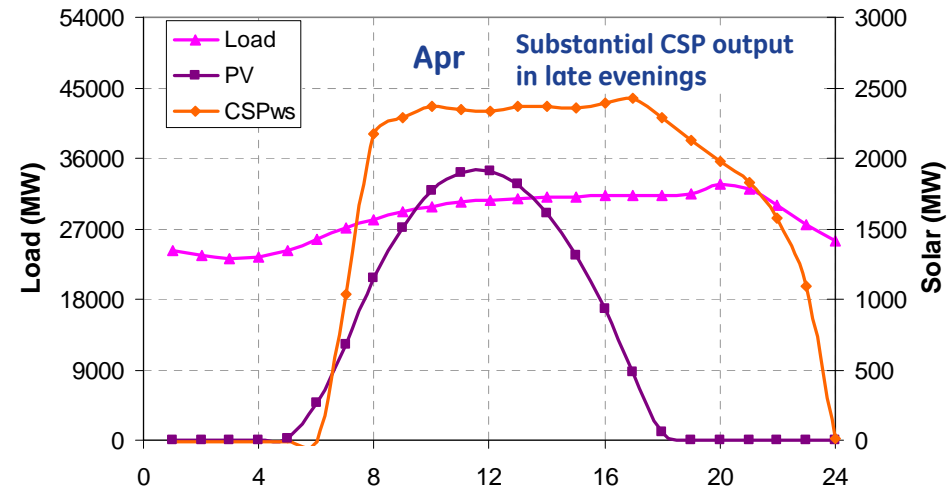
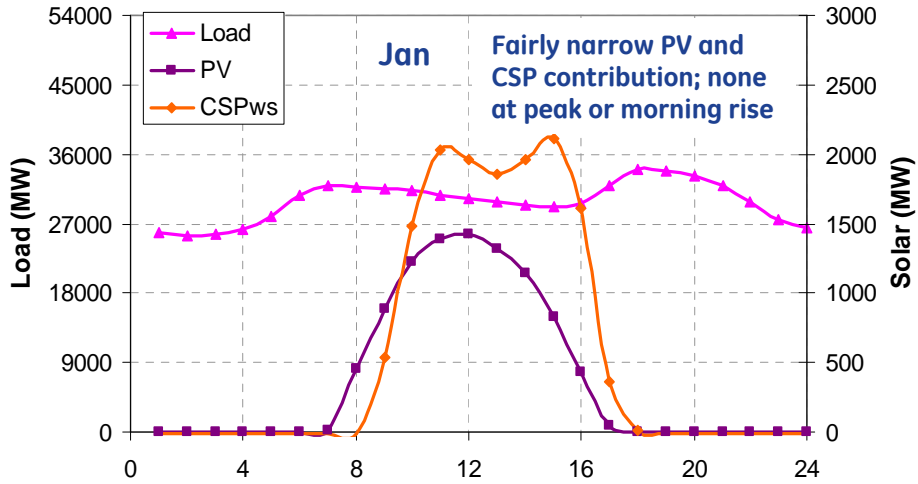


Solar tends to complement wind variation over the day



Source: NREL Western Wind & Solar Integration Study

# Study Area CSPws and PV Average Daily Profiles By Seasonal Month (30% In Area Scenario)

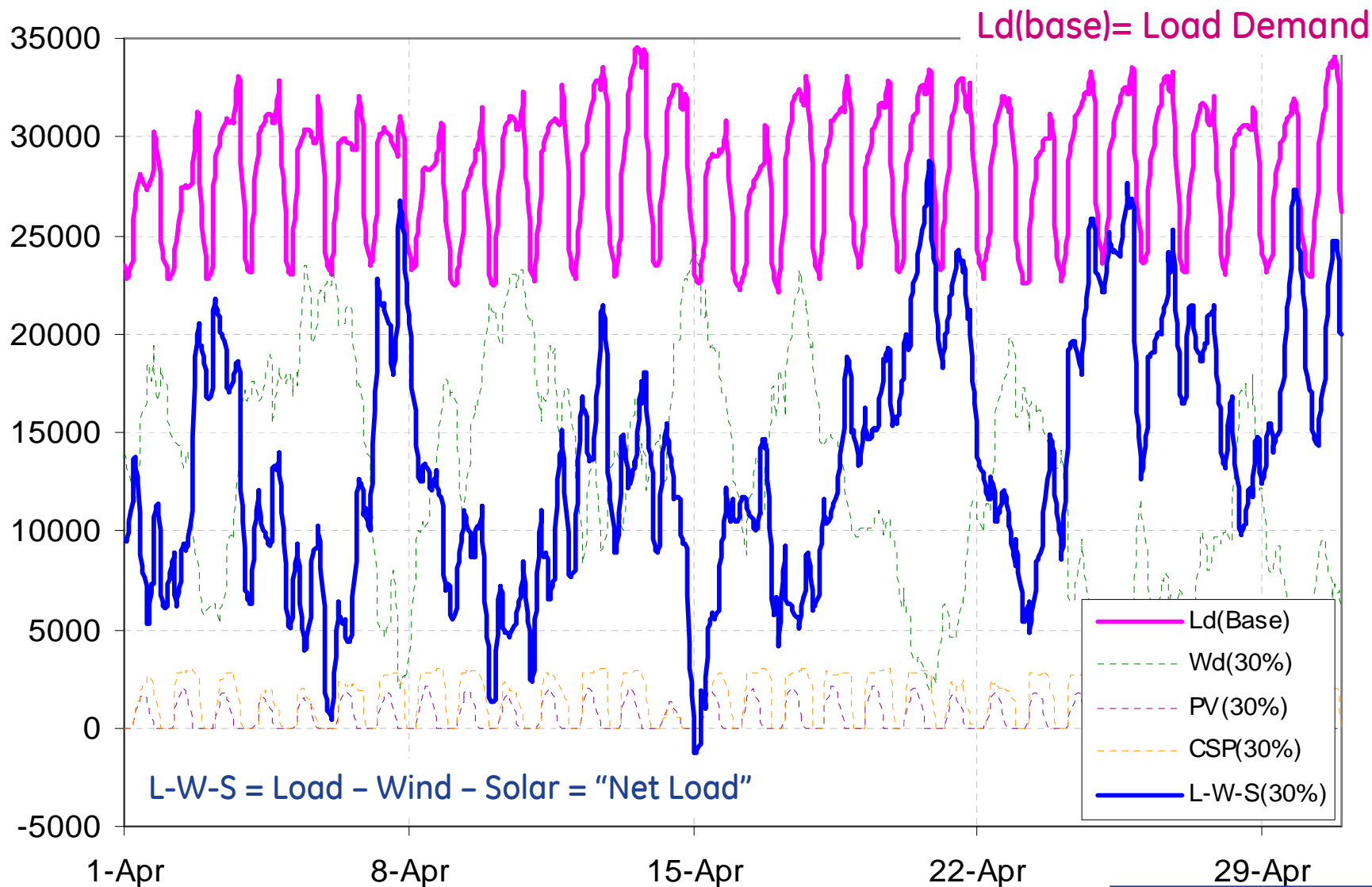


# Operations...



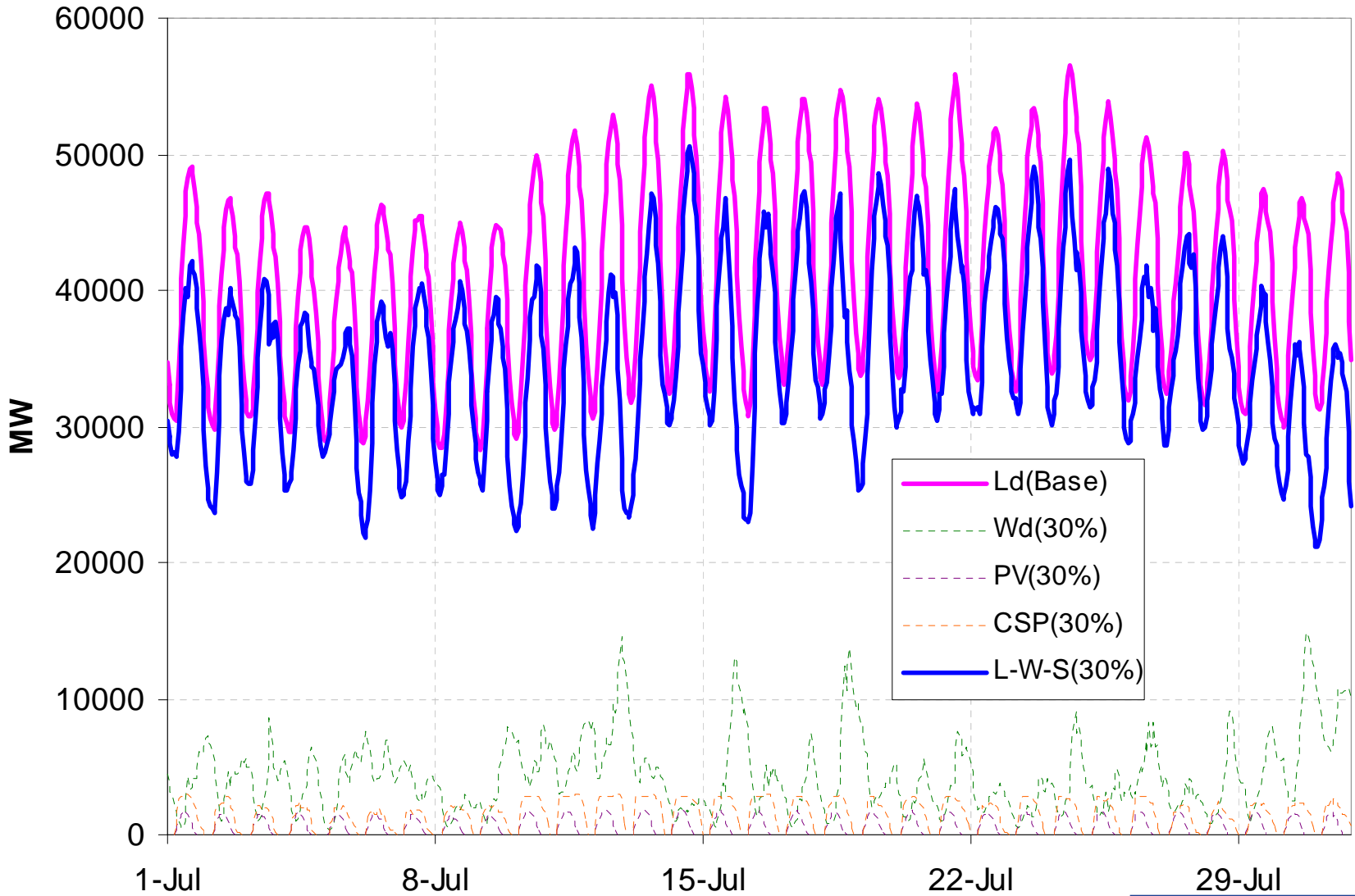
# Study Footprint Total Load, Wind and Solar Variation Over Month of April

(30% Wind Energy in Footprint)

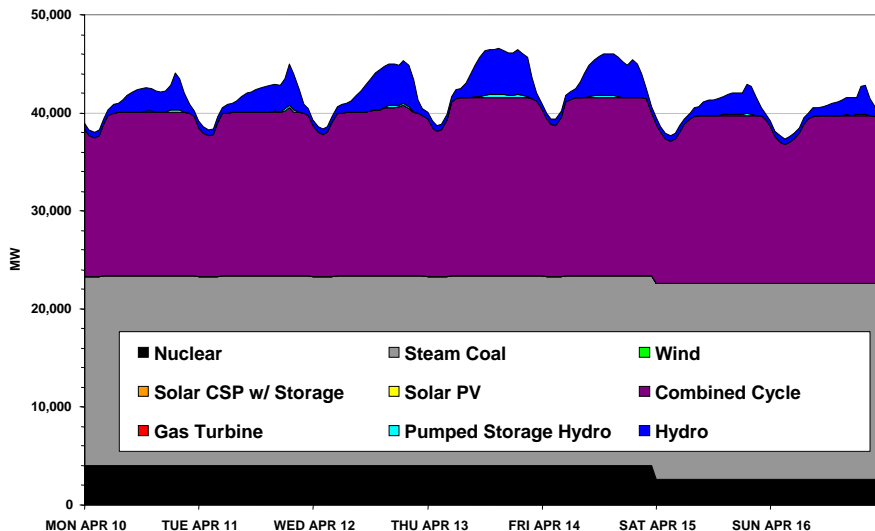


# Study Footprint Total Load, Wind and Solar Variation Over Month of July

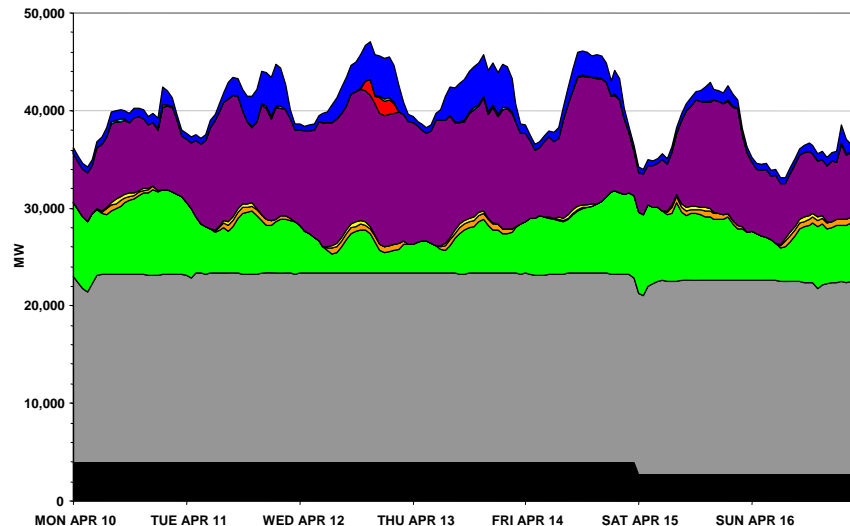
(30% Wind Energy in Footprint)



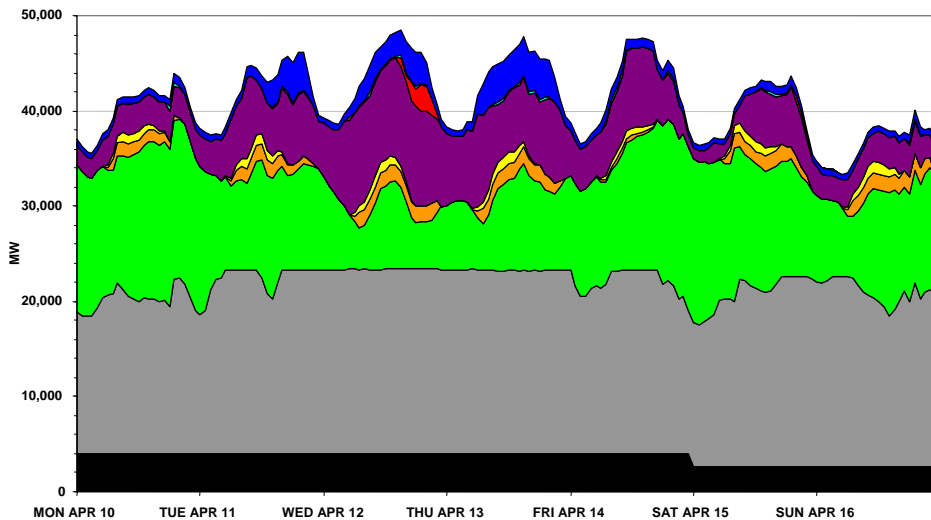
Study Area Dispatch - Week of April 10th – No Renewables



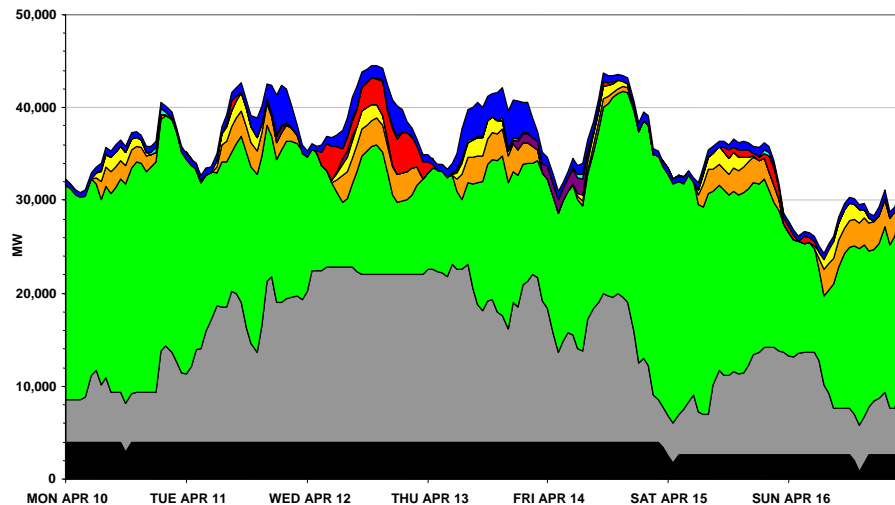
Study Area Dispatch - Week of April 10th - 10% Renewables



Study Area Dispatch - Week of April 10th - 20% Renewables



Study Area Dispatch - Week of April 10th - 30% Renewables



# Data Requirements (what we might need in future)

One year (or more, depending on study) of 10-minute time synchronized wind and solar power data for each of the sites. 10-minute resolution:

- has been used effectively in recent studies
- (roughly) the lower limit for resolution using meso-scale analytical techniques

One year (or more) of hourly, day-ahead solar power forecast data

Higher resolution time synchronized wind and solar power data for selected windows (e.g. 1-3 hours) of interest

- Selected windows typically screened from longer-term data and system considerations
- Resolution of 1-2 second sampling needed for small or granular systems [experience jury is out on what “small or granular means” – needs thought and depends on the focus of the study]
- Resolution of 1-2 minute needed for larger system analysis

Solar plant size, type, substation location for each site

Each data must be time synchronized for the future study year(s)

- **Maintain solar/wind/load time and space relationship.**



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