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High Fidelity Solar Forecasting Demonstration for Grid Integration

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Project Sponsors and Partners

CPUC

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Costshare:

Partners:

Project Goals

- Reduce solar integration costs through more accurate solar forecasting
- Demonstrate distributed generation and system level solar forecasting
- Demonstrate forecast applications to net load forecasting and feeder control

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Solar Resource Assessment and Forecasting

Task Overview

- Task 2: Demonstrate forecast performance during meteorological conditions with greatest impact on SDG&E operations and recommend monitoring improvements
- Task 3: Day-Ahead Solar forecast models for marine layer clouds
- Task 4: Localized Solar Forecasting and Distribution Feeder Modeling
- Task 5: Forecast Integration with Utility Models for Resource Adequacy

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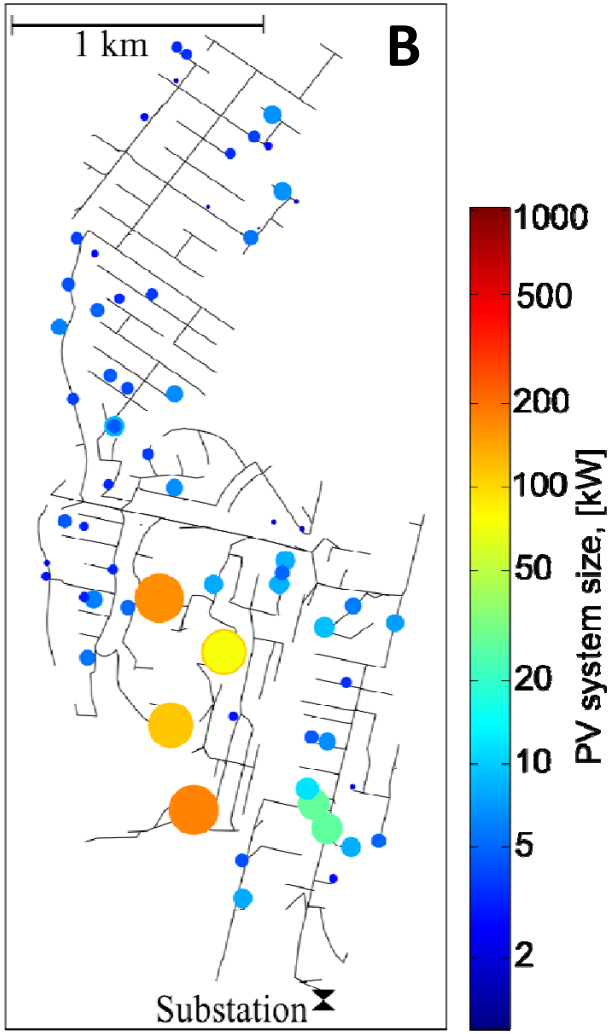
Agenda Overview

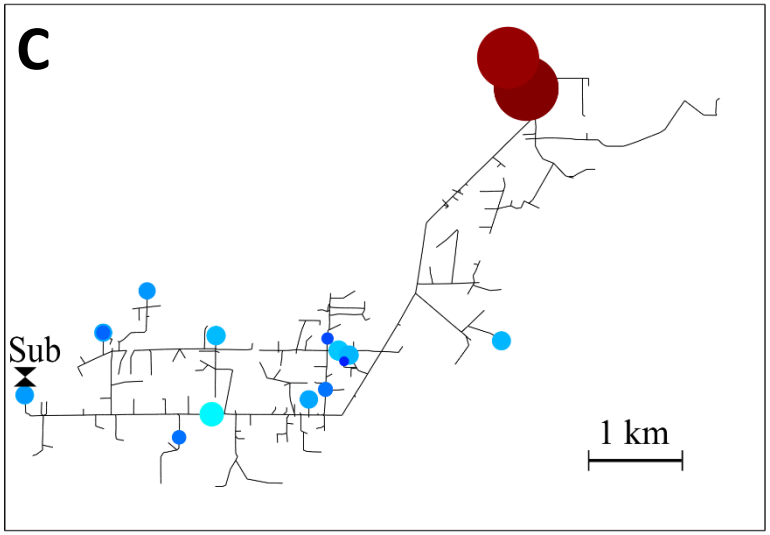
- High PV penetration impacts on the distribution system
  - Five distribution feeders
  - Historical large ramp rates
  - Distribution system power flow simulations:
    - Sky imager solar resource assessment Questions
    - Distribution system simulation of PV impacts with highly resolved data
    - Sky imager forecasting and transformer tap operation control
    - Questions
  - Net load forecasting
- System-wide forecast demonstration
  - Optimizing ground monitoring networks
  - Day-ahead solar forecasting marine layer clouds
  - Questions

Distribution Feeder Properties

- Urban and rural feeders
- PV systems up to 2MW
- PV penetration = PV capacity / max load levels from 0% to 200% (simulated).
- Generated based on properties of existing systems

Circuit	A	B	C	D	E
Feeder length (km)	178	40	35	52	116
# Loads	2246	3761	1466	471	1169
Total peak load (MW)	11.1	8.3	4.8	3.7	6.7
# Capacitor banks	2	2	2	1	2
# Transformers & VRs	7	3	1	1	2





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Largest Aggregate PV Ramp Rates

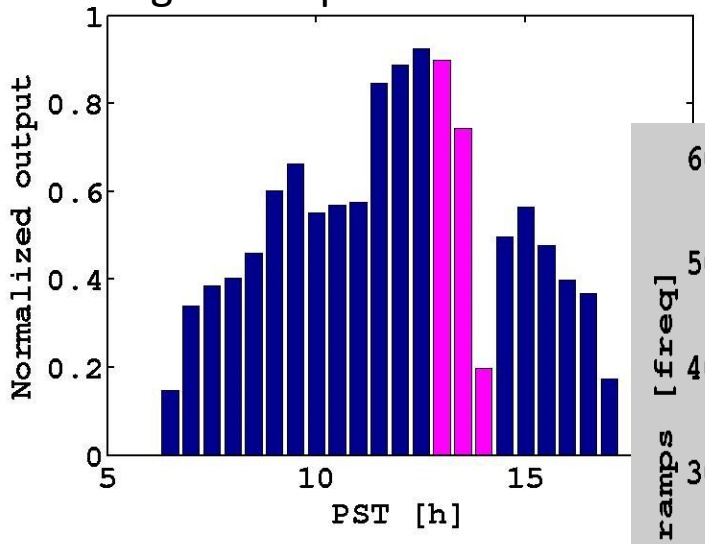
5 Feeders, 1 Year, Satellite Solar Resource

Largest Aggregate Feeder PV Ramp Rates

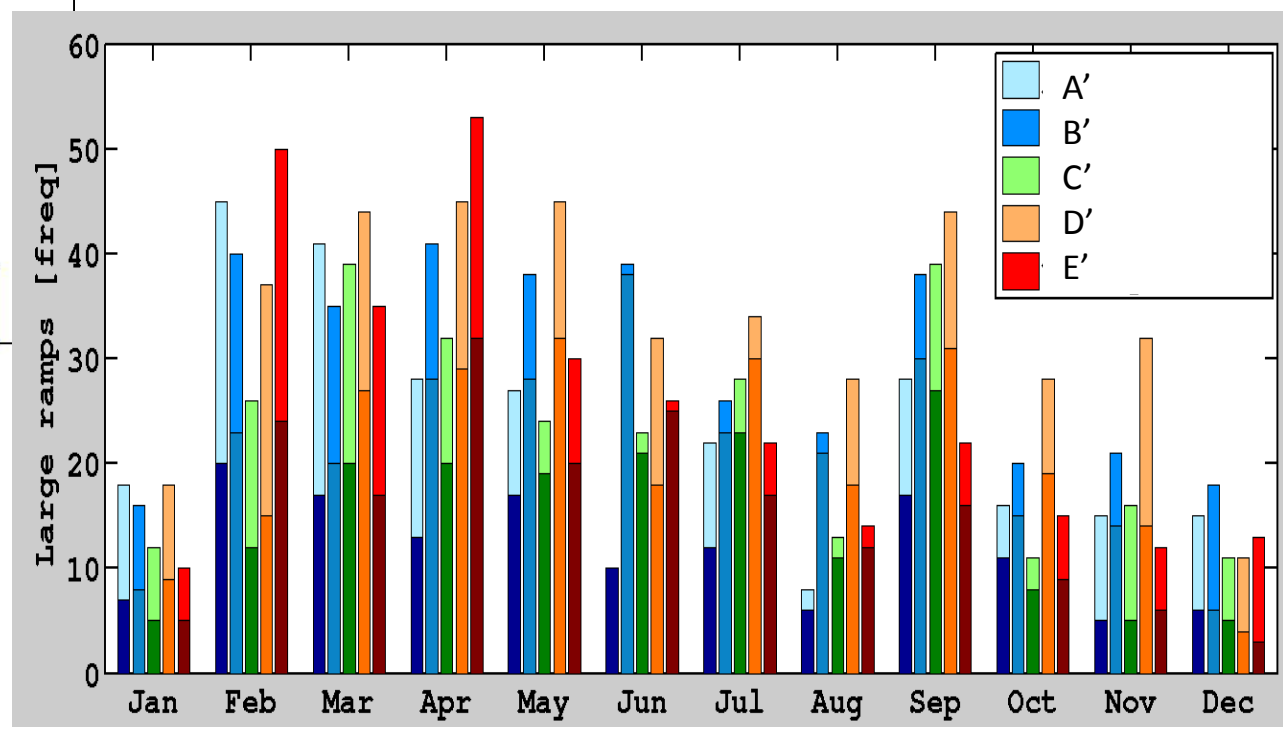
Input:

- SolarAnywhere 30 min satellite solar resource data
- 2011 real PV fleets

Largest ramp at coastal feeder:



Number of ramps > 27% PTC capacity / hour:



Large Ramp Rates Conclusions

- Limited geographic diversity on distribution feeders for 30 min+ ramps
  - Large aggregate ramps
- Ramps driven by Feb – April storms and May - July morning marine layer
- Small difference across SDG&E territory
- Weather forecast models have limited skill in forecasting daily variability.

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Distribution System High PV Penetration Modeling and Impact Mitigation Though Forecasting

5 Feeders, 3 Months, Sky Imager
Solar Resource

Agenda Sky Imager Power Flow

- Sky imager resource assessment and forecasting on SDG&E feeders
- Distribution feeder modeling using sky imager solar resource maps
- Real-time control of transformer tap changes using solar forecasts

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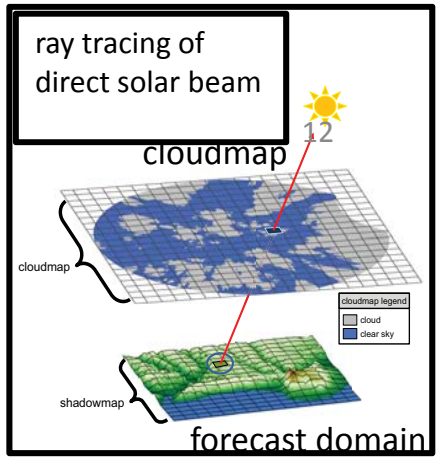
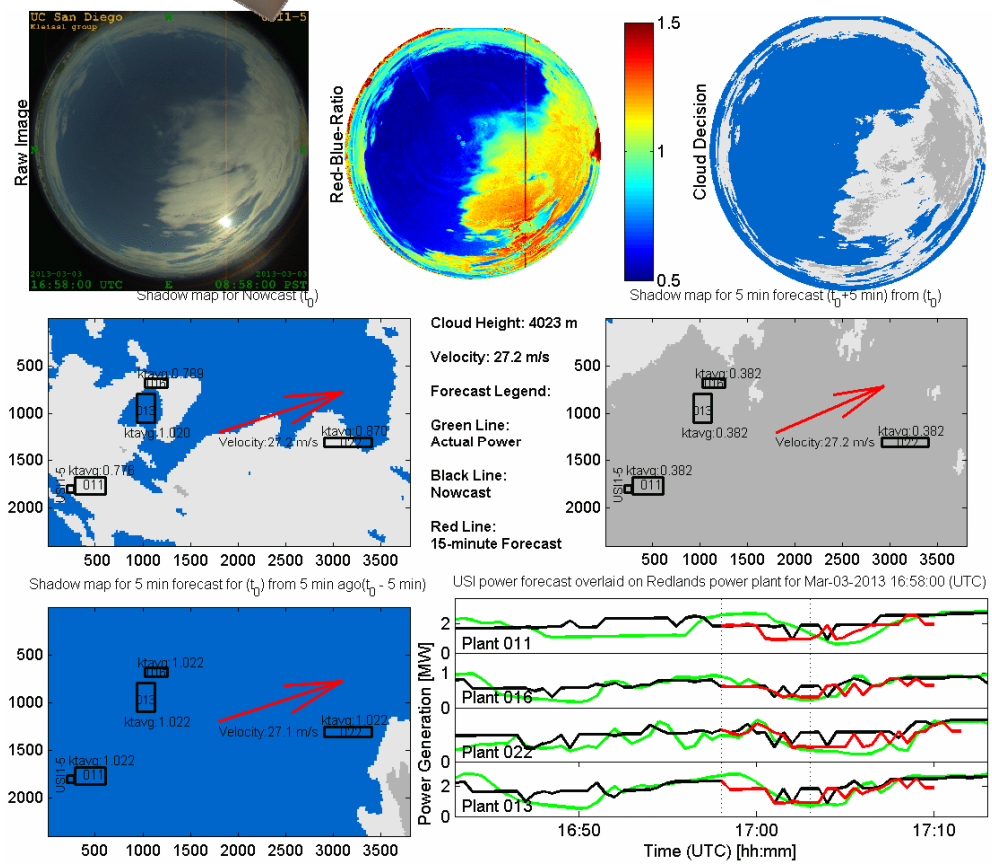
Solar resource assessment with sky imager

- In 'resource assessment' mode to generate input data for the PV impact research.
- 30 sec, 10m x 10m resolution.
- Basic steps [1,2]:
  - Cloud detection
  - Cloud height determination
  - ~~Cloud motion vectors~~
  - Projection on the ground for irradiance maps
  - Convert from irradiance to power





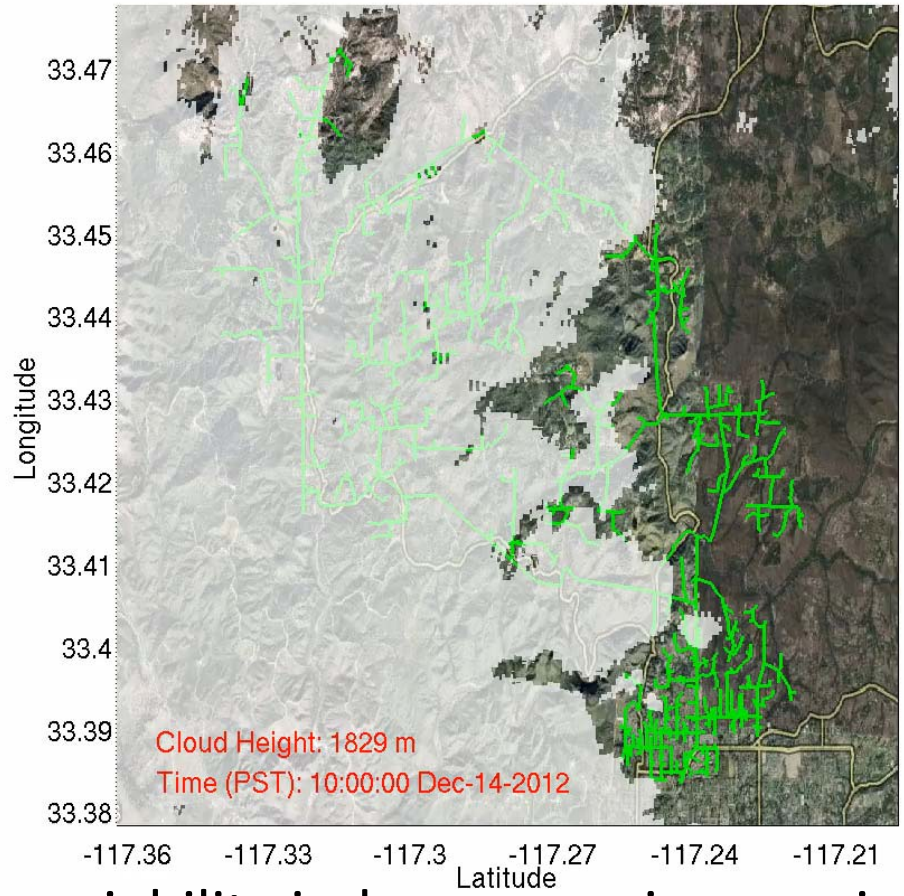
[1] Chow et al., 2011; [2] Yang et al., 2014

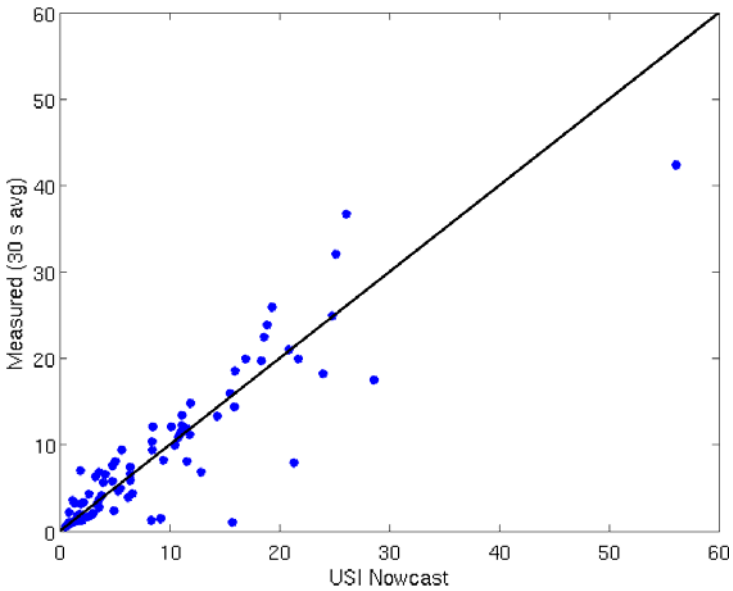
Sample of the forecasting process with sky imager

Sky imager resource assessment for DSS

- Novelty: High resolution and distributed generation profiles
- Location-specific solar irradiance for each PV system

Clouds overlaid on the distribution feeder on Dec 14, 2012.





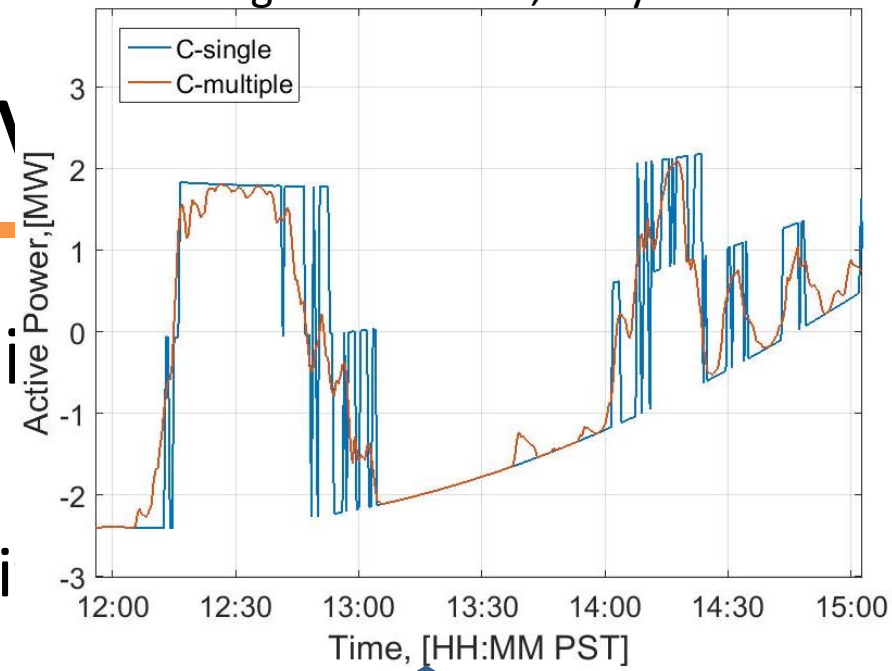
Daily variability index comparison against ground measurement:

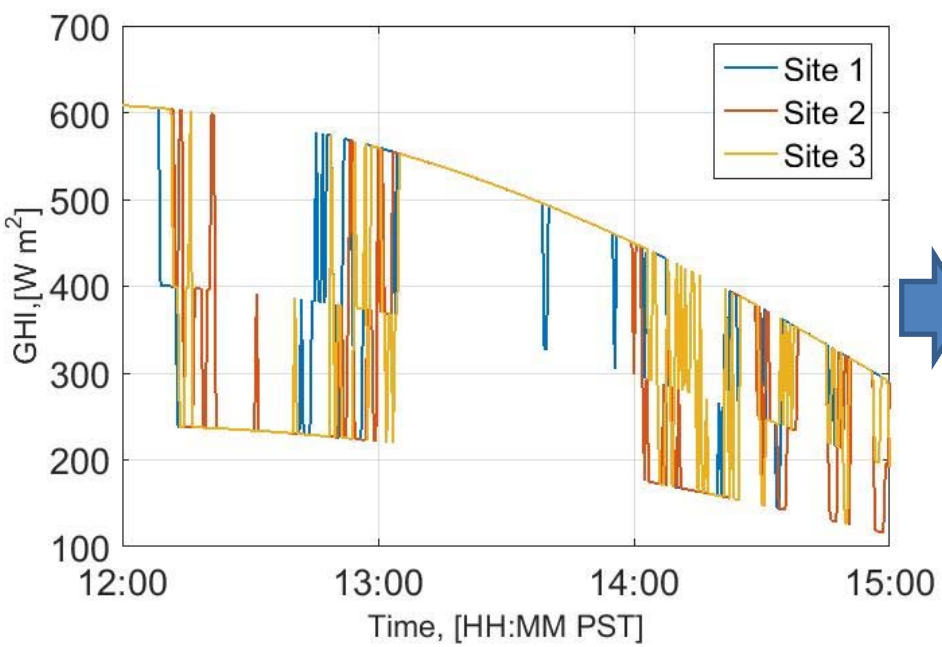
Corr coef = 0.90, MBE = 1.6, MAE = 2.0

Impacts of V

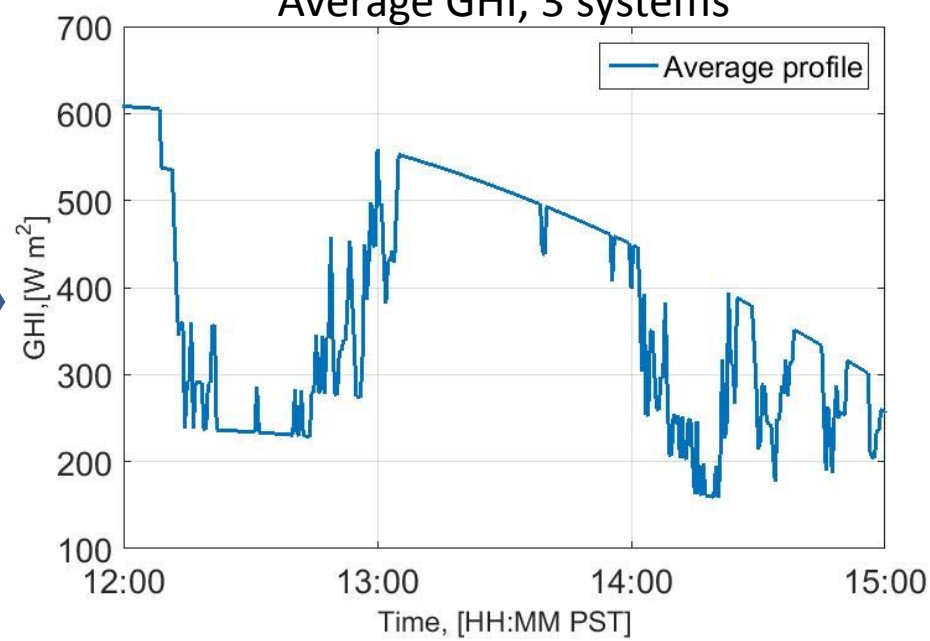
- Spatiotemporal variabili
  smooths the aggregate
  - No impact in clear condi
    overcast conditions.

Average feeder load, all systems





Average GHI, 3 systems



Agenda Sky Imager Power Flow

- Sky imager resource assessment and forecasting on SDG&E feeders
- Questions?
- Distribution feeder modeling using sky imager solar resource maps
- Real-time control of transformer tap changes using solar forecasts

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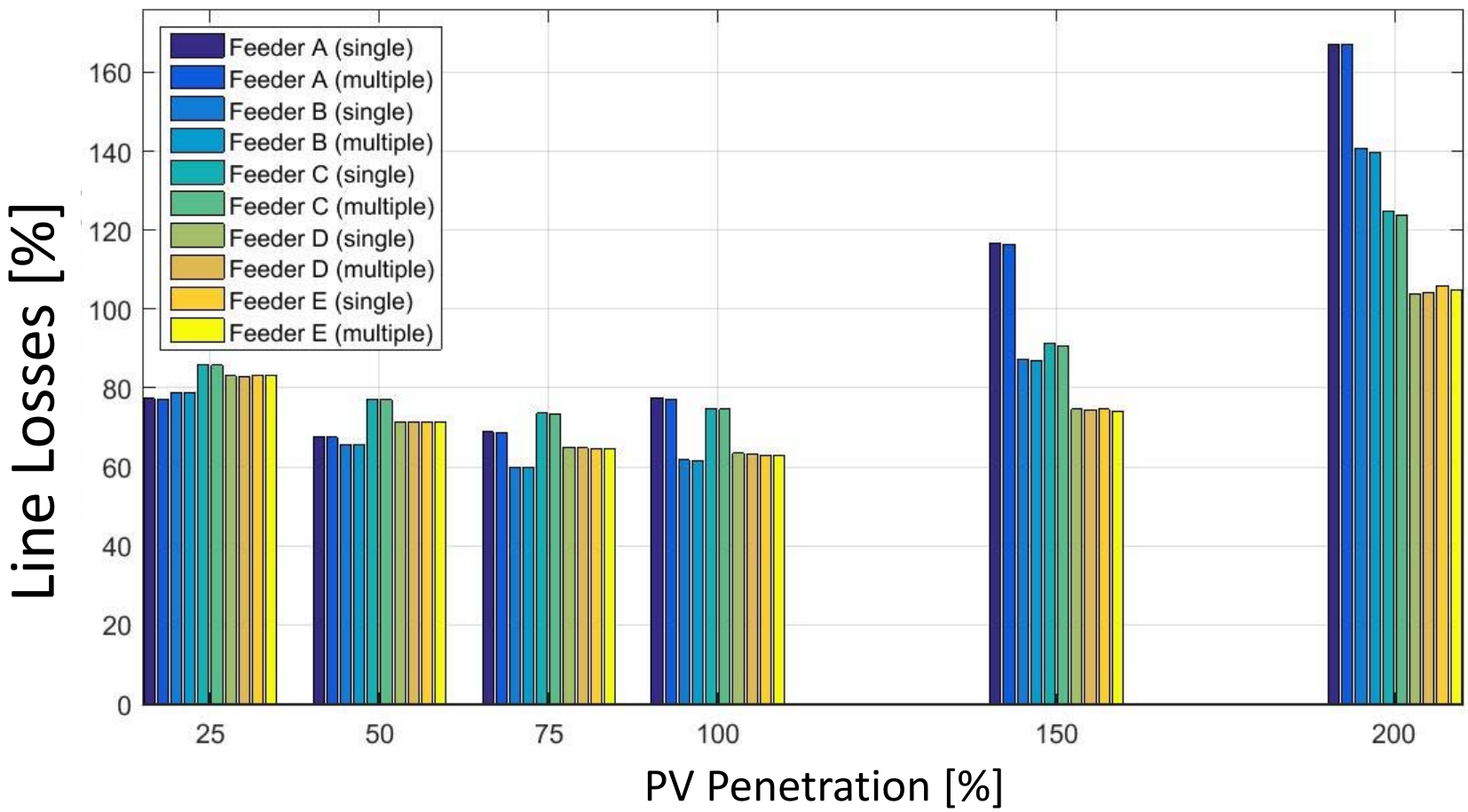
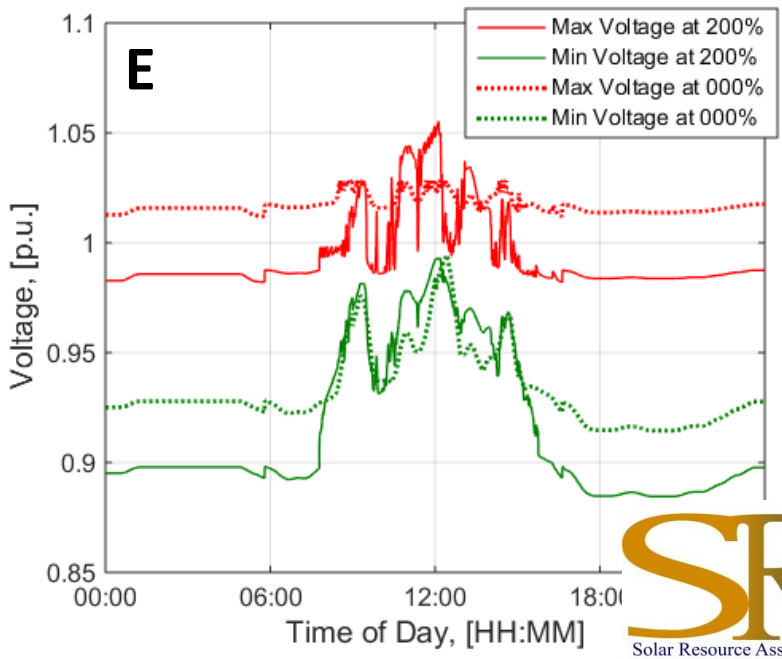
Line Losses

- Line losses first decrease, then increase after 50% to 100% penetration
- ~1% smaller line losses for 'multiple' PV profiles



Voltage extremes comparison

- Feeder max voltage
  - Noon: If noon is clear or overcast, no change
  - Increase with PV penetration
- Feeder min voltage
  - Night: PV variability not a contributing factor



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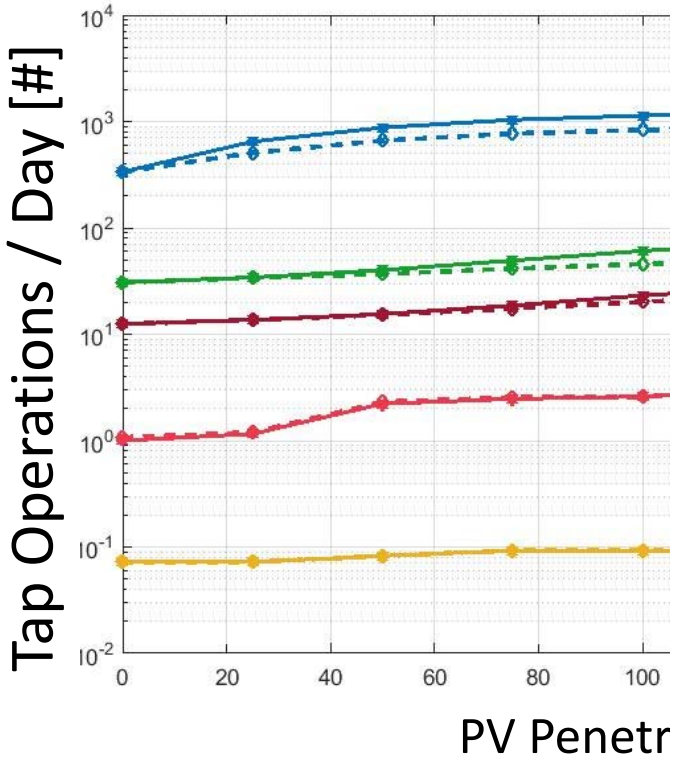
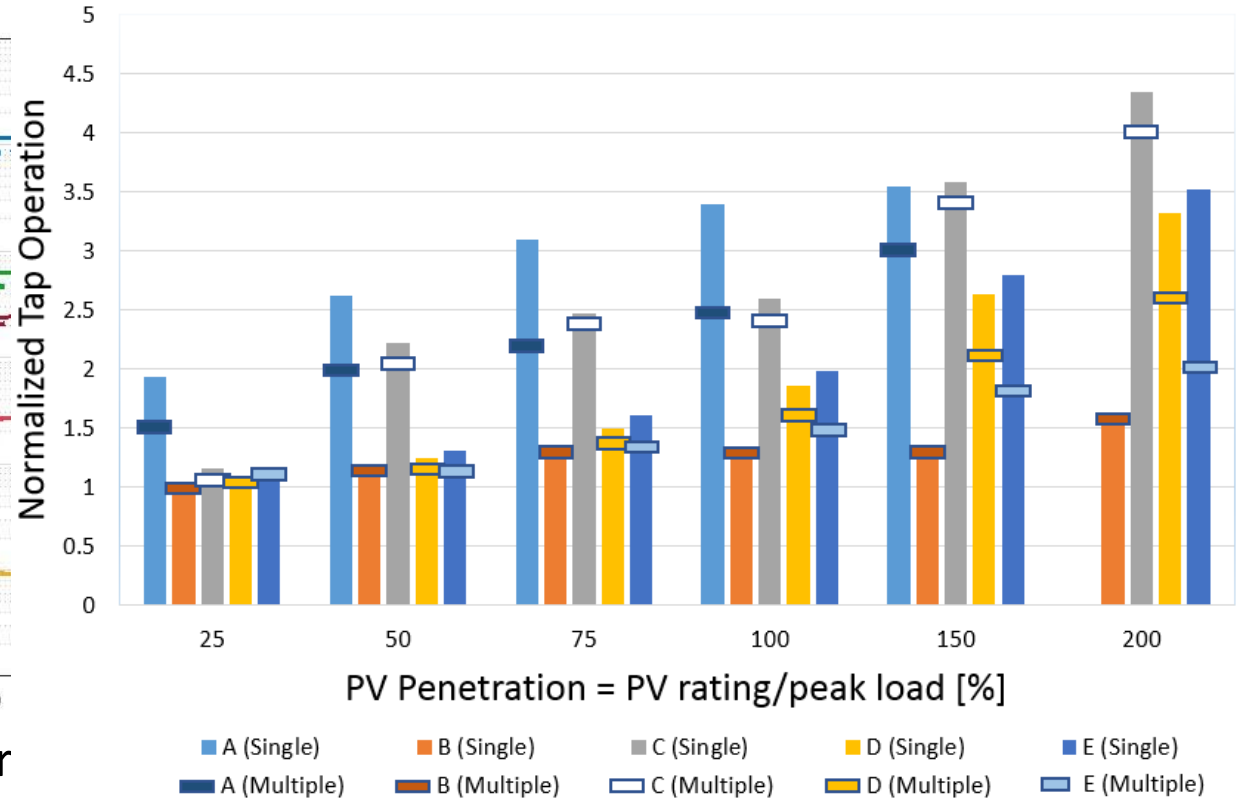
Tap Operations (TO)

- Daytime TO increase with PV penetration
  - Large range of TO from <<1 to 100s per day
- Same PV profile (single) overestimates TO
  - 8% for 25% pen to 46% overestimation for 200% penetration
  - 70% overestimation for feeders A, E





Agenda Sky Imager Power Flow

- Sky imager resource assessment and forecasting on SDG&E feeders
- Distribution feeder modeling using sky imager solar resource maps
- Simulated real-time control of transformer tap changes using solar forecasts

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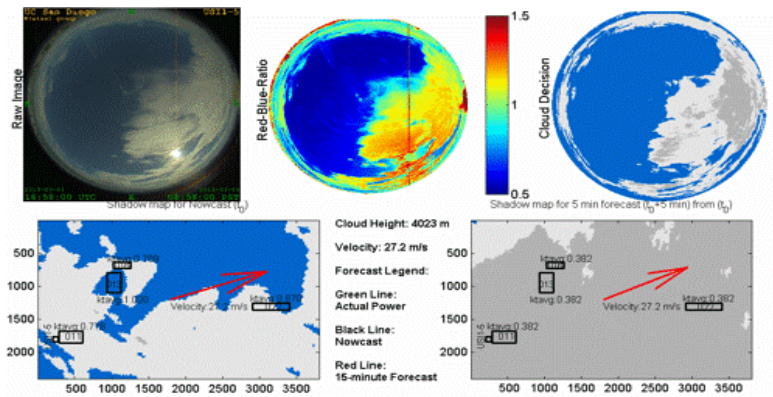
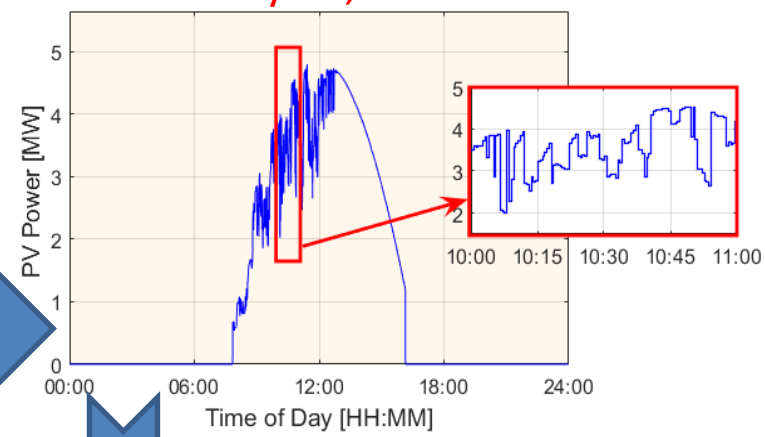
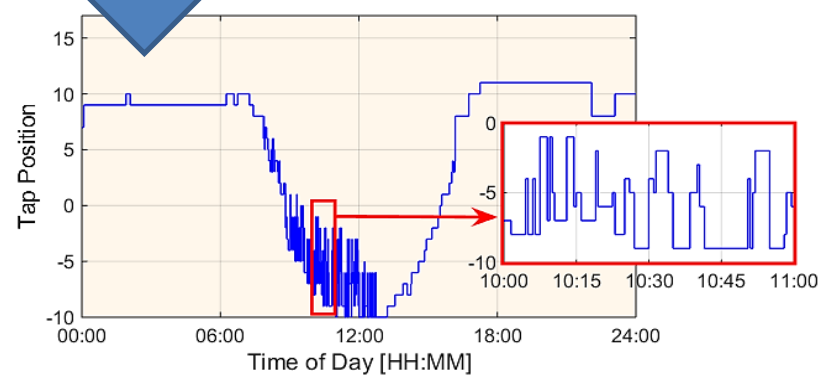
Potentially Unnecessary TO



January 19, 2015



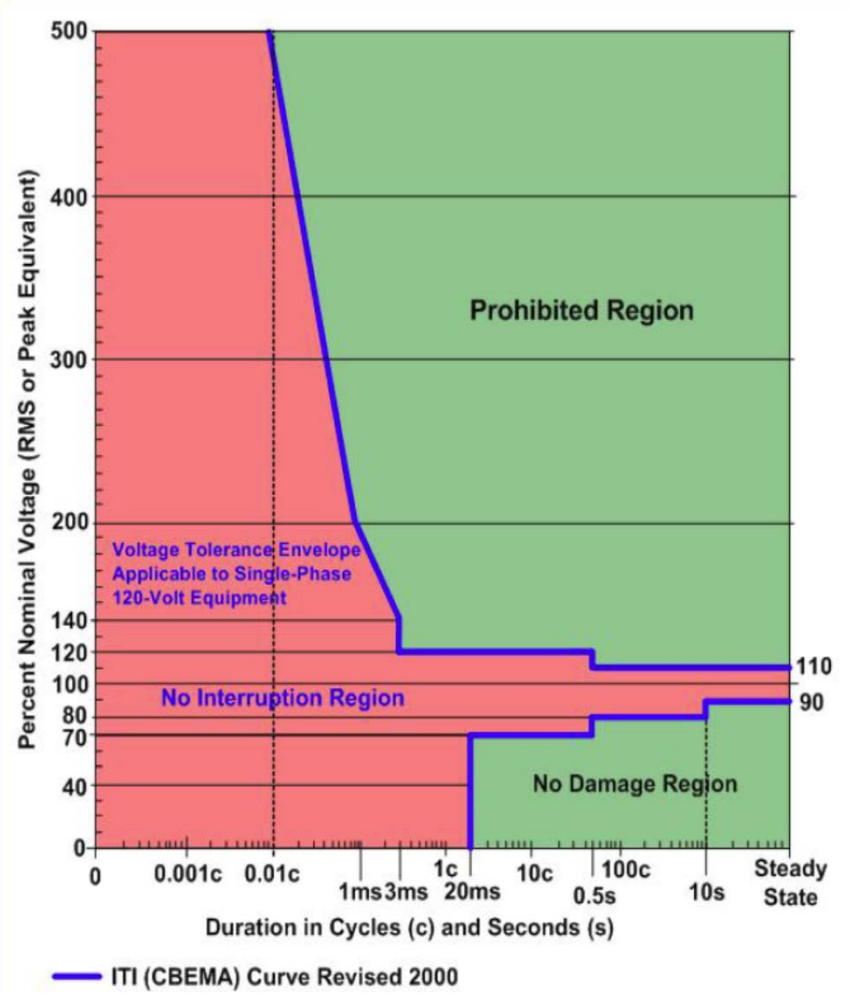


- At 100% PV Penetration
  - 500 tap operations (TO) from 8 to 16 PST
  - 135 TO from 10 to 11 PST
- Normal #operation of OLTC: 20 TO/day [1]

[1] ABB. On-Load Tap-Changers, types UCC and UCD with motor-drive mechanism, type BUE – Installation and Commissioning Guide. . [Online]. *5*. Available: https://library.e.abb.com/public/f95b7dc5c0bafaeec1256d3400231cda/1ZSE%205492-117%20en%20Rev%205.pdf

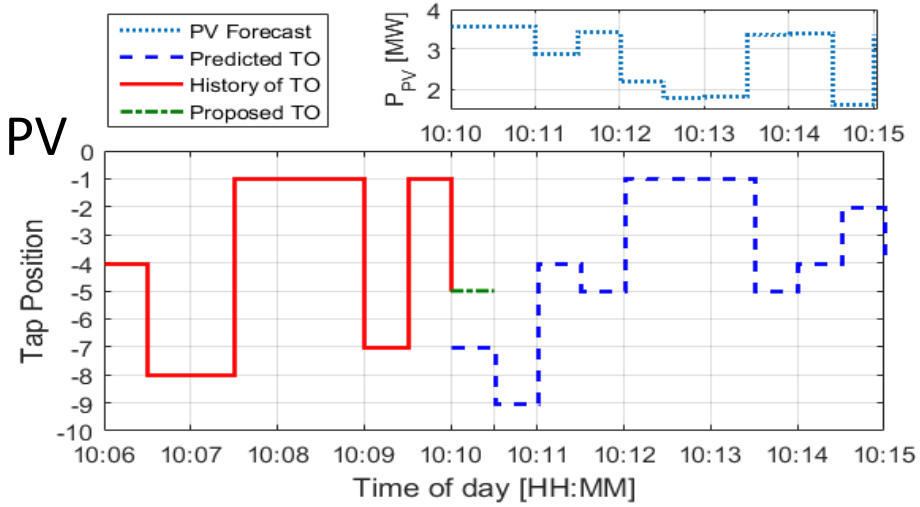
Justification of TO Reduction

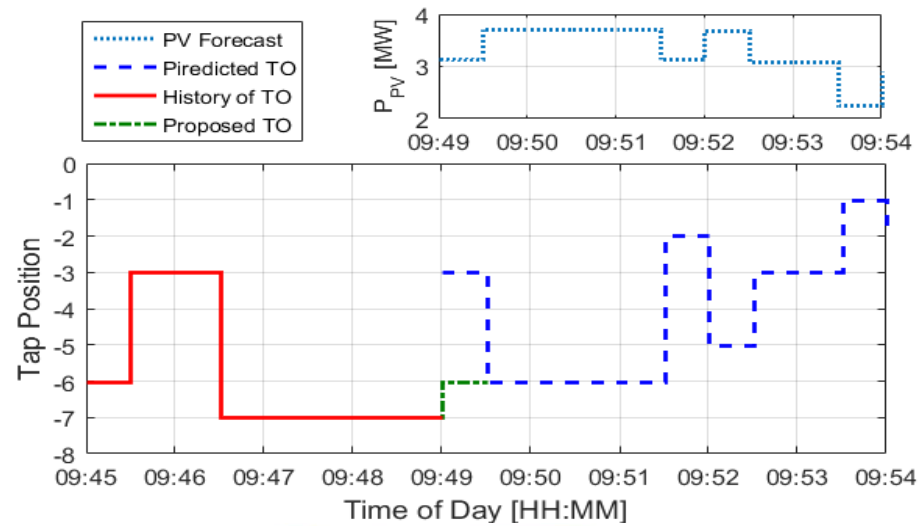
- High TO due to temporary variation of PV generation
- TO delay can cause TO to be out of phase with cloud cover
- Temporary voltage violations are acceptable at some levels (graph from ITIC-CBEMA)



Predictive TO Reduction

- At each time:
  - Simulate the feeder with forecasted PV outputs for the next 5 minutes
  - Observe the projected tap positions
  - Rule 1:
    - Observation: Tap reversal
    - Action: No tap operation
  - Rule 2:
    - Observation: Varying tap on one side
    - Action: Minimize TO
  - Go to next time step





- Forecast update frequency: 30 sec

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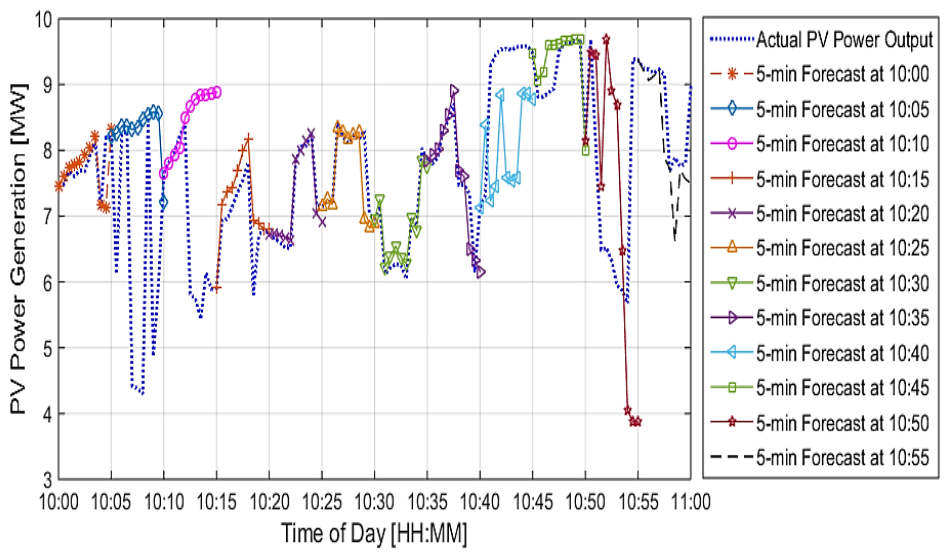
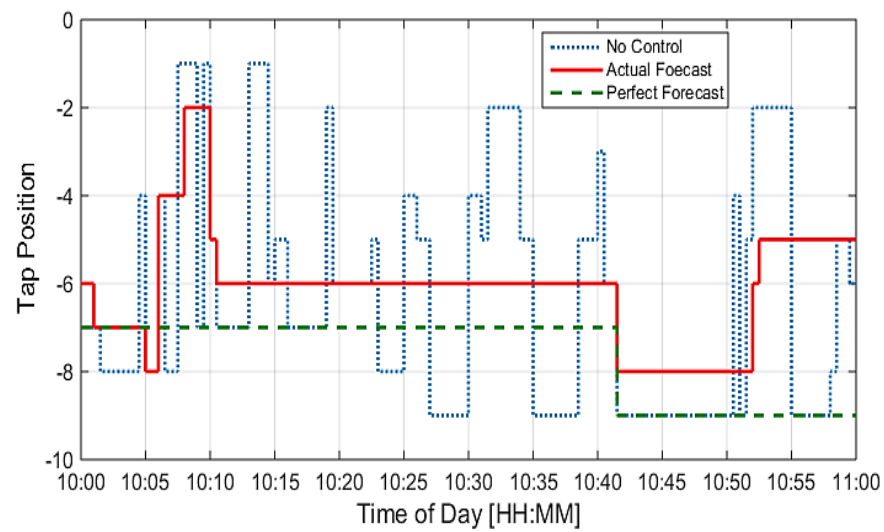
Example TO Reduction

- #TO on Jan 19, 10:00am - 12:30pm
  - No control: 135 TO
  - Actual forecast: 17 TO
  - Perfect Forecast: 2 TO





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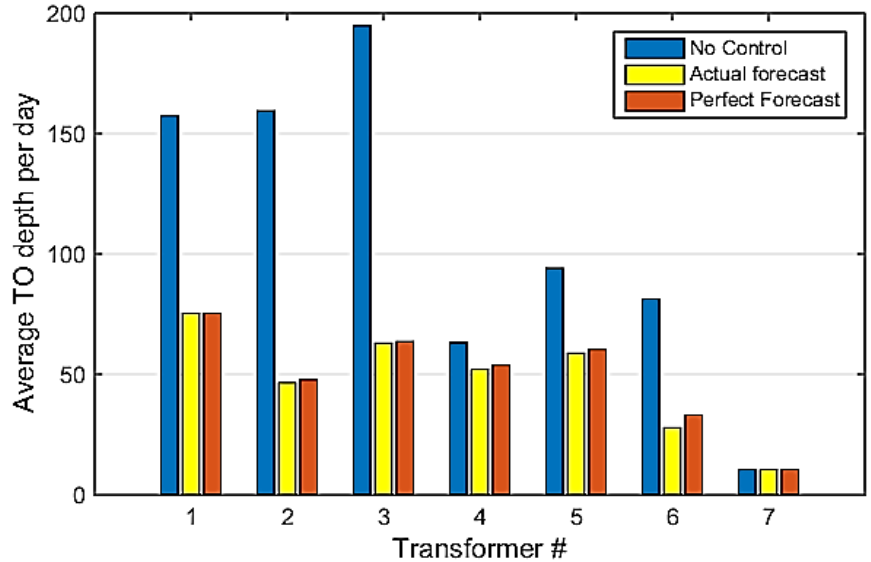
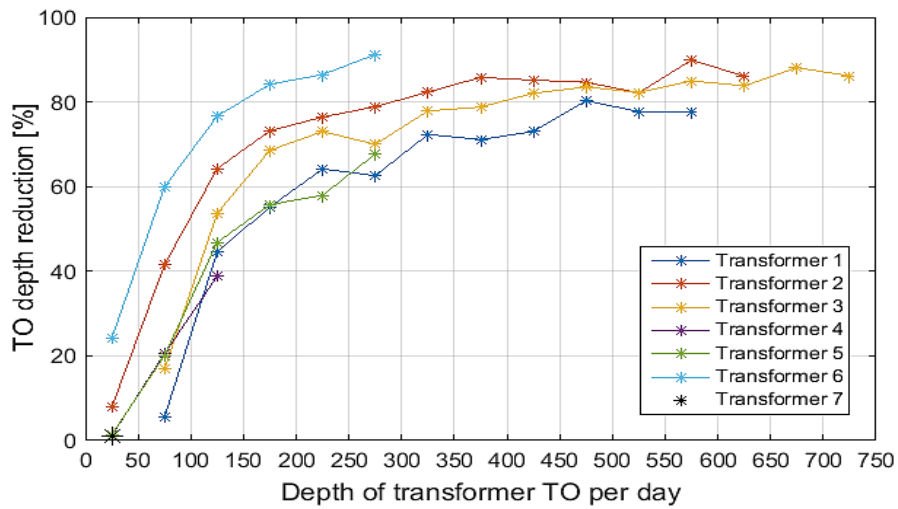
TO Reduction Statistics

- Perfect forecast scenario
  - Average 55% reduction
  - Maximum 79%
  - Similar results for actual forecast
- TO Reduction vs. initial #TO
  - Xfm3: Higher TO, higher reduction
  - Xfm7: Low TO, zero reduction





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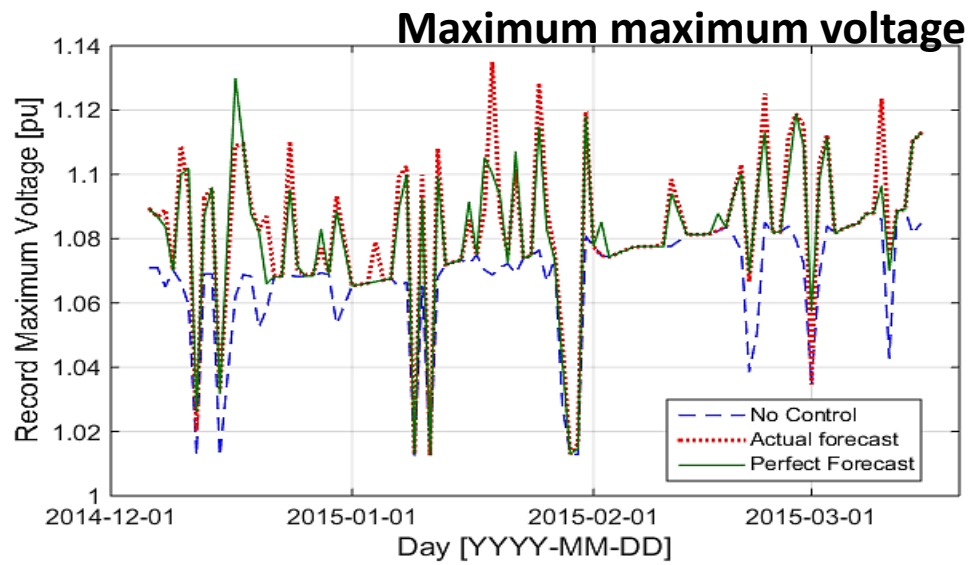
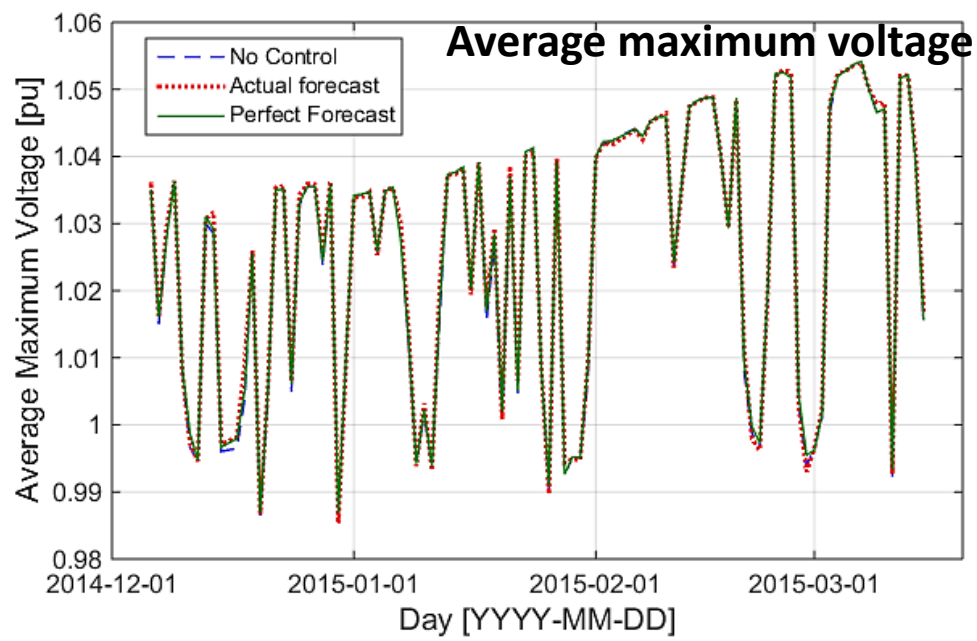
Impacts on Voltage Quality

- Max Max voltage exceeds the limits because:
  - Exceedance in base case
  - TO reduction
- Voltages typically similar as w/o TO control, but a few large excursions





Conclusions – High Pen Impacts

- Geographic diversity acts to smooth PV power output profiles across a distribution feeder
  - Sky images provide realistic high resolution spatio-temporal irradiance
- Reduction in voltage variability, line losses (albeit small), tap operations
  - Max and min voltage not significantly affected
  - Reduction primarily in partly cloudy conditions
- Tap operations are overestimated by up to 70% at 200% penetration
  - Depends on feeder and penetration level
- Predictive Tap Operation Reduction Using Sky Imager data
  - Algorithm robust against real forecast error
  - TO are reduced by another 56%
  - Rare adverse effect on voltage quality, but still concerning
- Irradiance fields freely available to other researchers

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Summary

- Ramp rate analysis sets bounds and allows creating scenarios for what voltage regulation is needed with high PV penetration.
  - Smart inverter penetration
  - Other voltage regulation equipment
- More accurate solar integration studies
  - Facilitate better decision on capital investment in mitigation measures
- Reduction in tap changes reduces O&M costs related to solar variability
- Questions?

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Distribution System Substation Net Load Forecasting

5 Feeders, 1.25 Years, Machine Learning Techniques

Operational Substation Net Load forecasts

- Goal: Real-time operational load forecast for Fast Demand Response Event
- Data: 3/1/2012 – 6/30/2013

Datasets

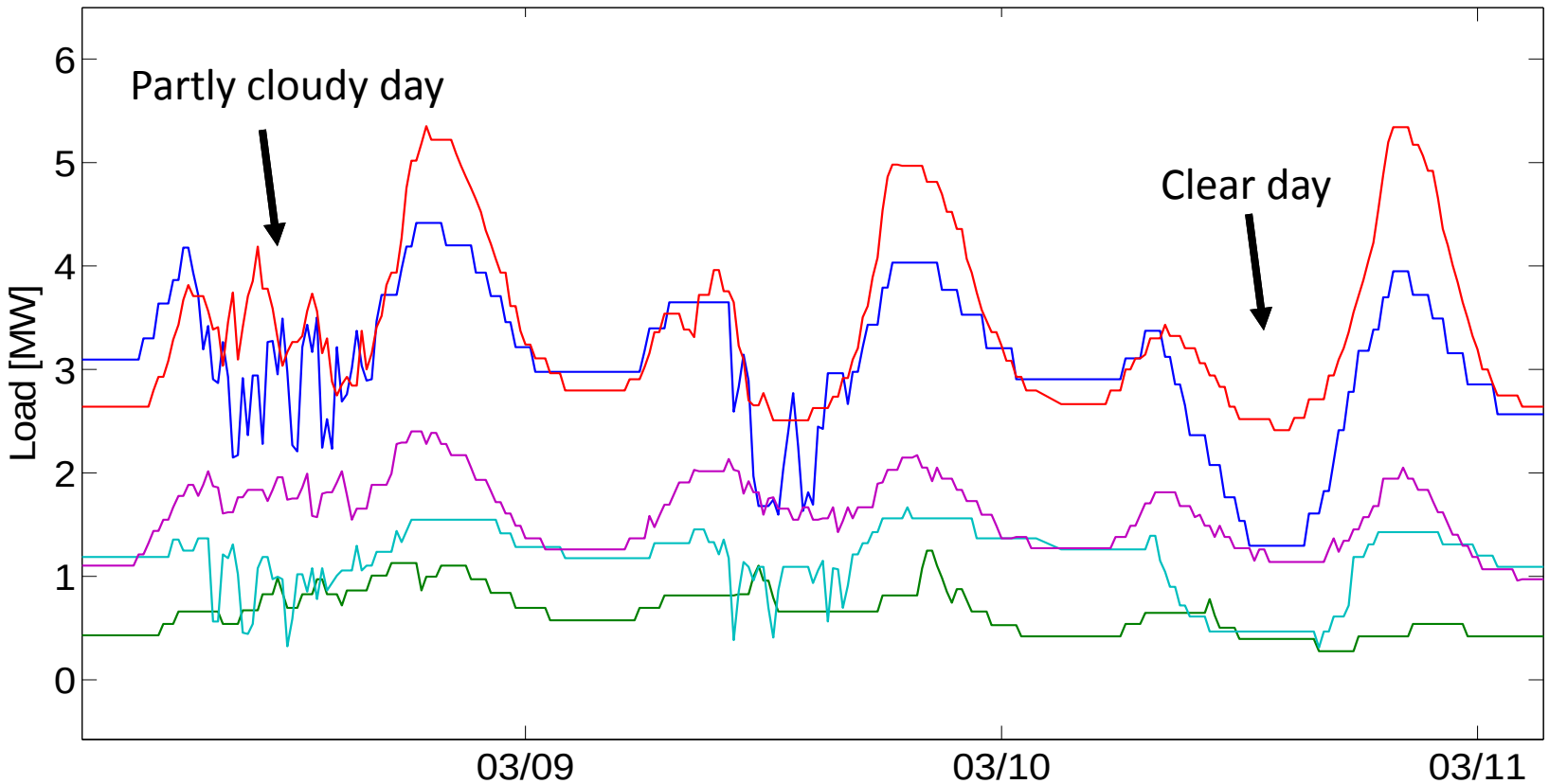
Load data set: 15-min resolution load time-series from five SDG&E feeders with different levels of solar penetration

Solar power data: Estimated solar-power using Solar Anywhere data with 30-min time resolution

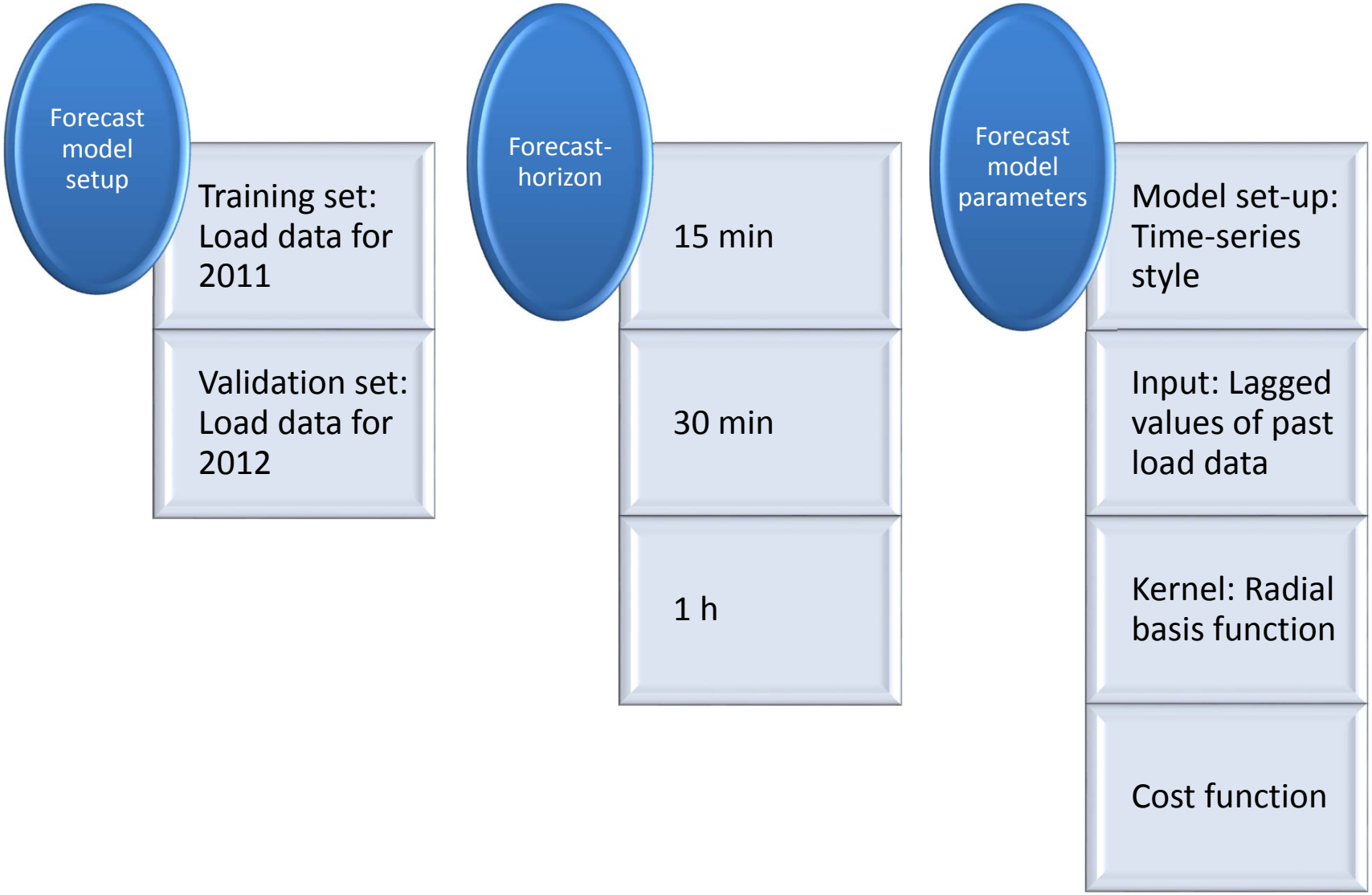
SDGE feeder name	Solar penetration
A*	24%
B*	13%
C*	9.3%
D*	5.8%
E*	2.4%

Feeder net load time-series

- Evening peak (residential)
- Daytime impact of solar PV

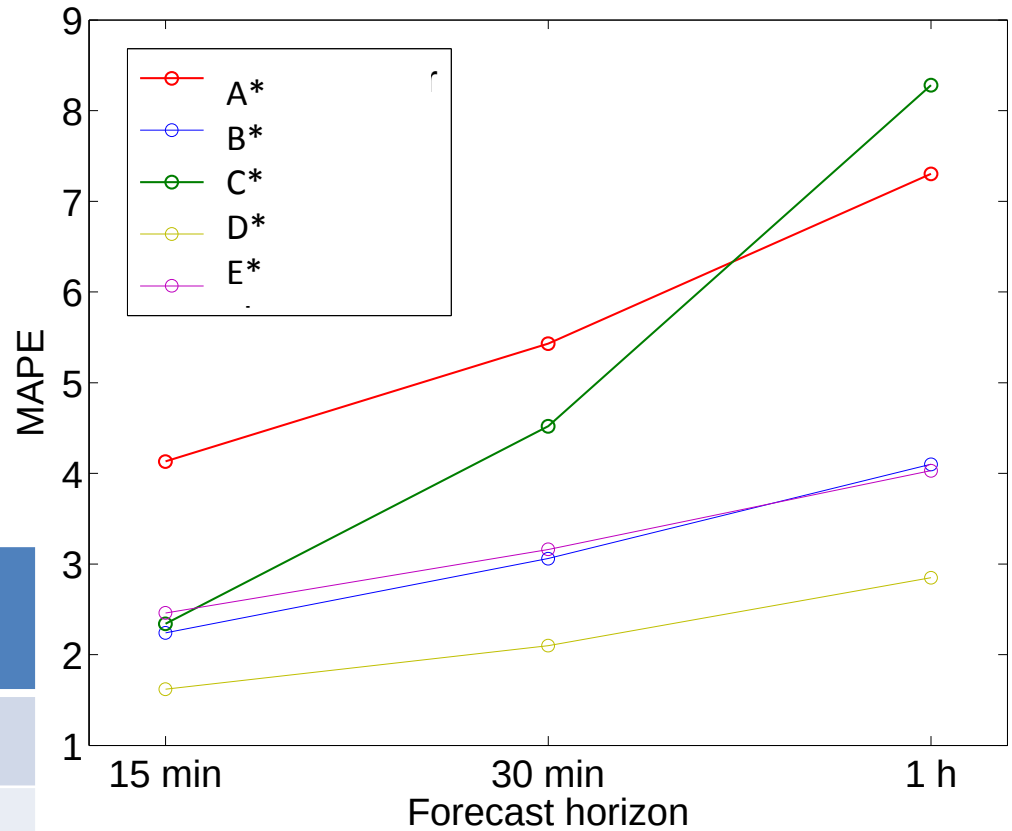


Net Load Forecast Methodology



Forecast Error versus Forecast Horizon

- Load forecast error increases with increasing forecast-horizon
- C load unpredictable due to sudden increase in load demand



Feeder - Solar Penetration [%]	MAPE at 30 min	R2
A – 23.8%	5.43	0.96
B – 13.3%	3.06	0.97
C – 9.2%	4.52	0.92
D – 5.8%	2.10	0.98
E – 2.4%	3.16	0.99

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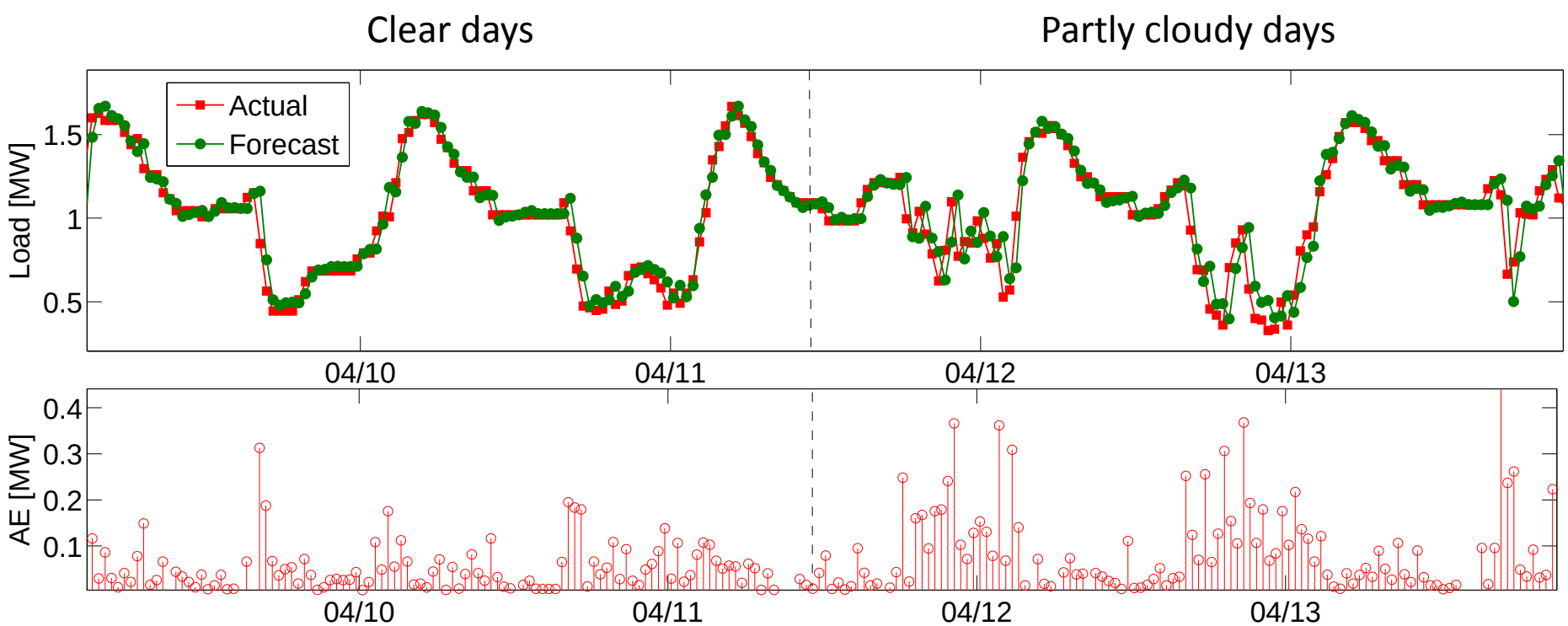
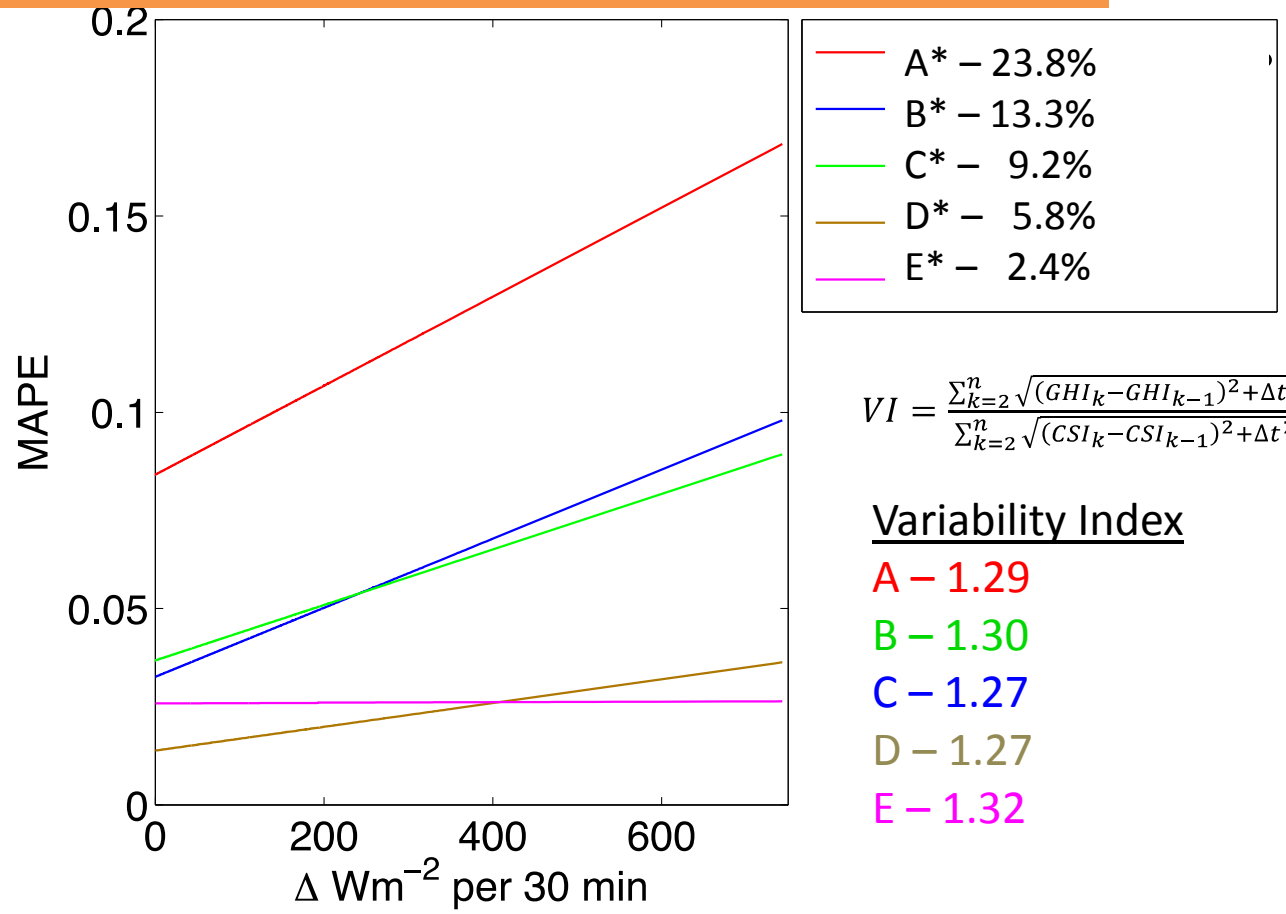
Impact of solar penetration on 30 min ahead load forecast at A*



- Absolute error increases for cloudy days especially during solar production time
- Since solar power data is at 30 min. resolution, further analysis is all based on 30-min ahead forecast

Error as function of solar penetration and variability



$$VI = \frac{\sum_{k=2}^{n}\sqrt{(GHI_k - GHI_{k-1})^2 + \Delta t^2}}{\sum_{k=2}^{n}\sqrt{(CSI_k - CSI_{k-1})^2 + \Delta t^2}}$$

Variability Index

A – 1.29

B – 1.30

C – 1.27

D – 1.27

E – 1.32

With low solar penetration, error is independent of solar variability whereas as solar penetration increases, the load forecast error increases and it is a linear function of solar variability.

Net Load Forecast Summary

- Under high PV penetration, solar penetration and solar variability drives the forecast error.
- Exogenous inputs like weather and solar forecast may further enhance forecast accuracy.
- Forecast models are ready to be implemented in real-time.
- Net load forecasts improve switching operations, power flow estimates, and outage management.

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System-wide Solar Resource Monitoring and Forecasting

Observation Targeting

- SDG&E has 100+ weather stations and 60+ are equipped with a pyranometer
- Identify locations that would benefit from greater station coverage for
  - Modeling real-time PV generation
  - Forecasting PV generation
- Methodology applicable anywhere

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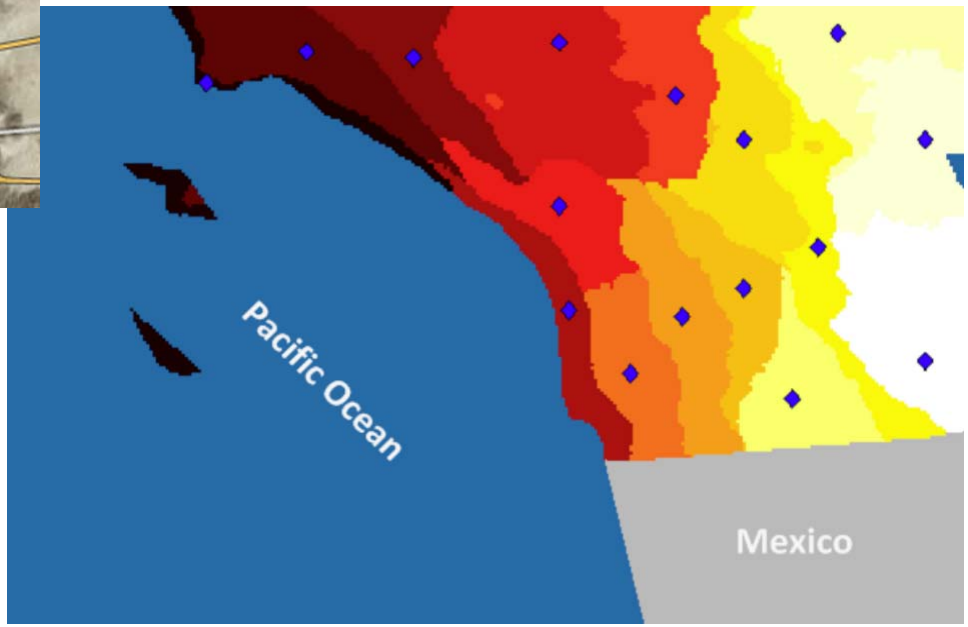
Observation Targeting

- Identified most critical locations for SDG&E pyranometers



- Solar variability climate zones

Results – Observation Targeting

- 8 coherent regions capture the daily variability over the SDG&E territory.
  - Optimal location for the placement of ground based sensors
- Utilities and system operators can tailor ground measurements to forecasting activities.
- Smarter investments in expensive monitoring infrastructure

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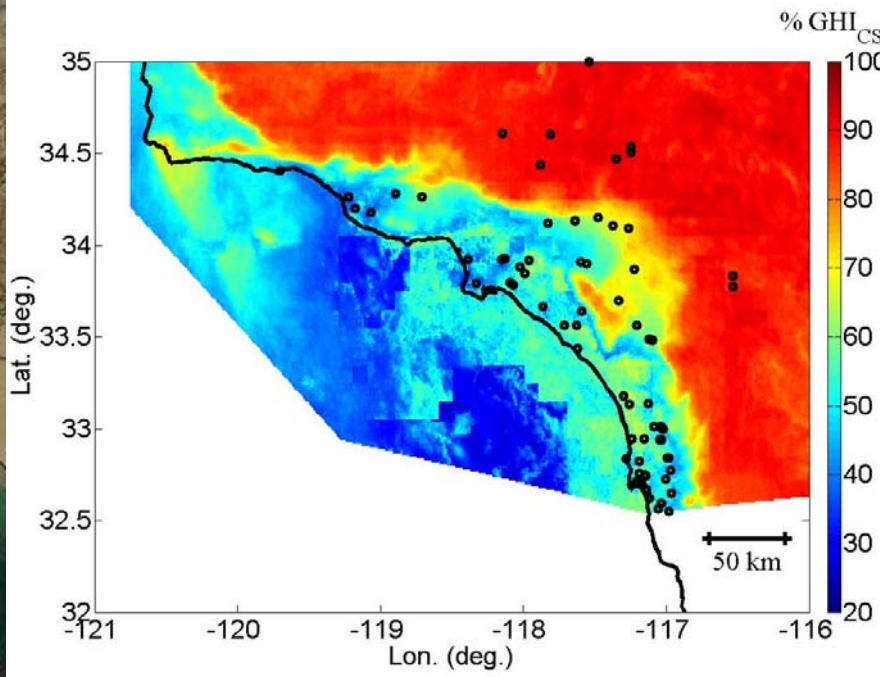

Task 3

Marine Layer Forecasting

Summer 2013 Trial

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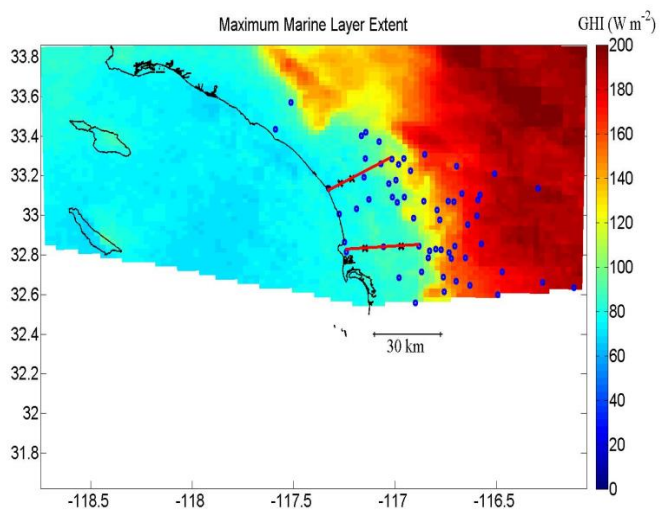
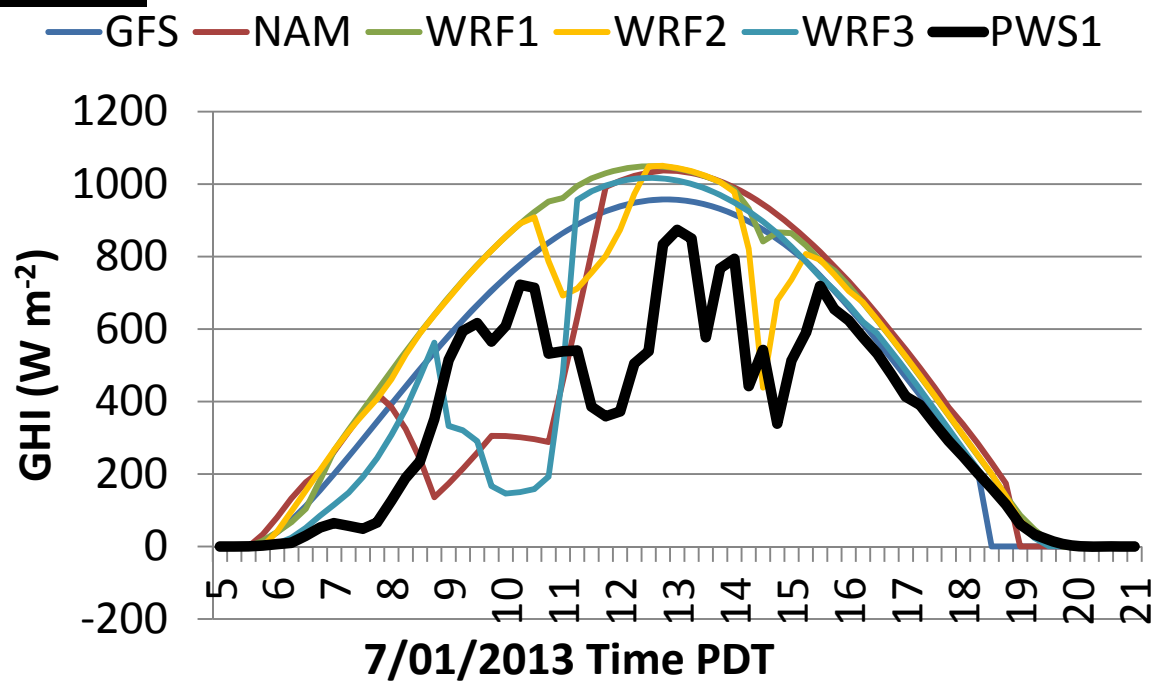
Forecast Trial

Irradiance forecasts created across San Diego County

a) UCSD High-Resolution Model
- 2.5 km
- Cloud Assimilation
- Physics parameterizations optimized for Marine Layer forecasting

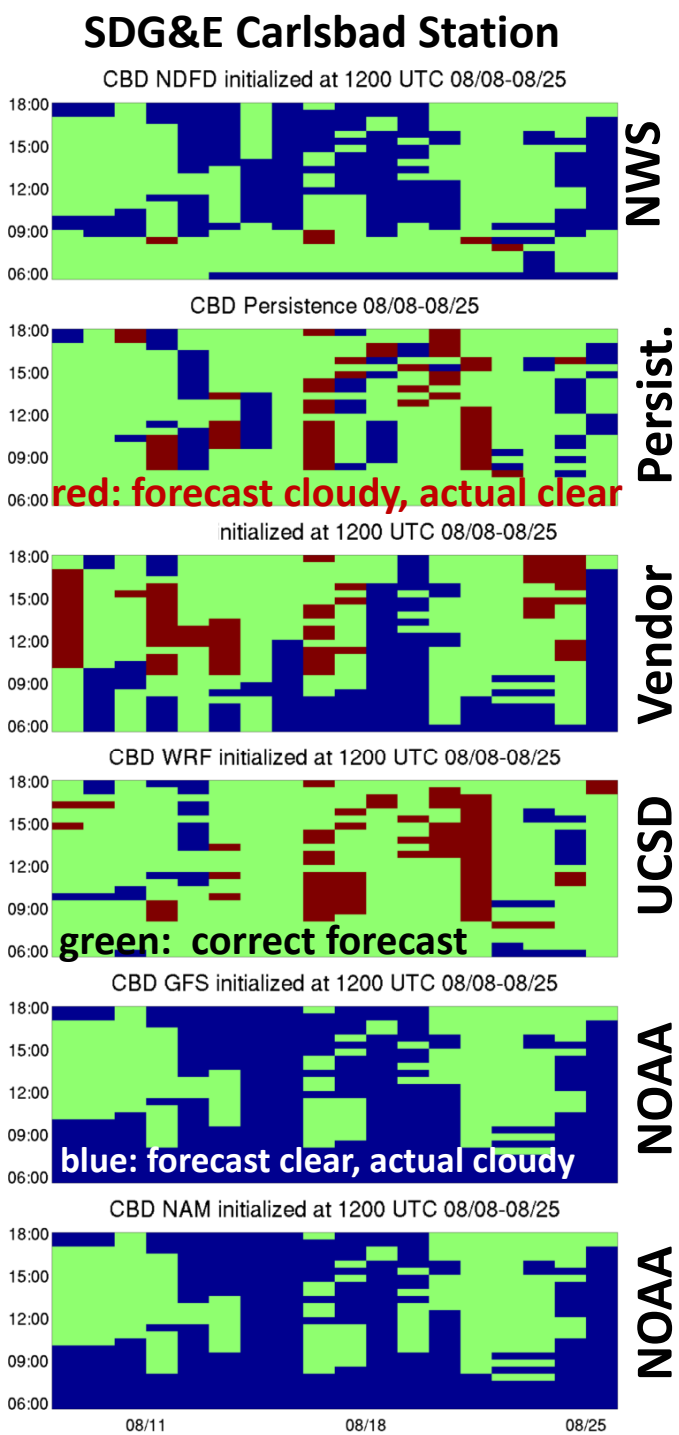
b) Operational NWS Models at lower Resolution
- North American Model + Global Forecast System



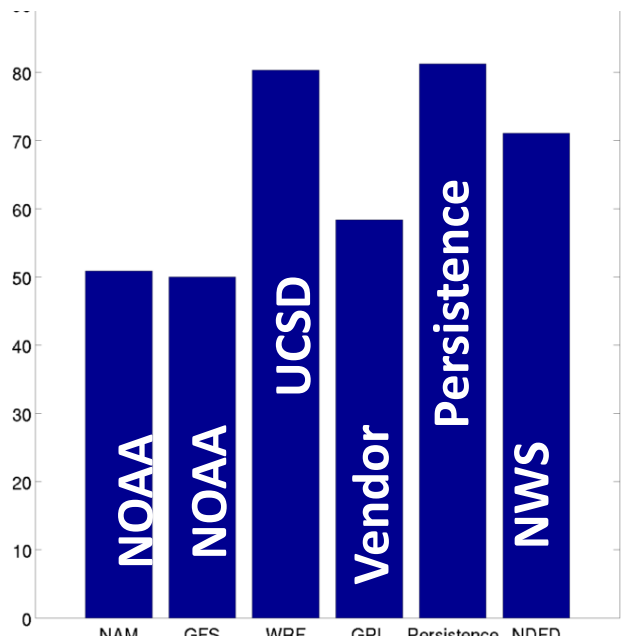


Forecast Results – Binary

Aug 8-25, 2013

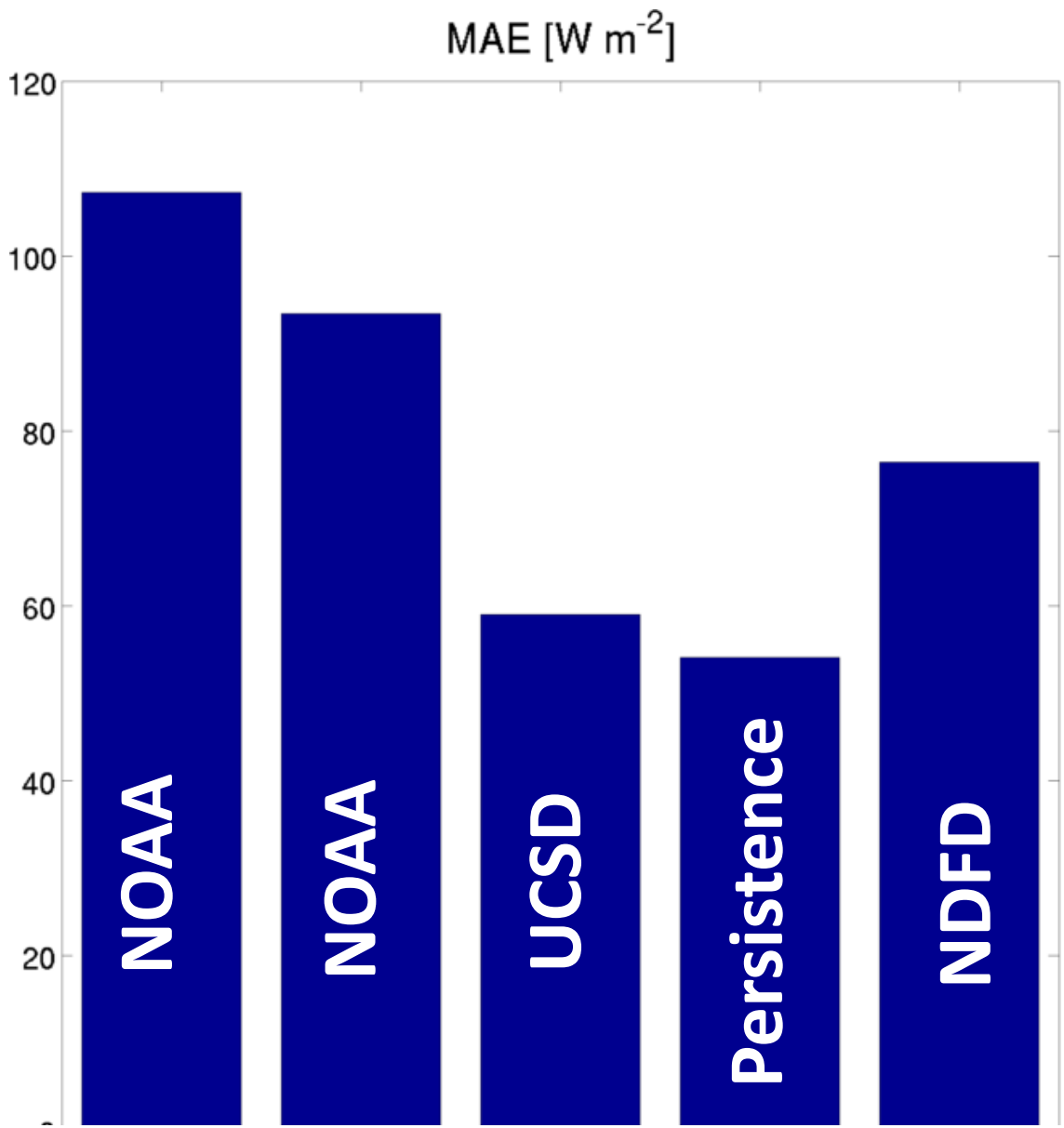


- NOAA models never cloudy
  - NWS post-processing helps
- UCSD, persistence best
- Skill score for all 8 stations:



Hit Score:
0.5 (Cloudy hit [%] + Clear hit [%])

Overall Forecast MAE – Raw Models



- NOAA / NWS models far worse than persistence
- But: persistence unable to capture changing conditions

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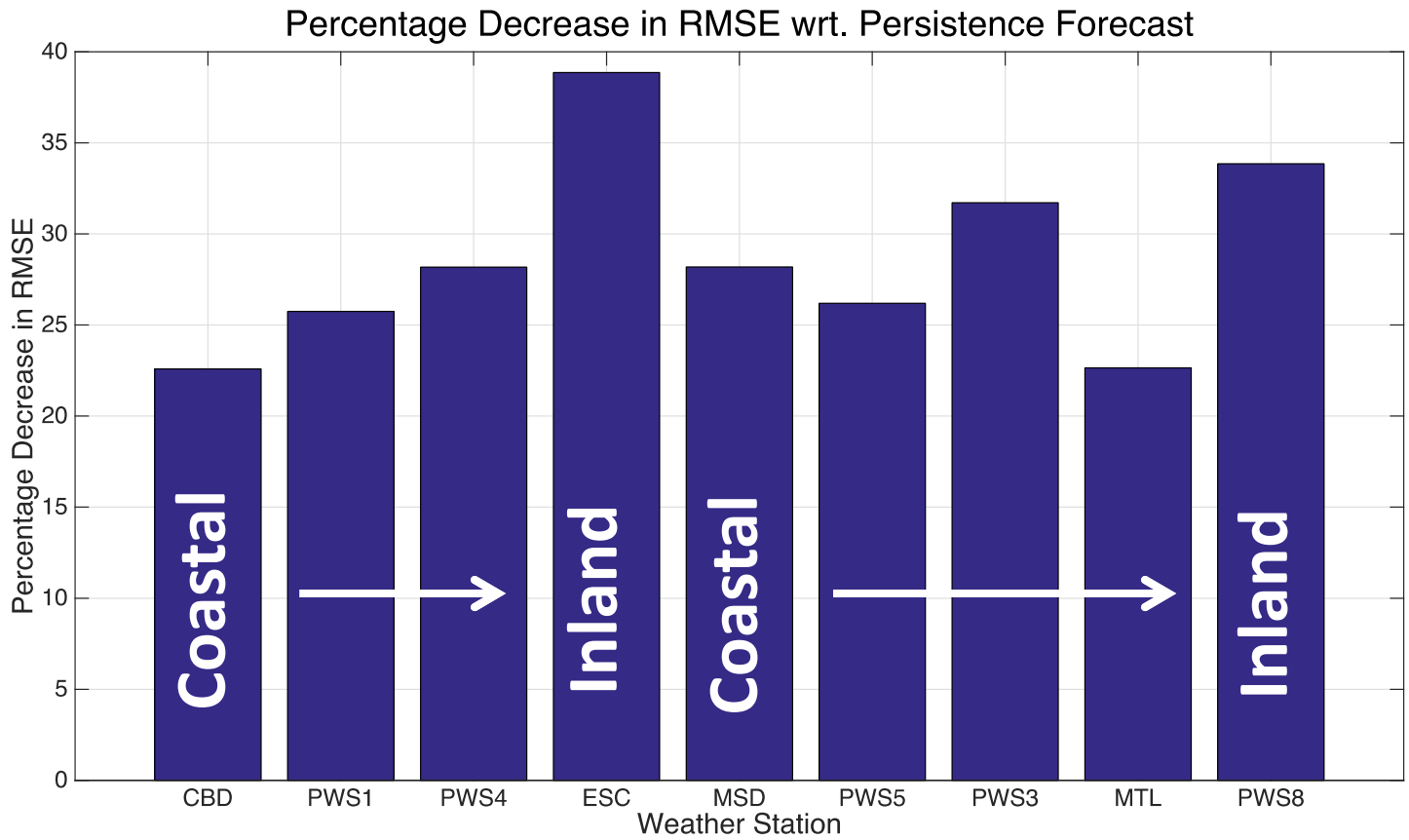
Ensemble System and Post-Processing

- Performance of raw NWP forecasts not satisfactory
- Ensemble forecast system based on WRF
- Taylor Expanded Solar Analog Forecasting postprocessor

Ensemble Name	Cumulus	Radiation	Microphysics
Cumulus1	Kain-Fritsch (1)	Dudhia (1) / RRTM (1)	
Microphysics8			Thompson (8) (8)
CLDDA			
CLDDA& Cumulus 3	Grell-Freitas (GF) (3)		

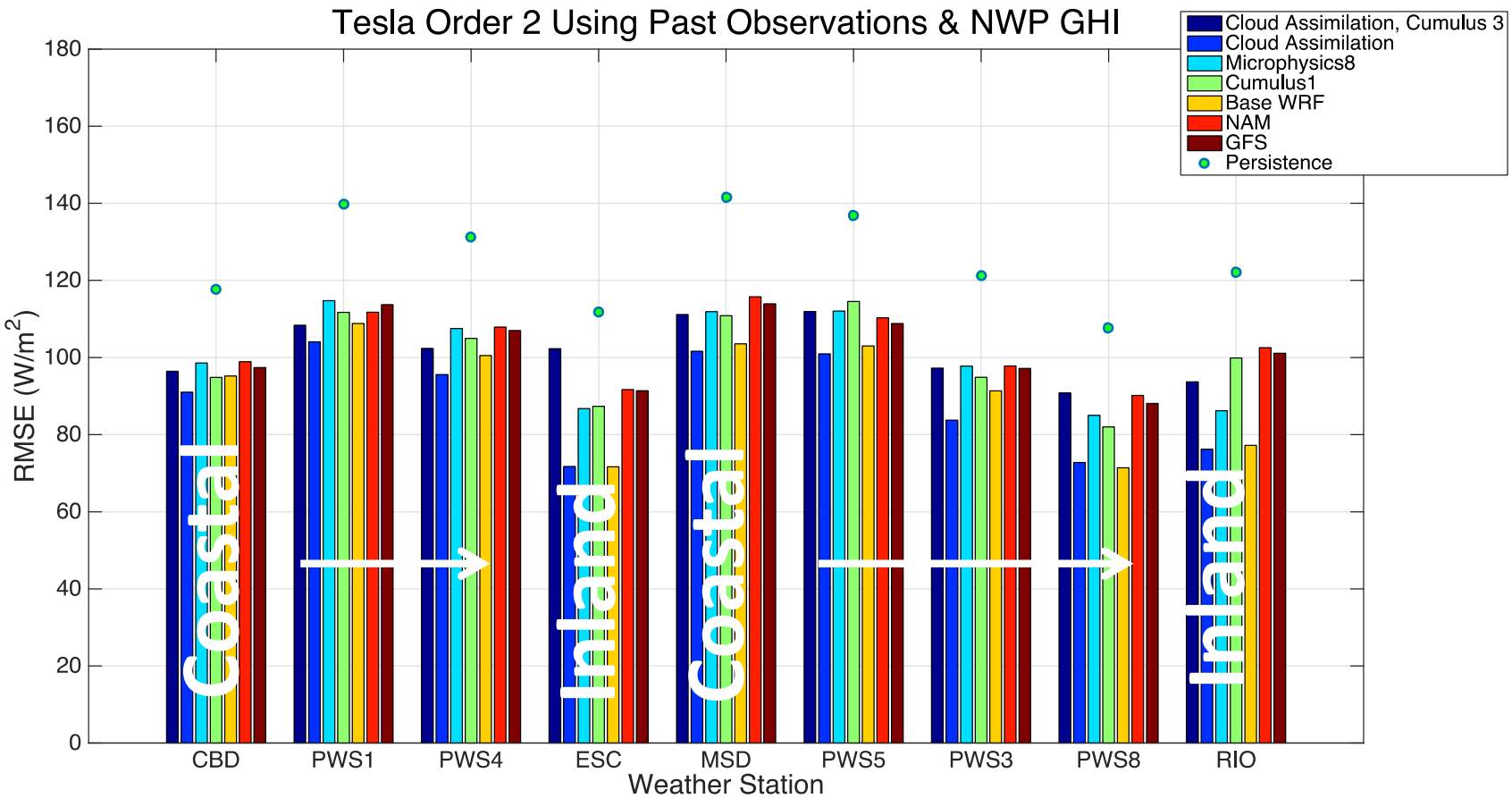
Postprocessed Ensemble Forecast System Results

- Best ensemble improves 20% to 40% over persistence



Ensemble Forecast System Results

- Difference by NWP
  - Small at coastal
  - Large at inland sites



Key Deliverables

- Available at calsolarresearch.org
- Optimal weather station locations
- Day-ahead marine layer forecast models and reports on validation
- Reports on distribution feeder modeling
- Report on net load forecasting

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Overall Summary / Outcomes

- Hours-ahead and day-ahead solar forecast now implemented at SDG&E
- Improved accuracy of distribution system modeling and forecasting tools
- Facilitates solar power integration through
  - Better foresight for power system operation
  - Better understanding of distribution system O&M costs and mitigation options
  - Smarter investment in monitoring infrastructure

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