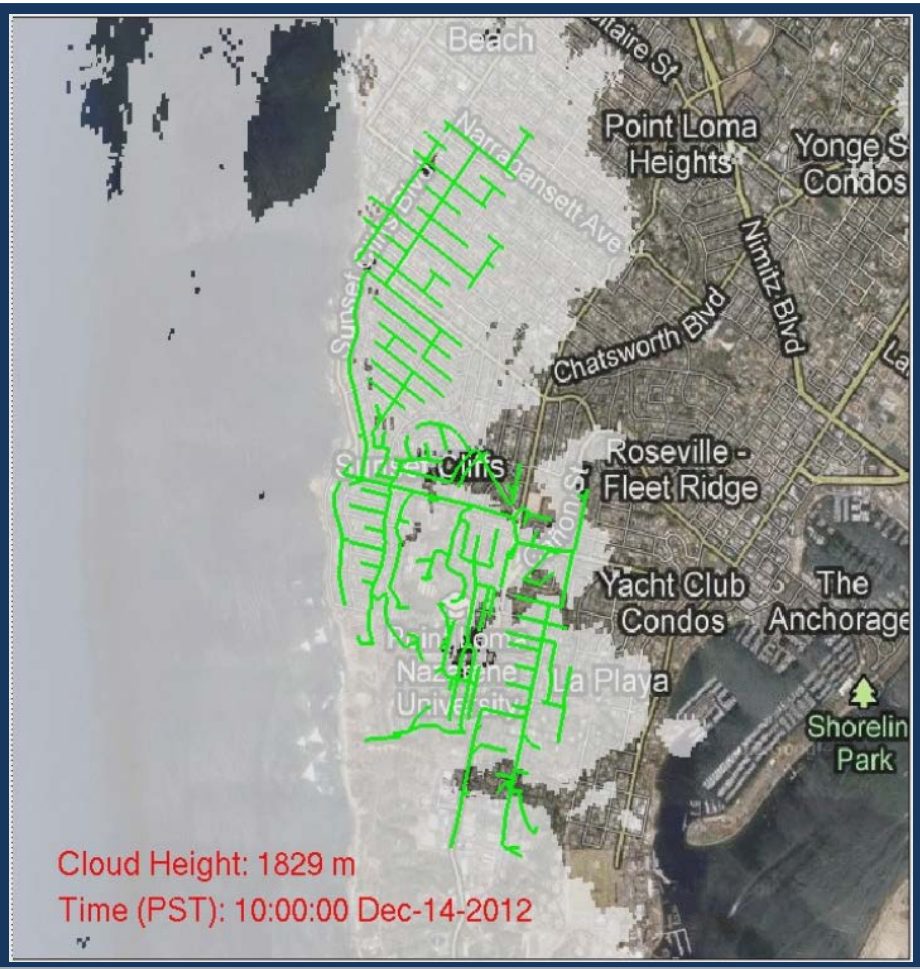
Sky Imager Forecasting for Distribution System Operation



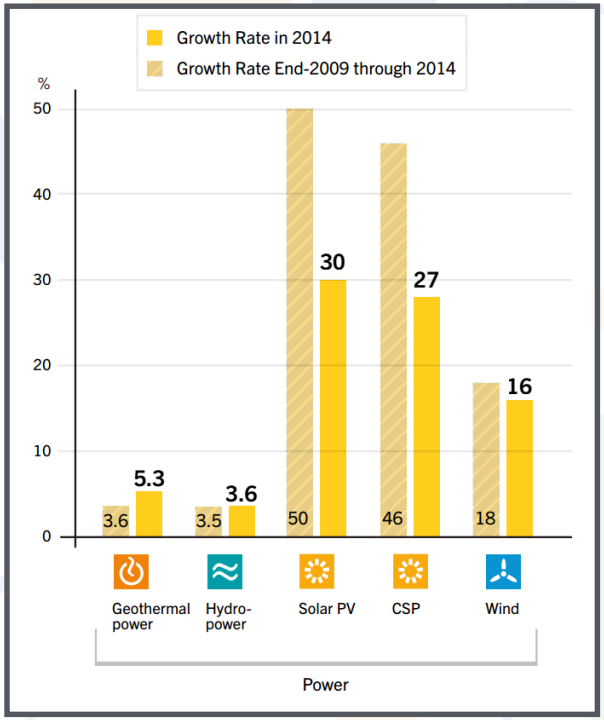
Projection of clouds using sky imagery on a feeder in San Diego

Andu Nguyen
Pablo Ubiratan
Vahid Dasfani
Keenan Murray
Oytun Babacan
Jan Kleissl

UCSD SRAF
solar resource and forecasting laboratory

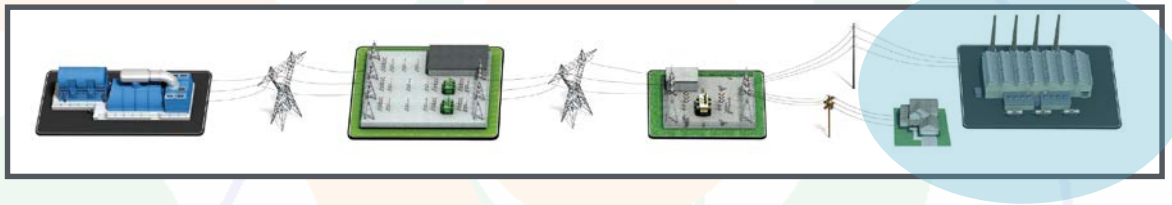
University of California, San Diego, Department of Mechanical and Aerospace Engineering, La Jolla, California, USA

Electric grid is transforming.



Solar is growing fast worldwide.

- More than 60% of *all photovoltaic (PV) capacity in operation worldwide* at the end of 2014 was added over the past three years



PV on distribution systems is growing even faster.

- U.S. added over 2 GW PV on distribution systems in 2015, growing 66% from 2014.

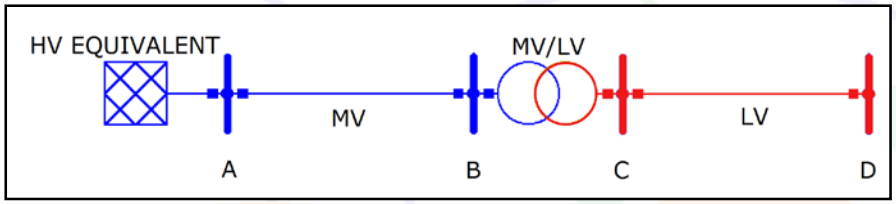
Grid is transforming but utilities cannot always cope with rapid expansion.

- 2014, Japan: Suspension of new grid connections for solar PV (after an addition of 9.7 GW solar PV in 2014)
- 2015, Hawaii: Restructuring the net metering program

[1]: REN21. Renewables 2015 Global Status Report [2]: SEIA/GTM Research Solar Market Insight 2015 Q4
[3] GE "Modular Substation Automation"

PV Affects Voltage

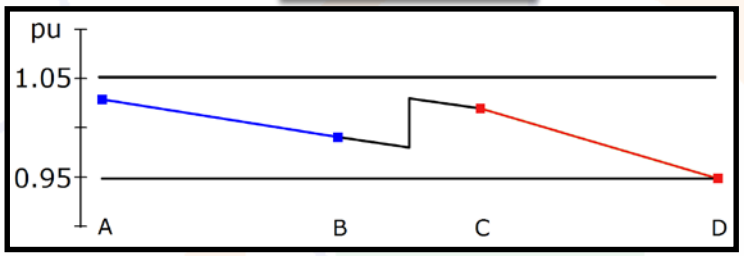
Consider a simplified power system

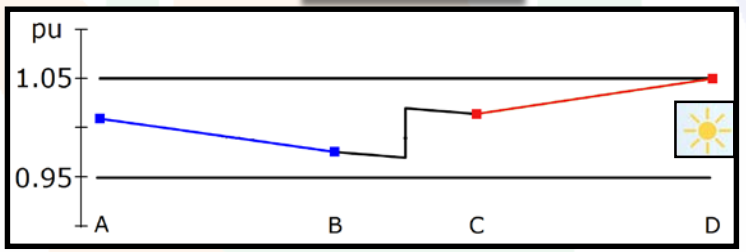


base case

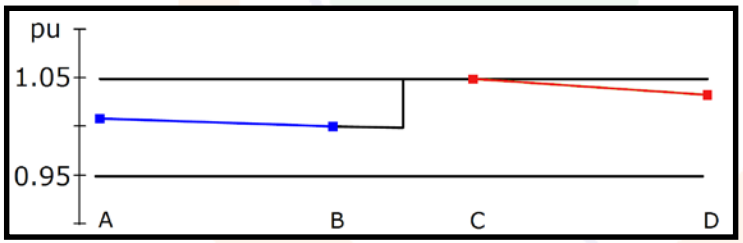
with PV

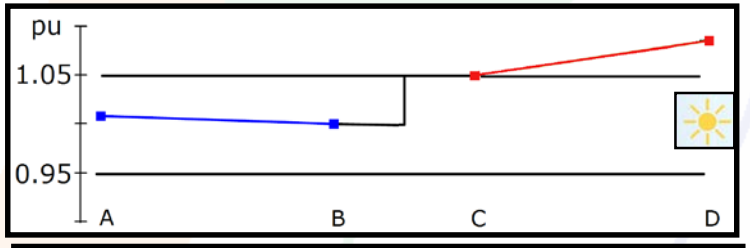
Max. Load

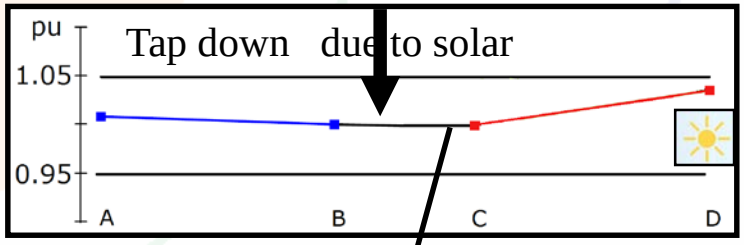




Min. Load







Transformer On-Load Tap Changer

[1]: IEA, Report IEA-PVPS T5-10, 2002

Outline

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I. High-Res Solar Data Input
   - Sky Imager

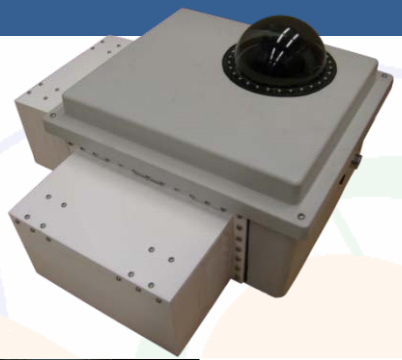
II. Distribution System Simulations
   - Distribution System Simulation (OpenDSS)
   - Feeder properties

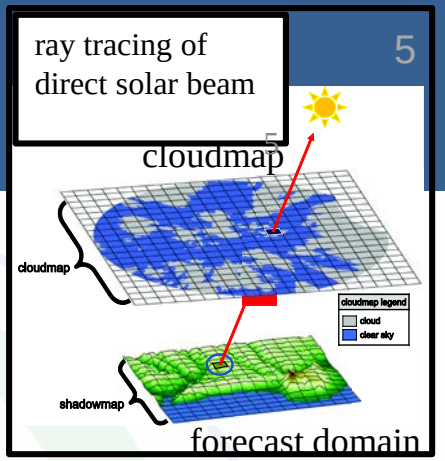
III. High PV Penetration Impacts
   - Same (single) profile for all PV
     versus
     multiple (different) profiles for PV from sky imager

IV. Mitigating Impacts through Solar Forecasting

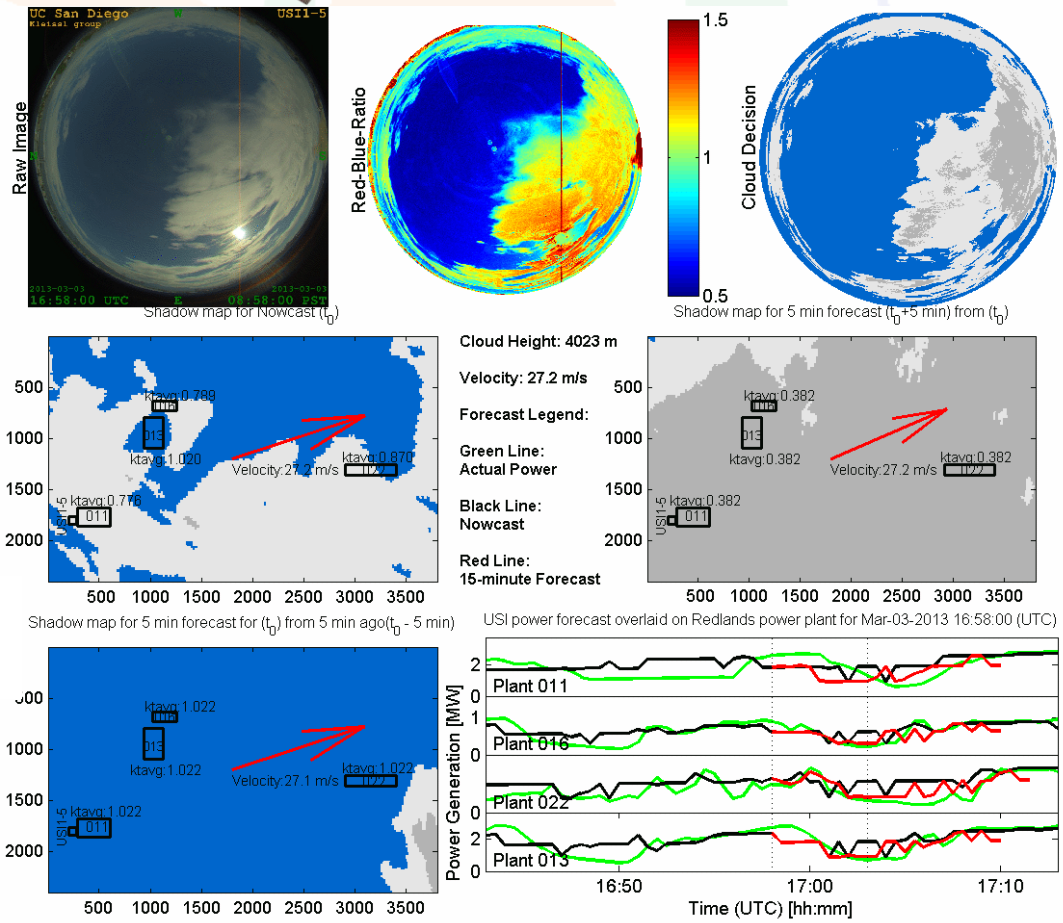
Solar resource assessment with sky imager

- 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





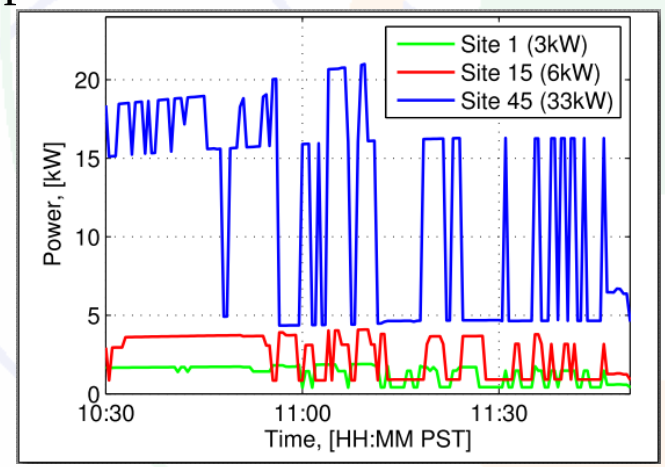
Sample of the forecasting process with sky imager



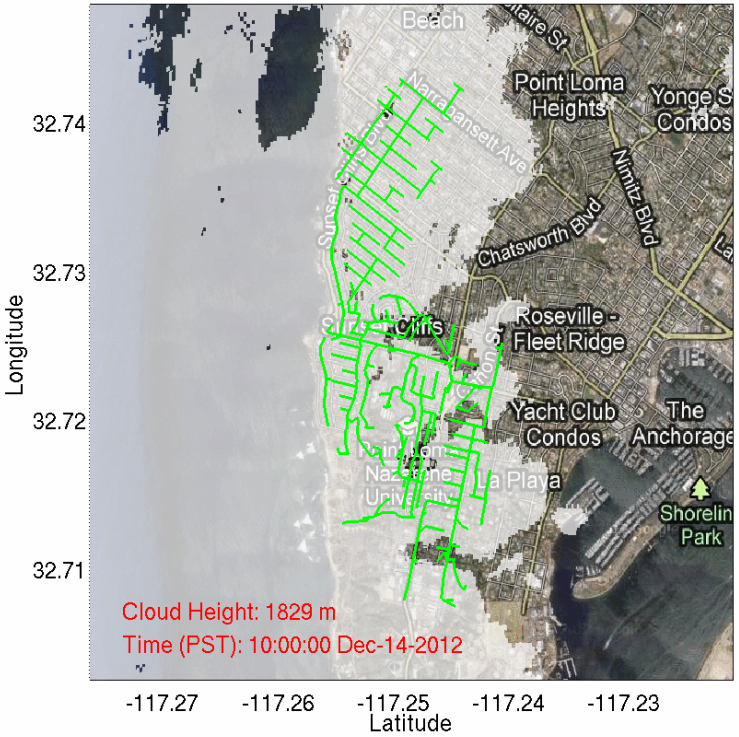
[1] Chow et al., 2011; [2] Yang et al., 2014

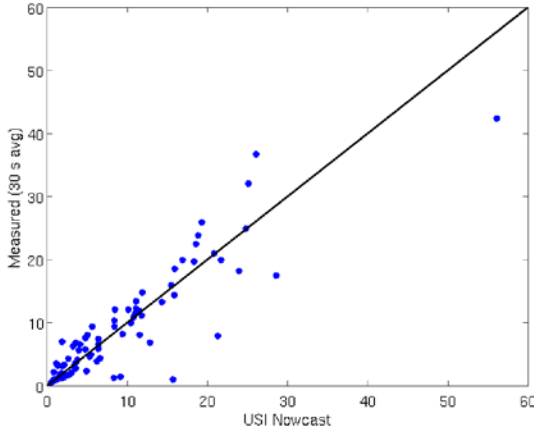
Sky imager resource assessment for DSS

- Novelty: High resolution and distributed generation profiles
- Based on the location of the PV systems, solar irradiance reaching the systems is calculated and converted to power forecast.



Cloud overlay on distribution feeder





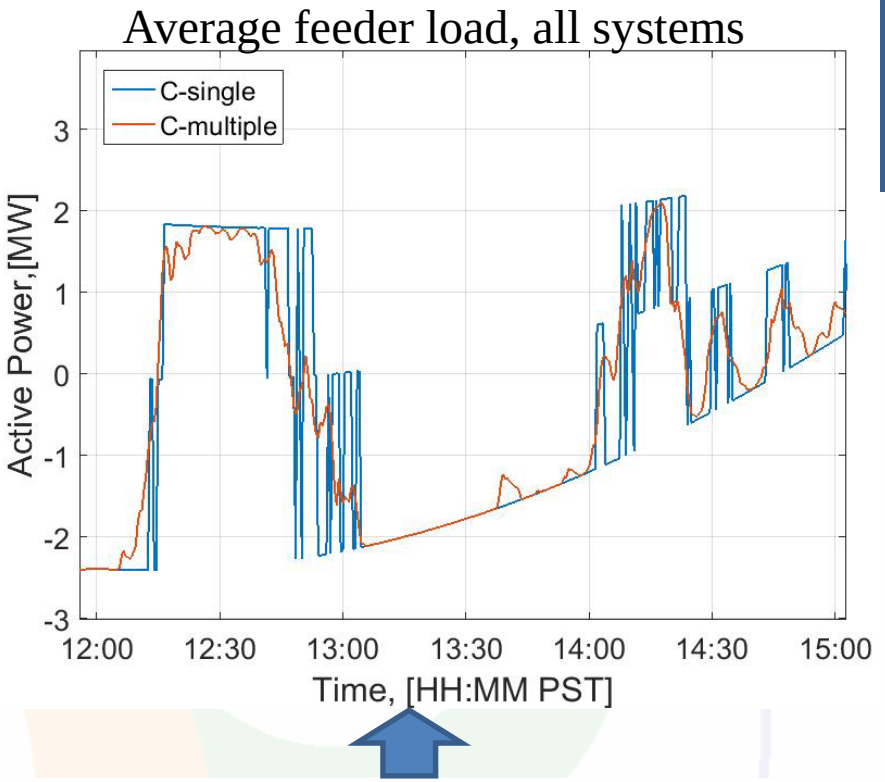
Daily variability index comparison against ground measurement:
Corr coef = 0.90, MBE = 1.6, MAE = 2.0

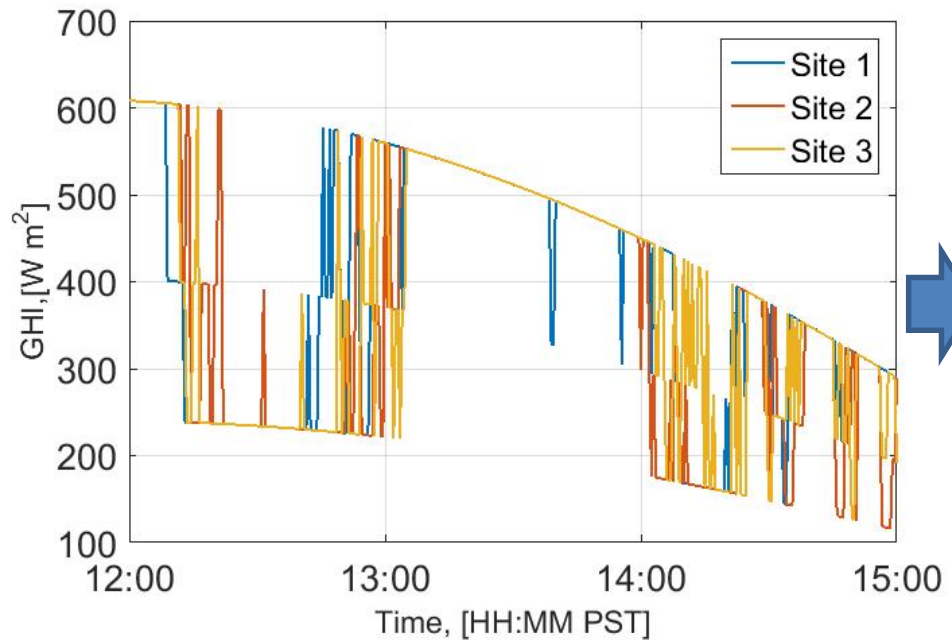
[1] Nguyen at. al 2014

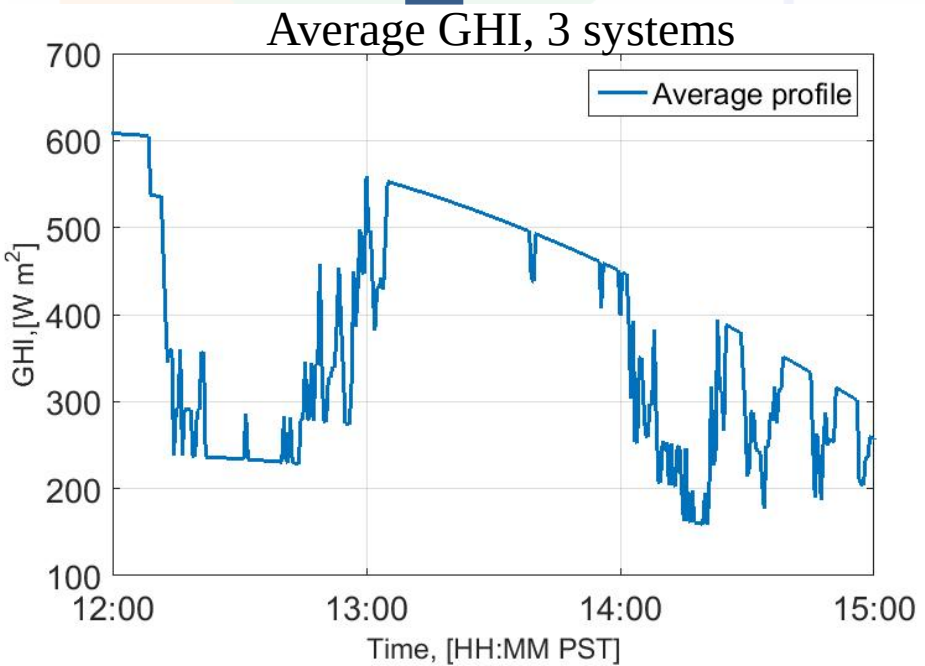
Solar Resource Assessment

Impacts of Variabili

- Spatiotemporal variability of clou power output
  - No impact in clear conditions. Small
  - Large reduction in variability in part
- Reduction in voltage variability c







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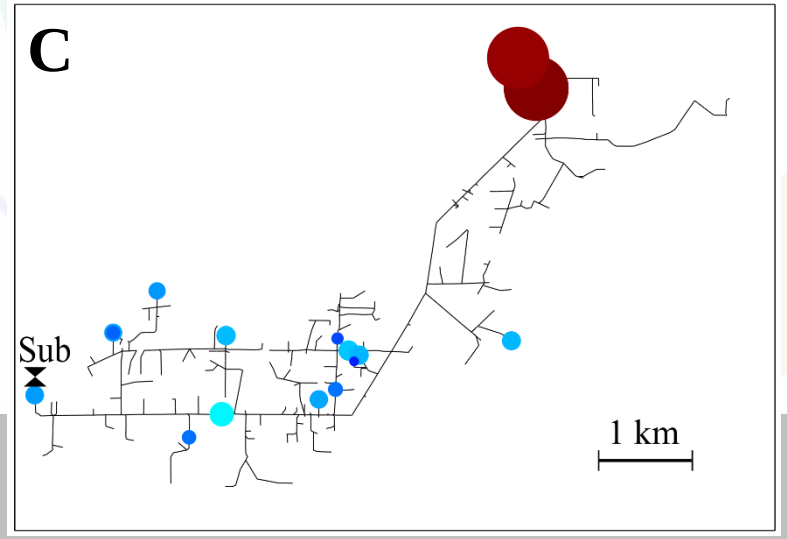
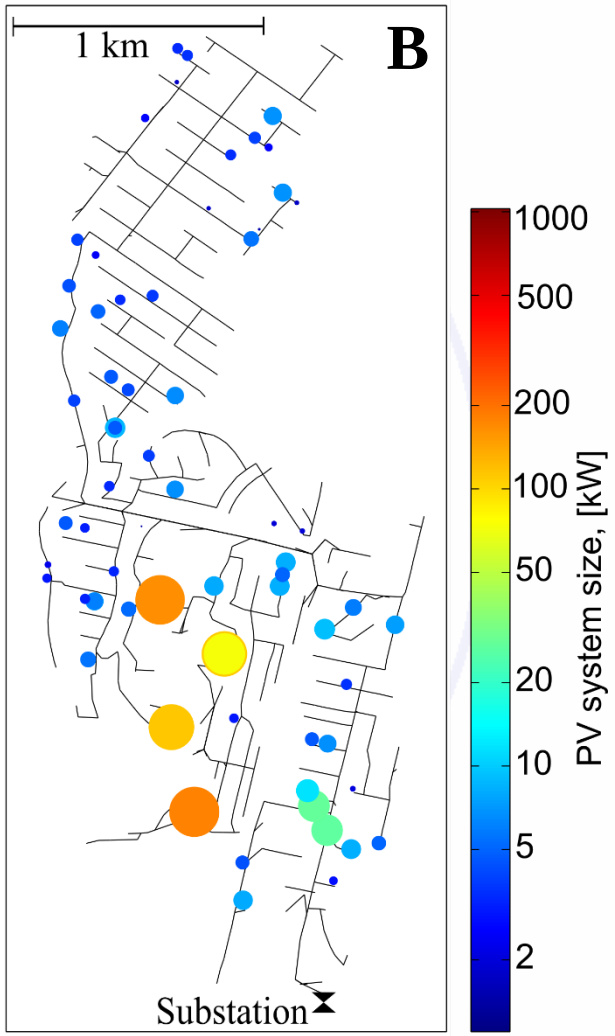
II. Distribution System Simulations

Distribution Feeder Properties

- Urban and rural feeders
- PV systems up to 2MW
- PV penetration levels from 0% to 200%.
- Generated based on properties of existing systems (azimuth, tilt, size)

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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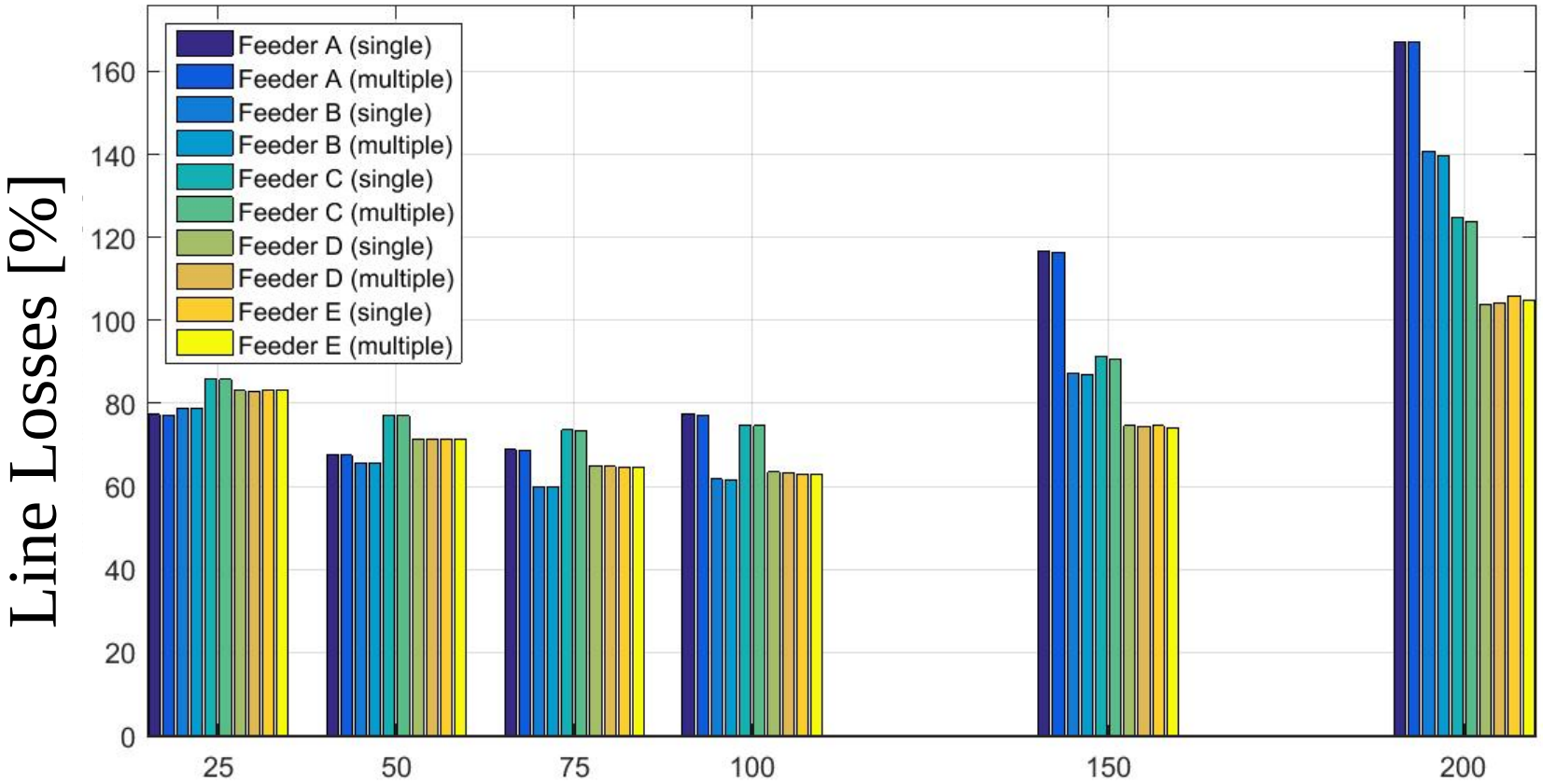
III. Reduction of PV Impacts Compared to the Standard Approach (Single Profile)

Line Losses

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



Tap Operations (TO)

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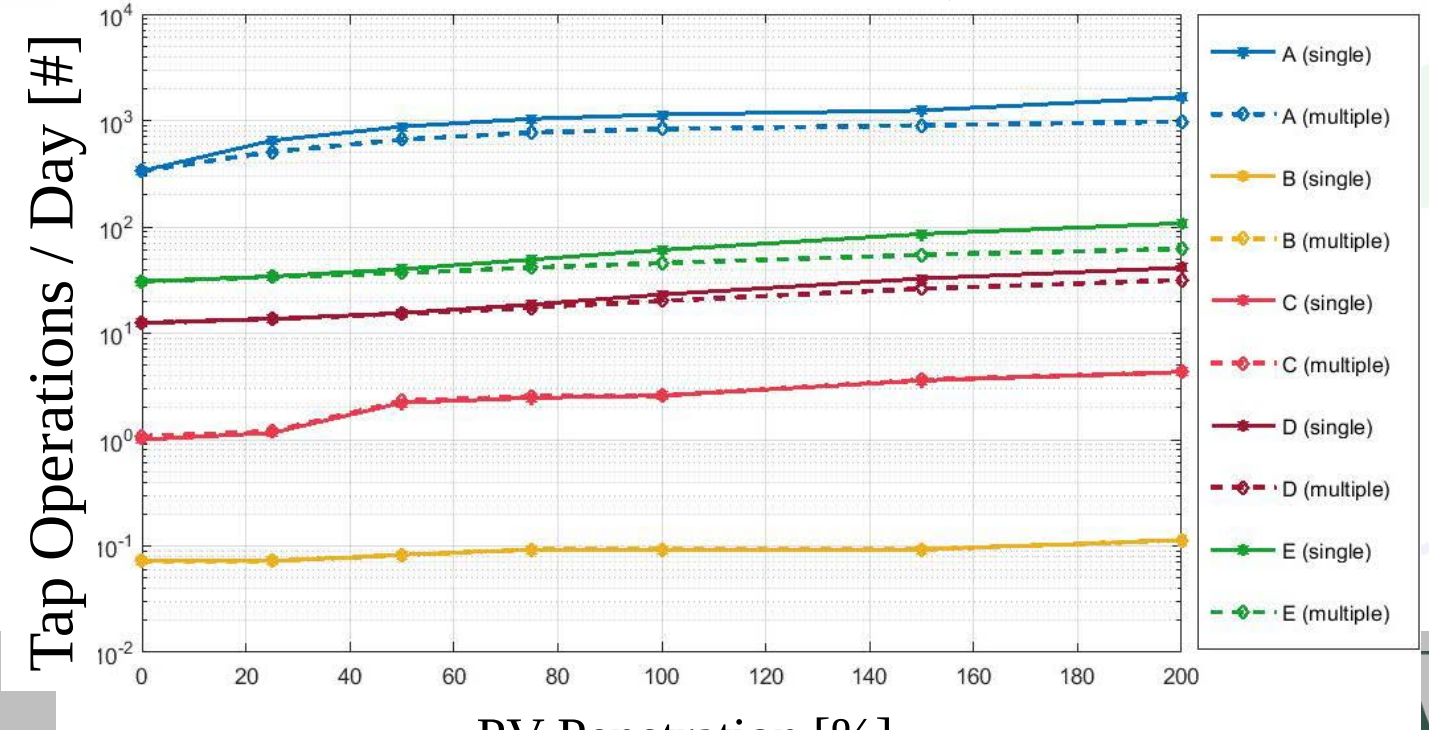
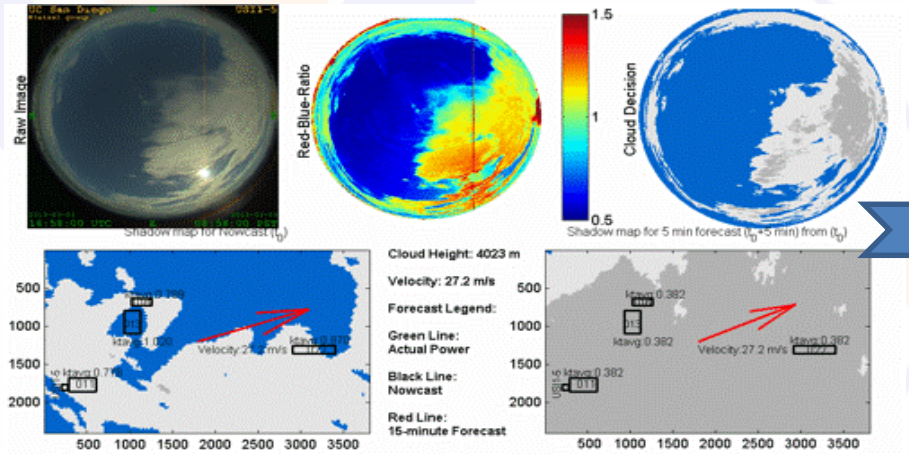
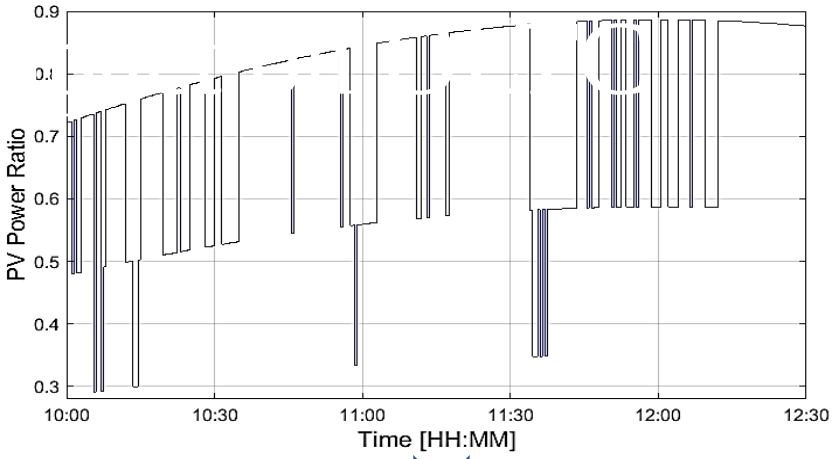
- Daytime TO increase with PV penetration
  - Large range of TO from << 1 to 100s per day
- Same PV profile (single) overestimates TO
  - 8% for 25% pen to 46% overestimation for 200% penetration
  - 70% overestimation for feeders A, E

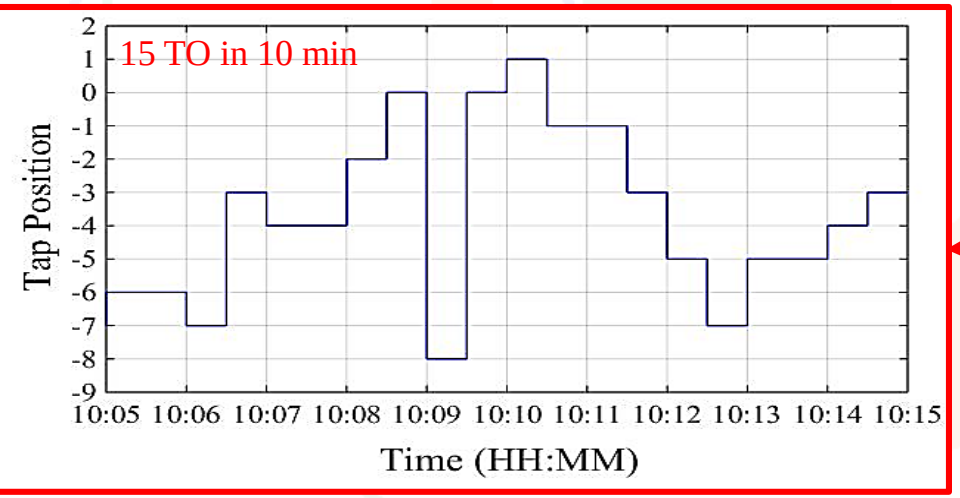


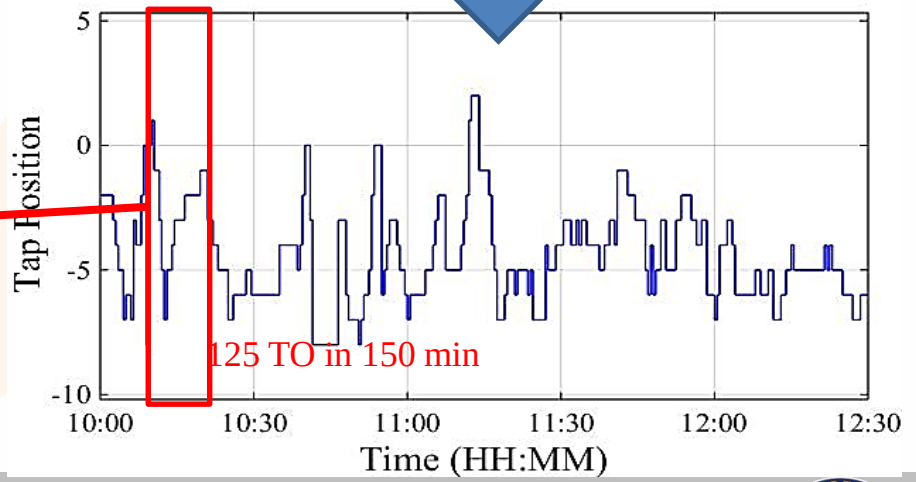
Log scale!

IV. Mitgating Tap Operations through Solar Forecasting





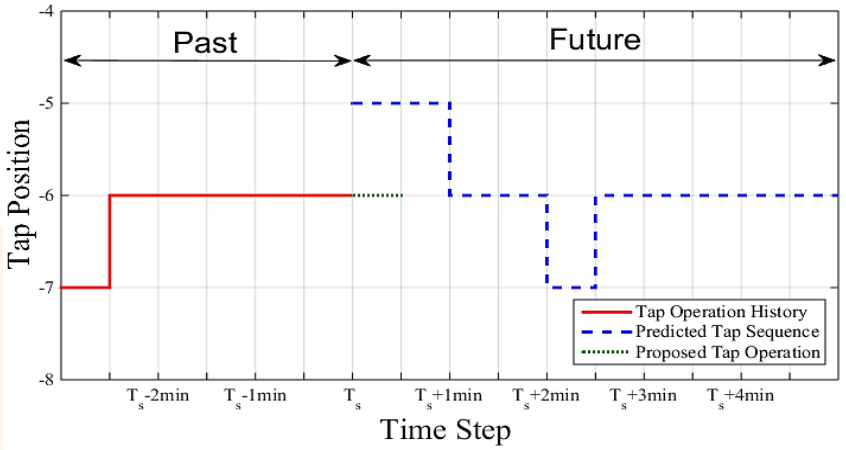


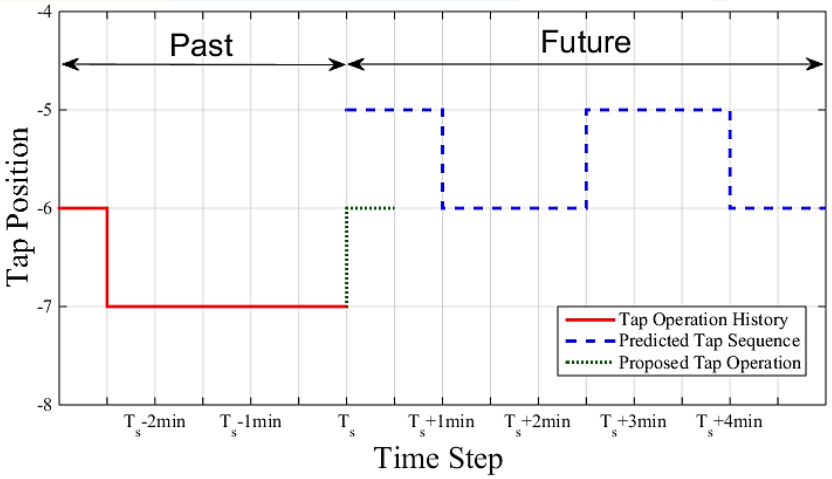


Approach: Use forecast to reduce TO

- At each time:
  - Simulate the grid for forecasted PV outputs for the next 15 minutes
  - Observe the projected tap positions
  - Rule 1:
    - Observation: Tap reversal
    - Action: No tap operation
  - Rule 2:
    - Observation: Varying tap on one side
    - Action: Minimum-depth TO
- Go to next time step

- Forecast update frequency: 5 sec
- Solution time: less than 3 sec

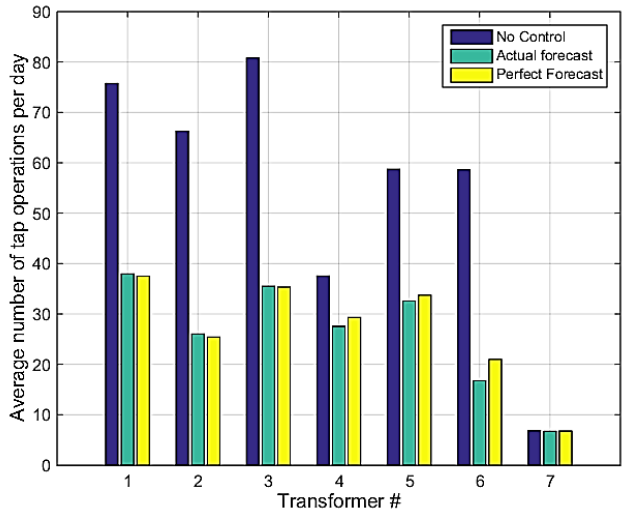


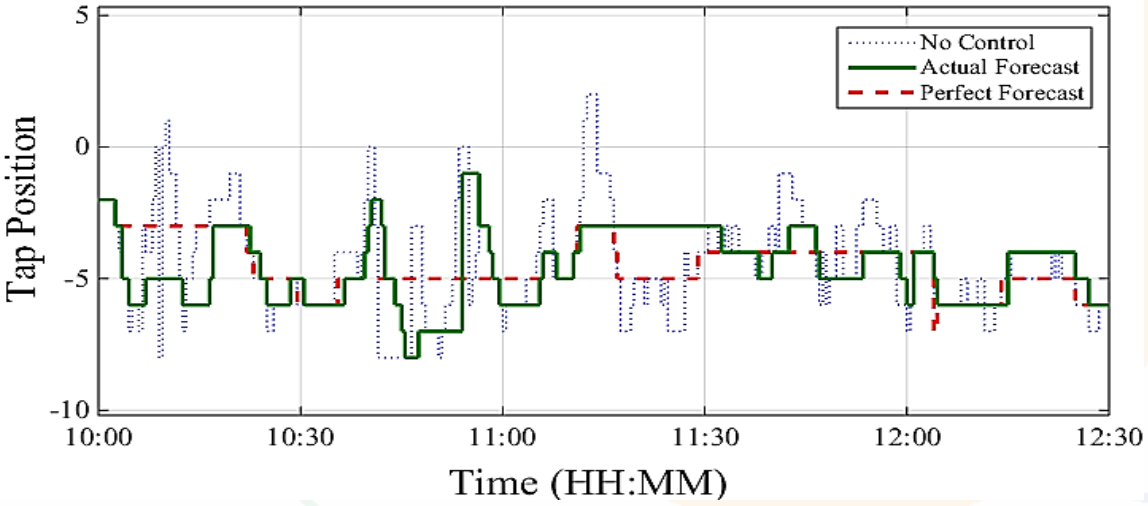


Simulated TO Reduction

- 100% PV penetration
- #TO on Jan 19, 10am~12:30pm
  - No control: 125 TO
  - Actual forecast: 46 TO
  - Perfect Forecast: 15 TO

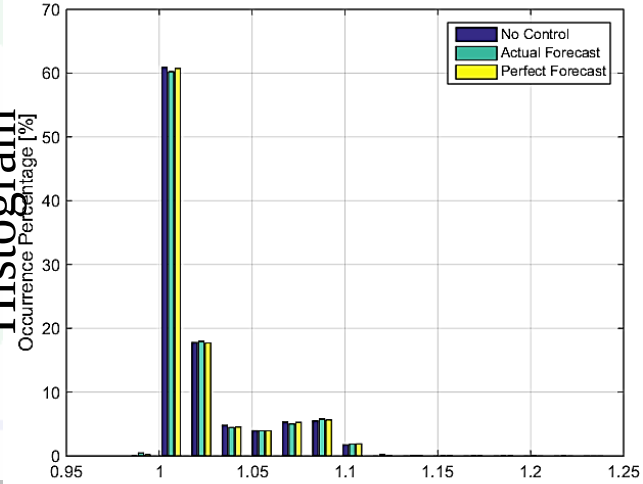
TO Depth





Voltage Quality Impacts

Histogram



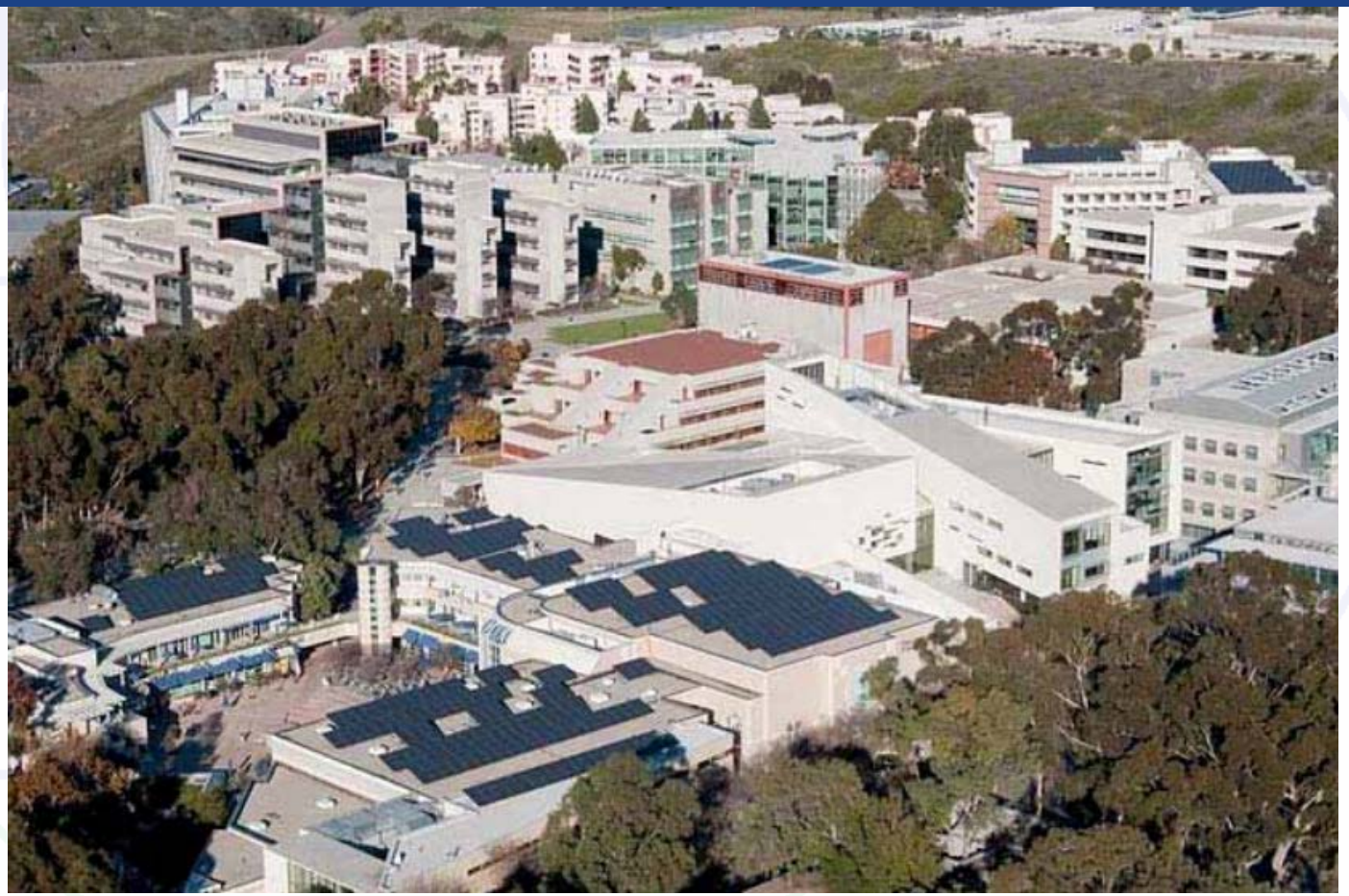
Maximum Voltage

Conclusions

- 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
- Solar forecast reduces unnecessary TOs
  - 60% reduction for high PV penetration
  - Not sensitive to forecast error

Thank you!

Funding: California Solar Initiative RD&D Program



Contact Jan at: jkleissl@ucsd.edu

SRAF Solar Resource Assessment and Forecasting Laboratory UCSD