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Solar Variability Reduction Using Off-Maximum Power Point Tracking and Energy Storage Systems

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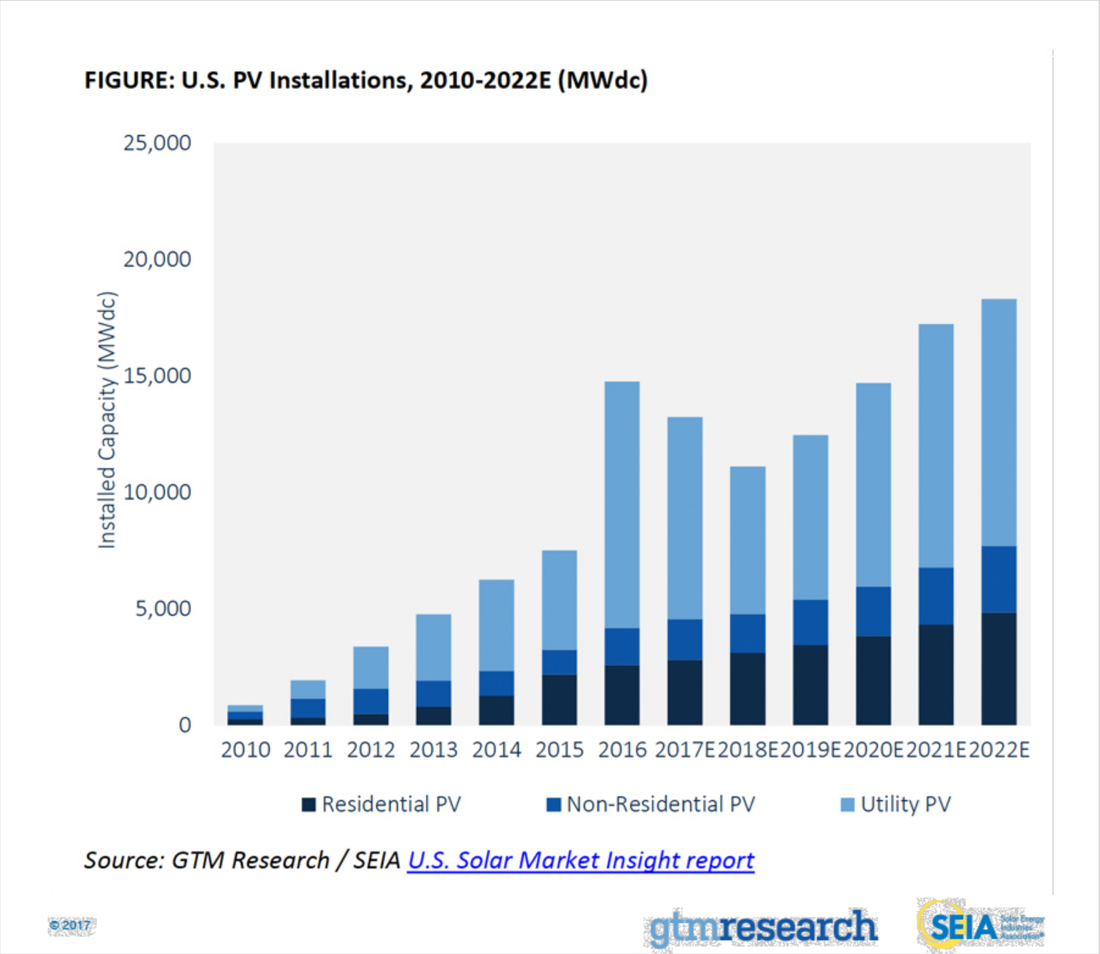
Supported by The Grainger Center for Electric Machinery and Electromechanics (CEME)

Outline

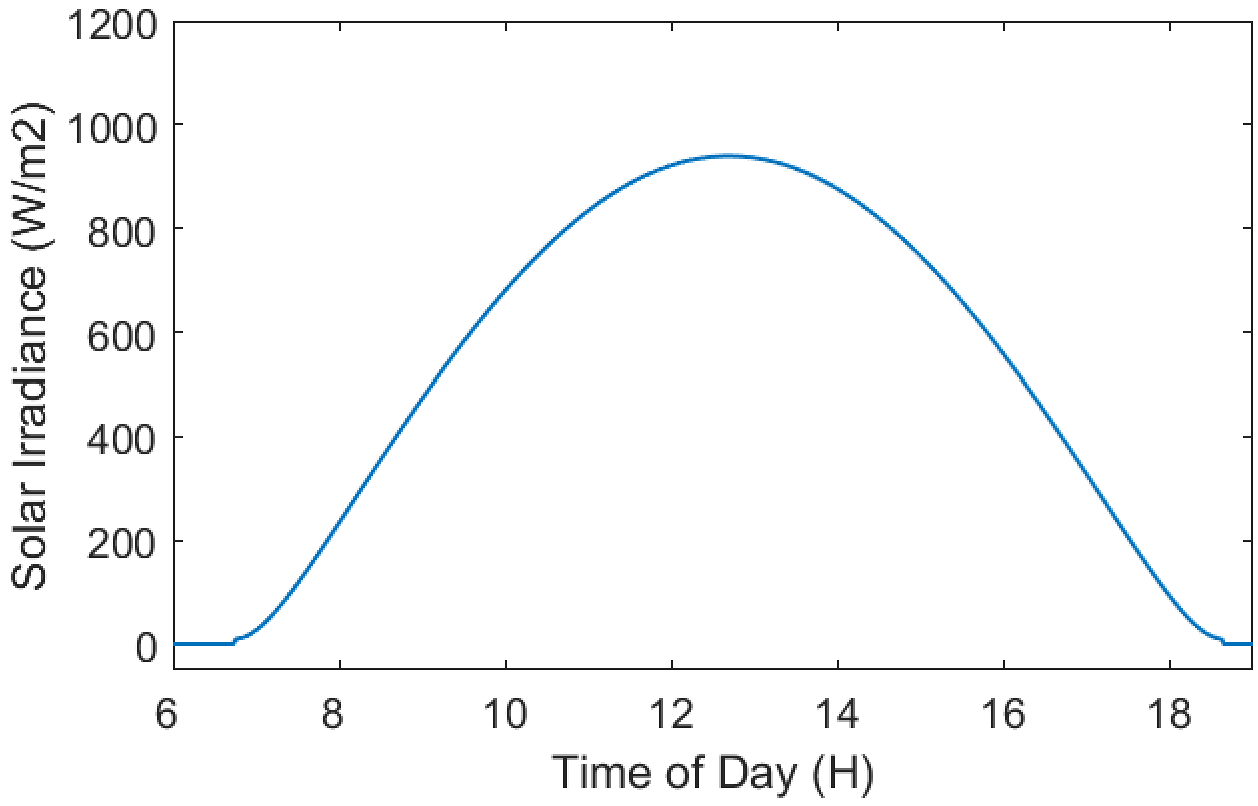
- Motivation for Research
  - Increasing Solar Capacity
  - Non-ignorable variability
- PV Control Strategy
  - Overview
  - Single plant simulation results
- Conclusion

Solar Growing Rapidly in USA

- US Solar Capacity
  - 2010: ~2.5 GW
  - 2016: ~45 GW
- No rotational inertia
  - Step-like changes in generation
- Poor predictability w/o forecasting
  - Negative load



PV Arrays Track Irradiance Profile



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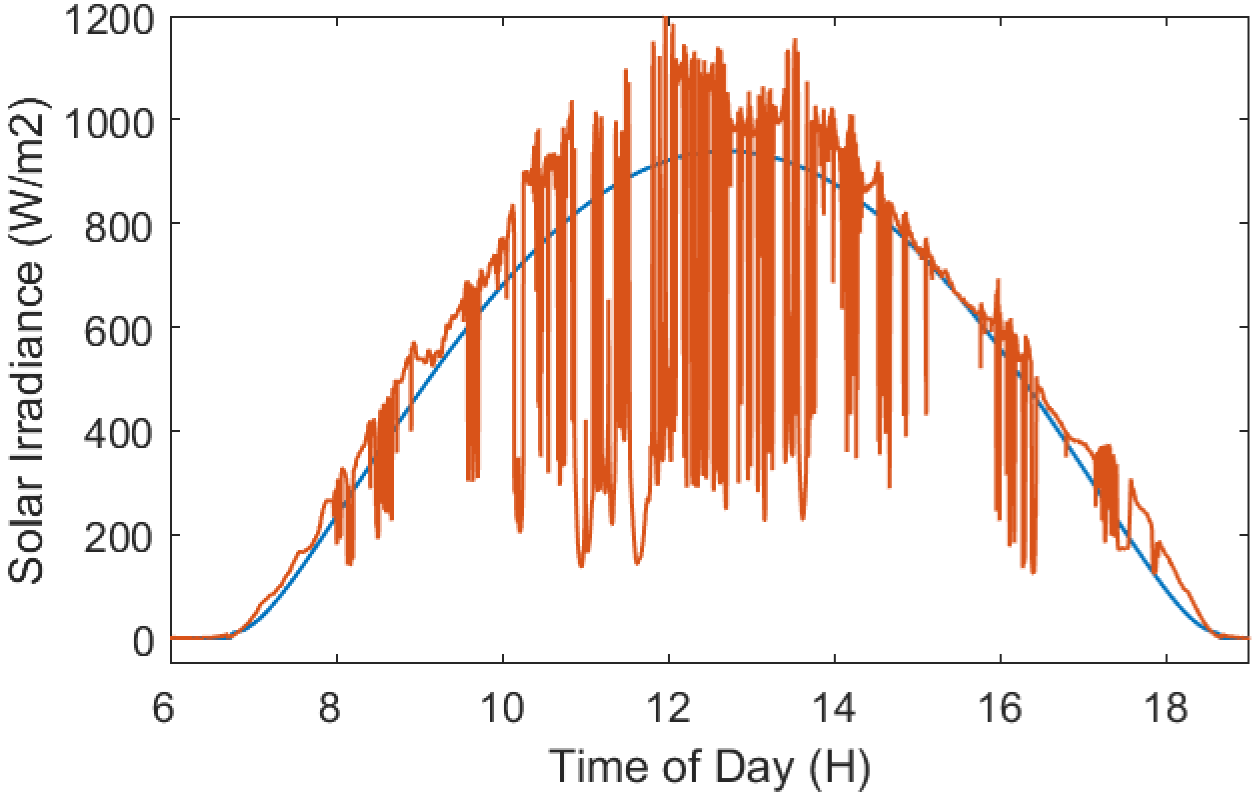

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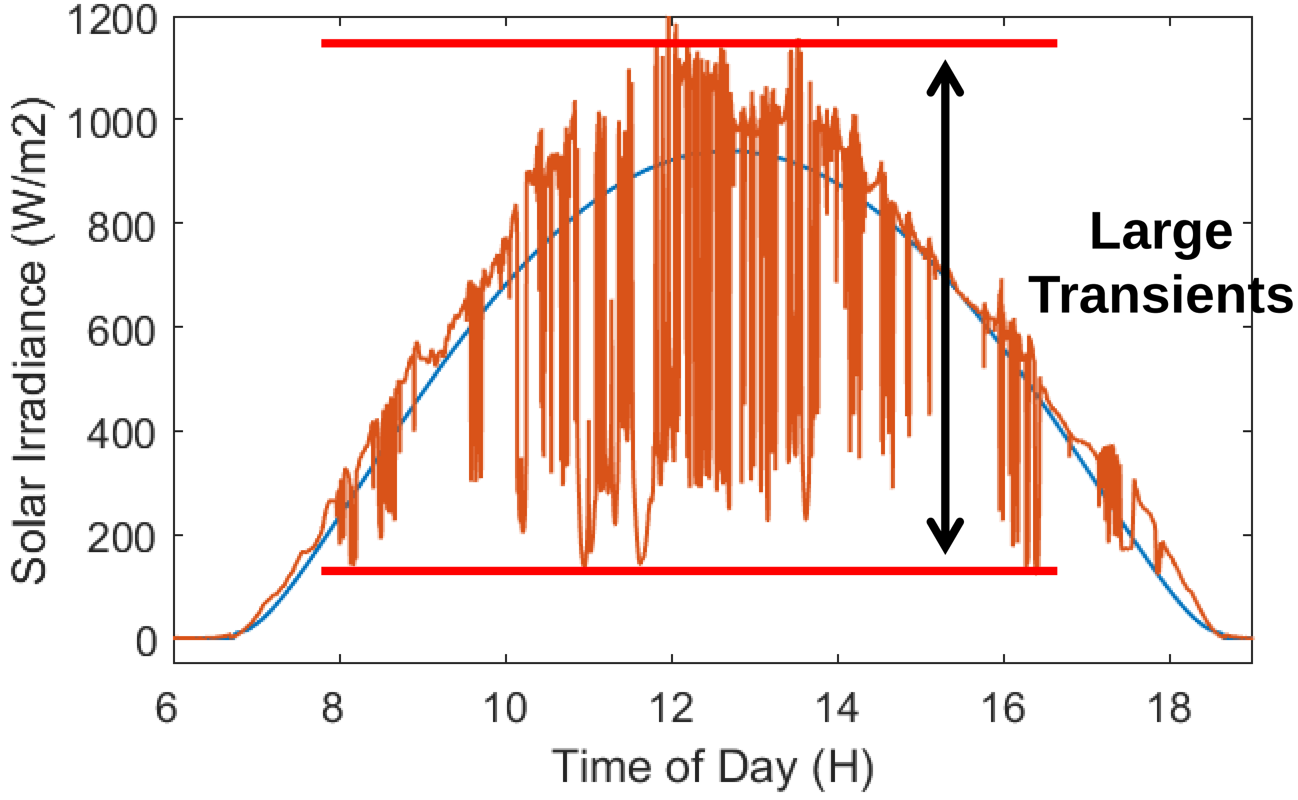
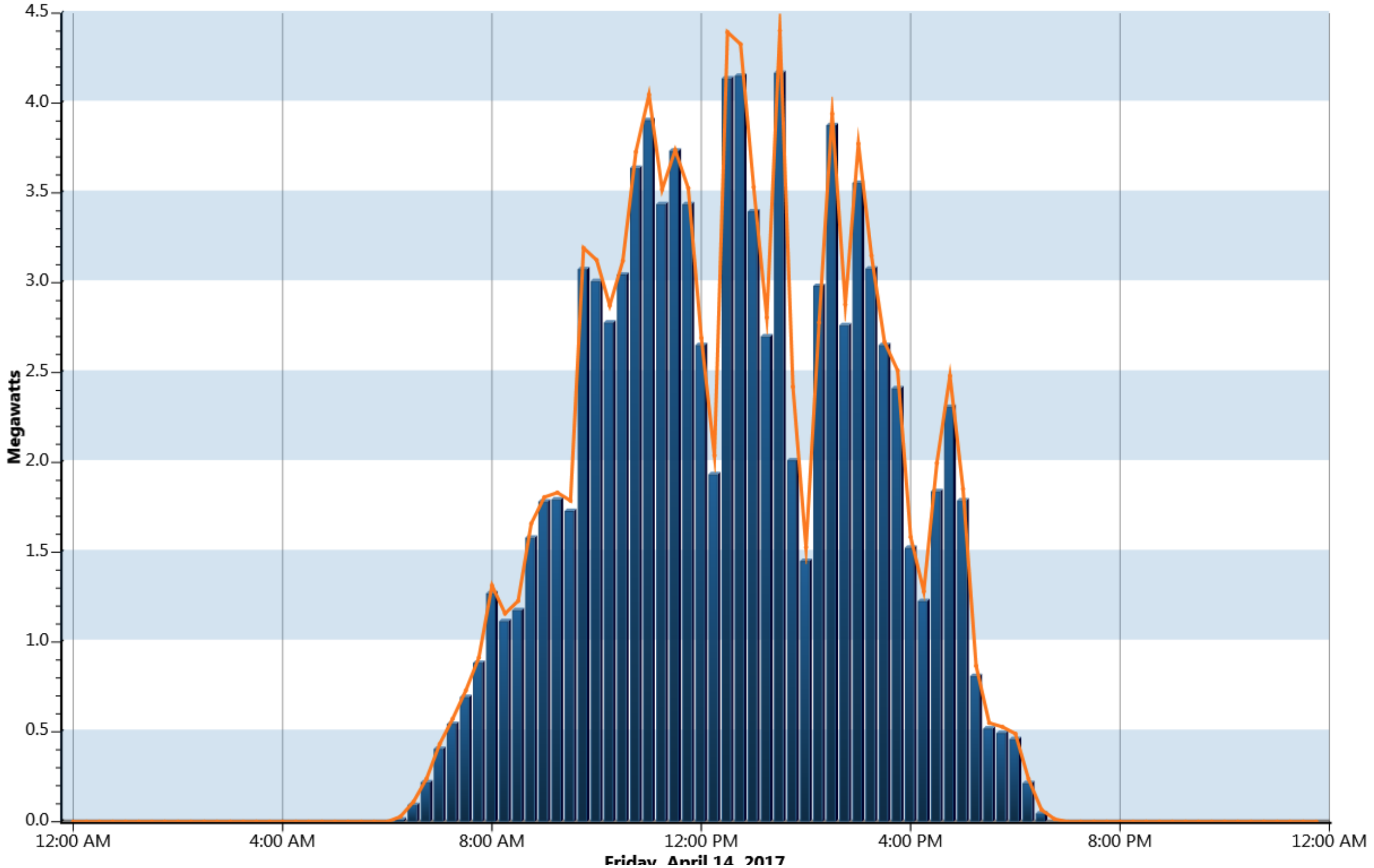


UoI Solar Farm



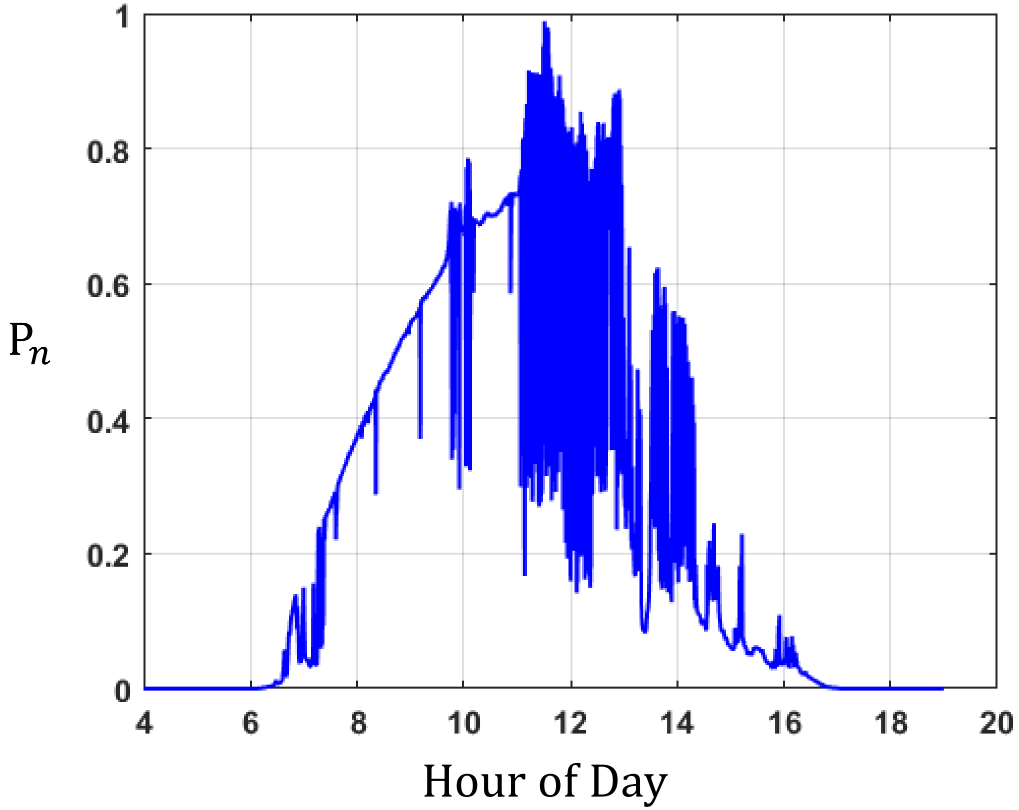
https://icap.sustainability.illinois.edu/project/solar-farm

Variability in Arrays

- Rely on the power grid to absorb transients
  - Increase spinning reserves with solar penetration
  - Limit solar capacity
- Rely on energy storage systems (ESS) to absorb transients
  - Battery, flywheel, capacitor, compressed air etc
  - Expensive, sized to maximum transient magnitude
  - Replaced several times over life of array
- Motivation
  - Reduce some of the variability through PV array control

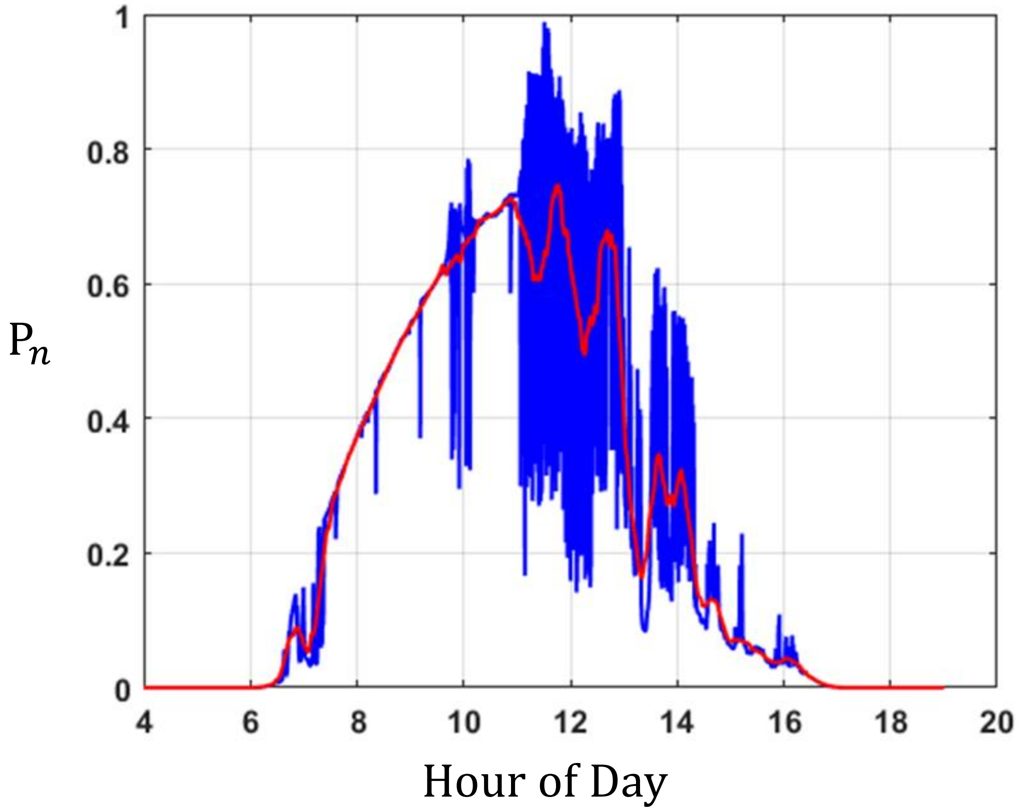
Standard Array Control

- Maximum Power Point Tracking (MPPT)
  - Best energy production
  - Greatest degree of variability
  - $P_n = \frac{P_{PV}}{P_{nameplate}}$

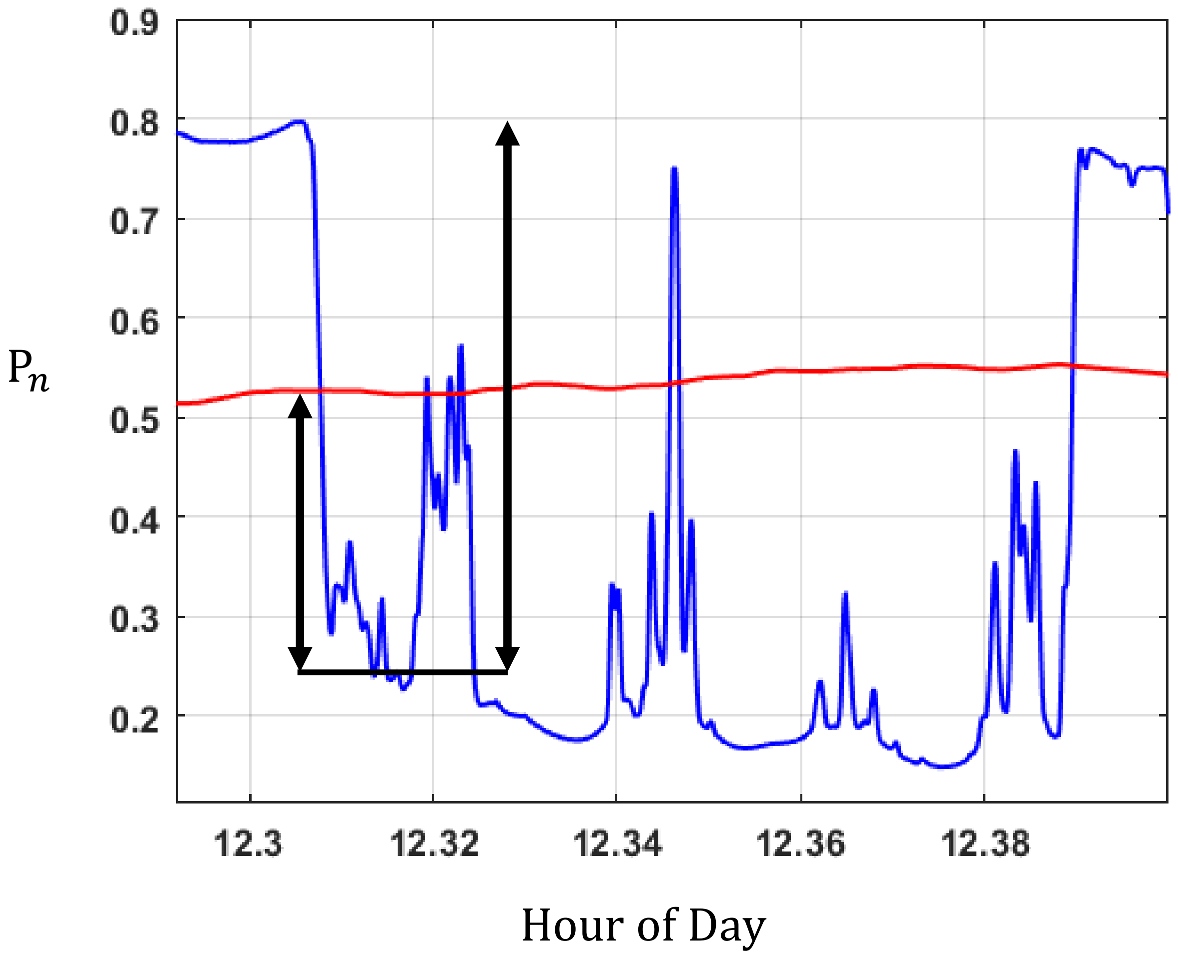


Proposed Array Control

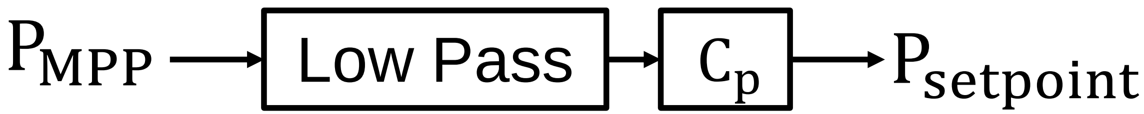
- Maximum Power Point Tracking (MPPT)
  - Best energy production
  - Greatest degree of variability
  - $P_n = \frac{P_{PV}}{P_{nameplate}}$
- Averaged MPP Set-point
  - Same energy production (if reachable)
  - Reduced variability (even if unreachable)
  - No high frequency variability (if reachable)



Reduced Set-point Helps Mitigates Step Changes



PV Plant Control

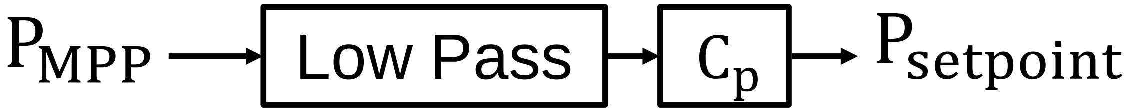


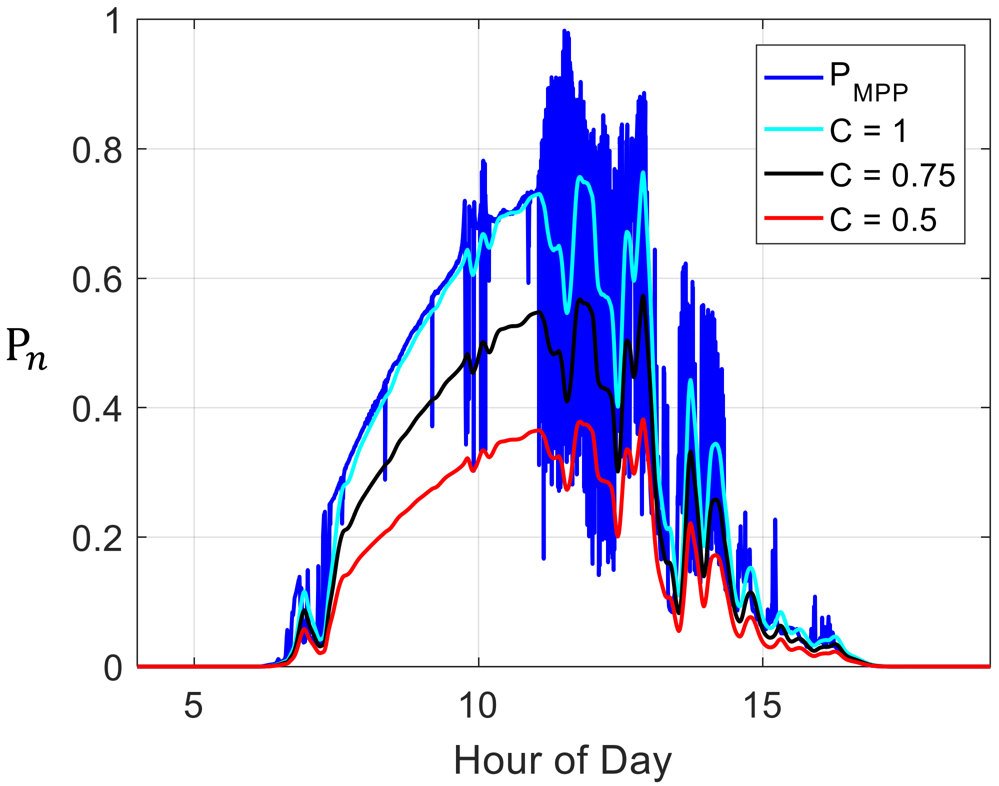
- Assumptions
  - Know P_{MPP}
  - Can operate plant anywhere up to P_{MPP}
- Low pass filter tracks low frequency (i.e average) of P_{MPP}
- Gain C_p is tuning parameter, $0 < C_p \leq 1$
- Goal: choose reachable setpoint such that

$$P_{PV} + P_{ESS} = P_{setpoint} = P_{grid}$$

Setting Gain Values

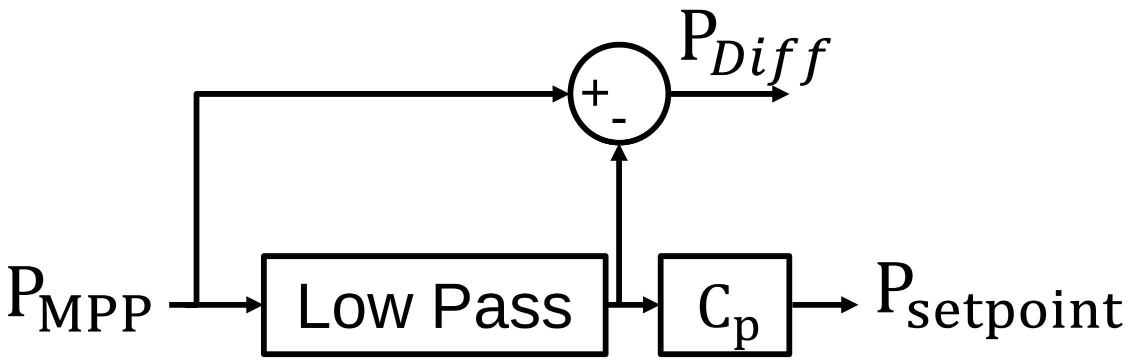
- Constant C_p gives bad performance
- Too high in variable intervals
  - Poor variability mitigation
- Too low in “calm” intervals
  - Poor energy harvest

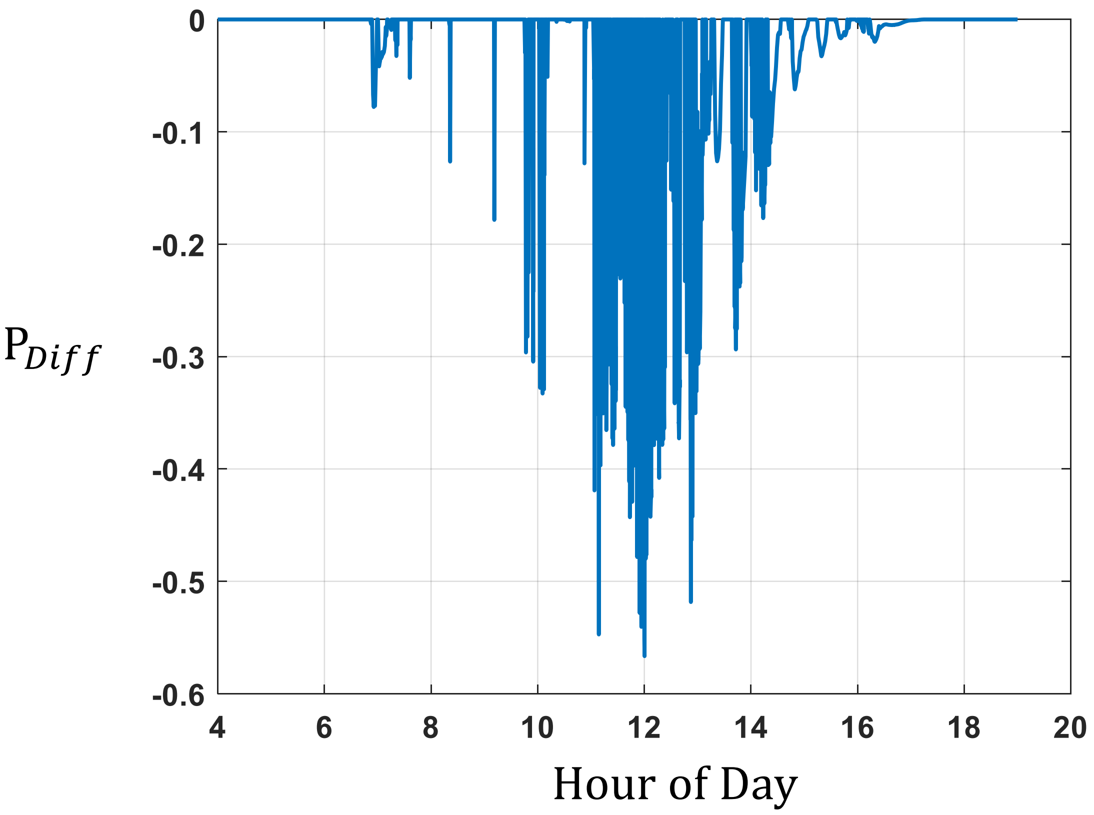




Adaptive Gain Values

- Update C_p throughout day
- Small error = low variability
- Large error = high variability

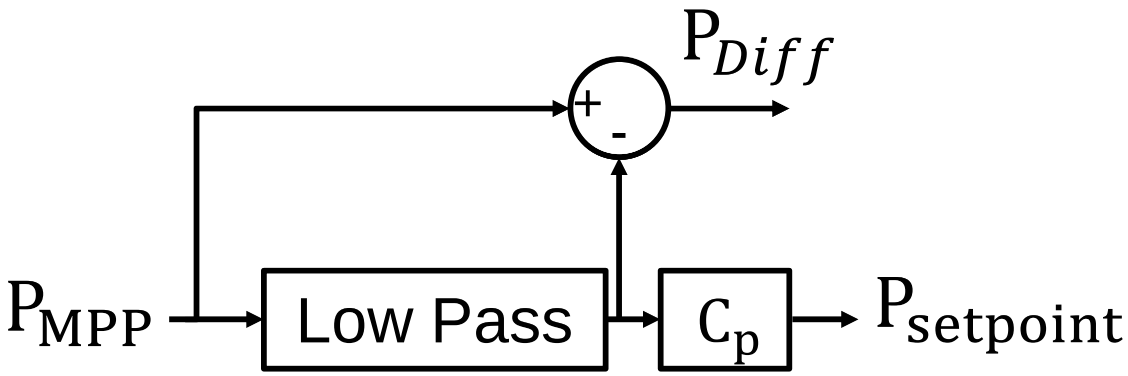


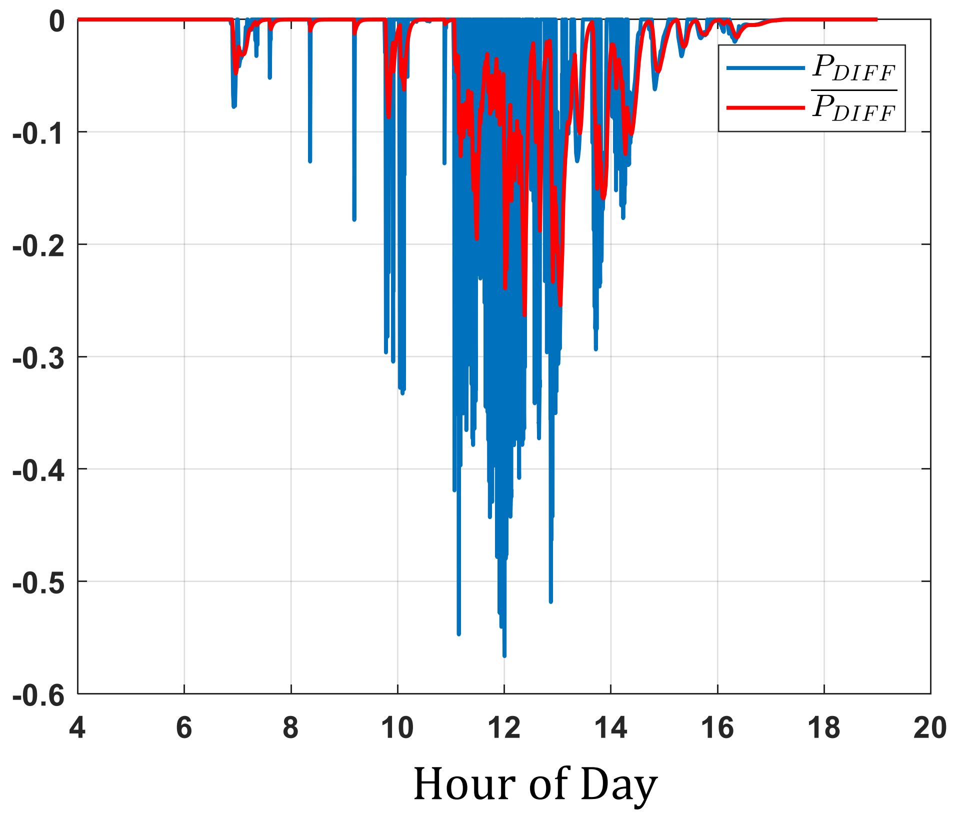


Adaptive Gain Values

$$C_p = \left(1 + k\overline{P_{Diff}}\right)$$

- k is tuning parameter based on:
  - Max. ESS Output
  - Cost of Variability





Linear Battery Models

$$0 \leq P_{Ch} \leq P_{Ch,Max}$$

$$0 \leq P_{Dis} \leq P_{Dis,Max}$$

$$E_{Bat}(t) = E_{bat}(t-1) + \eta P_{ch} \Delta t$$

$$E_{Bat}(t) = E_{bat}(t-1) + P_{dis} \Delta t$$

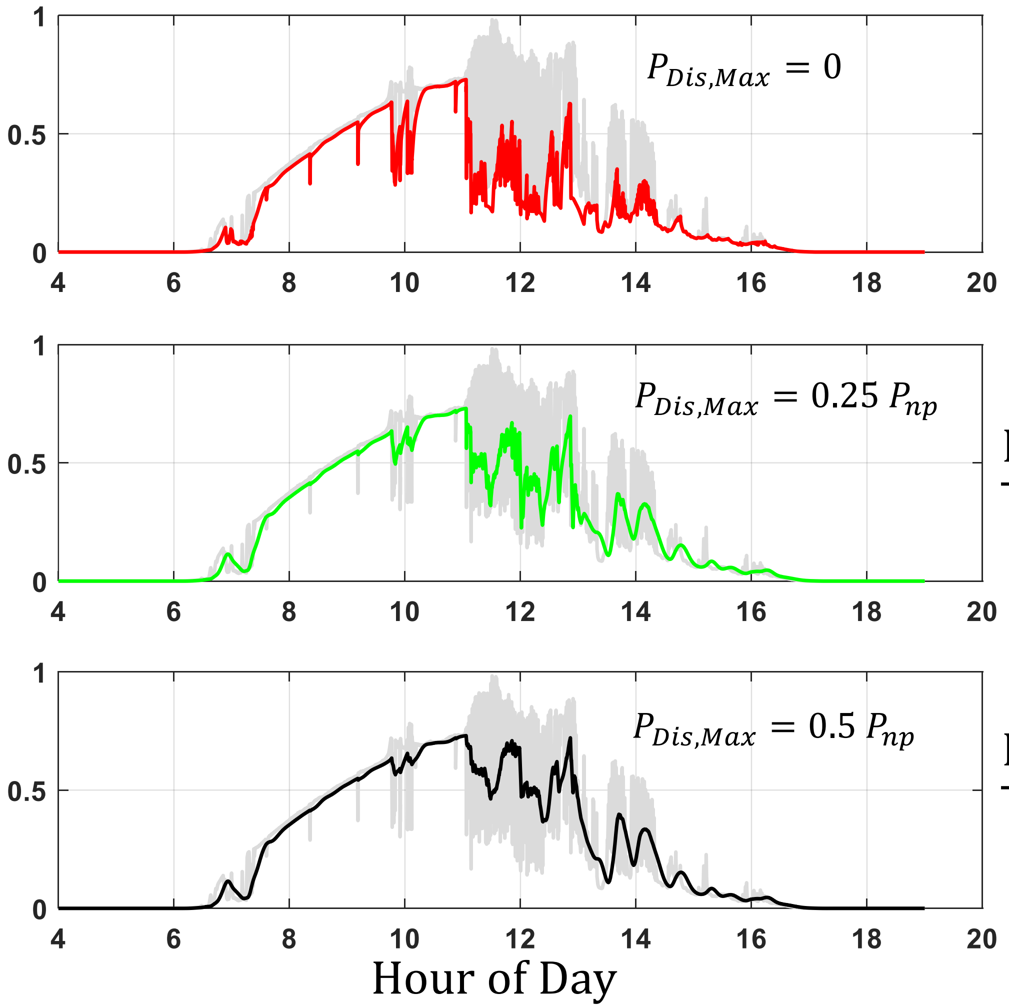
$$0 < E_{Bat}(t) \leq E_{Bat,Max}$$

Table 3: Tesla Powerwall Specifications [13]

Property	Value
Price	$3000
Capacity	7 kWh
Power	2.0 kW continuous, 3.3 kW peak
Efficiency	92%
Voltage	350 – 450 V
Current	5.8 A nominal, 8.6 A peak
Weight	100 kg
Dimensions	1300 mm x 860 mm x 180 mm

$$C\ rating \approx 0.5\ C$$

http://www.nrel.gov/docs/fy16osti/64987.pdf

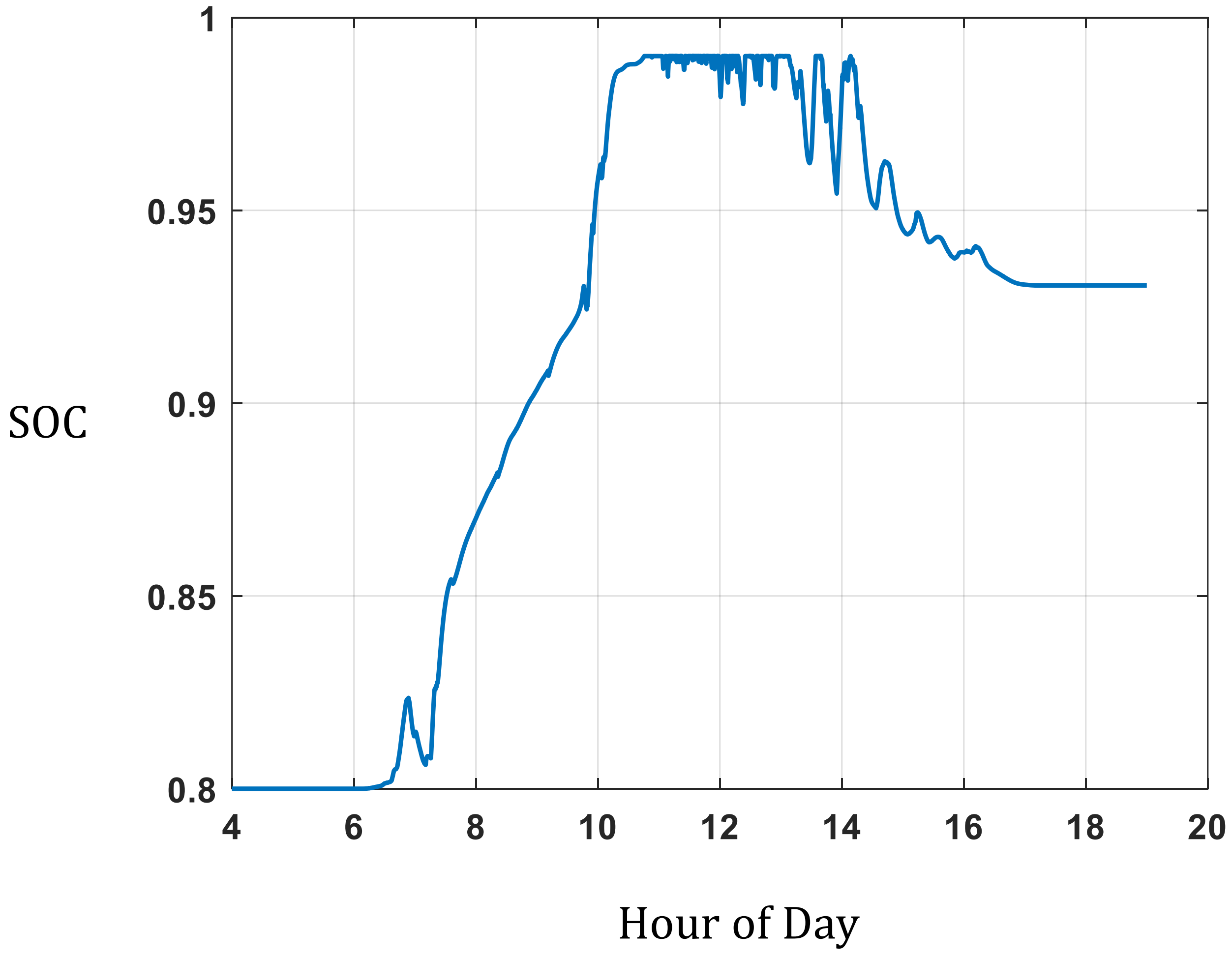


$$\frac{P_{PV}}{P_{MPP}} = 0.76$$

$$\frac{P_{PV.Bat}}{P_{MPP}} = 0.90$$

$$\frac{P_{PV,Bat}}{P_{MPP}} = 0.95$$

Battery State of Charge, $P_{Dis,Max} = 0.25\, P_{np}$

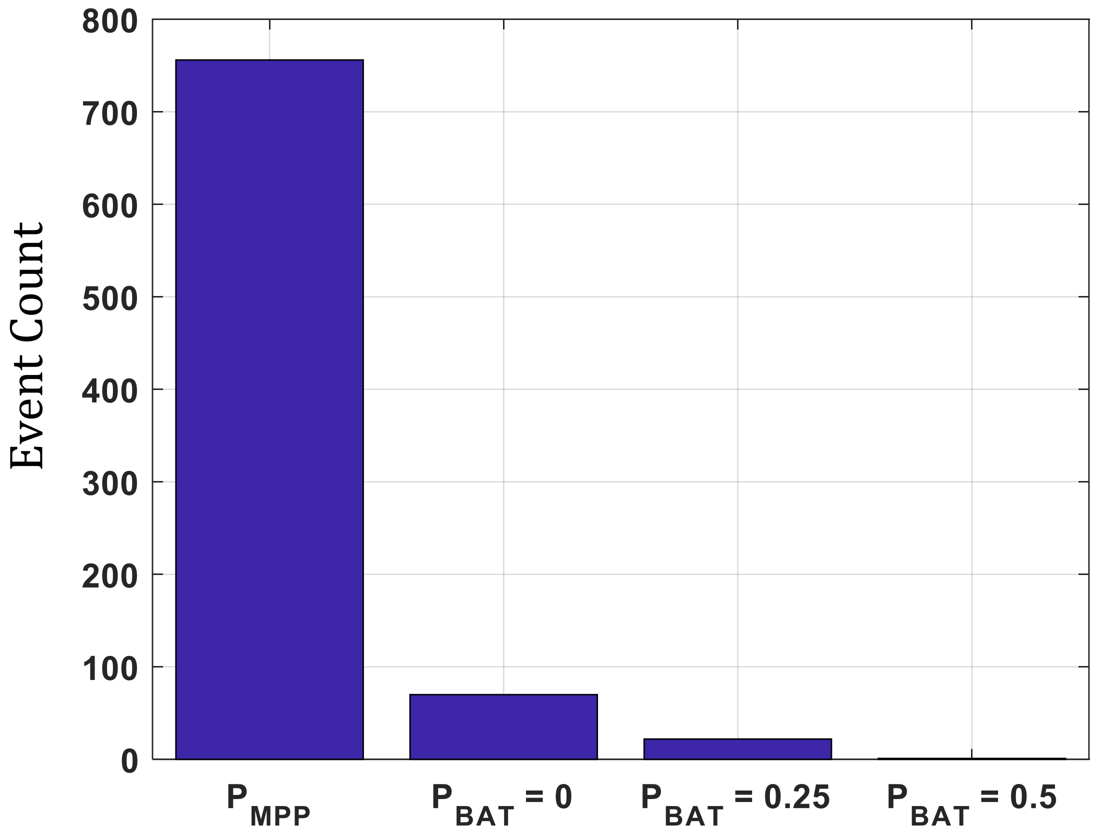


Variability Reduction: Ramp Rate Detection

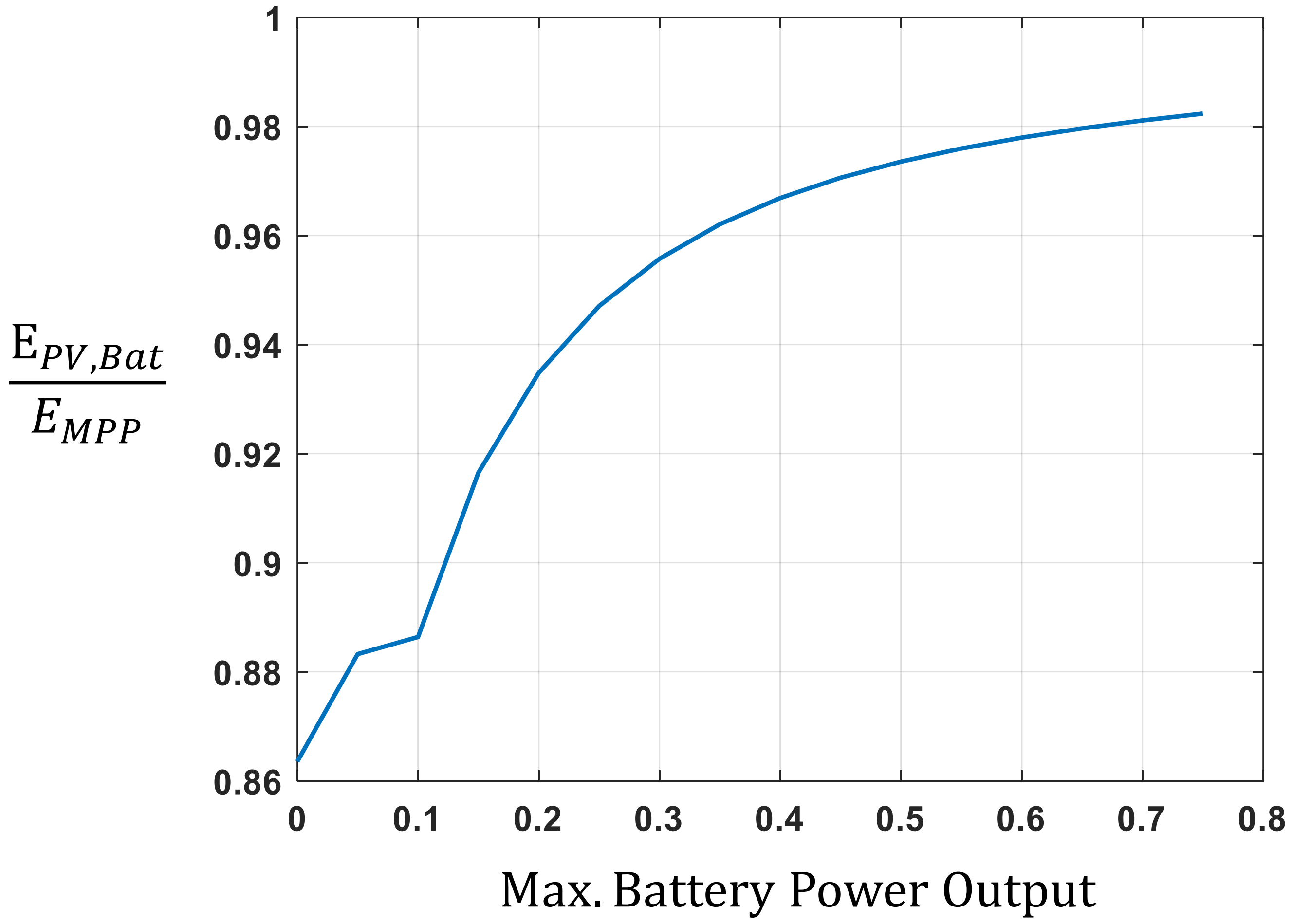
- $Ramp\ Rate(RR) = \frac{\Delta P}{\Delta t}$

- Let P_{max} be the rated nameplate power of the array

$$RR\ Violation\ Event = \frac{\Delta P}{\Delta t} > \frac{10\%\ P_{max}}{min}$$

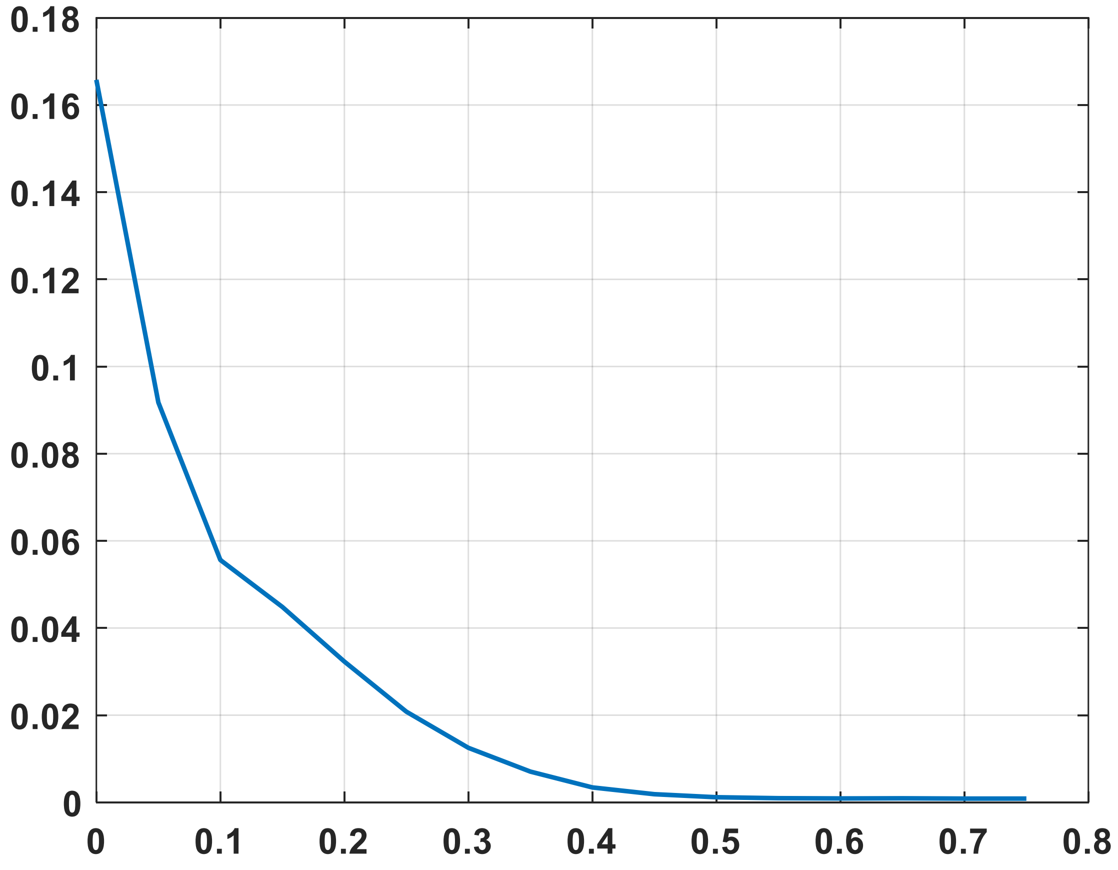


Annual Energy Harvest



Annual Variability Reduction

$$\frac{Event\ Count\ P_{PV,BAT}}{Event\ Count\ P_{MPP}}$$



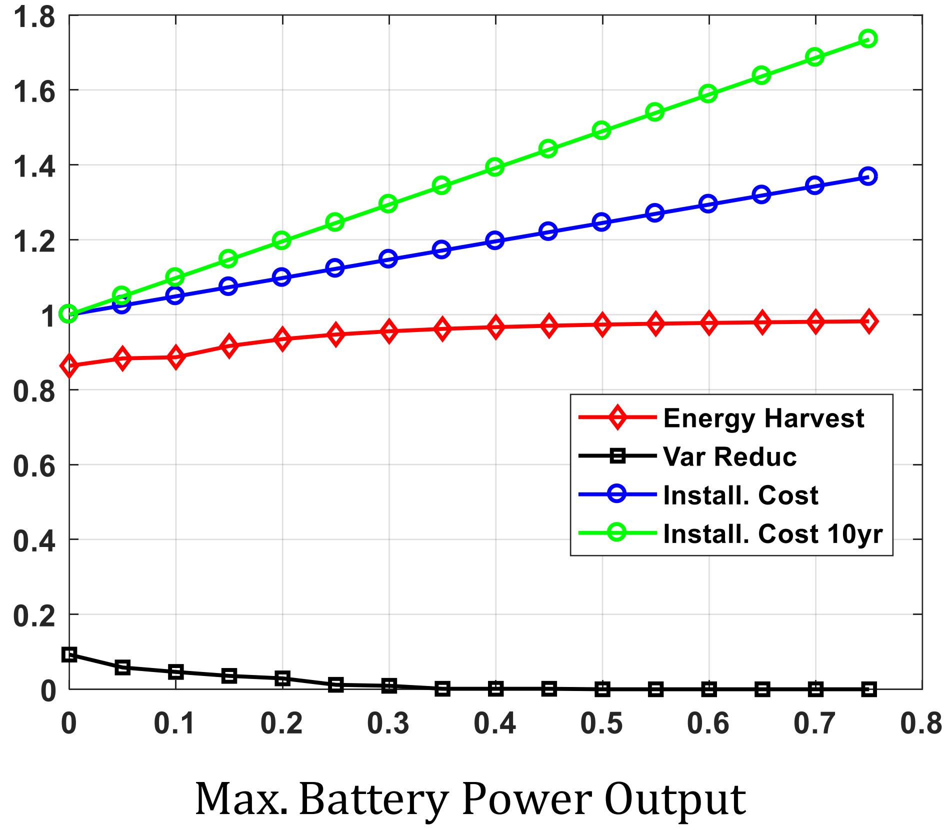
Max. Battery Power Output

Single Plant Results

- Assumes
  - PV Array: $2.45/Wdc*
  - Battery: $0.7/Wdc*
- Curves normalized to P_{MPP} array
- Economic cost/benefits to reduce variability

$$J(x) = x\left(\frac{Energy}{Cost}\right) + (1-x)Var$$

$$0 \leq x \leq 1$$



*http://www.nrel.gov/docs/fy16osti/64987.pdf

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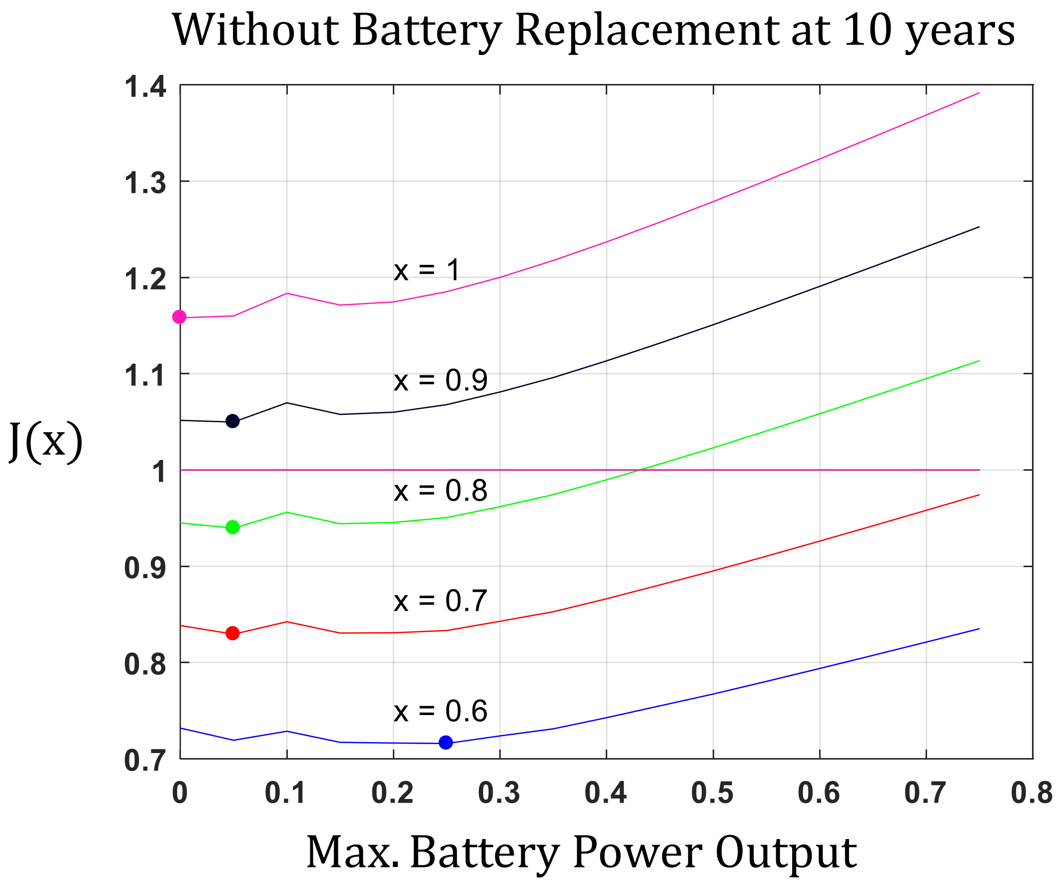
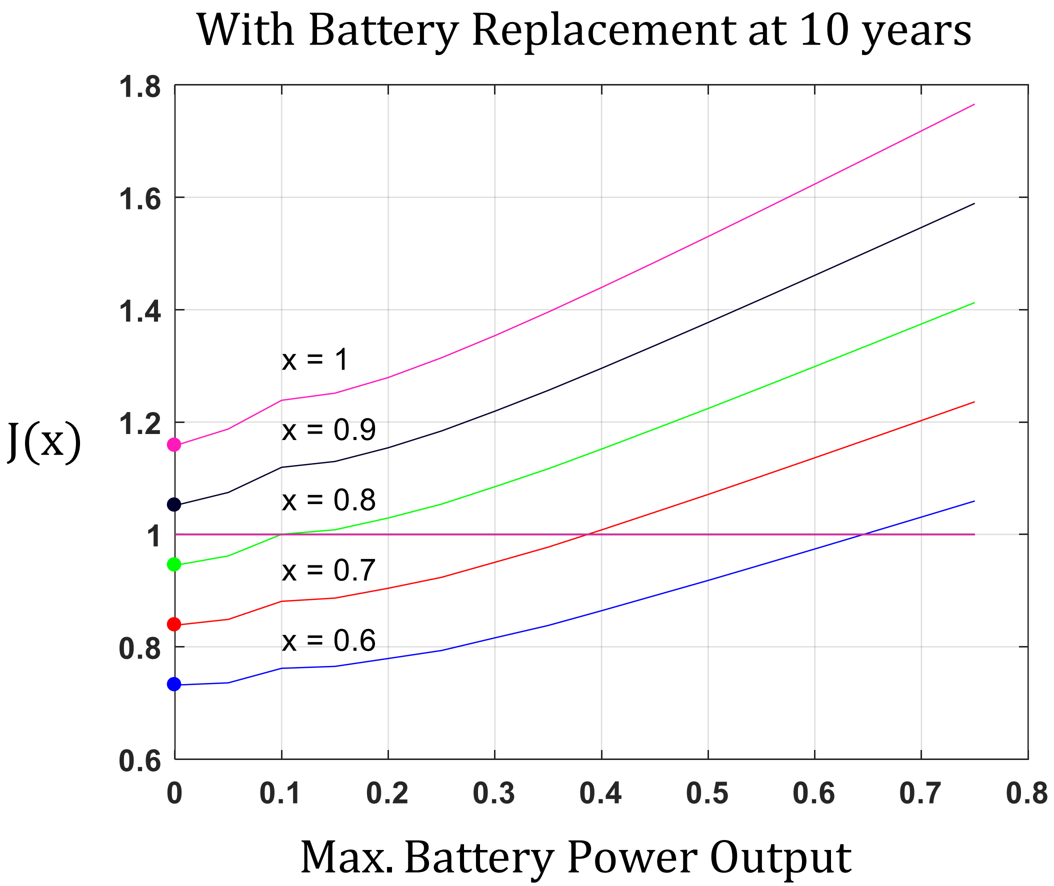


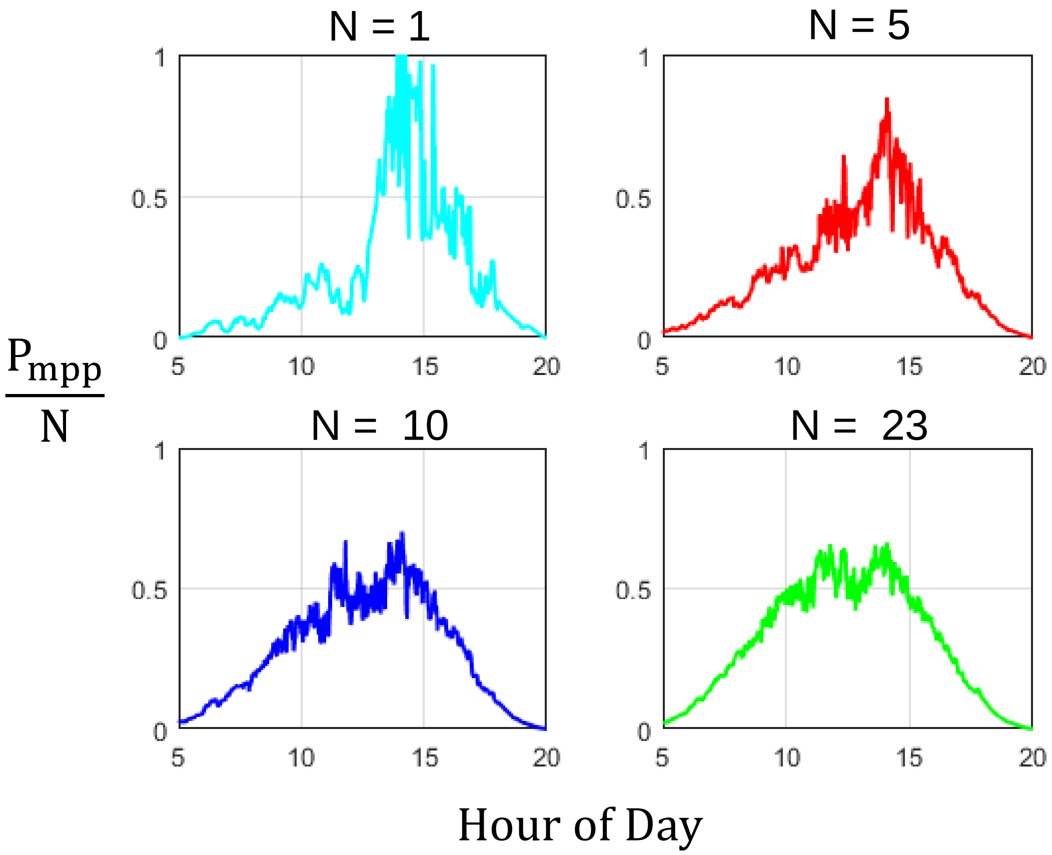


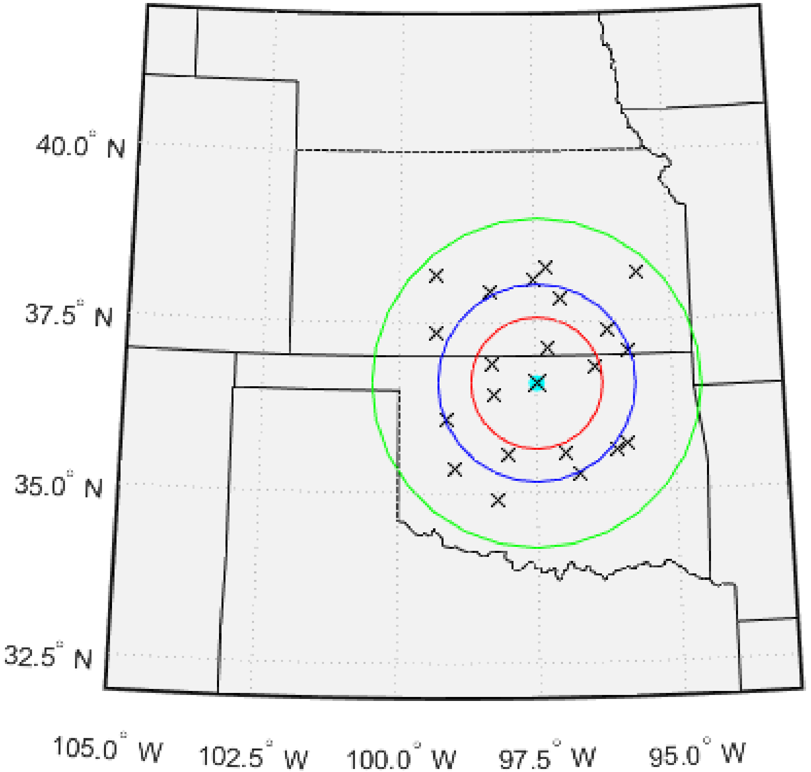
Conclusions

- Variability growing concern as solar capacity increases
- Solutions to mitigating variability must be economically feasible
  - Removes trivial solutions (i.e very large battery system)
- Reduced plant control can reduce need for larger components
  - Ultimately may be more economical than always operating at MPP

Questions?

Geographic Smoothing





https://www.arm.gov/data