Community-Scale Storage with Distributed PV to Mitigate Variability and Enable High Penetration of PV

NEXT GENERATION PHOTOVOLTAICS CENTER

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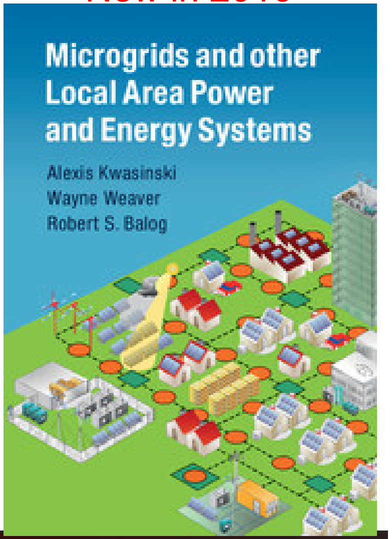
Renewable Energy & Advanced Power Electronics Research Laboratory

http://energy.ece.tamu.edu/REAPER

Dr. Robert S. Balog, PhD, PE

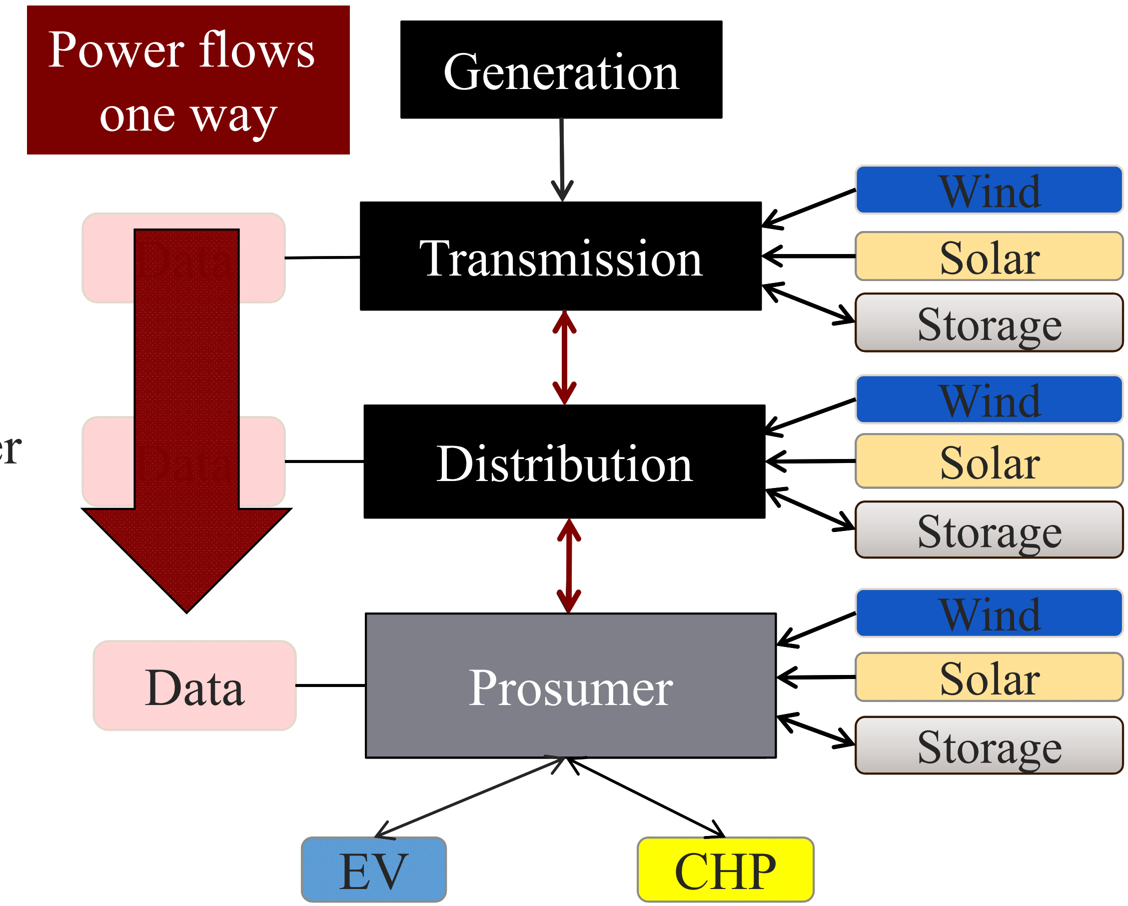
- Associate Professor (with tenure), Texas A&M University, College Station USA, **joint appointment** with Texas A&M University at Qatar
  - 1996, BS. Electrical Engineering, Rutgers University
  - 2006, Ph.D. Power Electronics, University of Illinois, Urbana-Champaign
  - Focus on power electronics in renewable energy systems, advanced power systems, grid integration, energy availability, load-side power conditioning, microgrids
  - Holistic photovoltaic energy systems: BOS, power electronics, system design, etc.
- Experience:
  - Research / R&D experience in power electronics since 1996 (PV since 2001).
  - 3 yrs *industry* responsible for developing microinverter and power electronics systems for residential PV (SolarBridge Technologies, acquired by SunPower 2014), secured initial $6MM venture capital to launch microinverter
  - 3 yrs *industry* developing lighting controls (Lutron Electronics)
  - Consulting: U.S. Army CERL, various companies; int'l: Turkey, Qatar, Turkmenistan
  - 16 issued U.S. patents (15 directly related to PV systems) + addt'l pending
  - 120+ IEEE internationally peer-reviewed conference and journal articles in power electronics
  - *Technical Program Chair* 2016 IEEE Energy Conversion Congress and Exposition
  - IEEE Senior Member; Membership-at-large for IEEE Power Electronics Society
  - Voting member of PV standards groups: UL 1741 and UL 1699B
- Select Awards:
  - 2011 Rutgers Distinguished Engineer Award
  - 2011 Admitted into the Hungarian Academy of Science (external body)
  - Best Poster Awards PVSC 2013, 2014, 2016 for balance of systems research

New in 2016



Transformation Towards a Clean Energy System

- 30 states adopted renewable portfolio standards
- Increased adoption of distributed energy resources such as photovoltaics, electric cars, combined heat and power systems, etc.
- Increased attention on local grids for resiliency and security
- California Rule 21 imposing more requirements on the inverter

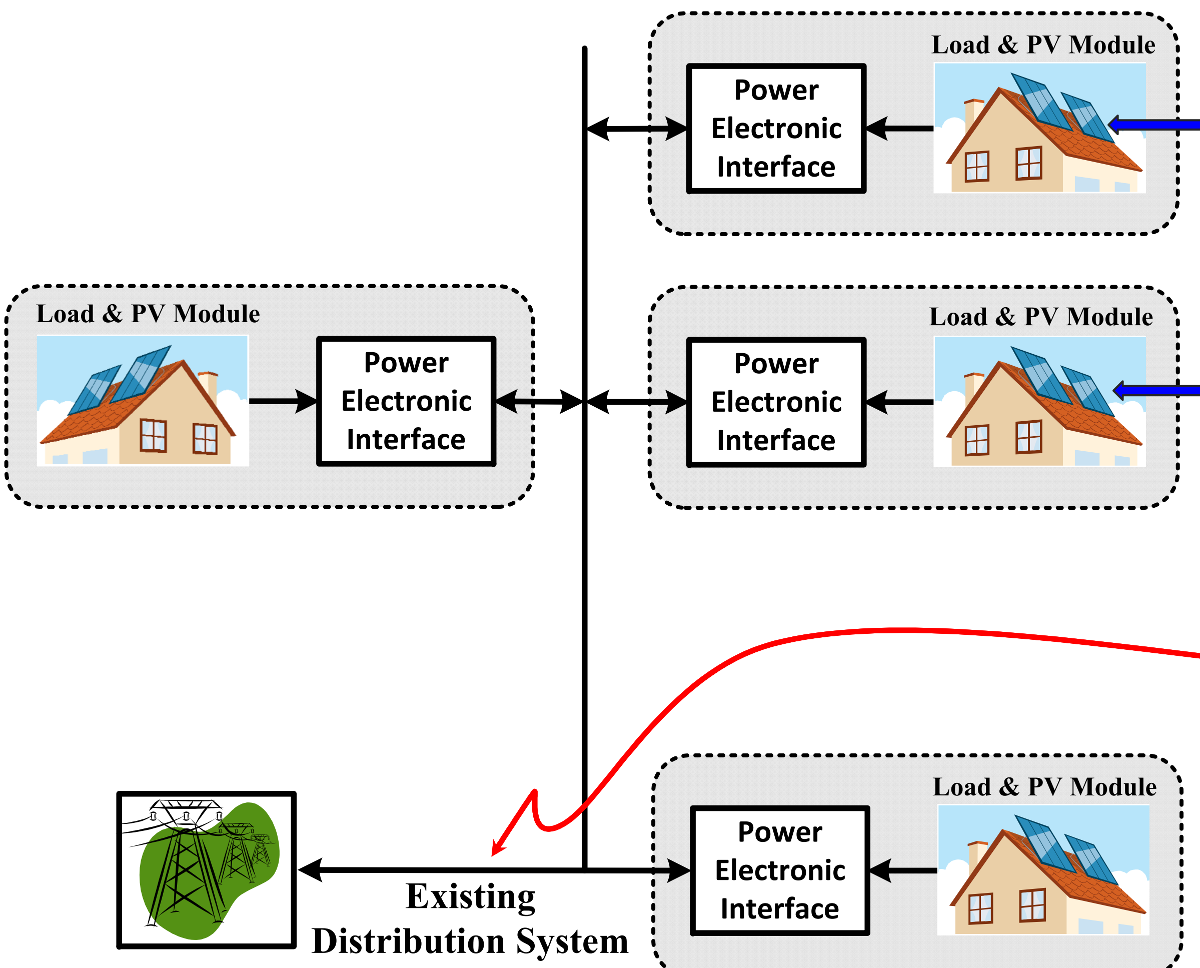


High Penetration Perceptions

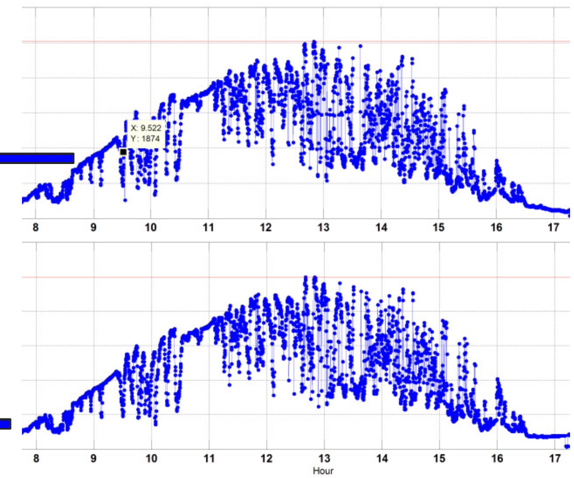
- High Penetration of Photovoltaic Systems into the Distribution Grid
  - **More than 30% penetration, indicating very high penetration**
- Grid Operations and High Penetration PV
  - High penetration is a concern ...
    - Adverse system performance and reliability of "new" power flow
    - Cost of mitigation of variability
    - Impact on spinning reserves to absorb variability
  - Distribution design and operation may exacerbate the concern
    - Feeder characteristics impedance
    - Voltage profile and reactive power flow
    - Protection coordination
    - Load characteristics (sometimes a load, sometimes a source)

May 25th, 2012, Germany generated 22.4GW, setting the world record for PV generation and nearly 40% penetration. **Their grid did not go unstable.**

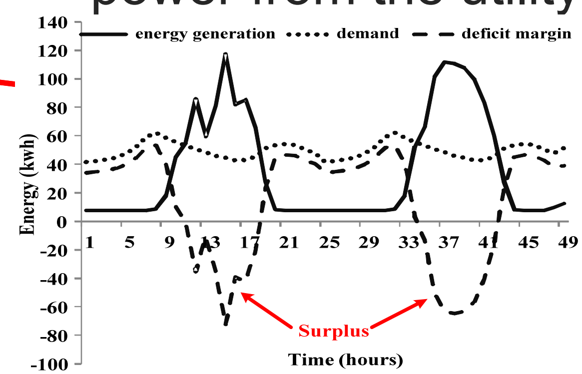
PV Case Study: Variability of Grid-Connected Solar Energy



Variable power output of PV



Results in variable power from the utility



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Myth Busters – Photovoltaic

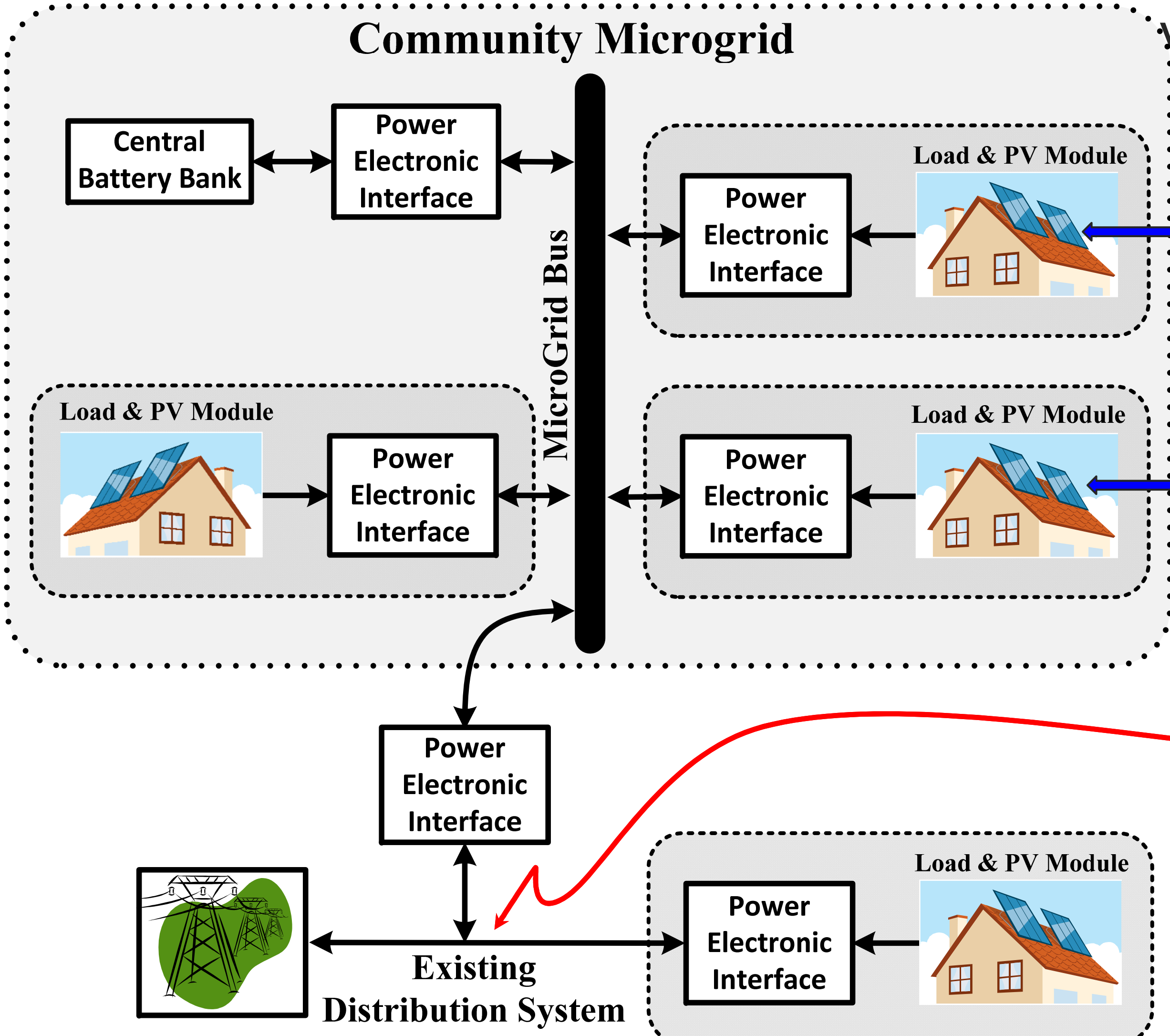
- Myth: PV is too variable and will cause widespread instabilities if high-penetration were achieved
- Observation: Dynamic differential variability is mitigated by the geographical distribution of PV generation, aided with small distributed storage

- Myth: PV requires grid-scale integration and grids-scale storage.
- Observation: small storage, co-located with PV mitigates the variability on the distribution system.

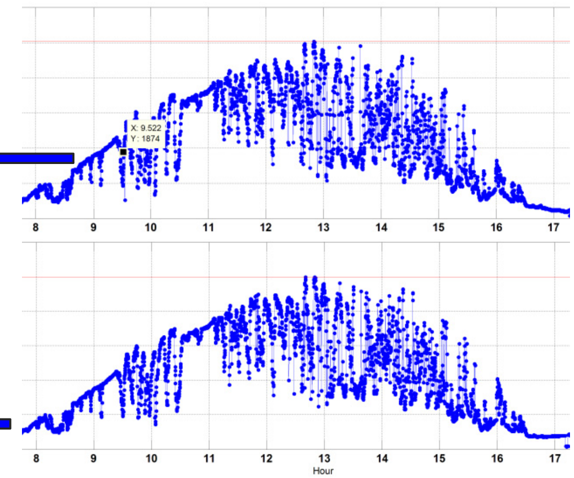
Local Power and Energy System

- GOAL:
  - Local system with co-located loads, sources, storage
  - Behind the fence from the utility perspective
  - Variability of solar is not seen by utility
  - Create opportunity to participate in energy markets

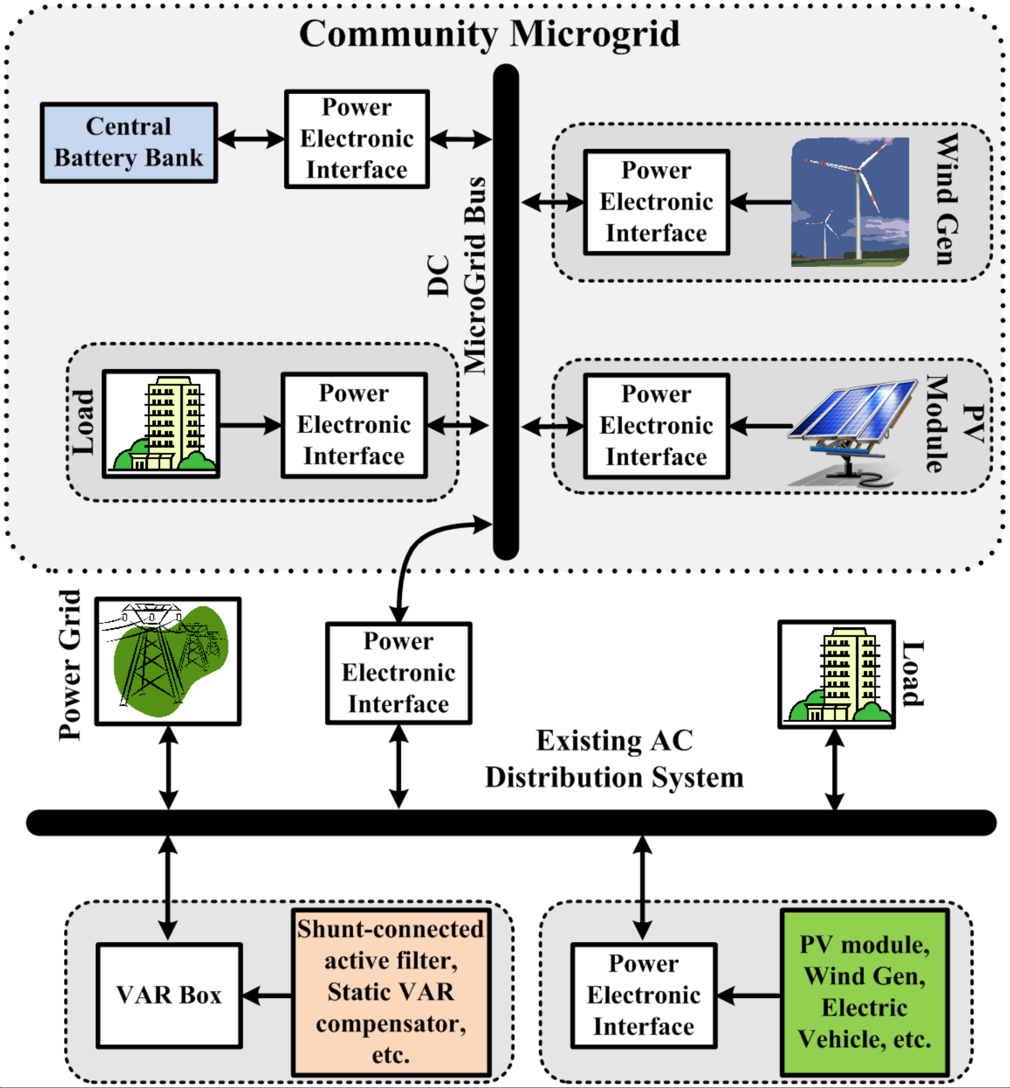
PV Case Study: Variability of Grid-Connected Solar Energy



Variable power output of PV

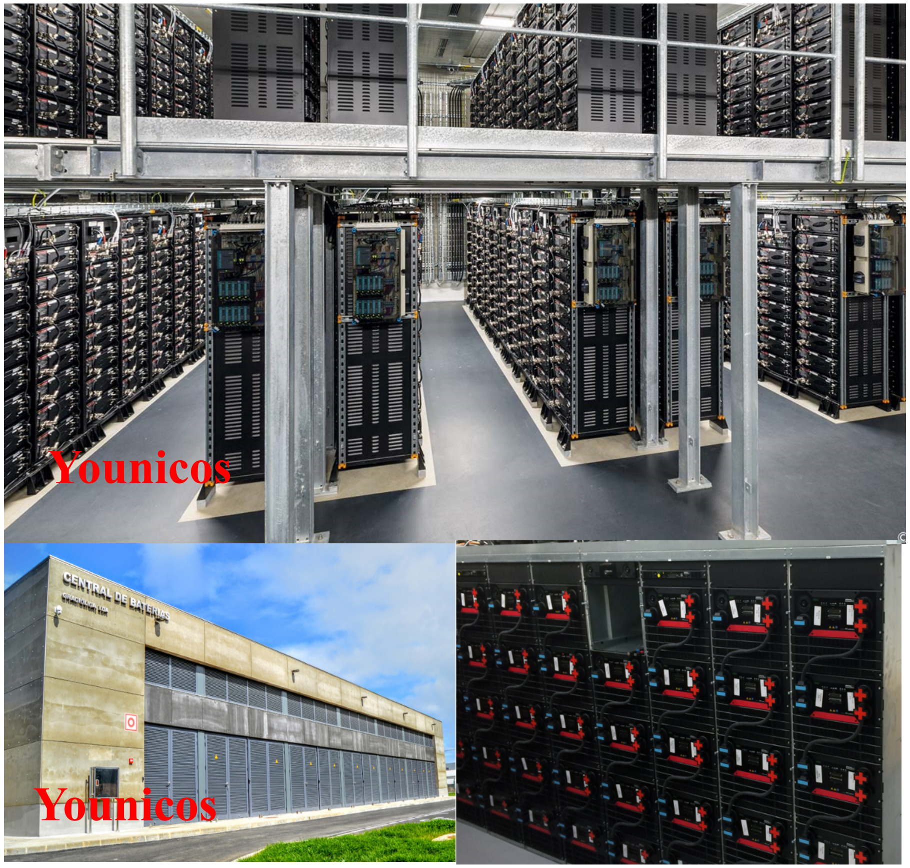


VISION: Local Area Power Electronics System (LAPES)



- Support high penetration of:
  - Distributed energy resources
  - Distributed storage
  - Prosumer loads
  - Bi-directional loads (EV)
- Differentiated service model for power quality and availability
- Interface to legacy Utility system
- Arbitrary "load profile" presented to utility.

Suitable Energy Storage Technology

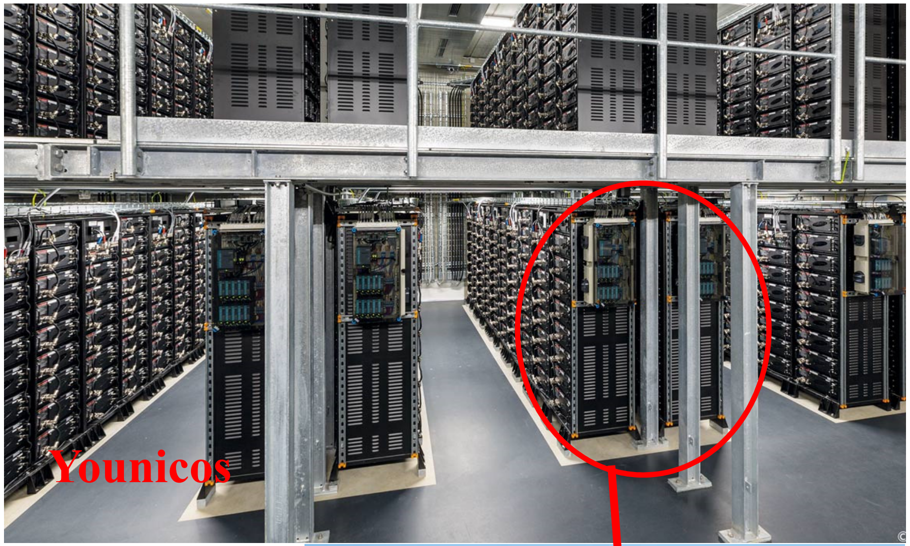


Example of Younicos battery energy storage: 5 MWh battery power plant in Schwerin, Germany

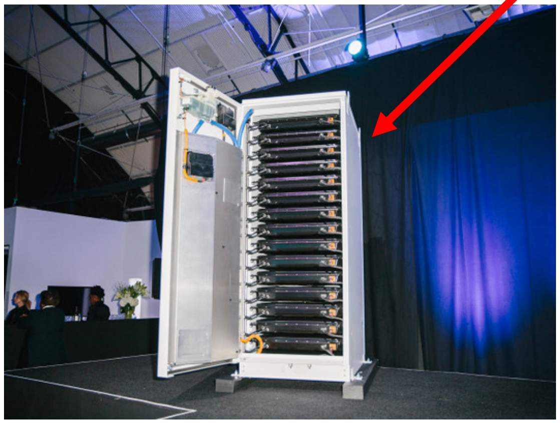
Example of Tesla solar energy and battery power wall on the island of Kauai

- Younicos energy storage example in Germany: 5 MWh battery power plant, 1,600 battery trays contain 25,600 lithium-manganese-oxide cell with ability to storage and supply energy within few milliseconds .
- Tesla power wall example in Hawaii: 52 MWh battery on the island of Kauai, Tesla power wall technology enabling distributed energy storage.

Suitable Energy Storage Technology



Younicos trailer-size energy storage system



One module of Tesla Powerwall

Locally Distributed PV

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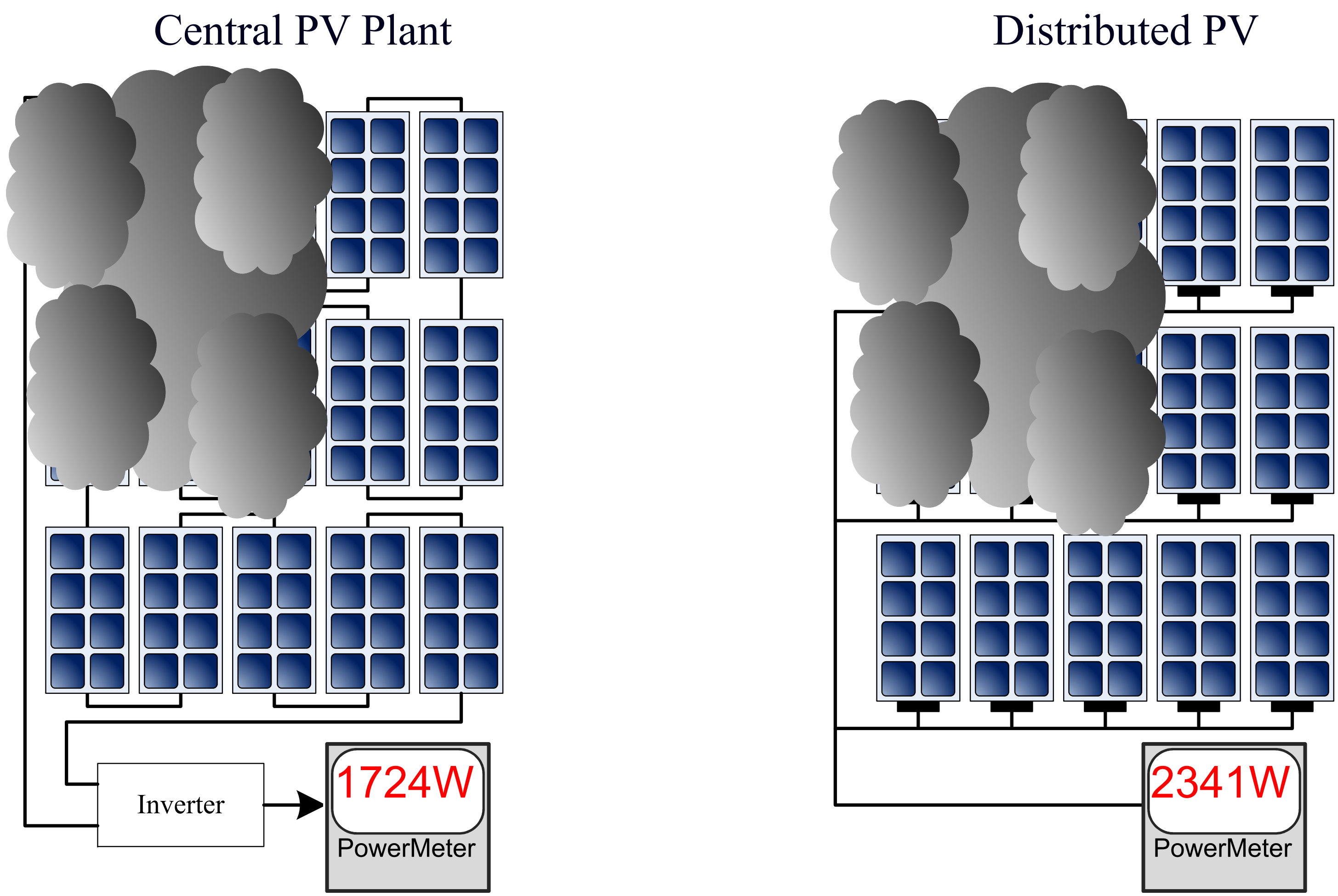
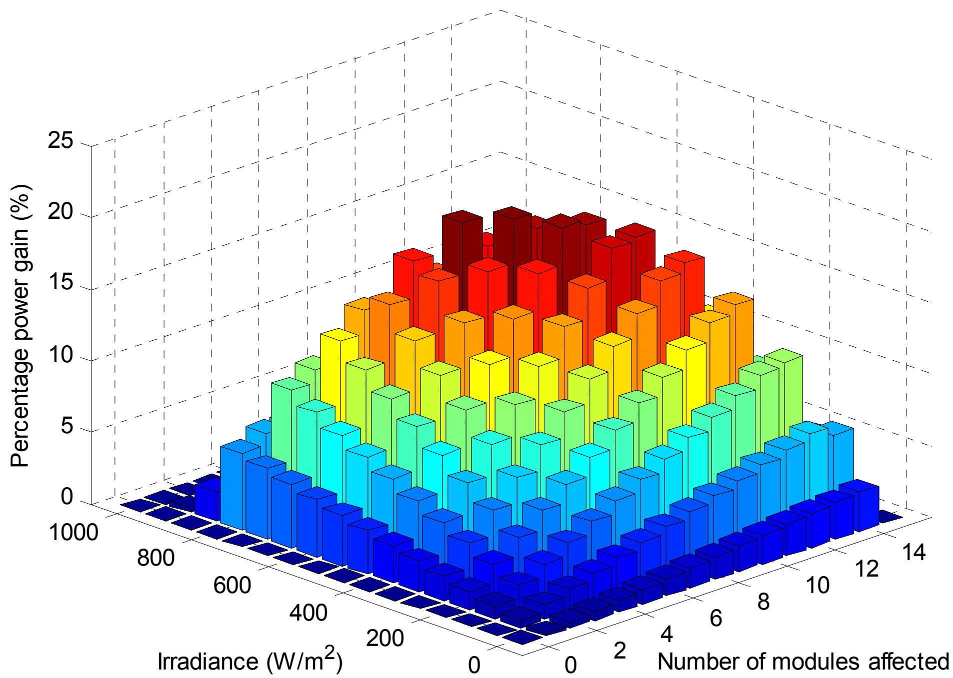
System Shading Scenarios

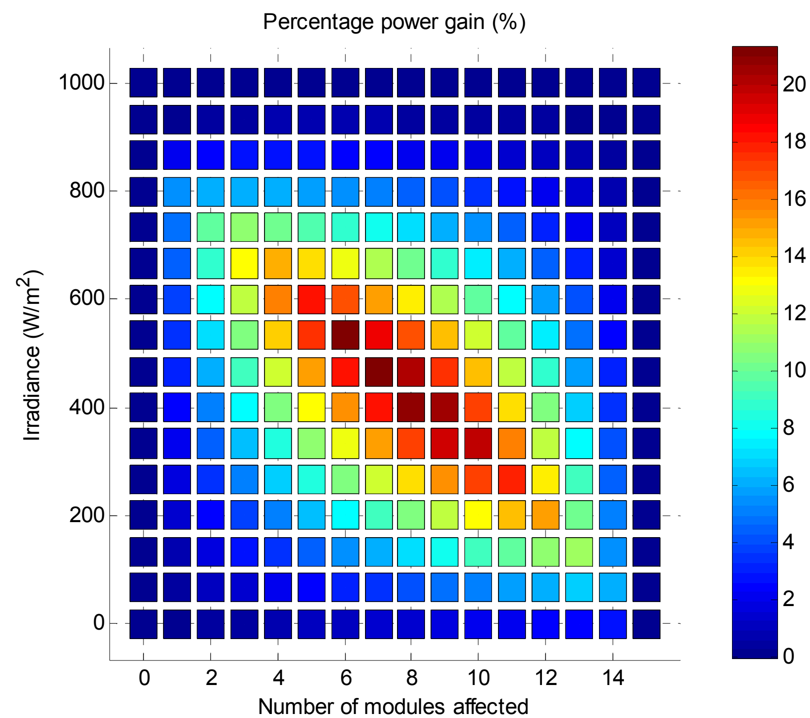


6 Modules Obstructed – Power Gain: 35.8%

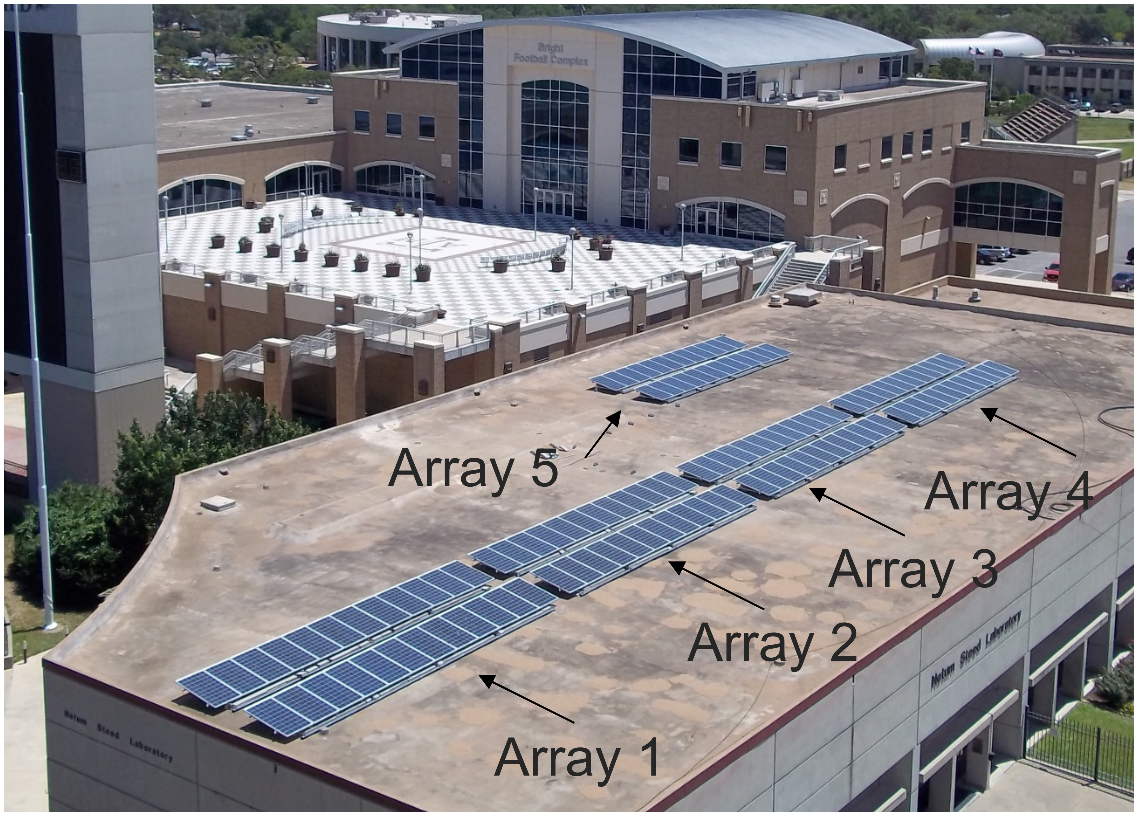
System Power Harvest Improvement

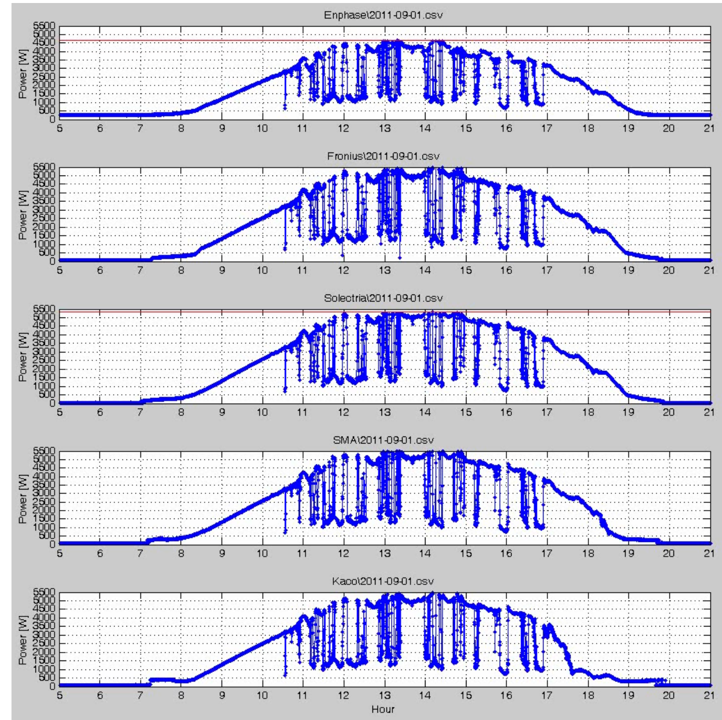
Rather than a single large plant, multiple distributed arrays allow each system to perform at peak harvest capability, regardless of transient and partial shading.





TAMU PV Testbed



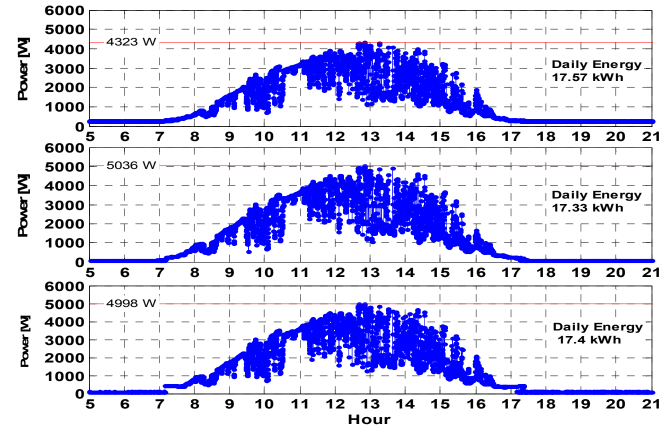


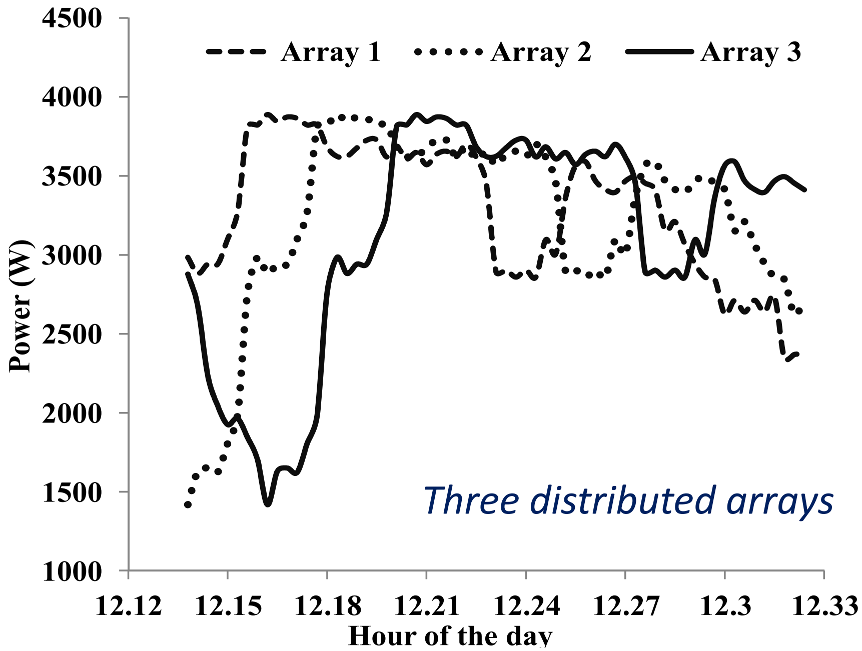
College Station Electrical Output Data
from Sep 1, 2011 to Sep 15, 2011

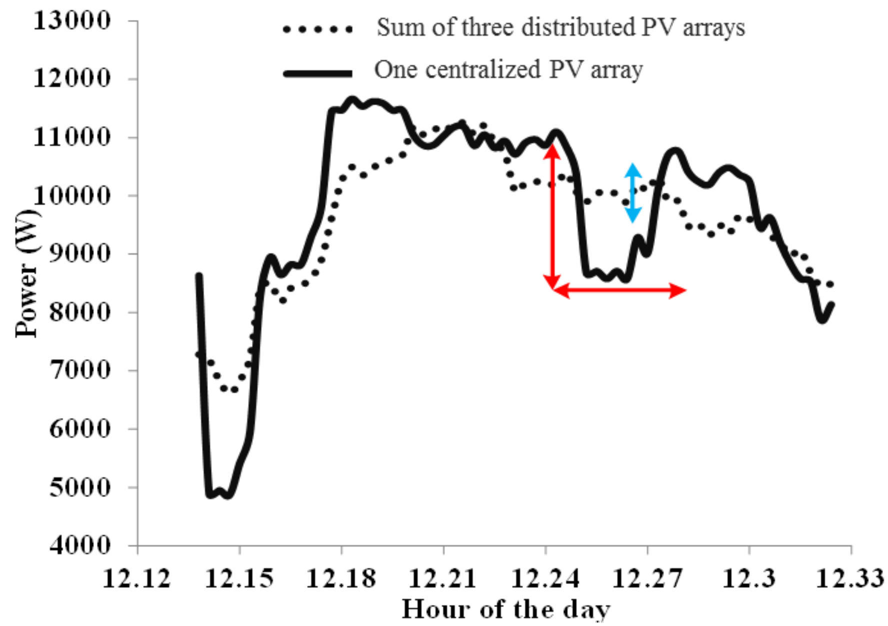
- 30kW system, 5 subarrays with separate MPPT inverters.
- Data sampled at 6sec intervals

High-Temporal Resolution of DG Reveals Variability Mitigation

- Examine the effect of small-scale geographical distribution of PV arrays (about 100-200 ft)
- Local phenomenon, suitable for campuses and communities
- Three independent arrays vs a single large array:







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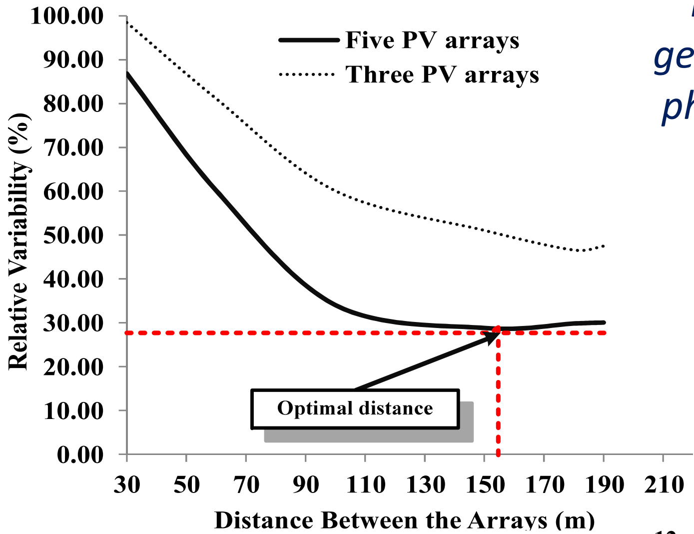
Geographical Distribution of Photovoltaic Arrays

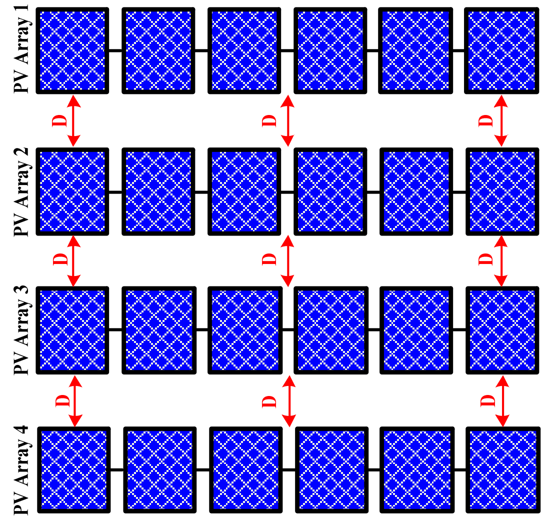


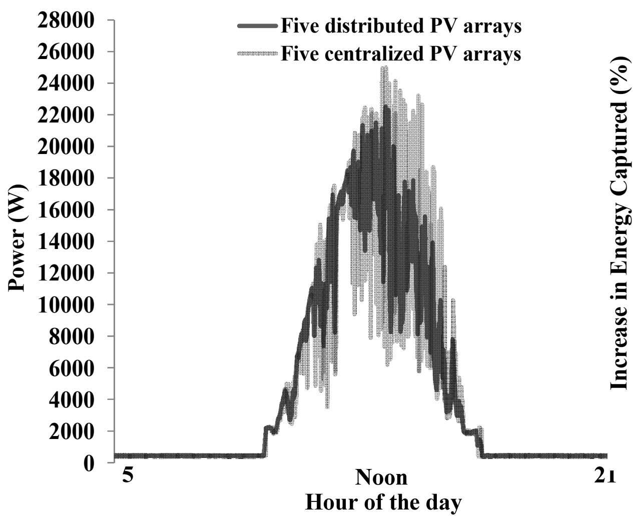
Relative variability versus geographical configuration of photovoltaic arrays for same installed capacity

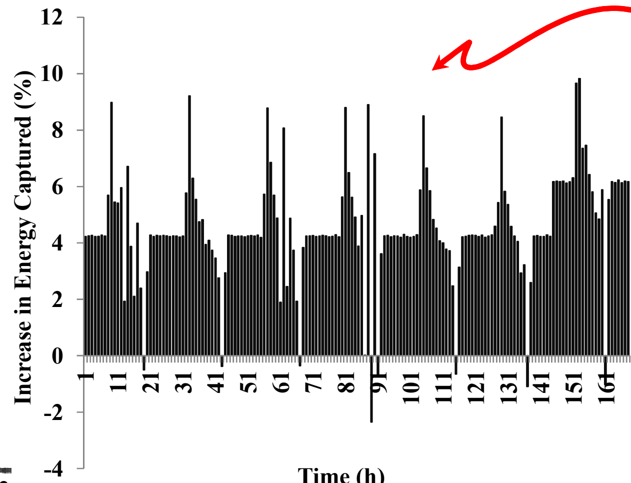
$$\sigma_T^{\sum N} = \frac{1}{P_{Peak}} \sqrt{Var\left[\sum_{n=1}^{N} \Delta P_T^n\right]}$$

$$\Delta P_T^n = P_t^n - P_{t+\Delta t}^n$$

$$\text{Relative variability} = \frac{\sigma_T^{\sum N}}{\sigma_T^1}$$







Increase in energy capture when 5 PV arrays are point-of-load located (D=100 meters) comparing to a centrally located PV system

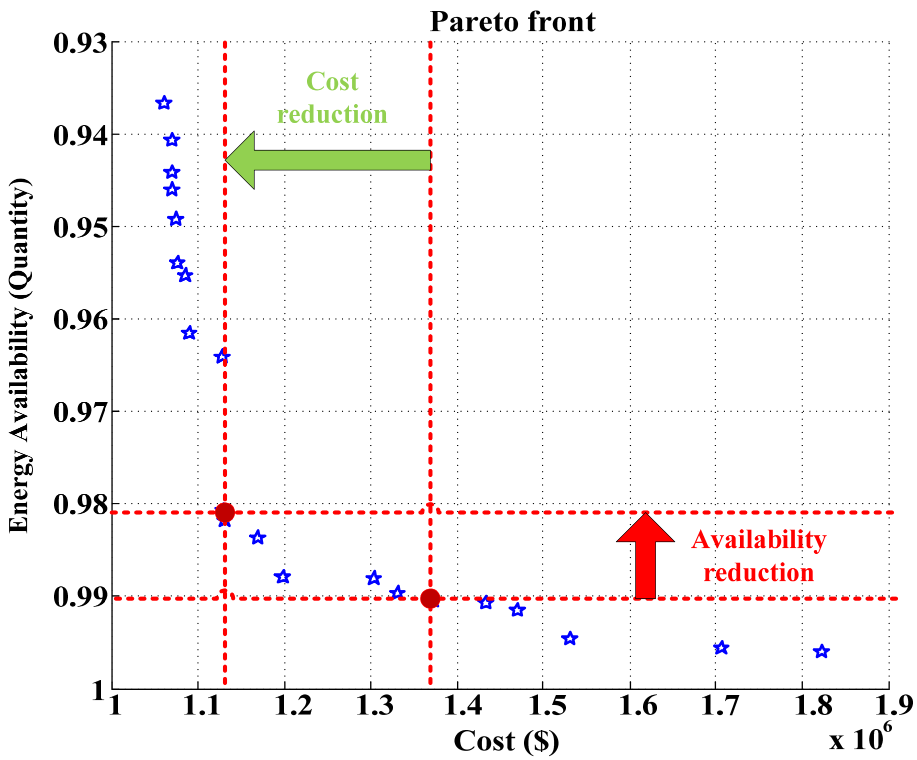
Optimization of Energy Storage

Techno-Economic Optimization

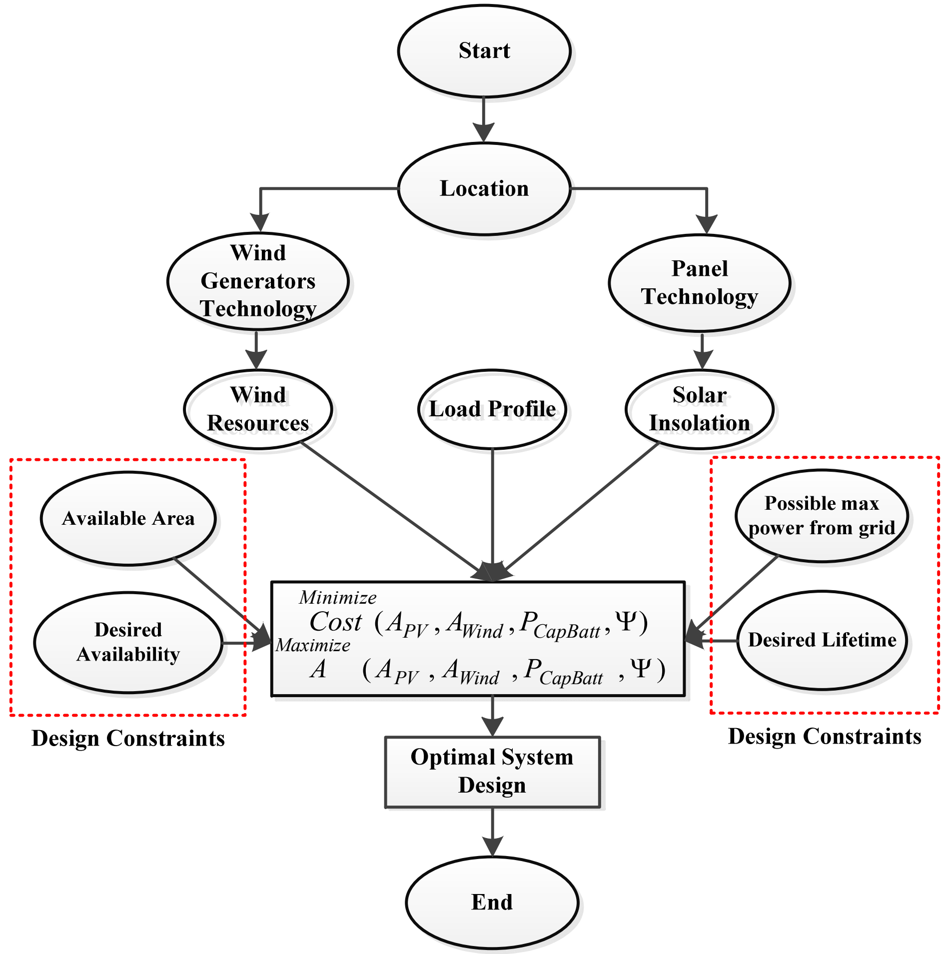
- GOAL: Given a constrained geographic distribution (separation distance of arrays), optimize the storage required.

- We normally think of optimizing technology.
- In reality, we need the right technology at the right cost.
- Techno-economic optimization enables the tradeoff to quantify the value-proposition.

Example of Hybrid Energy System Optimization



Pareto frontier reveals the set of optimal solutions for the LAPES



Design and optimization procedure of the LAPES

Energy Availability Model

Technical Objective: energy availability. The availability can be formulated for duration *T* time

$$A = 1 - \frac{DNM}{D} \quad \Rightarrow \quad \underset{A}{Maximize}\left(A_{PV}, A_{Wind}, P_{CapBatt}, \Psi\right)$$

$$DNM = \sum_{t=1}^{T}\begin{pmatrix} P_{\underset{MIN}{Batt}}(t) - P_{\underset{SOC}{Batt}}(t) - \\ \left(P_{PV}(t) + P_{Wind}(t) + P_{Grid}(t) - P_{D}(t)\right) \times u(t) \end{pmatrix}$$

$$P_{Grid} = \Psi \times \left(P_D(t) - P_{PV}(t) - P_{Wind}(t) - P_{Batt}(t)\right)$$

$$P_{PV} = Insolation \times A_{PV} \times \eta_{PV}$$

$$P_{Wind} = P_{WTG} \times A_{Wind} \times \eta_{Wind}$$

Ψ: Ratio of power imported from grid
D: Yearly demand
DNM: Demand not met
A_{PV}: PV area
$A_{Wind,}$: Wind area
$P_{CapBatt}$: Battery capacity
T :Operational duration under consideration
*A:*Index of availability
η_{PV} : Photovoltaic system efficiency
η_{Wind} : Wind turbine system efficiency

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Cost Modelling of System Components

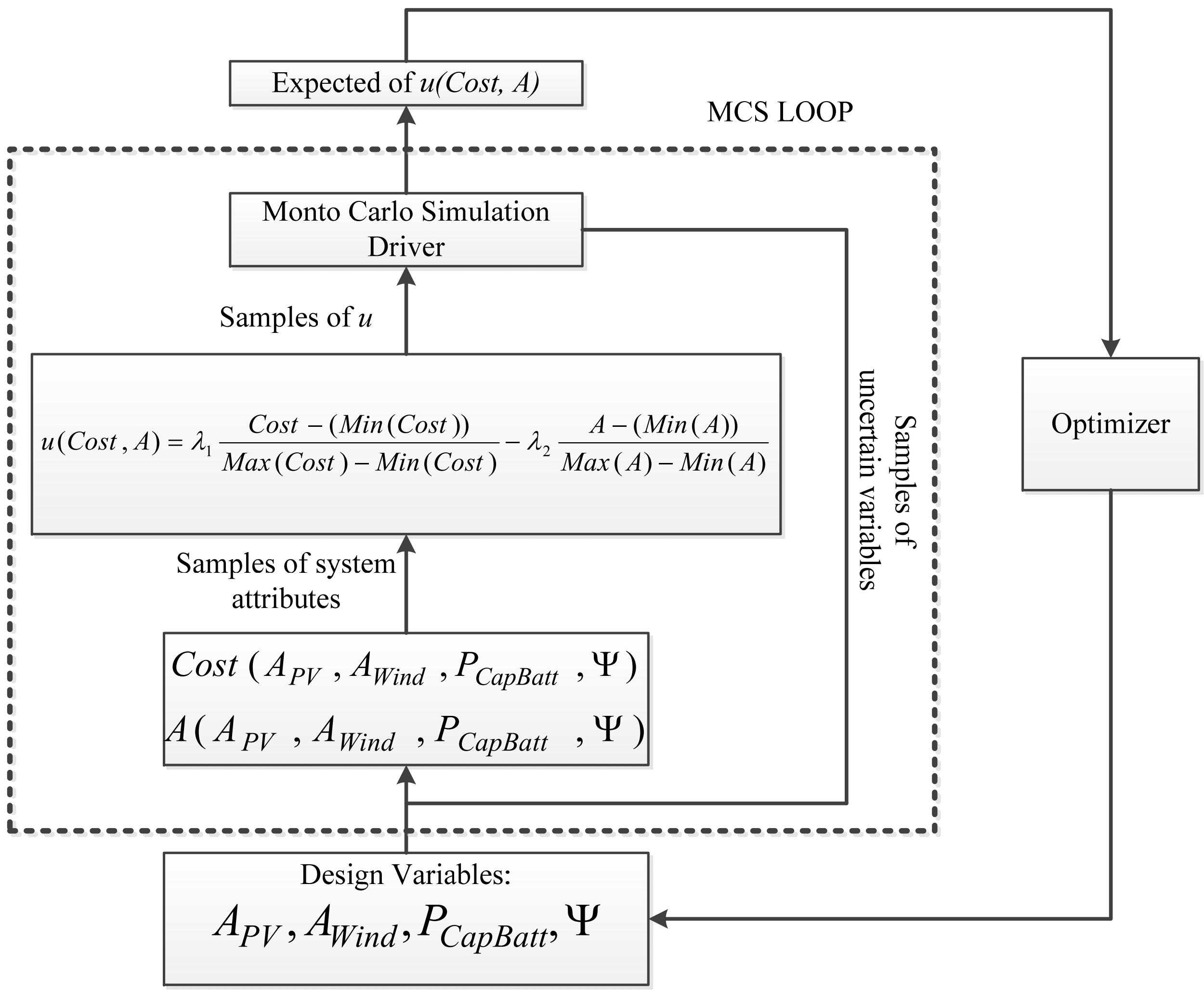
Economic Objective: cost, with $A_{PV,} A_{Wind,} P_{CapBatt}$ and Ψ as design parameters

$$Cost = C_{Grid} + \frac{\sum\limits_{i=PV,Wind,Batt} (I_i + OM_i)}{N} \quad \Rightarrow \quad \underset{Minimize}{Cost}\ (A_{PV}, A_{Wind}, P_{CapBatt}, \Psi)$$

PV Cost Modeling	Wind Cost Modeling
$I_{PV} = \lambda_{PV} \times A_{PV}$ $OM_{PV} = OM_{yearly} \times A_{PV} \times \sum_{i=1}^{N} \left(\frac{1+\vartheta}{1+\gamma}\right)^{i}$	$I_{wind} = \lambda_{wind} \times A_{wind}$ $OM_{wind} = OM_{yearly} \times A_{wind} \times \sum_{i=1}^{N} \left(\frac{1+\vartheta}{1+\gamma}\right)^{i}$
Battery Bank Cost Modeling	**Grid Cost Modeling**
$I_{Batt} = \lambda_{Batt} \times P_{Cab\_Batt}$ $OM_{Batt} = OM_{yearly-Batt} \times P_{yearly-Batt} \times \sum_{i=1}^{T_b} \left(\frac{1+\gamma}{1+\beta}\right)^{(i-1)N_{Batt}}$	$C_{grid} = \sum_{i=1}^{T} P_{g,t} \times \lambda_{Grid}$ $P_{Grid} = \Psi \times \left(P_D(t) - P_{PV}(t) - P_{Wind}(t) - P_{Batt}(t)\right)$

Optimization of LAPES under Uncertainty

- Data-driven models have limitations
- Inherent uncertainty of solar insolation, wind speed, and load data



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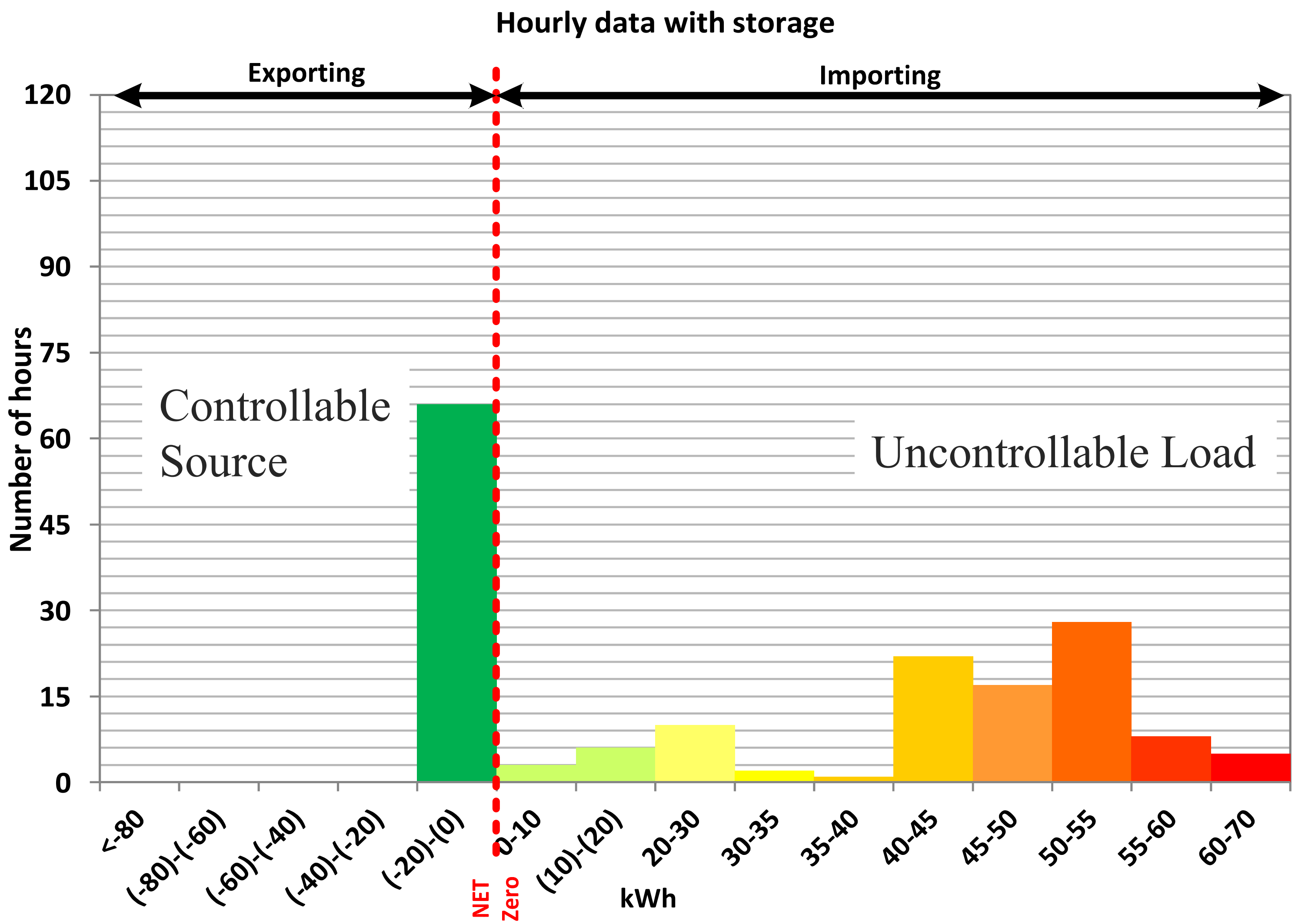
Examples of Temporal Resolution and Optimized Storage

Temporal Resolution



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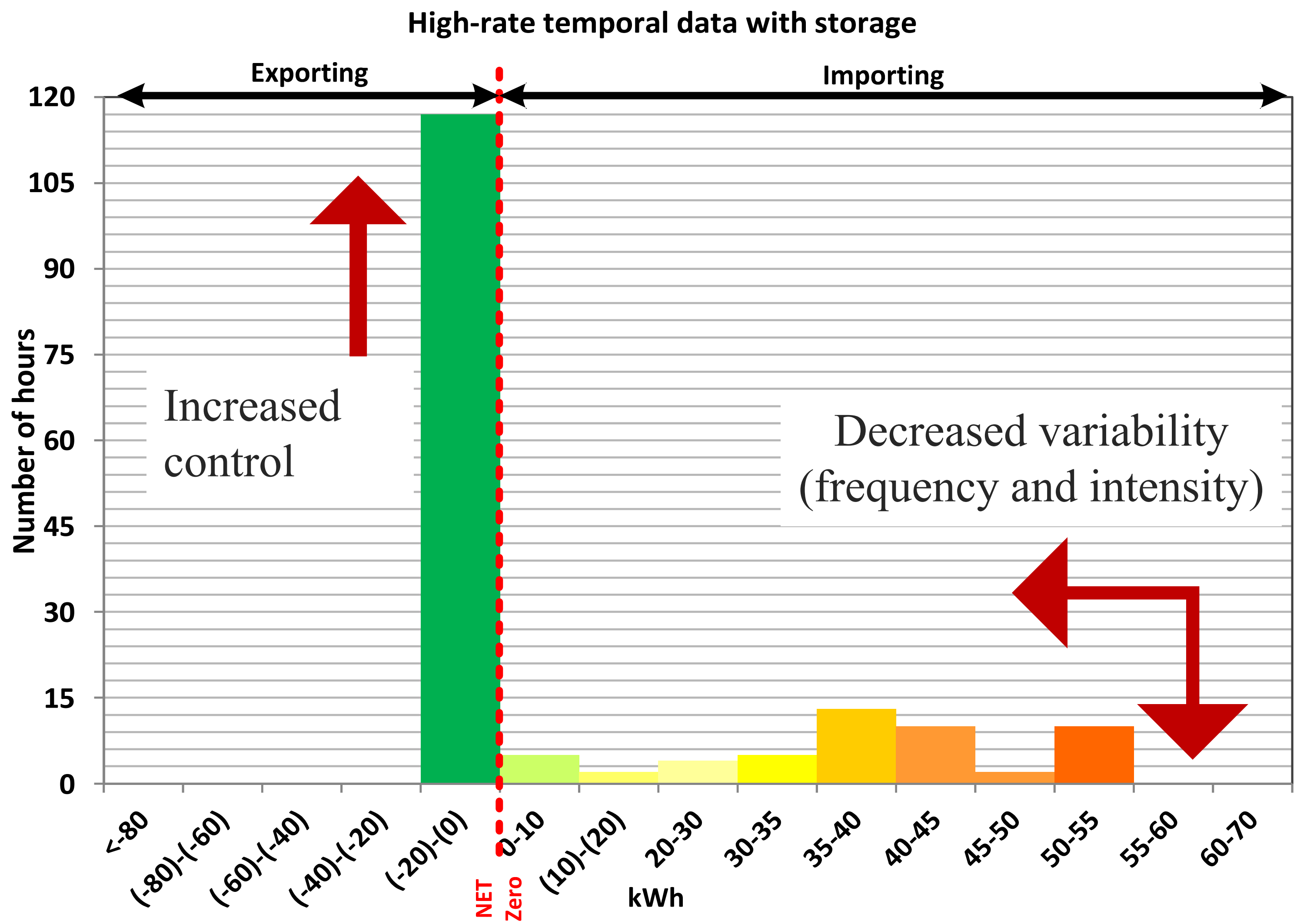
Temporal Resolution



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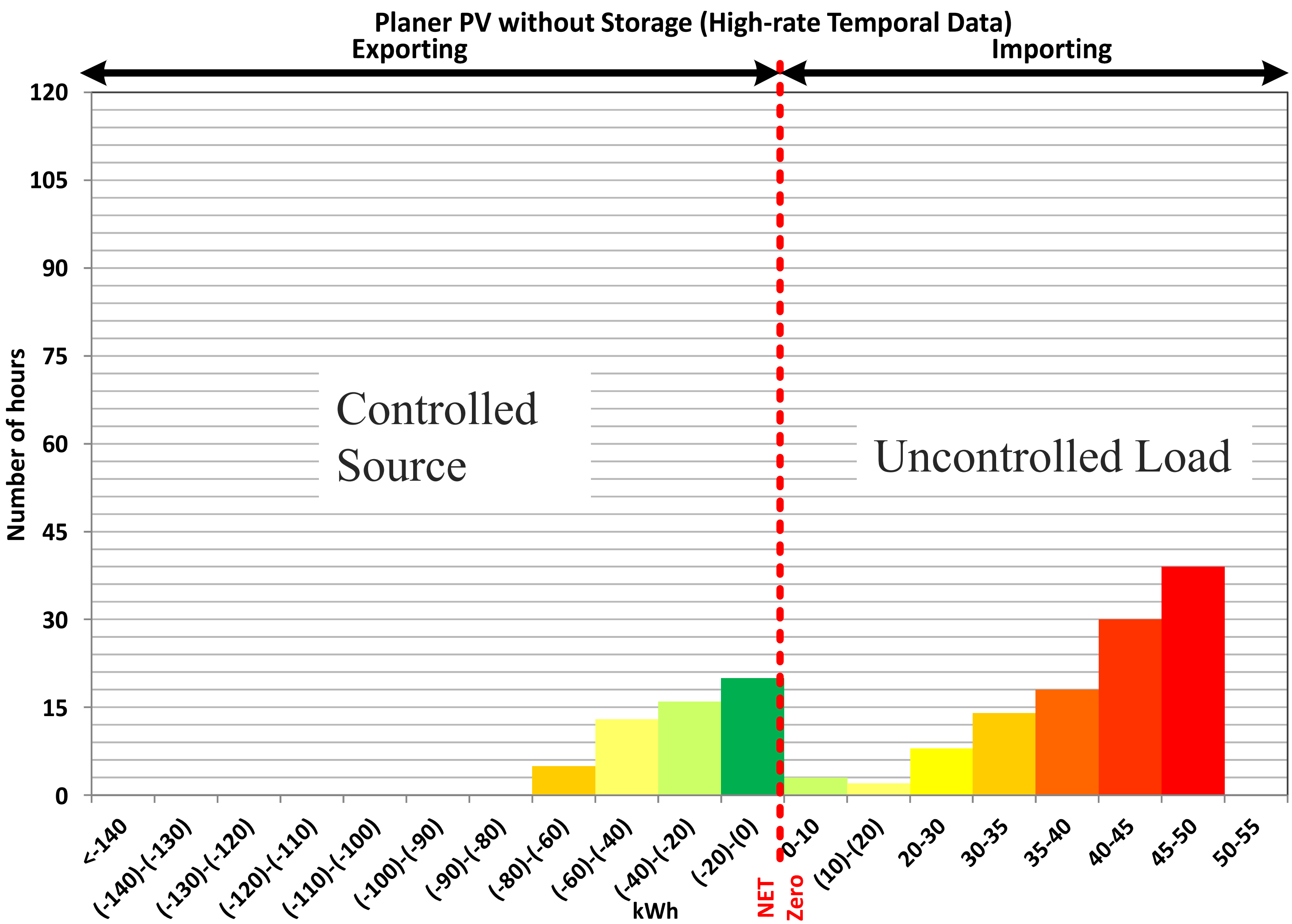
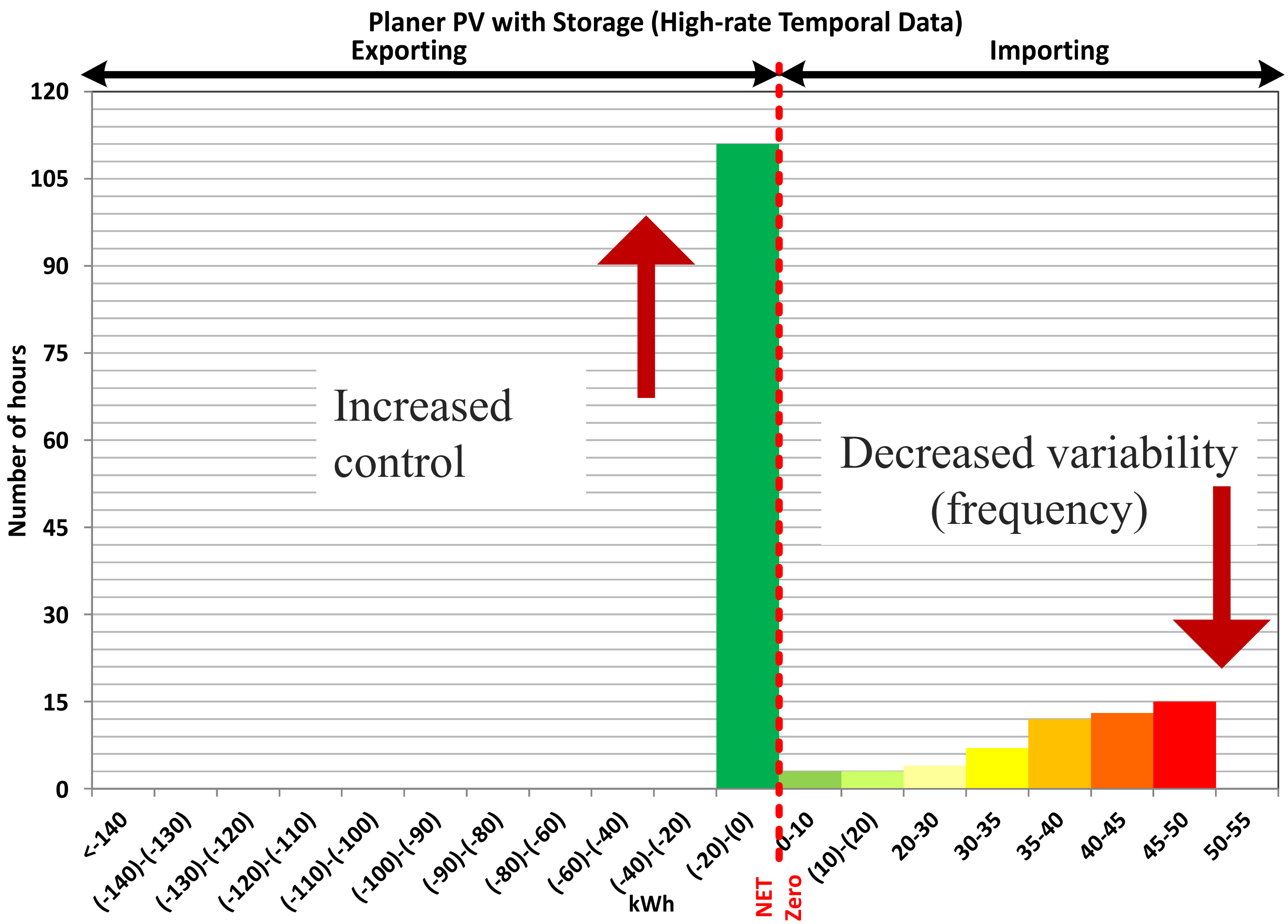
Optimized Community Storage



Optimized Community Storage



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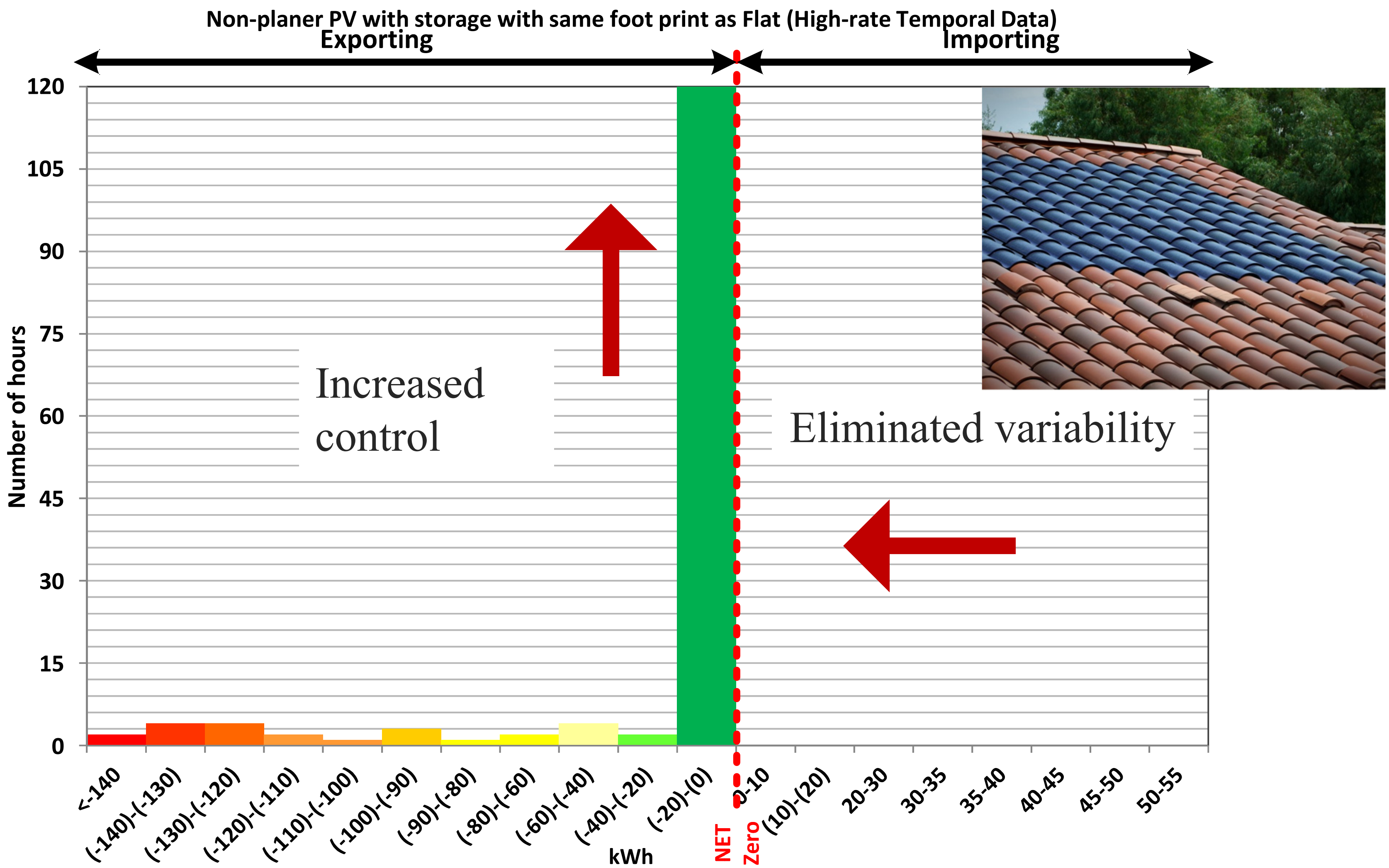
Terracotta Solar Roof Tiles



Published papers

1. A. Kwasinski, W. Weaver, and R. S. Balog, Microgrids and other local area power and energy systems: Cambridge University Press, 2016.
2. S. Xiao, M. B. Shadmand, R. S. Balog, and H. Abu Rub, "Model Predictive Control of Multi-String PV Systems with Battery Back-Up in a Community DC Microgrid," in *IEEE Applied Power Electronics Conference & Exposition* (APEC), March 2017.
3. M. B. Shadmand, R. S. Balog, and H. Abu Rub, "Model Predictive Control of PV Sources in a Smart DC Distribution System: Maximum Power Point Tracking and Droop Control," *IEEE Transactions on Energy Conversion*, vol.29, no.4, pp.913-921, Oct. 2014, November 2014.
4. M. B. Shadmand, R. S. Balog, and M. D. Johnson, "Predicting Variability of High Penetration Photovoltaic Systems in a Community Microgrid by Analyzing High Temporal Rate Data," *IEEE Transactions on Sustainable Energy*-Special Section on Microgrids for Sustainable Energy Systems, vol.5, no.4, pp.1434-1442, Oct. 2014.
5. M. B. Shadmand and R. S. Balog, "Multi-Objective Optimization of Photovoltaic-Wind Hybrid System for Community Smart DC Grid Microgrid," *IEEE Transactions on Smart Grid-Special Issue on DC Distribution Systems*, vol.5, no.5, pp.2635-2643, Sept. 2014.
6. M. B. Shadmand and R. S. Balog, "Mitigating Variability of High Penetration Photovoltaic Systems in a Community Smart Microgrid using Non-Flat Photovoltaic Modules," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, Sept 2013.
7. M. B. Shadmand and R. S. Balog, "Design Considerations for Long-Term Remote Photovoltaic-Based Power Supply using Non-Planar Photovoltaic Modules," in *IEEE Technologies for Homeland Security (HST)*, November 2013. "**Invited Paper**"
8. M. B. Shadmand and R. S. Balog, "Optimization of Photovoltaic-Wind Hybrid System for Apartment Complexes and Other Community Living Environments by Minimizing Excess Capacity," in *IEEE Photovoltaic Specialist Conference (PVSC)*, June 2012, pp. 531-536.

Published papers

9. M. B. Shadmand, M. Pasupuleti, and R. S. Balog, “Photovoltaic-Wind Hybrid System with Battery Backup, Optimized for Apartment Complexes and other Community Living Environments," in *IEEE Energy Conversion Congress and Exposition* (ECCE), Sept 2011, pp. 3626-3632.
10. M. B. Shadmand and R. S. Balog, “Remote Photovoltaic Power Supply,” presented at Summer Institute on Flooding, Center for Emergency Informatics, Disaster City, TX, 03-05 Jun, 2014. **“Best Poster Award”**
11. M. B. Shadmand and R. S. Balog, “Optimization of Photovoltaic-Wind Hybrid System for Apartment Complexes,” presented at 2nd Annual Smart grid Workshop, TAMU, College Station, TX, 08 April, 2014.
12. M. B. Shadmand and R. S. Balog, “Mitigating Variability of High Penetration Photovoltaic Systems in a Community Smart Grid”, presented at Southeastern Conference Symposium (SEC) Symposium, February, 2013, Atlanta, Georgia.
13. M. B. Shadmand, M. Pasupuleti, O. Kotun, and R. S. Balog, "Photovoltaic-Wind Hybrid System with Battery Backup Optimized for the State of Texas," presented at *Young Engineers and Scientists Symposium: Alternative Energies - A Global Perspective, an NSF supported workshop at Texas A&M University*, Jan 10-12, 2011.

Thank you!