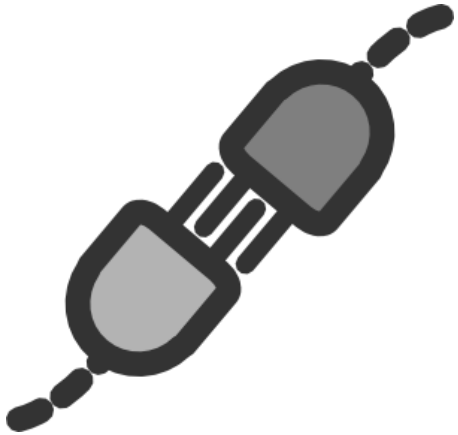
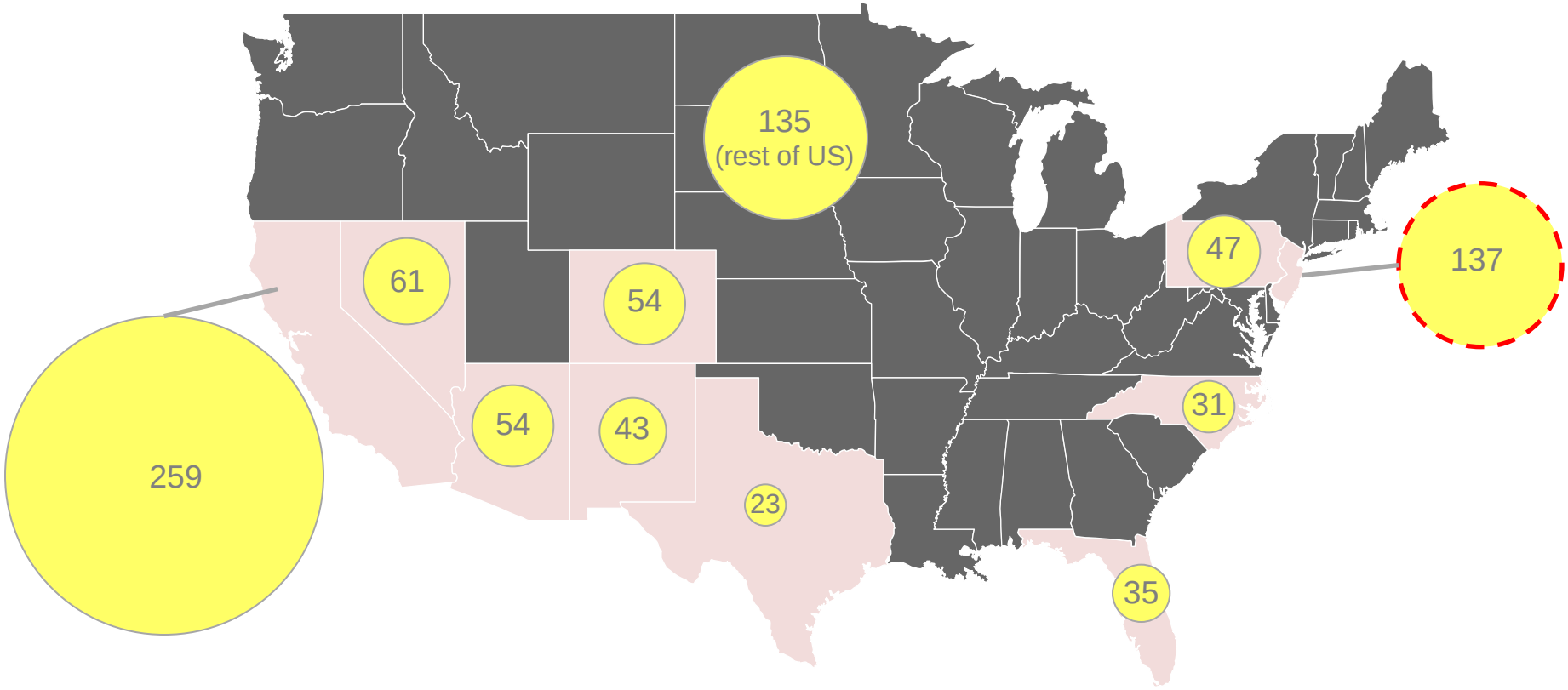
Integration Challenges of Photovoltaic Distributed Generation on Power Distribution Systems



Overview

- Existing & Pending PV Generation
- PV System Impact on the Grid
- Steady State and Dynamic Modeling
- Study Results & Mitigation Solutions
- PV Analytics and observations from installed systems

2010 solar PV installations in US: top 10 states (MWs)



Source: SEIA; all amounts shown are MWs

Pepco Holdings, Inc.

3 states and Washington DC in mid-Atlantic US

pepco
A PHI Company

648 sq mi (*575 in MD)*

782,000 cust (*528,000 in MD)*

4 and 13kV distribution

delmarva power
A PHI Company

5,400 sq mi (*3,500 in MD)*

498,000 cust (*199,000 in MD)*

4, 12, 25 and 34kV distribution

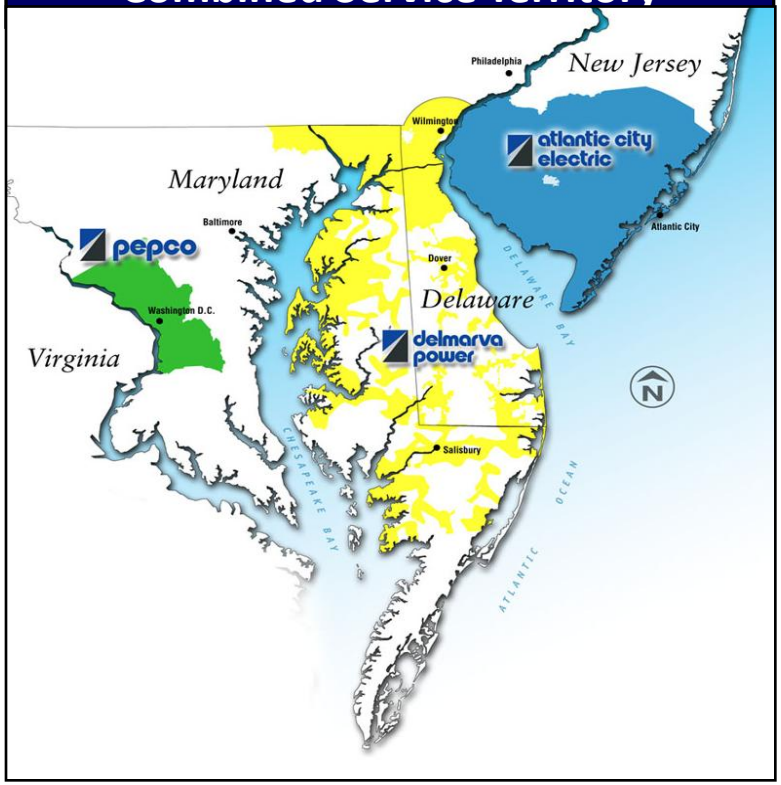
atlantic city electric
A PHI Company

2,700 sq mi

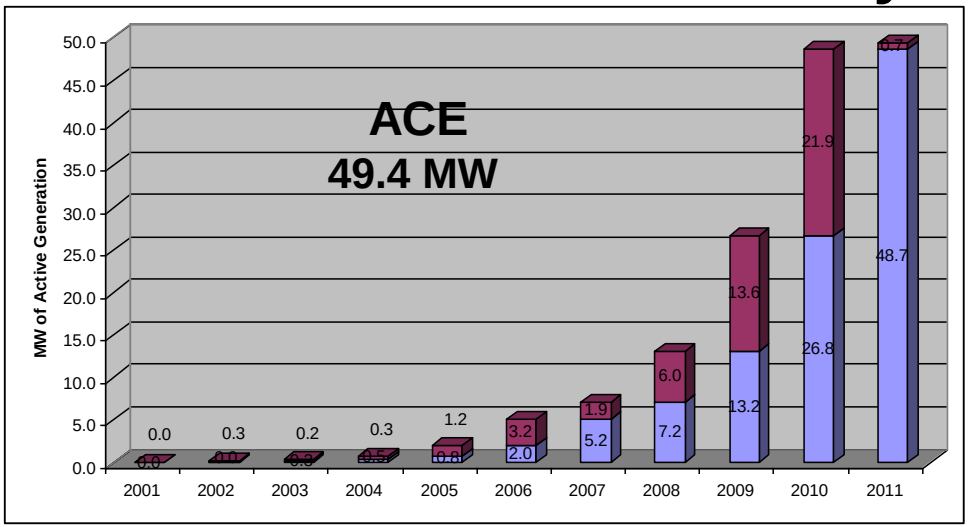
546,000 cust

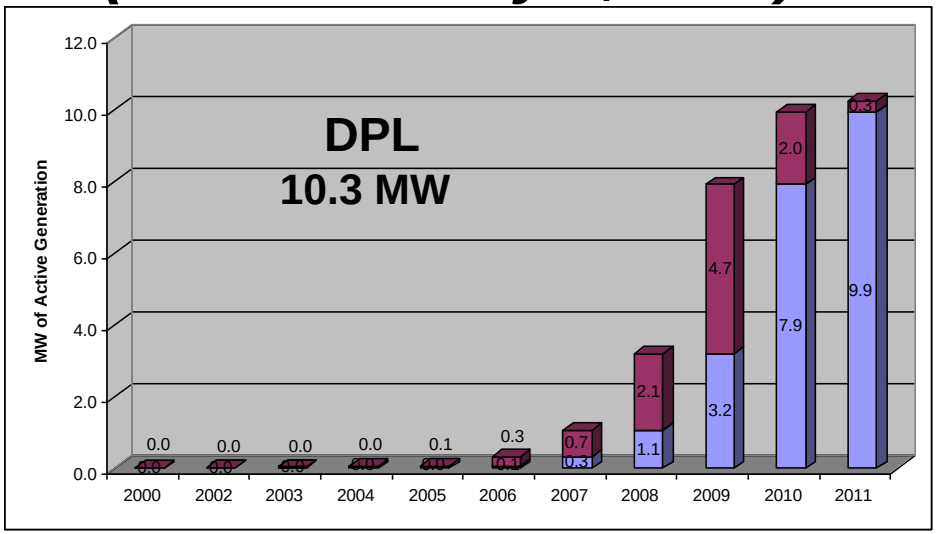
4, 12, 23, and 34kV distribution

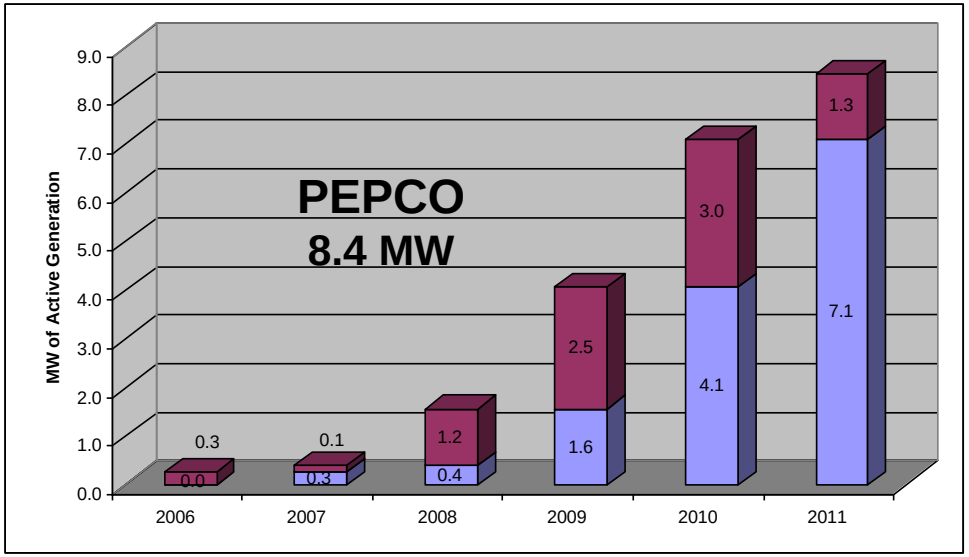
Combined Service Territory



Installed Solar PV DG By Year *(MW as of July 1, 2011)*







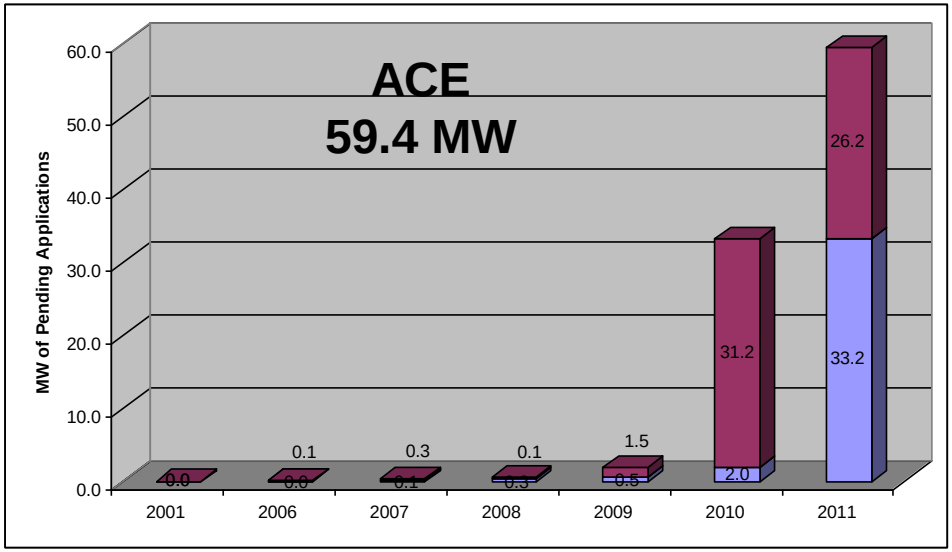
New
Existing

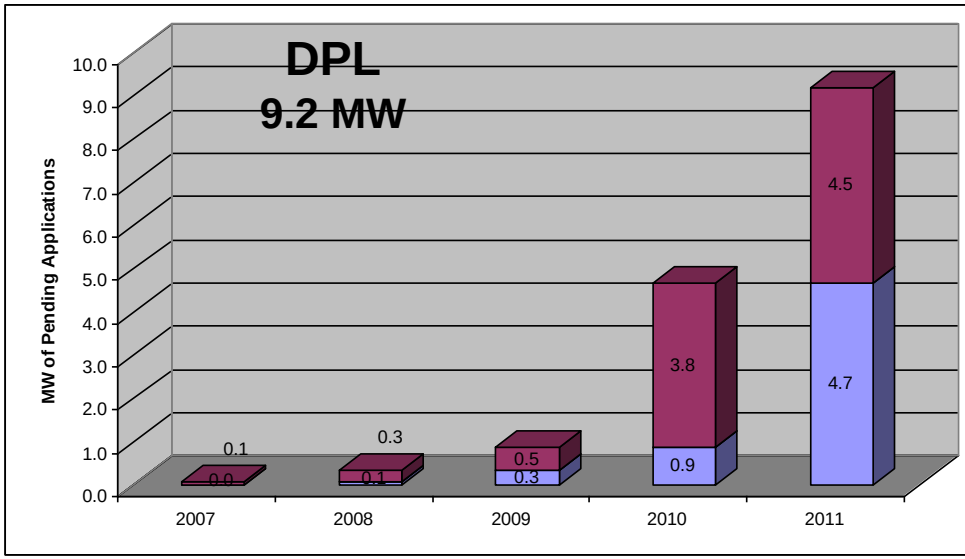
Note different "Y" axis scales for visibility

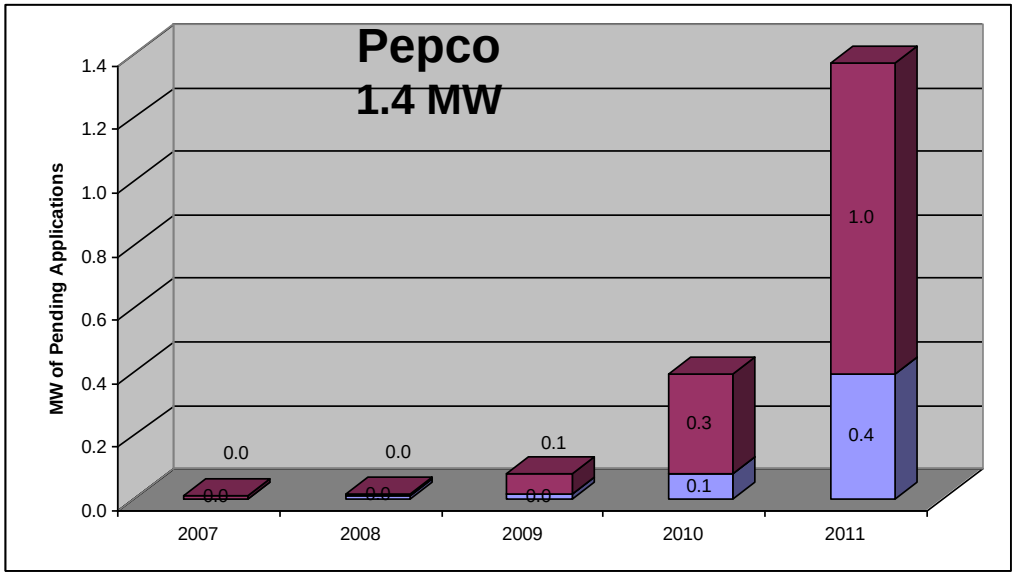
IEEE PES Power & Energy Society®

IEEE

Pending Solar PV NEM *(MW as of July 1, 2011)*







New
Existing

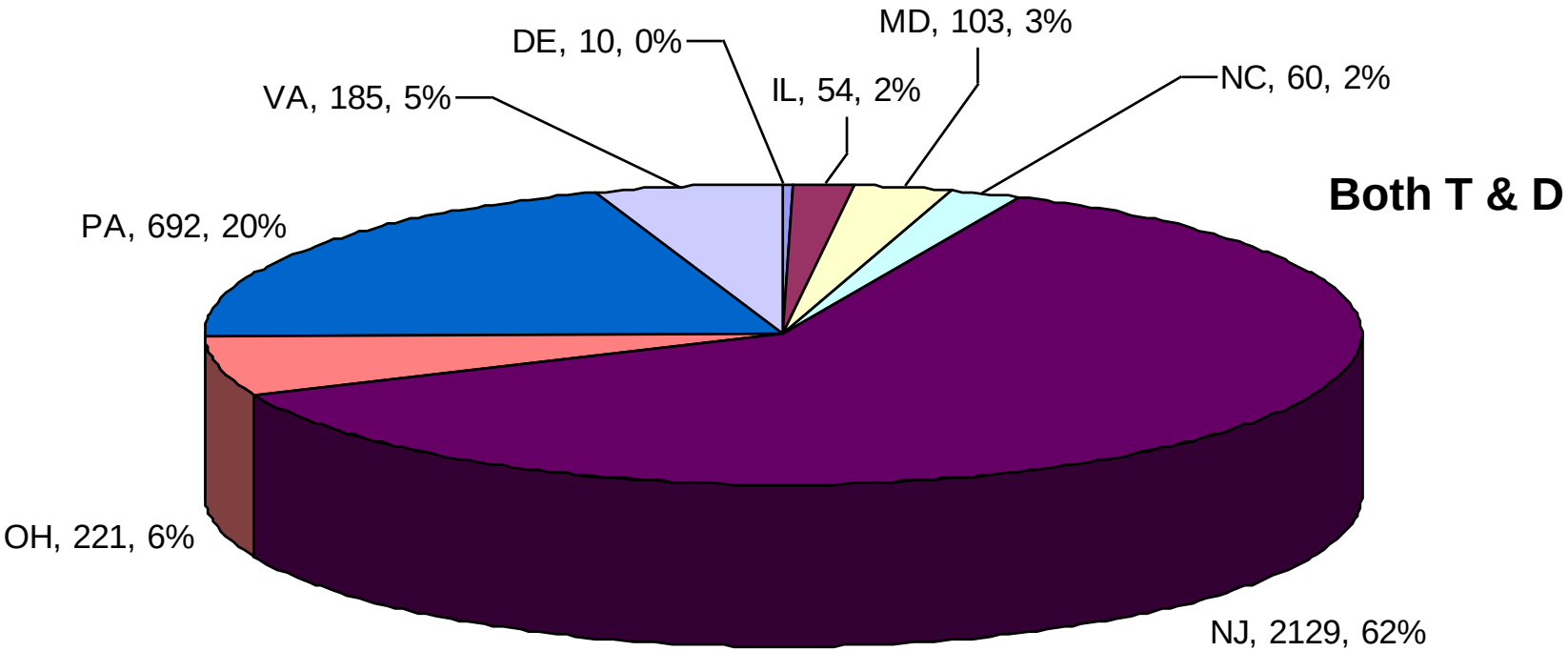
Note different "Y" axis scales for visibility

IEEE PES Power & Energy Society®

IEEE

PJM Solar Project Queue

(State, MW, Percentage as of July 1, 2011)



572 projects in New Jersey

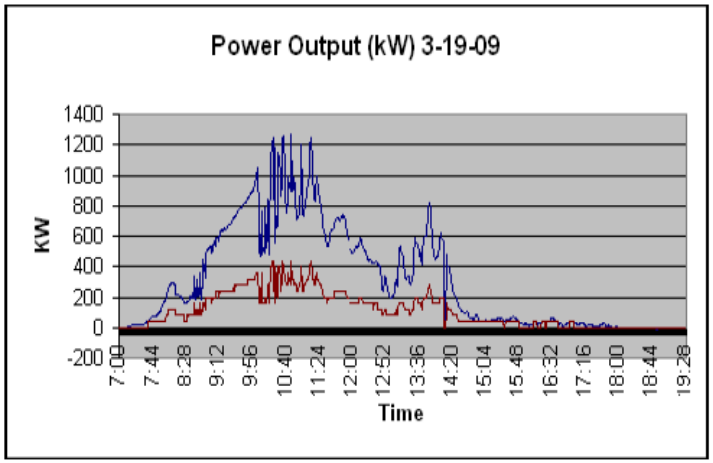
RPS Goals vs. Forecasted Peak Loads

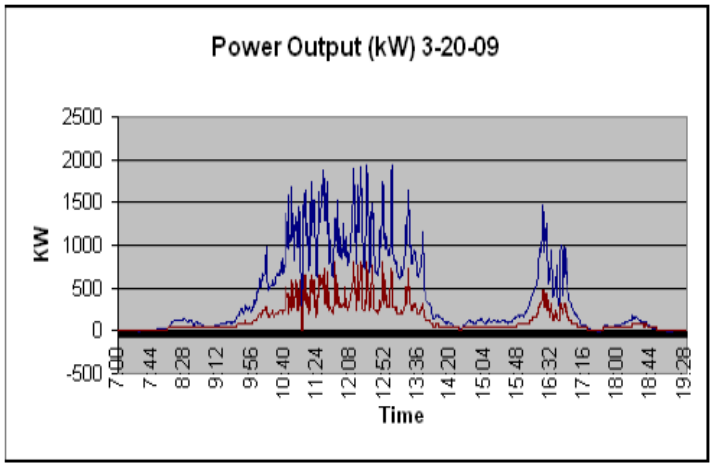
High level view of the NJ Target versus state peak load forecast

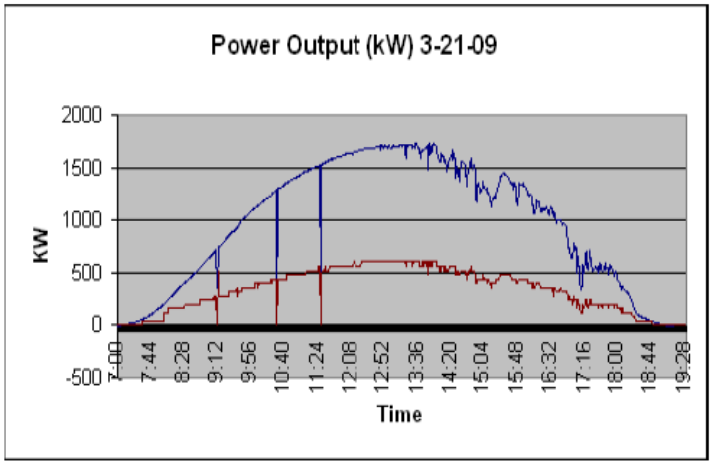
	NJ Solar Targets				PJM Forecast (MWs)									
Year	GWH Target	Needed Capacity (MW)	New Capacity Needed (MW)		50/50 Fcst Peak ACE	50/50 Fcst Peak JCPL	50/50 Fcst Peak PSEG	50/50 Fcst Peak O&R	State Total		90/10 Fcst Peak ACE	90/10 Fcst Peak JCPL	90/10 Fcst Peak PSEG	90/10 Fcst Peak O&R	State Total
2011	360	257			2,897	6,625	11,147	444	**21,113**		3,073	7,065	11,707	471	**22,316**
2012	442	315	59		3,032	6,843	11,427	452	**21,754**		3,213	7,239	77,908	482	**88,842**
2013	596	425	110		3,136	7,000	11,621	462	**22,219**		3,322	7,434	12,169	491	**23,416**
2014	772	551	126		3,198	7,115	11,771	468	**22,552**		3,386	7,607	12,414	498	**23,905**
2015	965	688	138		3,249	7,212	11,907	473	**22,841**		3,436	7,710	12,543	503	**24,192**
2016	1,150	820	132		3,288	7,323	12,006	477	**23,094**		3,481	7,807	12,651	508	**24,447**
2017	1,357	968	148		3,332	7,373	12,105	481	**23,291**		3,522	7,897	12,767	513	**24,699**
2018	1,591	1,135	167		3,372	7,451	12,194	483	**23,500**		3,569	7,903	12,800	517	**24,789**
2019	1,858	1,326	190		3,405	7,533	12,305	489	**23,732**		3,601	8,020	12,903	522	**25,046**
2020	2,164	1,544	218		3,443	7,611	12,428	493	**23,975**		3,638	8,149	13,200	526	**25,513**
2021	2,518	1,797	253		3,470	7,658	12,498	496	**24,122**		3,672	8,219	13,200	529	**25,620**
2022	2,928	2,089	293		3,500	7,790	12,575	499	**24,364**		3,704	8,295	13,279	533	**25,811**
2023	3,433	2,449	360		3,535	7,794	12,645	503	**24,477**		3,733	8,365	13,365	536	**25,999**
2024	3,989	2,846	397		3,565	7,877	12,722	505	**24,669**		3,769	8,397	13,378	540	**26,084**
2025	4,610	3,289	443		3,601	7,967	12,848	509	**24,925**		3,810	8,535	13,598	544	**26,487**
2026	5,316	3,793	504												

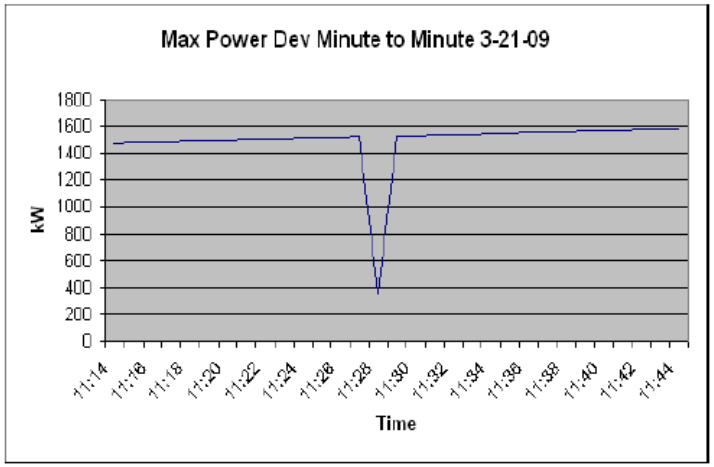
Distribution System Impacts

Atlantic City Convention Center PV





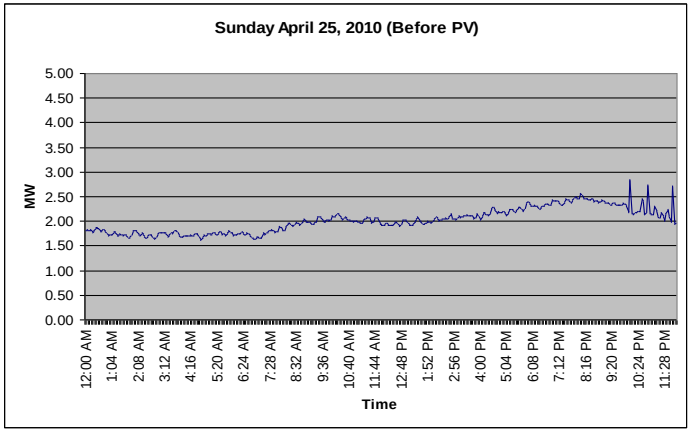


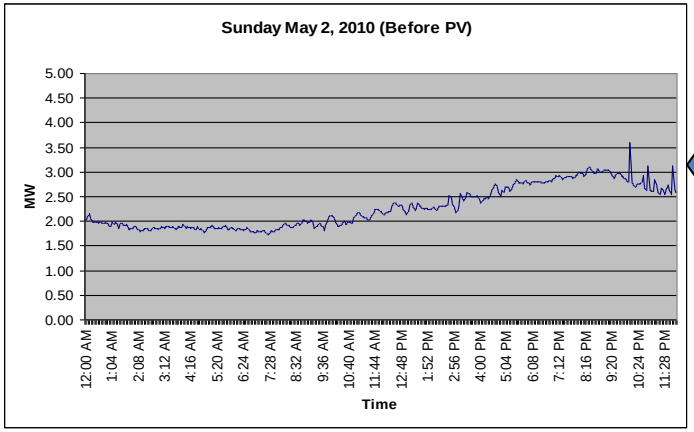


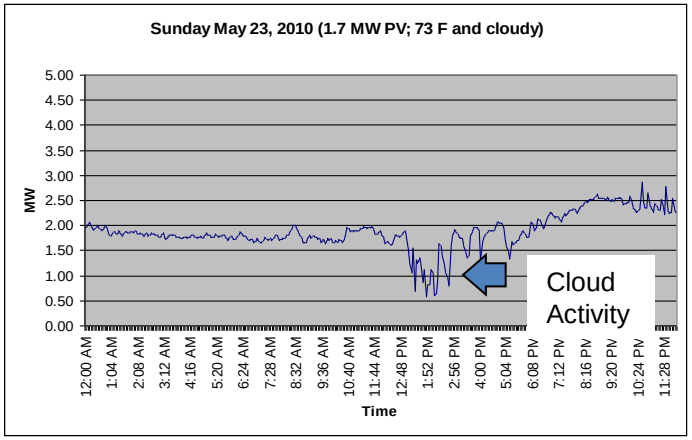
■ Total Output (kW) – One Minute Data ■ Irradiance (Scaled)

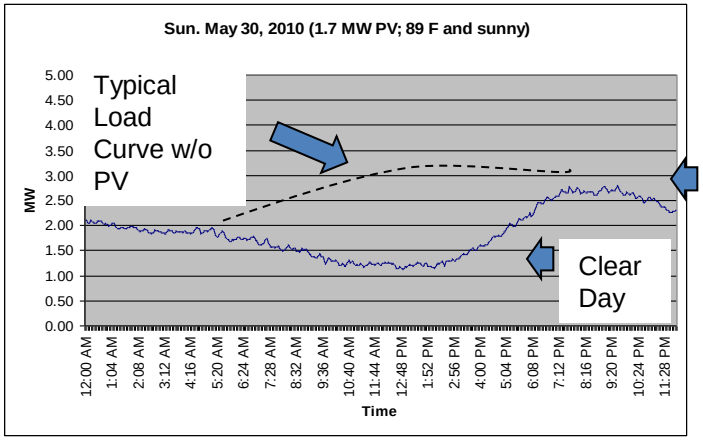
Distribution System Impacts (cont.)

Distribution Feeder -- Sunday Load Profile Before and After 1.7 MW PV Installation









Need for steady state and dynamic simulations

- Some expected impacts are:
  - Reverse power flow
  - Interaction with capacitor banks and voltage regulators
  - Voltage variations(transient and steady state)
  - Real and Reactive power fluctuations
  - Potential impacts on overcurrent and overvoltage protection systems
  - Losses increase and power factor modification
  - Voltage unbalance (single-phase PV-DG)
  - Harmonics (e.g., potential THD increase)
- These impacts can only be studied through simulations, we have to use both steady state software (e.g., SynerGEE, CYMDIST, Windmil), and "dynamic" simulation software such as PSCAD, EMTP, etc

Steady state simulation overview

- Inputs
  - Typical PV-DG injection profile
  - Installed PV-DG capacity (kW)
  - Feeder models (distribution analysis software)
  - Feeder load curves and status (if available) and settings of voltage control equipment (voltage regulators and capacitor)

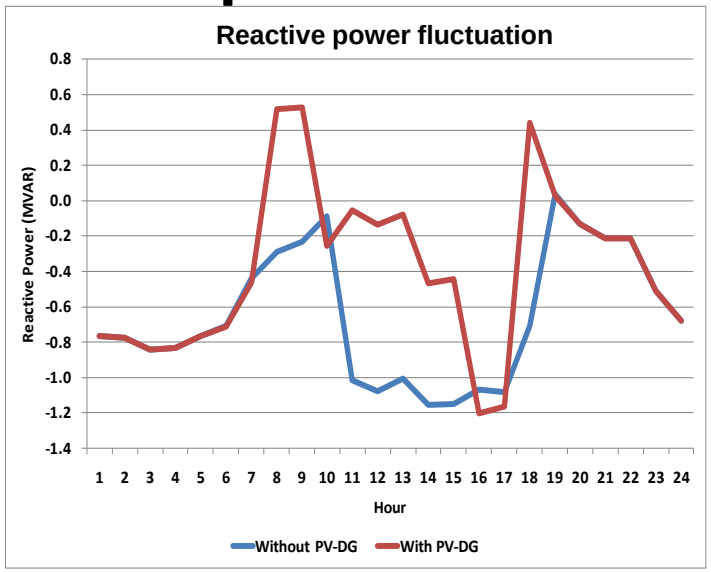
Dynamic simulation overview

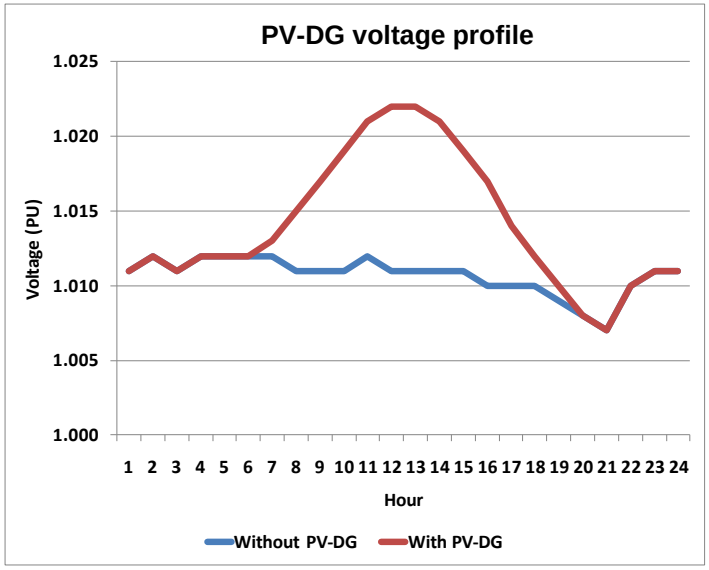
- Study focus
  - Large-scale integration of solar PV generation
    - Utility scale PV-DG (three-phase)
    - Residential PV-DG (single-phase)
  - Impact of PV-DG intermittency, islanding and feeder transient and switching phenomena

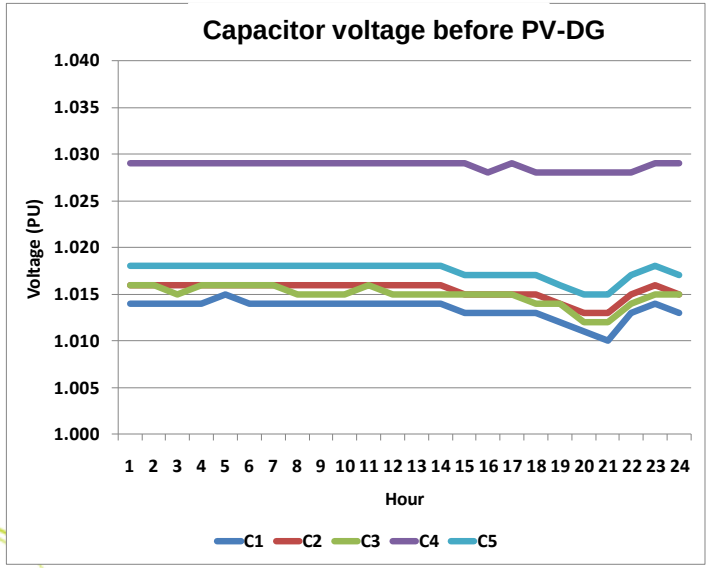
Dynamic simulation overview (cont.)

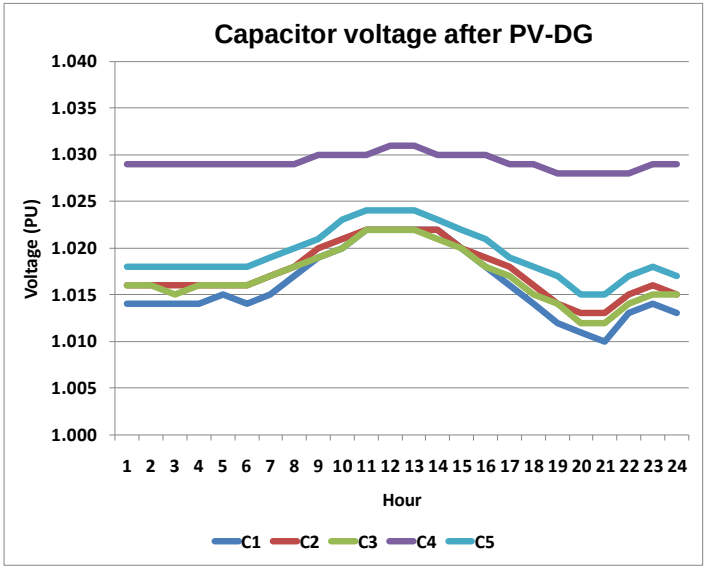
- Typical study scenarios
  - Sudden change in solar irradiance
    - Step increase (0% to 100% PV-DG)
    - Step decrease (100% to 0% PV-DG)
  - Feeder voltage variations
    - Intermittent PV-DG output profile
  - Islanding cases:
    - Opening of feeder circuit breaker
    - Power balance: PV generation = load

Reactive power fluctuation

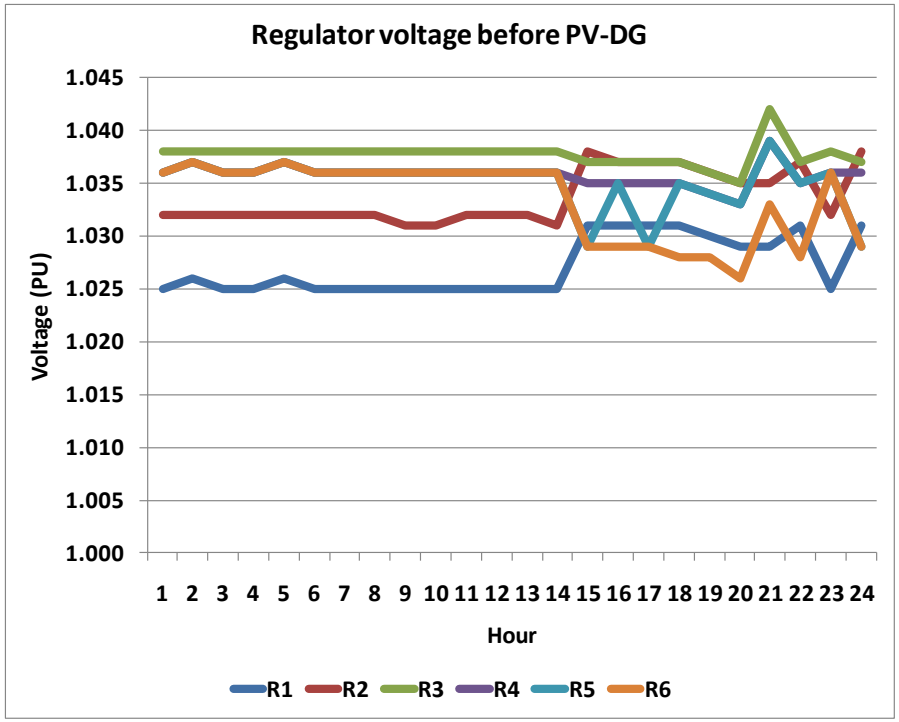


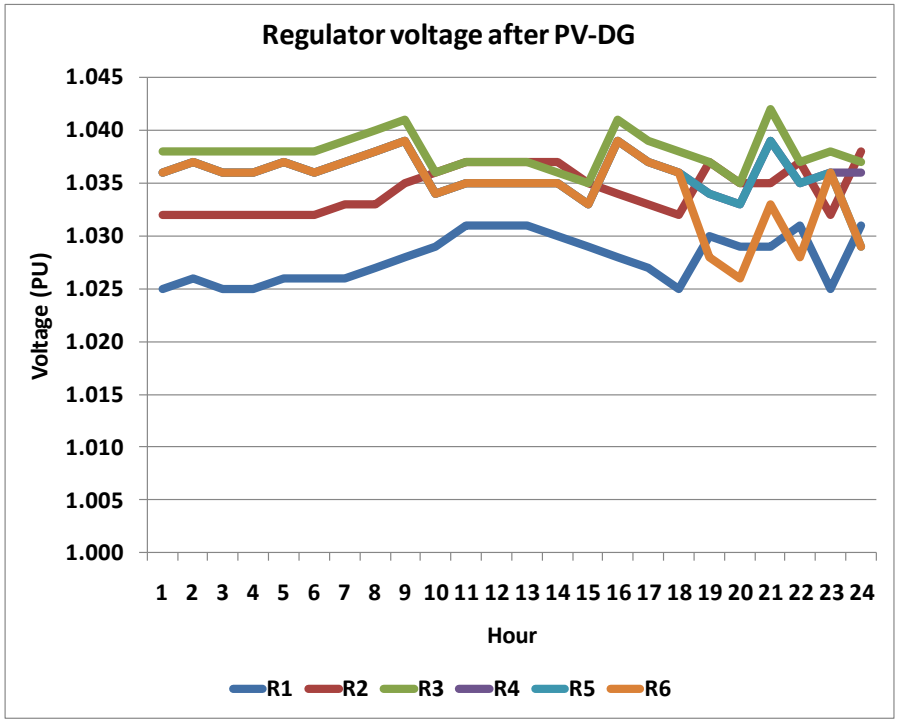






Interaction with voltage regulators

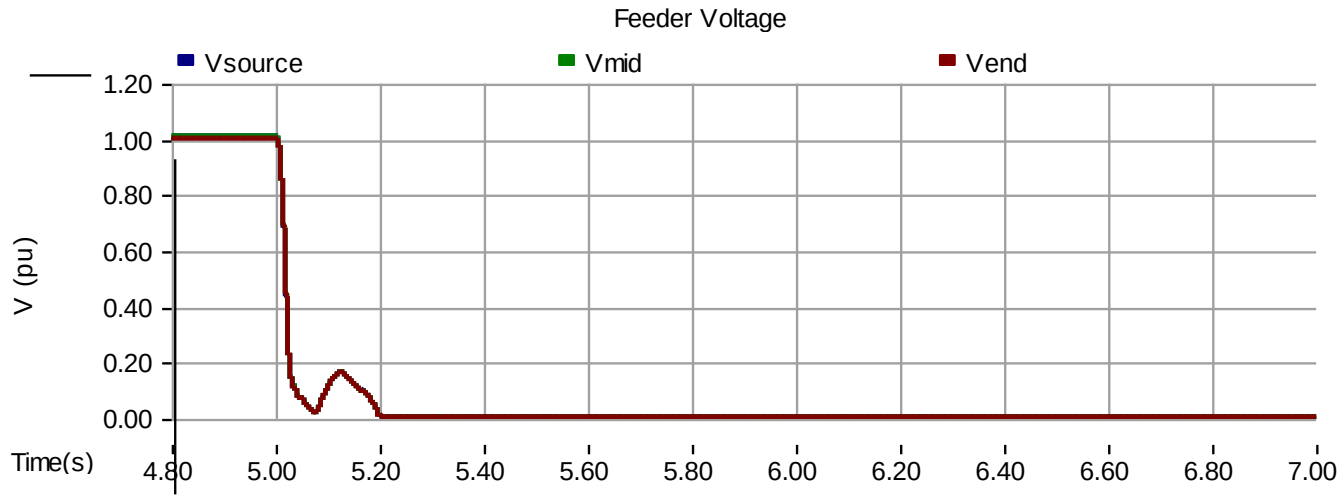




Impacts due to islanding of utility scale PV-DG

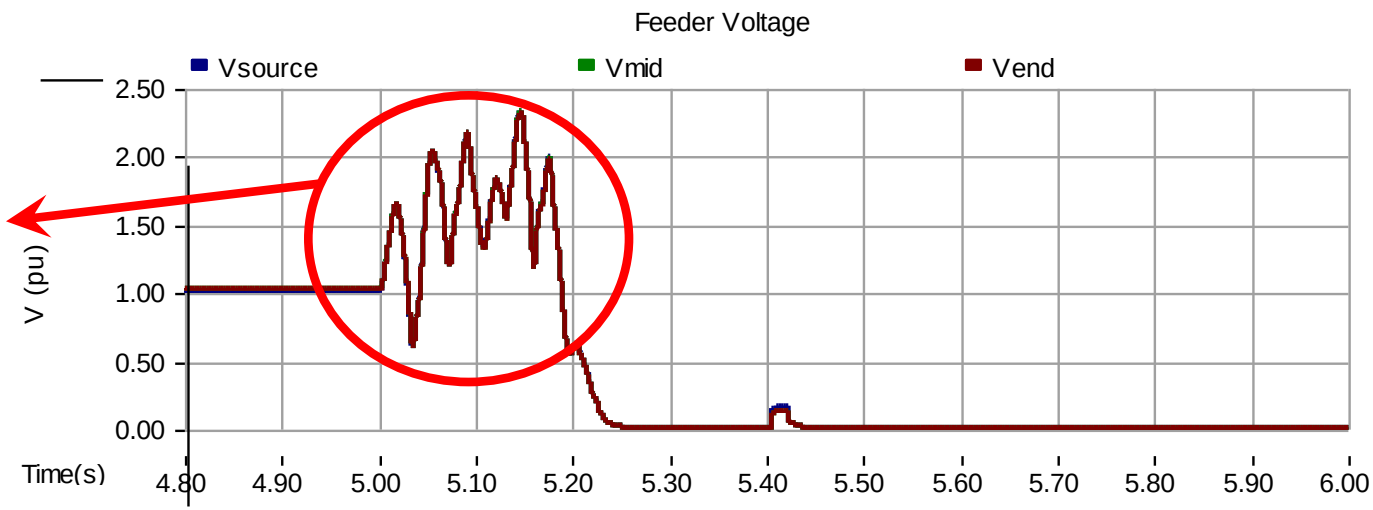
- Opening feeder main circuit breaker at t = 5 second

No PV-DG



100% PV-DG

TOV for about 0.2 sec



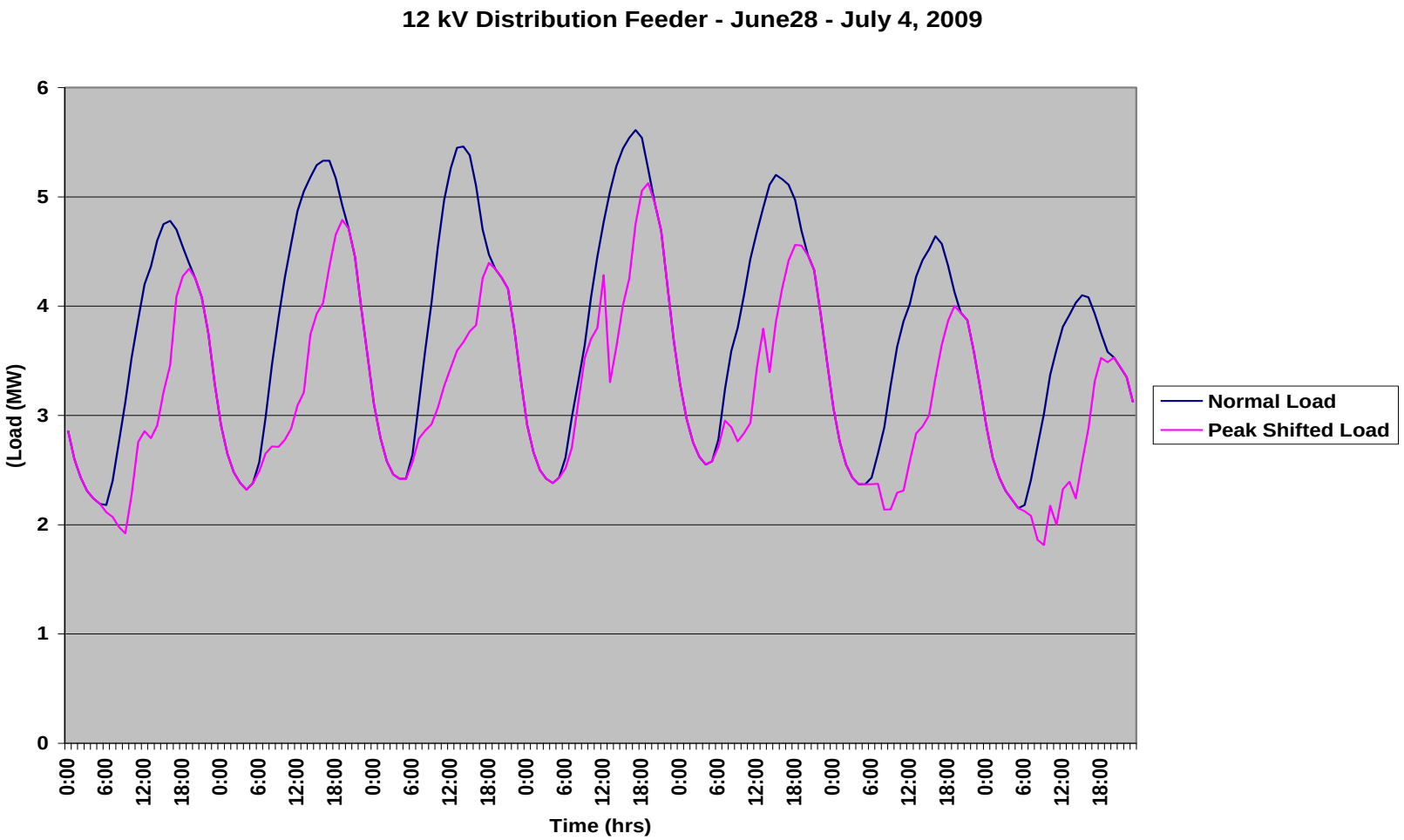
Mitigation measures

- The objective of the mitigation measures is to reduce or minimize impacts caused by the interconnection of PV-DG to distribution systems
- Common mitigation measures include:
  - Operating PV-DG at leading power factor (absorbing VArs)
  - Modifying operation mode of line voltage regulators (e.g., to cogeneration or bidirectional modes)
  - Relocating capacitor banks and modifying settings of capacitor banks (e.g., switching off fixed capacitor banks and modifying switch off and switch on settings of voltage-controlled banks)
  - Modifying reference voltage of Load Tap Changers (LTCs) and compensating current on Line Drop Compensation (LDC) applications
  - Using express feeders for interconnection of large utility-scale PV-DG facilities

Mitigation measures

- More advanced mitigation measures may include:
  - Using Distributed Storage (DS)
  - Installing Static Synchronous Compensator (STATCOM) at the PV-DG location
  - Implementing a dynamic VAr compensation scheme via PV-DG inverters
  - Installing distribution reactors at the PV-DG location
  - Increasing express feeder design voltage (e.g., using 25 kV instead of 13.2 kV)
  - Advanced Volt/Var Management
  - Flexible Load Control

Potential impact of PV on Load Profile



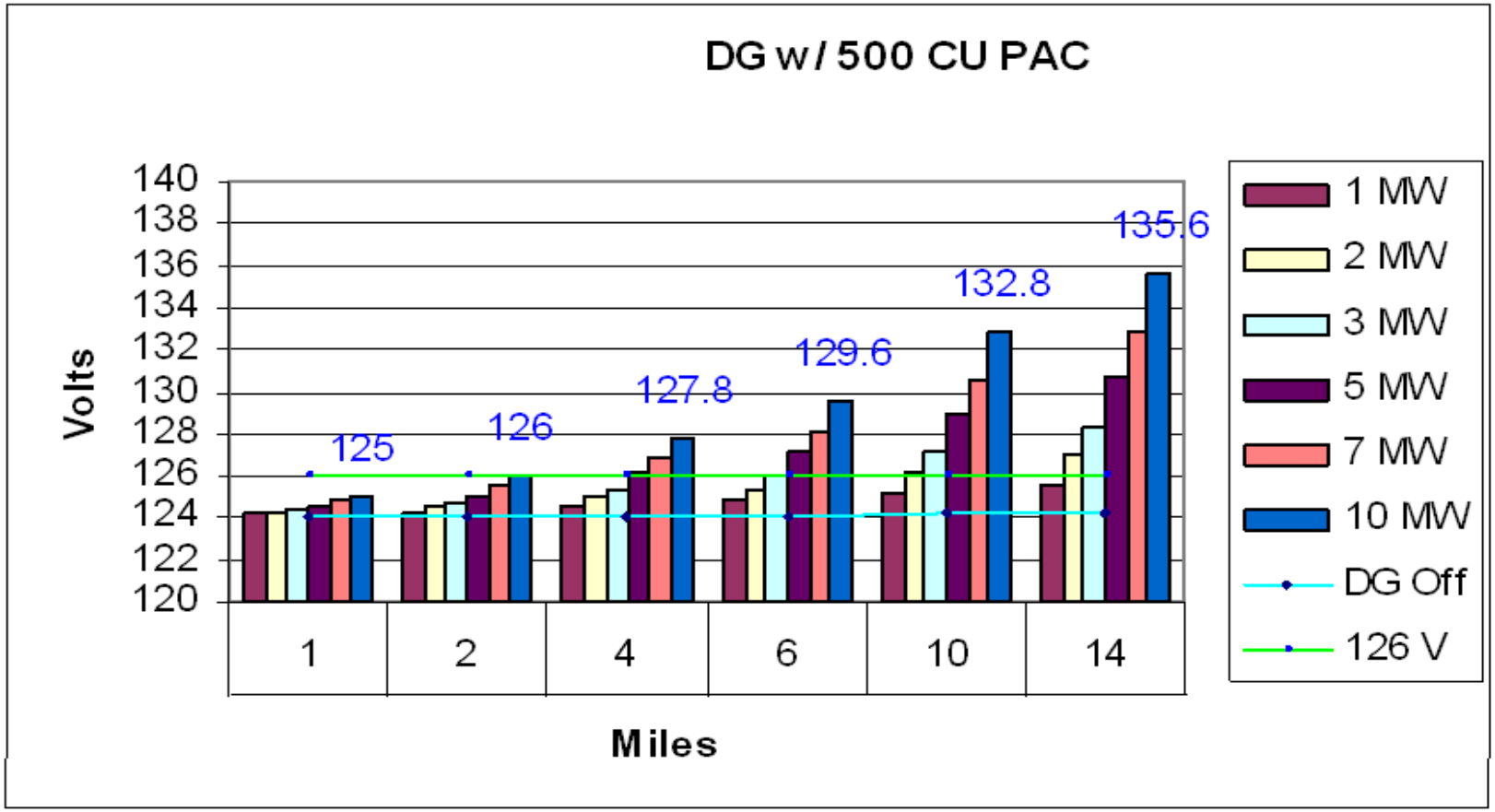
PV Impact on Peak Load Results

- 103 daily peak load hours were shifted by the PV output

Number of Hours Peak was Shifted by	2 hrs	3 hrs	4 hrs	5 hrs	6(+) hrs
Number of Occurrences	28	37	14	14	10

- A system with a PV peak output of 2 MW, lowered the annual peak load of a distribution circuit by 0.44 MW, or about 22% of the PV capacity.

Voltage at PV Site with varying DG Size & Distance (500 CU PAC), 12.47kV Circuit



% Demand Loss Based on Distance and Output for an Express Feeder w/500 CU PAC, 12.47kV Circuit

Peak Loss (%)		Length (miles)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AC Generation (MW)	1	0%	0%	0%	0%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	2%	2%	2%	2%	2%	2%
	2	0%	0%	1%	1%	1%	1%	1%	2%	2%	2%	2%	2%	3%	3%	3%	3%	3%	4%	4%	4%
	3	0%	1%	1%	1%	2%	2%	2%	2%	3%	3%	3%	4%	4%	4%	5%	5%	5%	5%	6%	6%
	4	0%	1%	1%	2%	2%	2%	3%	3%	4%	4%	4%	5%	5%	6%	6%	6%	7%	7%	8%	8%
	5	1%	1%	2%	2%	3%	3%	4%	4%	5%	5%	6%	6%	7%	7%	8%	8%	9%	9%	10%	10%
	6	1%	1%	2%	2%	3%	4%	4%	5%	5%	6%	7%	7%	8%	8%	9%	10%	10%	11%	12%	12%
	7	1%	1%	2%	3%	4%	4%	5%	6%	6%	7%	8%	8%	9%	10%	11%	11%	12%	13%	13%	14%
	8	1%	2%	2%	3%	4%	5%	6%	6%	7%	8%	9%	10%	11%	11%	12%	13%	14%	15%	15%	16%
	9	1%	2%	3%	4%	5%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%	15%	16%	17%	18%
	10	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%	16%	17%	18%	19%	20%
	11	1%	2%	3%	4%	6%	7%	8%	9%	10%	11%	12%	13%	14%	16%	17%	18%	19%	20%	21%	22%
	12	1%	2%	4%	5%	6%	7%	8%	10%	11%	12%	13%	15%	16%	17%	18%	19%	21%	22%	23%	24%
	13	1%	3%	4%	5%	7%	8%	9%	11%	12%	13%	14%	16%	17%	18%	20%	21%	22%	24%	25%	26%
	14	1%	3%	4%	6%	7%	8%	10%	11%	13%	14%	16%	17%	18%	20%	21%	23%	24%	25%	27%	28%
	15	2%	3%	5%	6%	8%	9%	11%	12%	14%	15%	17%	18%	20%	21%	23%	24%	26%	27%	29%	30%
	16	2%	3%	5%	6%	8%	10%	11%	13%	15%	16%	18%	19%	21%	23%	24%	26%	28%	29%	31%	32%
	17	2%	3%	5%	7%	9%	10%	12%	14%	15%	17%	19%	21%	22%	24%	26%	28%	29%	31%	33%	34%
	18	2%	4%	5%	7%	9%	11%	13%	15%	16%	18%	20%	22%	24%	25%	27%	29%	31%	33%	35%	36%
	19	2%	4%	6%	8%	10%	12%	13%	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	38%
	20	2%	4%	6%	8%	10%	12%	14%	16%	18%	20%	22%	24%	26%	28%	30%	32%	34%	36%	38%	40%

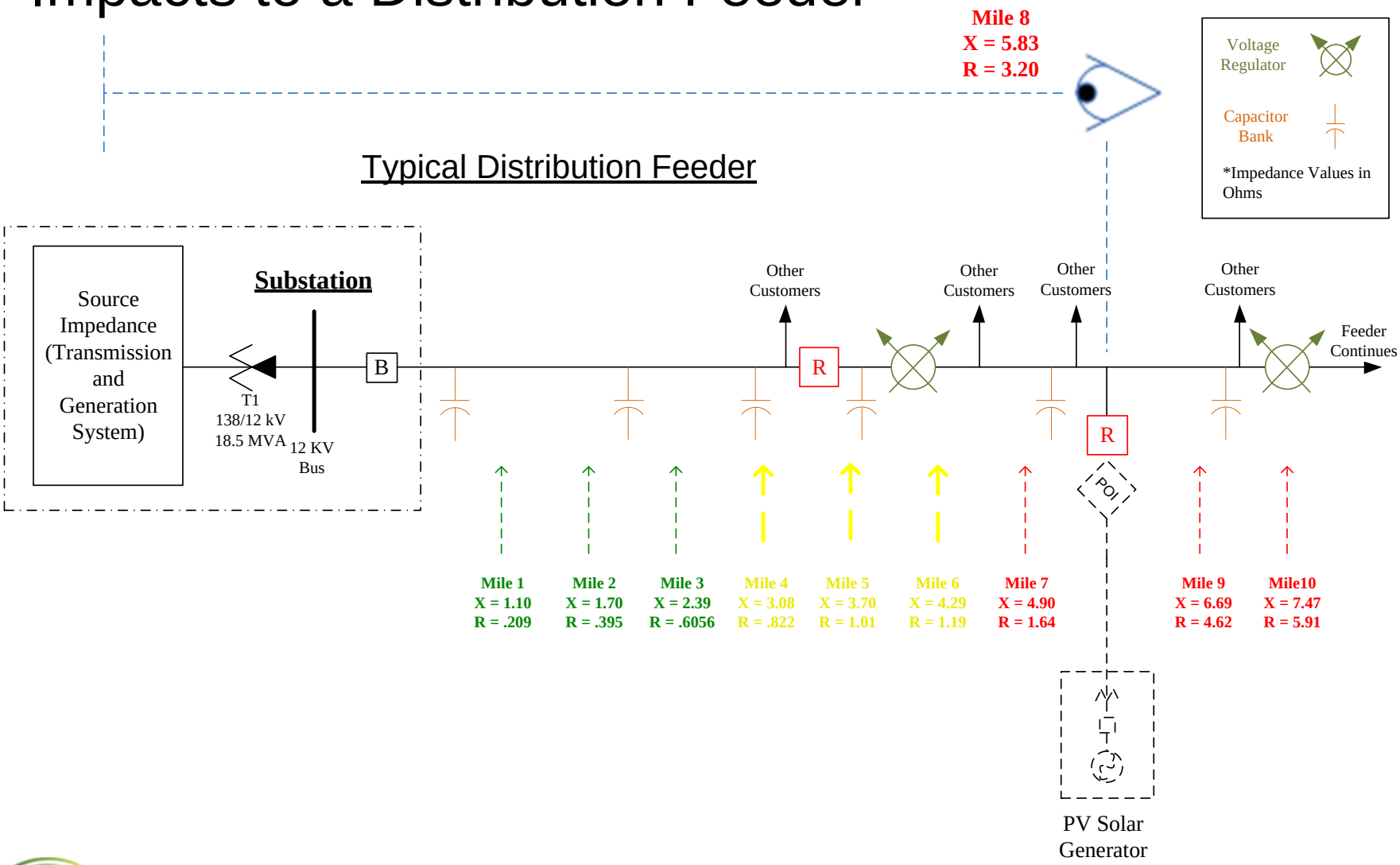
Note: The Load Losses will be little bit less if with 1000 AL PAC Cable.

% Annual Energy Loss based on Distance w/ 500 PAC Cable, 12.47 kV Circuit

Annual Energy Loss (%)		Length (miles)																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AC Generation (MW)	1	0.1%	0.2%	0.2%	0.3%	0.4%	0.5%	0.5%	0.6%	0.7%	0.8%	0.9%	0.9%	1.0%	1.1%	1.2%	1.2%	1.3%	1.4%	1.5%	1.5%
	2	0.2%	0.3%	0.5%	0.6%	0.8%	0.9%	1.1%	1.2%	1.4%	1.5%	1.7%	1.9%	2.0%	2.2%	2.3%	2.5%	2.6%	2.8%	2.9%	3.1%
	3	0.2%	0.5%	0.7%	0.9%	1.2%	1.4%	1.6%	1.9%	2.1%	2.3%	2.6%	2.8%	3.0%	3.2%	3.5%	3.7%	3.9%	4.2%	4.4%	4.6%
	4	0.3%	0.6%	0.9%	1.2%	1.5%	1.9%	2.2%	2.5%	2.8%	3.1%	3.4%	3.7%	4.0%	4.3%	4.6%	4.9%	5.3%	5.6%	5.9%	6.2%
	5	0.4%	0.8%	1.2%	1.5%	1.9%	2.3%	2.7%	3.1%	3.5%	3.9%	4.3%	4.6%	5.0%	5.4%	5.8%	6.2%	6.6%	7.0%	7.3%	7.7%
	6	0.5%	0.9%	1.4%	1.9%	2.3%	2.8%	3.2%	3.7%	4.2%	4.6%	5.1%	5.6%	6.0%	6.5%	7.0%	7.4%	7.9%	8.3%	8.8%	9.3%
	7	0.5%	1.1%	1.6%	2.2%	2.7%	3.2%	3.8%	4.3%	4.9%	5.4%	6.0%	6.5%	7.0%	7.6%	8.1%	8.7%	9.2%	9.7%	10.3%	10.8%
	8	0.6%	1.2%	1.9%	2.5%	3.1%	3.7%	4.3%	4.9%	5.6%	6.2%	6.8%	7.4%	8.0%	8.7%	9.3%	9.9%	10.5%	11.1%	11.7%	12.4%
	9	0.7%	1.4%	2.1%	2.8%	3.5%	4.2%	4.9%	5.6%	6.3%	7.0%	7.7%	8.3%	9.0%	9.7%	10.4%	11.1%	11.8%	12.5%	13.2%	13.9%
	10	0.8%	1.5%	2.3%	3.1%	3.9%	4.6%	5.4%	6.2%	7.0%	7.7%	8.5%	9.3%	10.0%	10.8%	11.6%	12.4%	13.1%	13.9%	14.7%	15.5%
	11	0.9%	1.7%	2.6%	3.4%	4.3%	5.1%	6.0%	6.8%	7.7%	8.5%	9.4%	10.2%	11.1%	11.9%	12.8%	13.6%	14.5%	15.3%	16.2%	17.0%
	12	0.9%	1.9%	2.8%	3.7%	4.6%	5.6%	6.5%	7.4%	8.3%	9.3%	10.2%	11.1%	12.1%	13.0%	13.9%	14.8%	15.8%	16.7%	17.6%	18.6%
	13	1.0%	2.0%	3.0%	4.0%	5.0%	6.0%	7.0%	8.0%	9.0%	10.0%	11.1%	12.1%	13.1%	14.1%	15.1%	16.1%	17.1%	18.1%	19.1%	20.1%
	14	1.1%	2.2%	3.2%	4.3%	5.4%	6.5%	7.6%	8.7%	9.7%	10.8%	11.9%	13.0%	14.1%	15.2%	16.2%	17.3%	18.4%	19.5%	20.6%	21.6%
	15	1.2%	2.3%	3.5%	4.6%	5.8%	7.0%	8.1%	9.3%	10.4%	11.6%	12.8%	13.9%	15.1%	16.2%	17.4%	18.6%	19.7%	20.9%	22.0%	23.2%
	16	1.2%	2.5%	3.7%	4.9%	6.2%	7.4%	8.7%	9.9%	11.1%	12.4%	13.6%	14.8%	16.1%	17.3%	18.6%	19.8%	21.0%	22.3%	23.5%	24.7%
	17	1.3%	2.6%	3.9%	5.3%	6.6%	7.9%	9.2%	10.5%	11.8%	13.1%	14.5%	15.8%	17.1%	18.4%	19.7%	21.0%	22.3%	23.7%	25.0%	26.3%
	18	1.4%	2.8%	4.2%	5.6%	7.0%	8.3%	9.7%	11.1%	12.5%	13.9%	15.3%	16.7%	18.1%	19.5%	20.9%	22.3%	23.7%	25.0%	26.4%	27.8%
	19	1.5%	2.9%	4.4%	5.9%	7.3%	8.8%	10.3%	11.7%	13.2%	14.7%	16.2%	17.6%	19.1%	20.6%	22.0%	23.5%	25.0%	26.4%	27.9%	29.4%
	20	1.5%	3.1%	4.6%	6.2%	7.7%	9.3%	10.8%	12.4%	13.9%	15.5%	17.0%	18.6%	20.1%	21.6%	23.2%	24.7%	26.3%	27.8%	29.4%	30.9%

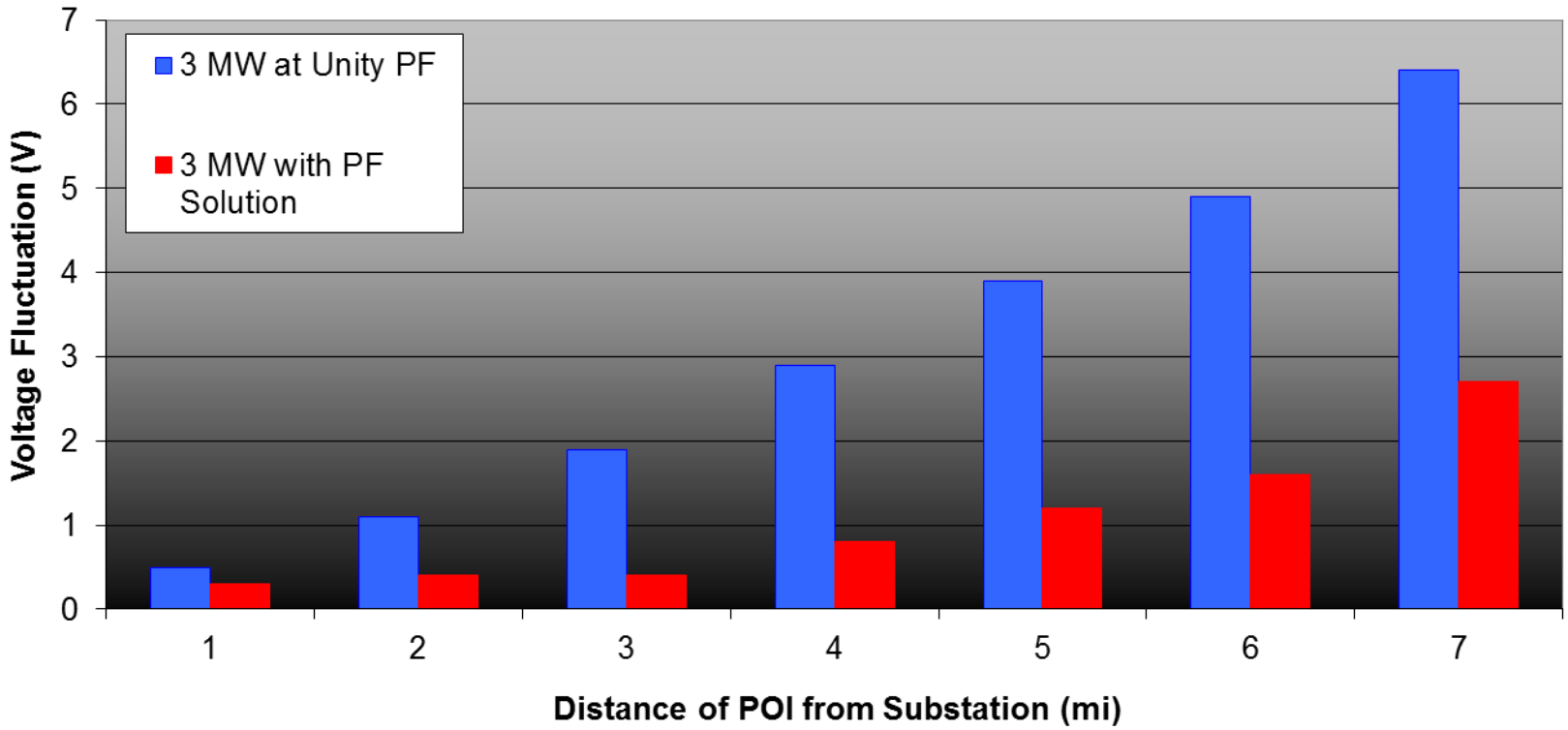
Note: The Load Losses will be a little bit less with 1000 AL PAC Cable.

Impacts to a Distribution Feeder

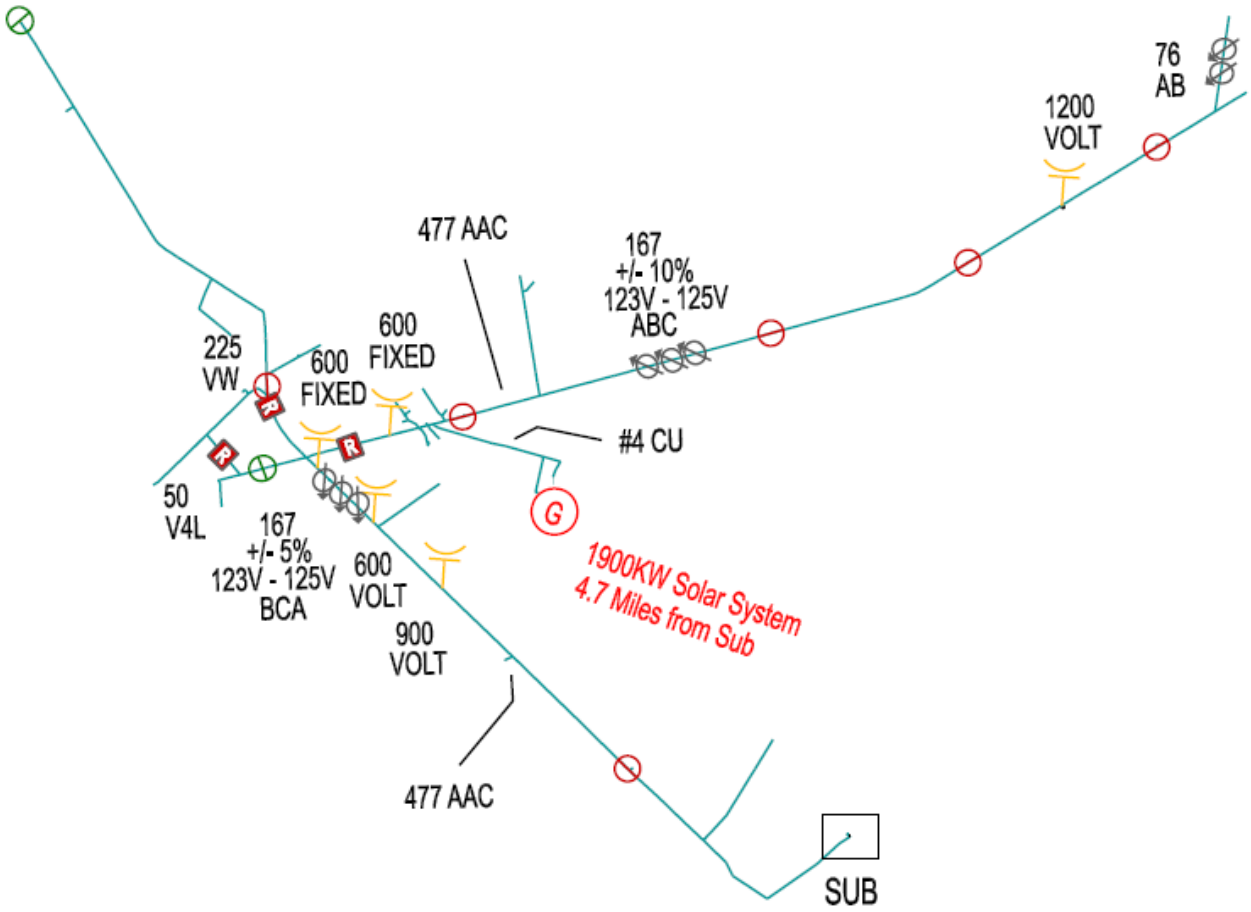


Absorbing Power Factor Solution For PV Inverters
3 MW System: Voltage Fluctuation at Point of Interconnection (POI) vs. Miles from Substation, 12.47kV Circuit

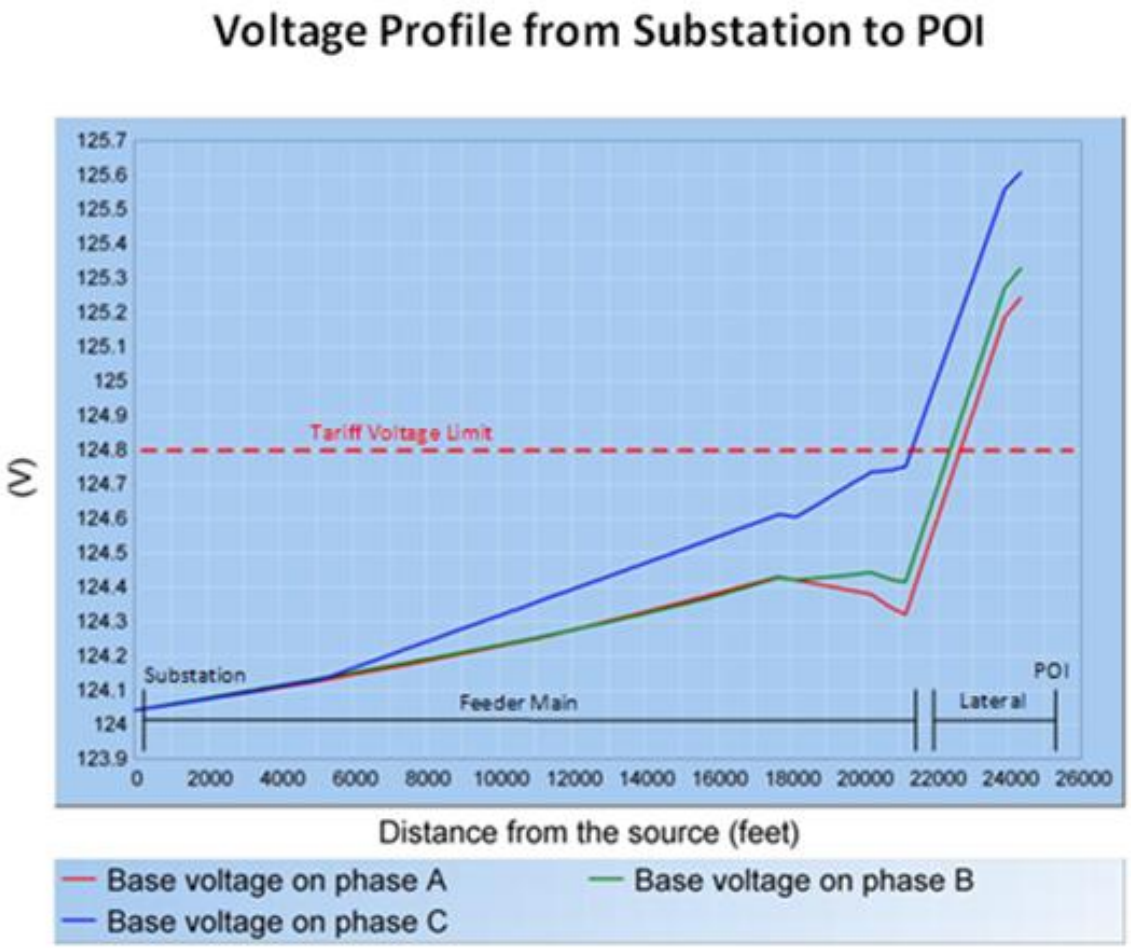
Power Factor Limited to +/- 0.95, typical 477 MCM Al Conductor



1.9 MW PV System (Feeder Nominal Voltage: 12,470V)



1.9 MW PV System



1.9 MW PV System – 3 Options to Mitigate Voltage Issues

Summary Table				
	*Maximum Steady State Voltage(V)	Maximum Voltage Fluctuation at the PV site(V)	Maximum Voltage Fluctuation at the Upstream Regulator(V)	Cost
Without Mitigation	125.3	2.3	1.0	$0
Absorbing Power Factor Solution**	124.0	1.2	0.2	$2,200
500KVA/1500kWh Battery Solution	125.0	0.5	0.1	$1,115,014
750KVA/3000kWh Battery Solution	124.7	0.0	0.0	$2,189,390
477 AAC Reconductor	124.9	1.3	1.1	$266,000

*All Maximum Steady State Voltages occurred during low load, expressed on a 120V base

**Absorbing Power Factor of .97 was used for this study

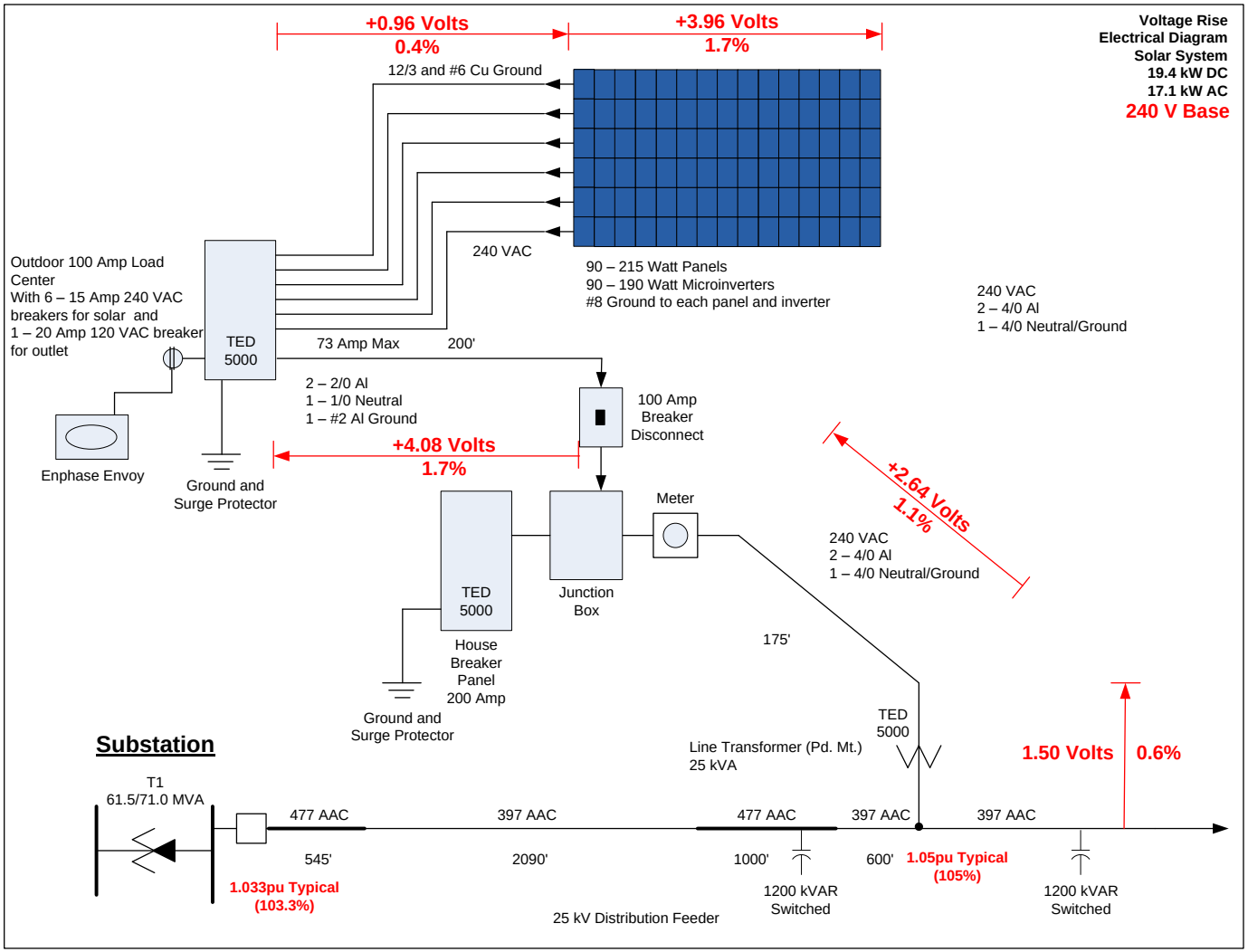
***The battery storage solution is unlike the other solutions and may have other operating value streams but also may have maintenance and/or replacement costs over the life of the solar system. These have not been investigated and included in this comparison.

Large Solar – 3+ MW to 20 MW

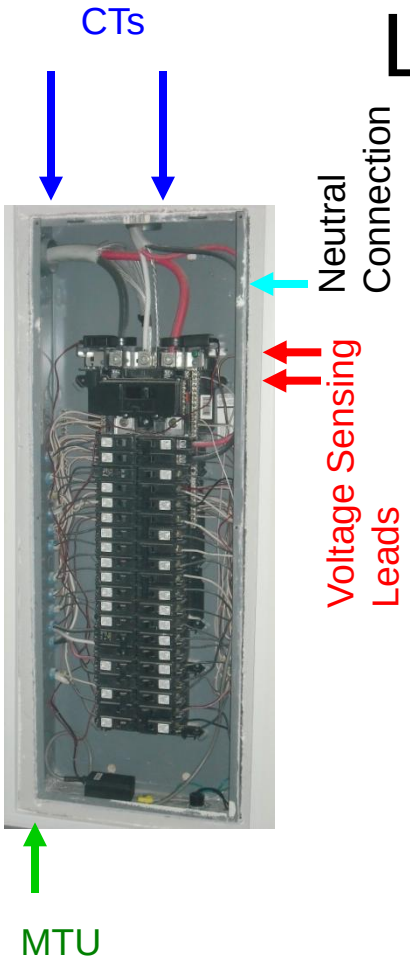
Medium Solar – 3 MW or less

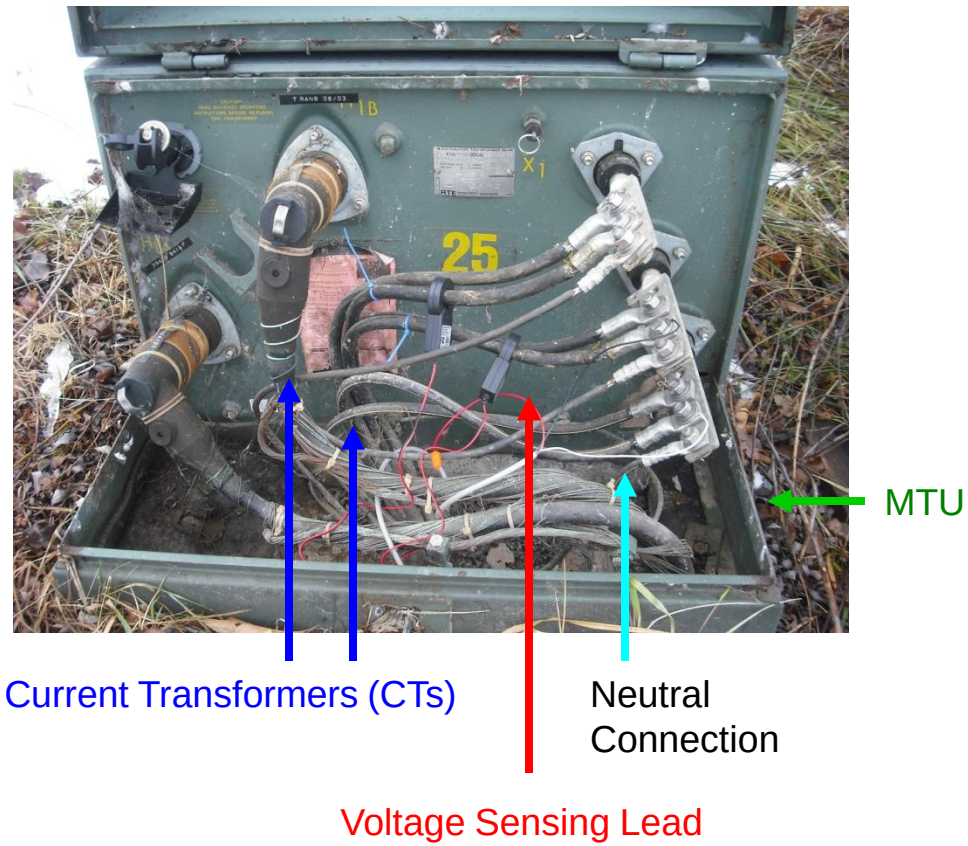
Residential Solar – 19.4 kW (DC)

Maximum Voltage Rise

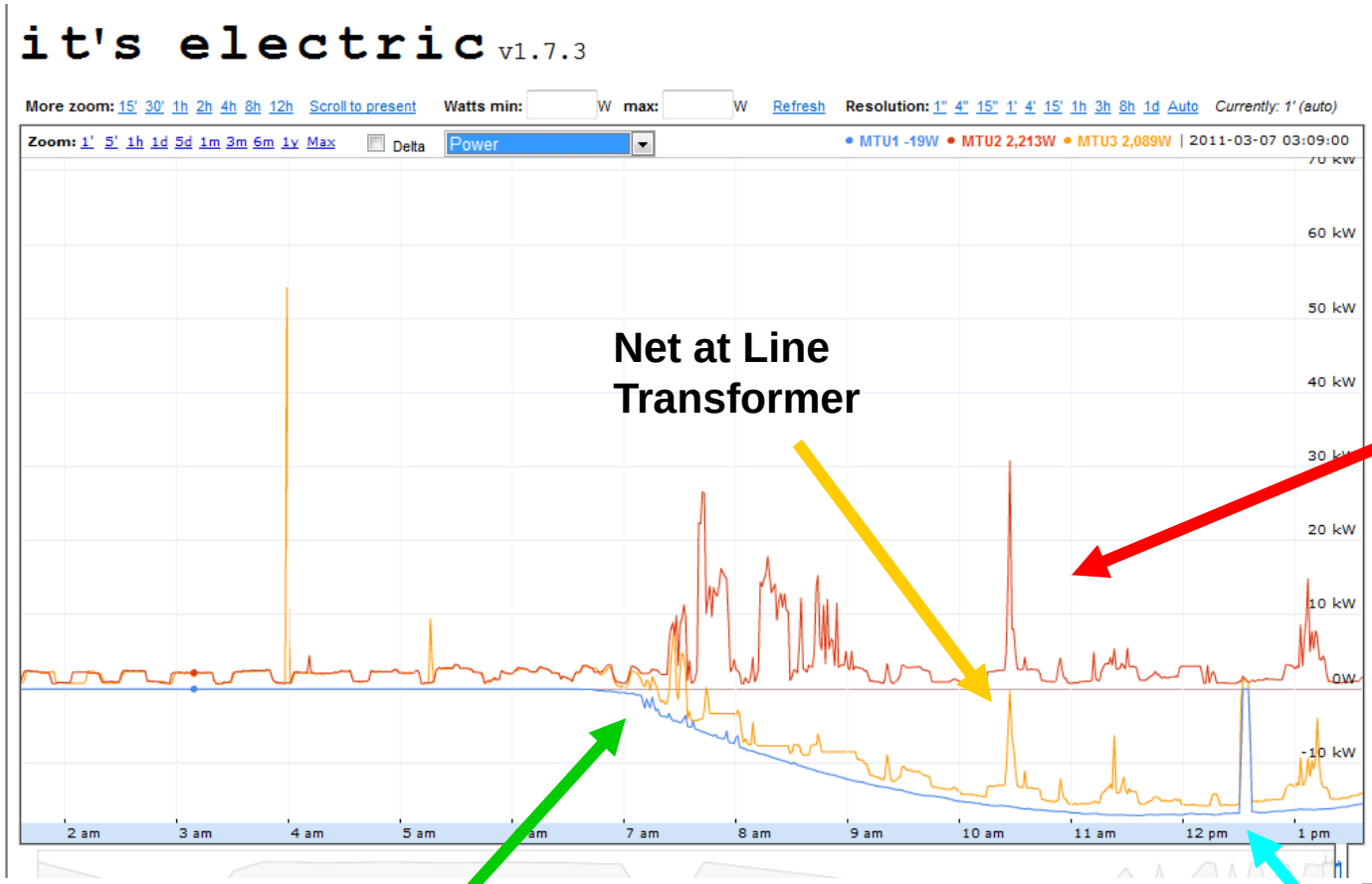


TED 5000 installed in House Panel and Line Transformer





Power vs. Time



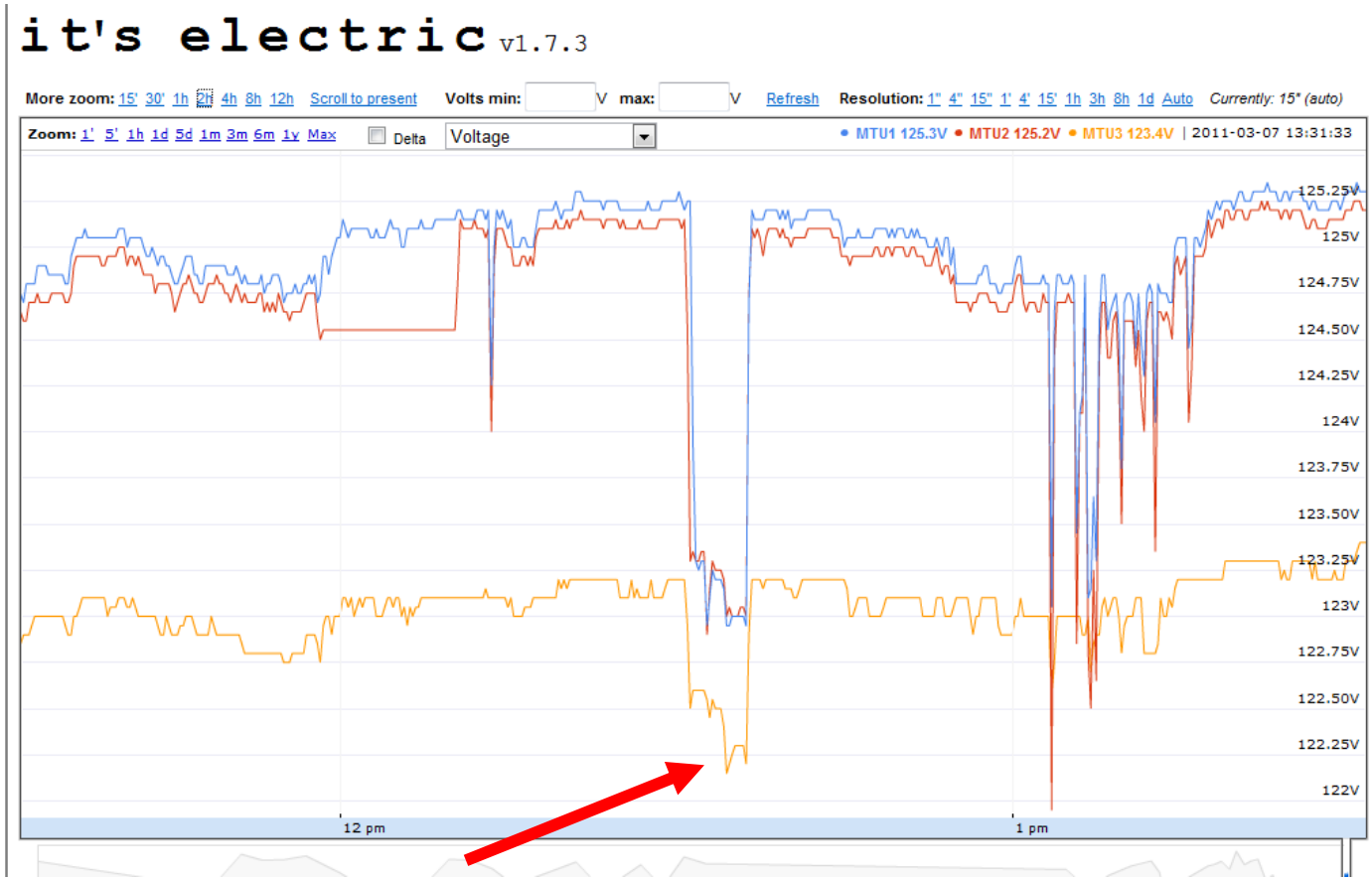
Net at Line Transformer

House Load

Solar Output

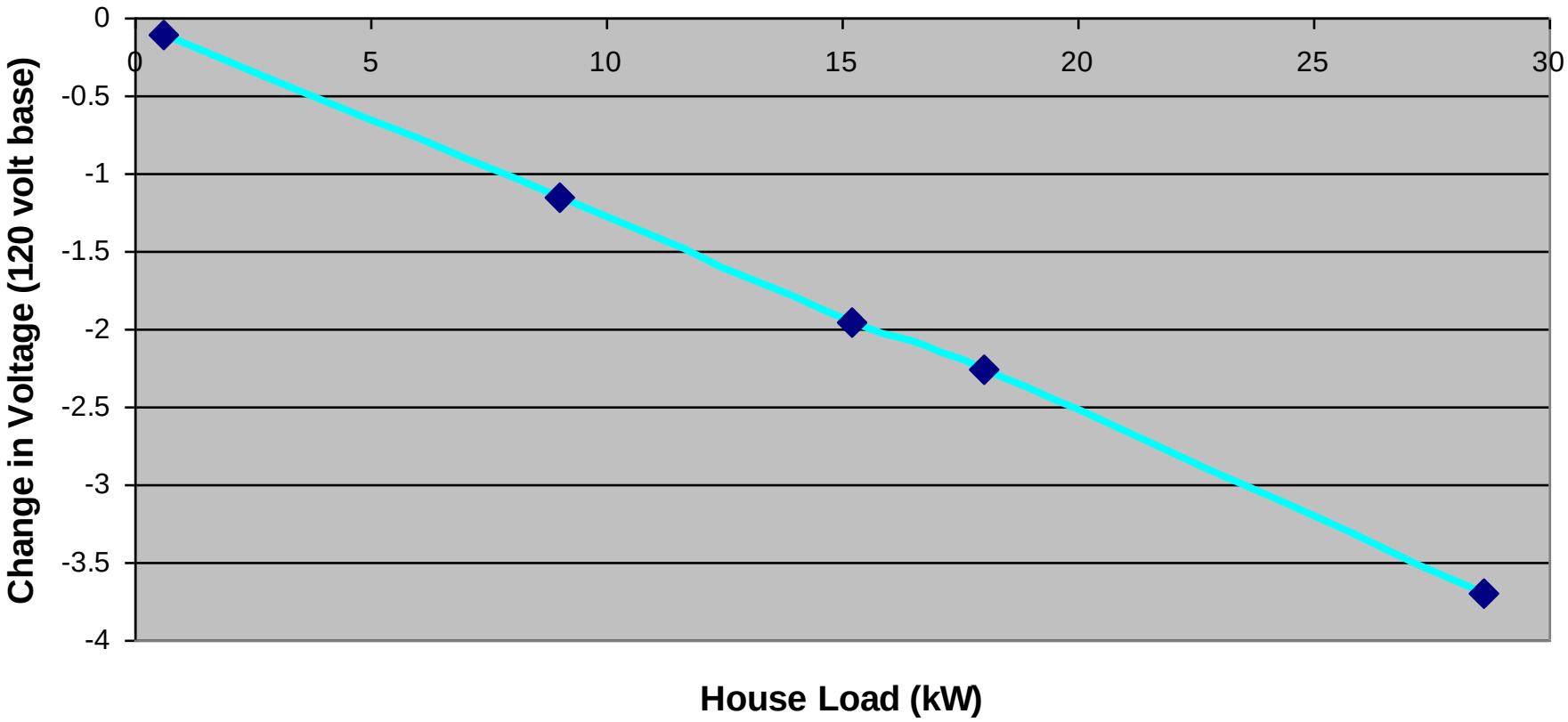
Turned PV System Off

Voltage vs. Time



Generation Voltage Drop (Rise) across Xfrmr = 0.75V/120V Base

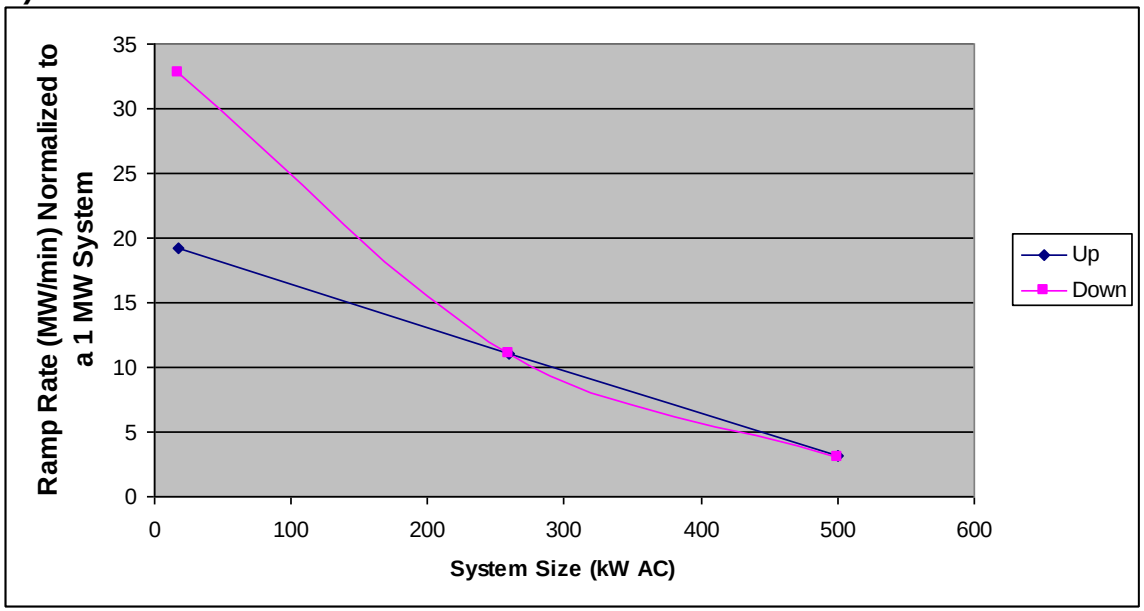
Voltage Drop vs. House Load



Ramp Rate Comparison

Comparison with Atlantic City Convention Center

	Max Ramp Up (MW/min) / 1MW System	Max Ramp Down (MW/min) / 1MW System
19.4 kW DC System – 90 – 190 W Microinverters	19.2	32.8
1.7 MW AC System - 260 kW Inverter	11.1	11.0
AC Conv Ctr (2.3 MW DC) - 500 kW Inverter	3.1	3.0



Questions?

Steve Steffel, PE

Pepco Holdings, Inc

Dr. Julio Romero Agüero

QUANTA Technology

Thank You!