Exploration of PV and Energy Storage for Substation Upgrade Deferral in SLC, Utah

Second Progress Report for
Rocky Mountain Power and Utah Clean Energy
Revised Version

Abraham Ellis, Mark Ralph, Garth Corey, Dan Borneo
Contact: aellis@sandia.gov

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
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Project Overview

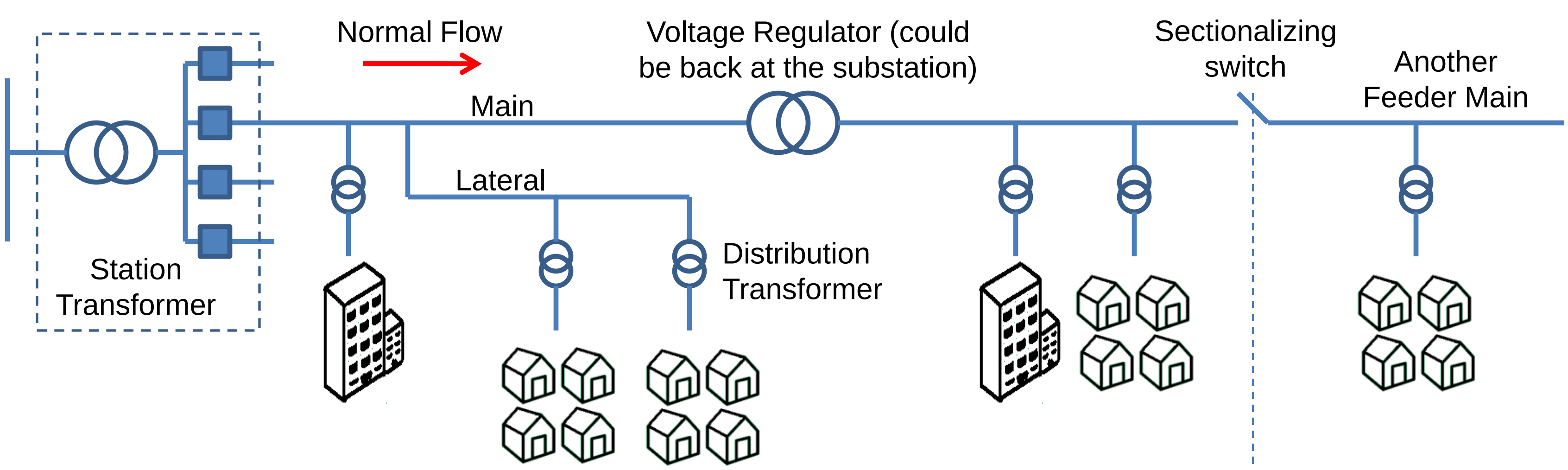
- Project Scope
  - Explore potential application of PV and energy storage for station/feeder upgrade deferral
    - Explore effect of azimuth and tilt angle optimization
    - Provide energy storage sizing example/methodology
    - Show how PV could impact sizing or effectiveness of energy storage
  - Discuss attributes of energy storage technology options
  - Discuss other added benefits of energy storage and PV at the distribution level, including voltage support and losses
  - Discuss other alternatives, including load transfer, demand response (rate incentives and direct control)
- Emphasize methodology, build analytical tool
  - Use actual data to illustrate

Progress Thus Far

- Analysis of load profiles for selected stations
  - Residential, Commercial
- Development of time-synchronized PV output data
  - Same location, same period
  - Different tilt (inclination), azimuth (orientation)
- Analysis “T&D capacity value” of 10% and 20% PV
  - Metric is reduction in exposure to overload
- Analysis of energy storage application
- EXEL Analysis Tool (internal)
- Finalizing SAND Report

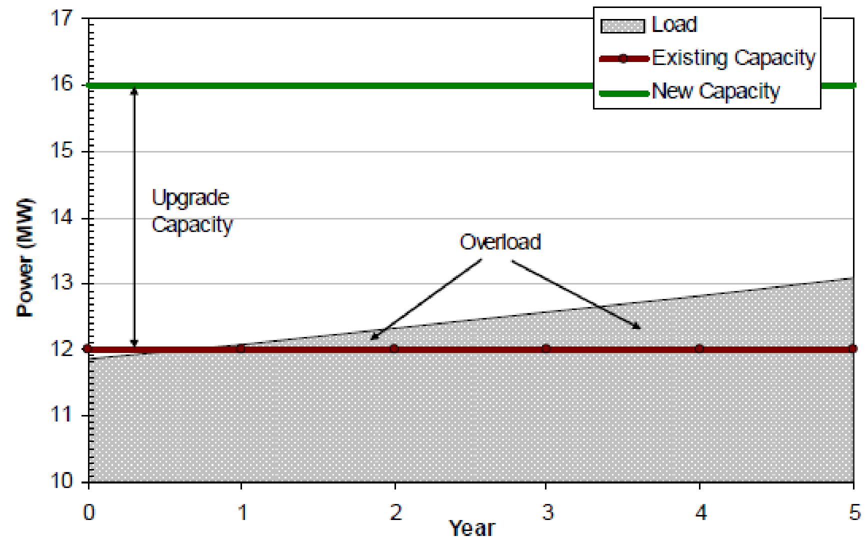
Distribution System Load Limits

- Distribution transformer
- Feeder main/lateral
- Voltage regulator (if present)
- **Station transformer**
- Sub-transmission and transmission



Deferral Value

- There is a cost associated with equipment upgrades
- The cost relates to the utilities annual revenue requirement (ARR)
  - ARR reflects principal, interest, dividend, taxes, insurance, etc
  - Annual revenue requirement ranges from 8% to 15%



Source: Energy Storage for the Electricity Grid, Benefits and Market Potential Assessment Guide SAND2010-0815

- Deferral value is equivalent to ***ARR × upgrade cost***

Deferral Value

- Example
  - A 12 MVA station transformer is upgrades with a new 16 MVA unit for a cost of $1,200,000. Assume that the annual fixed charge rate is 11%, and that there is no residual value.
  - The annual cost to own the new transformer is
    $0.11 \times \$1,200,000 = \$132,000$
  - The *deferral value* for 1 year is also *$132,000*
  - In this case, the *marginal cost* of the T&D upgrade is
    $\$1,200,000 / 4\ MVA = \$300,000\ per\ MVA$

NOTE: Based on recent information, the marginal cost for a similar distribution station upgrade in SLC is closer to $150,000 per MVA

Deferral Value

- Marginal Cost of system upgrades is a useful measure of the deferral value, and how alternatives compare

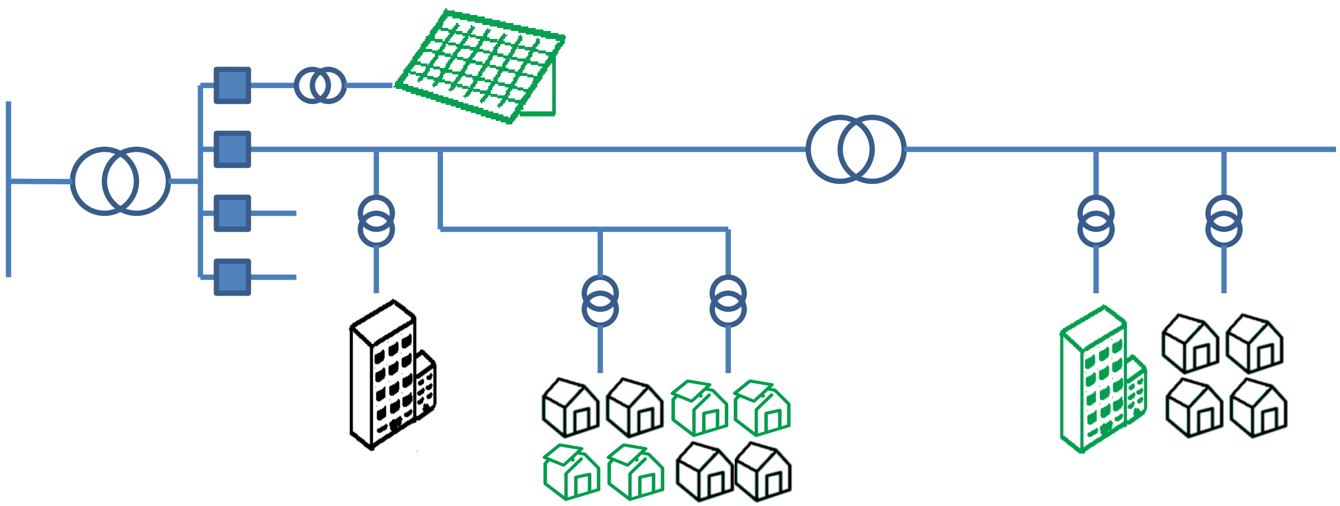
FERC Form1 Account	Marginal Cost ($/MVA) National 1989 to 1998	Marginal Cost ($/MVA) PJM 1989 to 1998	Average Cost ($/MVA) National 1998	Average Cost ($/MVA) PJM 1998
Dist Land (360)	2,639	5,653	1,501	2,978
Dist Structures (361)	2,481	5,538	1,219	3,408
Dist Station Equip (362)	32,869	57,248	16,925	25,820
Dist Battery Storage (363)	2	0	0	0
Dist Poles & Towers (364)	50,390	50,746	22,403	24,457
Dist Overhead Conduct (365)	52,059	63,363	22,246	28,366
Dist Undgr Conduit (366)	13,815	23,739	6,428	12,376
Dist Undgr Conduct (367)	44,226	65,121	18,043	26,885
Dist Transformers (368)	40,787	39,757	23,656	24,715
Dist Services (369)	26,553	34,494	11,888	16,433
Dist Meters (370)	13,625	14,045	7,655	8,989
Dist Installations (371)	2,854	4,858	1,133	1,327
Dist Leased Property (372)	-131	1	42	6
Dist Street Lights (373)	8,034	10,175	4,438	4,610
Dist Total	290,203	374,737	137,576	180,369
Trans Total	80,650	64,876	52,229	48,681
Total Dist and Transmission	370,853	439,613	189,805	229,050

Source: The data is from 105 utilities selected from the intersection of utilities for these accounts in both 1989 and 1998 included in the POWERdat database (Resource Data International, Inc.). This data was originally from data collected in FERC Form 1.

Marginal cost of utility equipment
Ref: Energy Storage for the Electricity Grid, Benefits and Market Potential Assessment Guide
SAND2010-0815
Chart Source: ORNL

T&D Value of PV Generation

- Reduces emissions and system losses
- Reduces feeder/transformer load
  - Possible opportunity for deferment of transformer/station replacement or upgrade
  - Benefit is specific to the situation
    - Need to study actual data to evaluate



Analysis of SLC Residential and Commercial Load Characteristics

(All data is in standard time)

Load/Station Characteristics

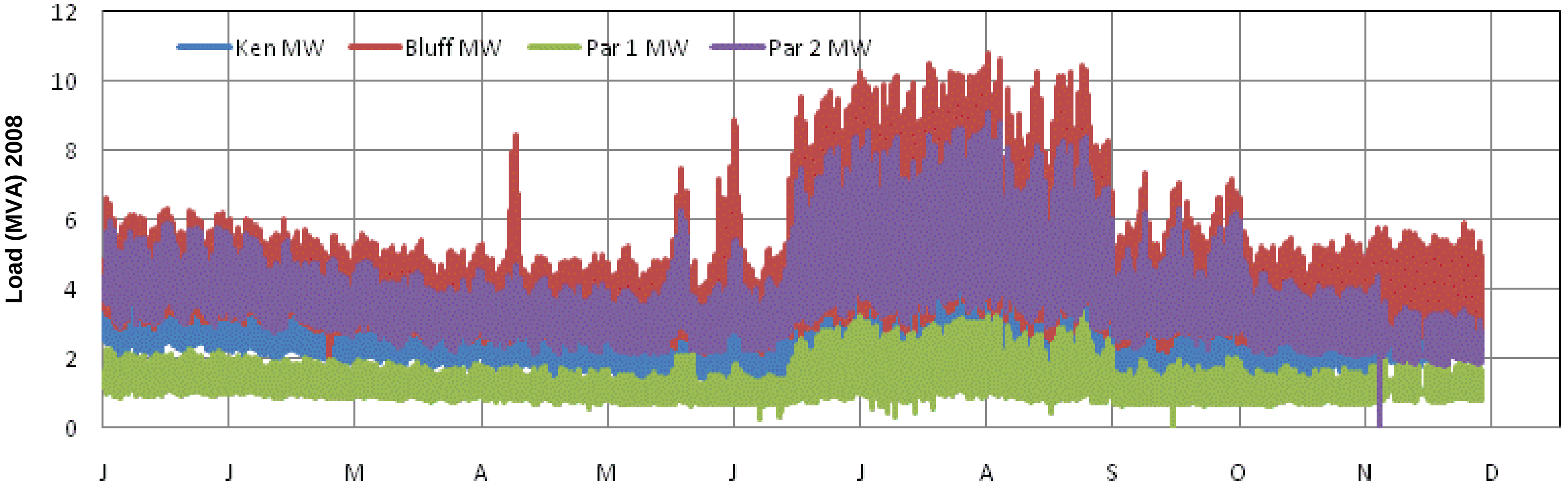
Station Name	Feeder Type	Transformer Rating (MVA)	Peak Load (MVA)	Growth rate AVG % per year	Utilization Factor	Load Factor
Kensington	**Residential**	**6.25**	**6.01**	**2.6%**	**96%**	**46%**
Bluffdale	Residential	14.0	11.2	6.1%	81%	40%
Parleys 1	Residential	6.25	3.5	8.3%	56%	39%
Parleys 2	Residential	9.75	9.61	1.0%	99%	42%
Draper 1	Residential	14.0	11.1	1.0%	79%	
Draper 2	Residential	16.0	9.4	3.2%	59%	
Terminal 11	Commercial/Light Ind.	14.0	6.7 [1]		48%	36%
Terminal 19	Commercial/Light Ind.	30.0	2.4		8%	51%
Grow 10, 14	Commercial/Light Ind.	28.0	10.1		36%	62%
Grow 15, 18	Commercial/Light Ind.	**30.0 [3]**	**8.4**	**4.0%**	**28%**	**66%**
Grow 17	Commercial/Light Ind.	16.0	3.2 [2]		20%	60%

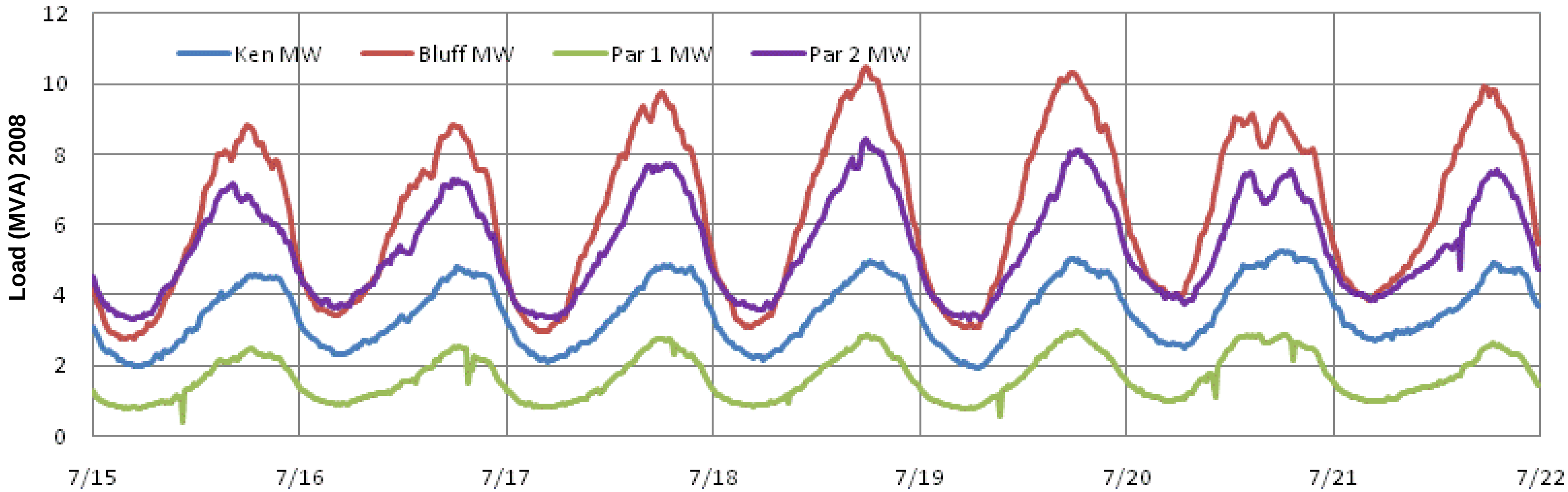
[1] Adjusted from 10/28 07:00 to 20/29 13:30 which contained a peak load of 7.9 MVA (load transfer?)
[2] Adjusted from 10/26 08:00 to 10/26 13:00 which contained a peak load of 14.4 MVA (load transfer?)
[3] Assumed rating of 9.5 MVA for illustration purposes
Data for residential load is calendar year 2008; data for commercial load is calendar year 2009

$$Utilization\ Factor = \frac{Peak\ Load}{Transformer\ Rating}$$

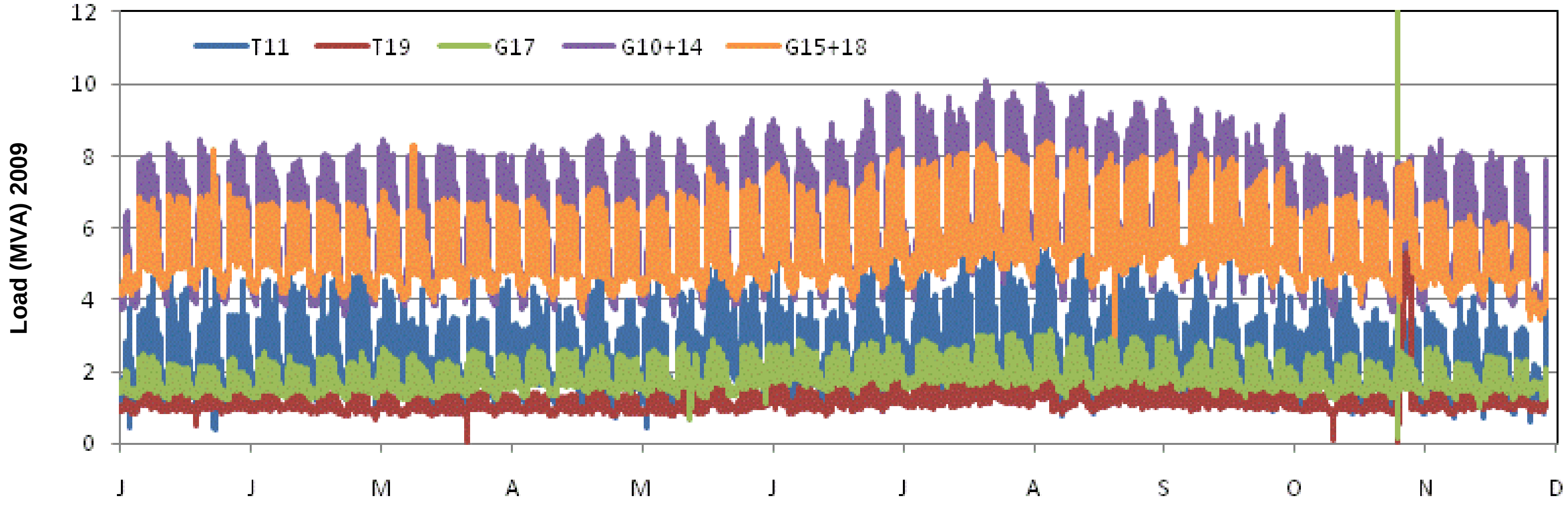
$$Load\ Factor = \frac{Average\ Load}{Peak\ Load}$$

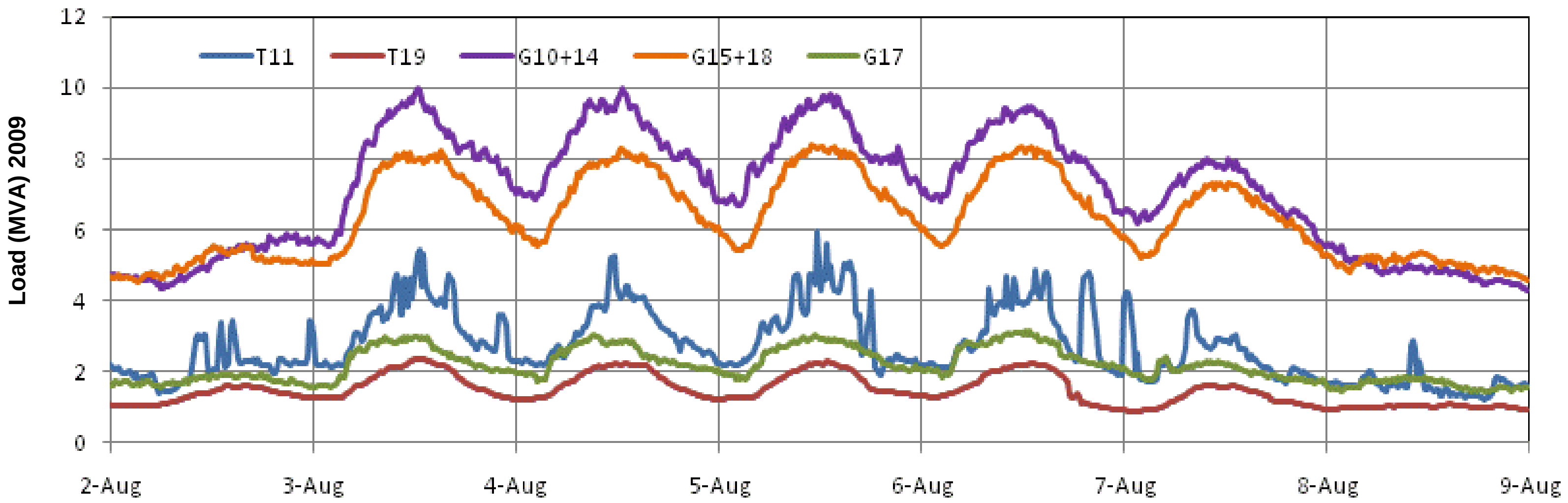
Sample of SLC Residential Load





Sample of SLC Commercial Load



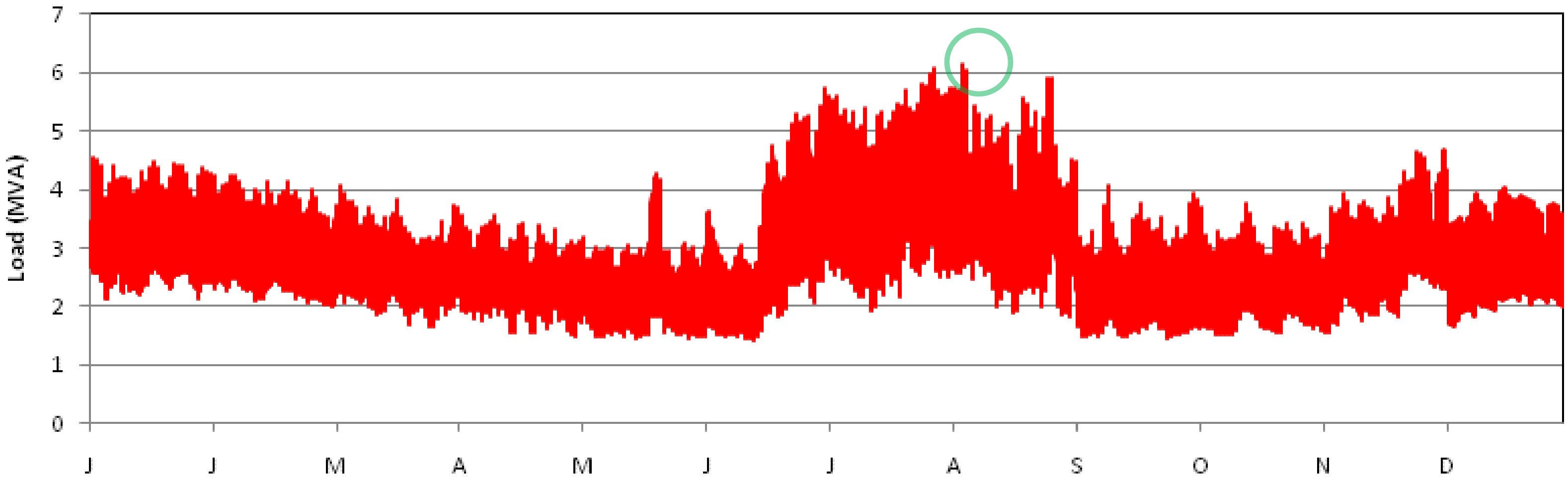


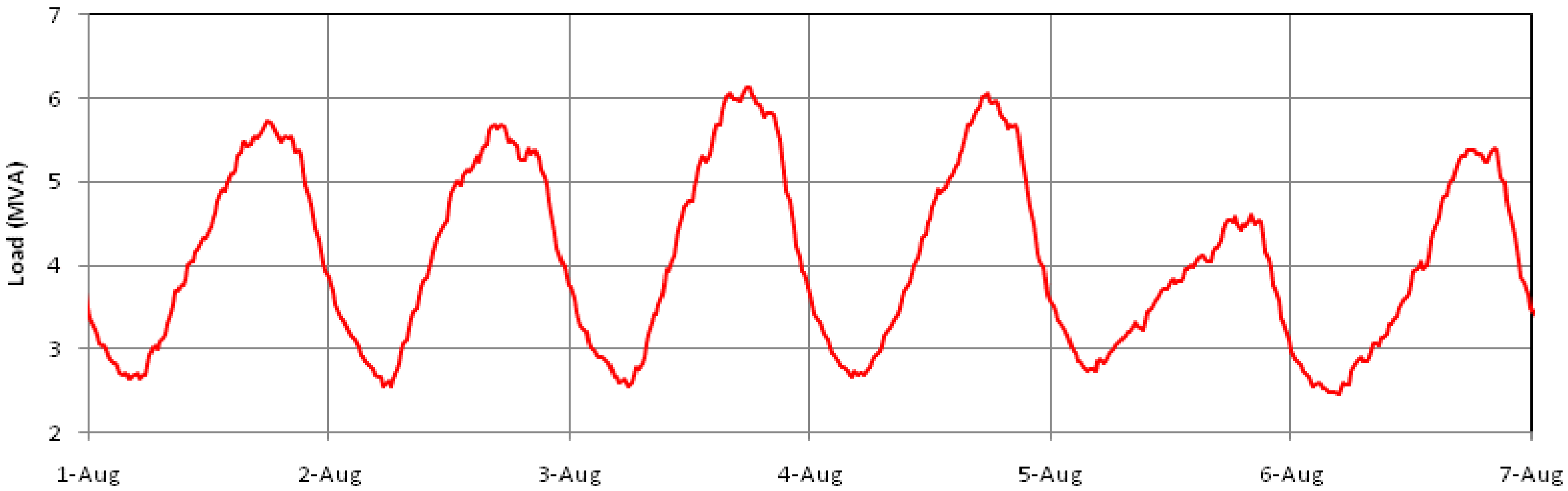
Criteria for Screening Feeders

- The benefit of PV with respect to station upgrade deferral is a function of load & feeder characteristics
- Feeders could be "ranked". For example:

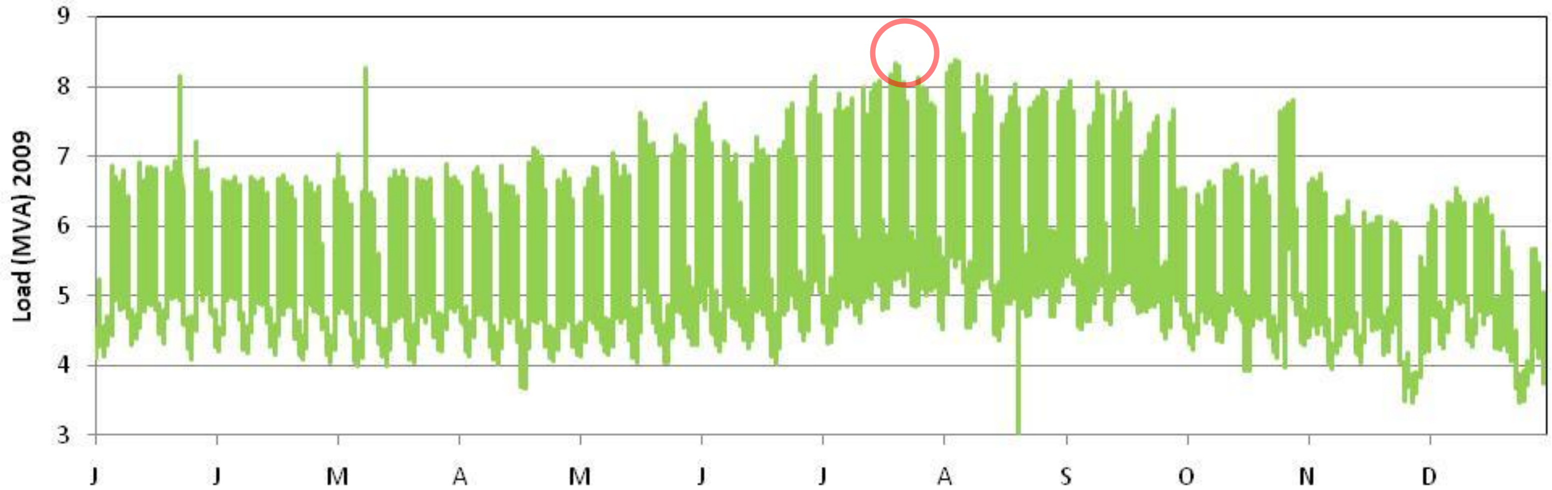
	Weight
Risk of overload exists (high utilization factor)	
Magnitude of overload (lower is better)	
Load growth rate (low is better)	
Load peak occurs during the daylight hours	
Feasibility of PV deployment (available rooftop/ground)	
Complicated or expensive alternatives for station upgrade	

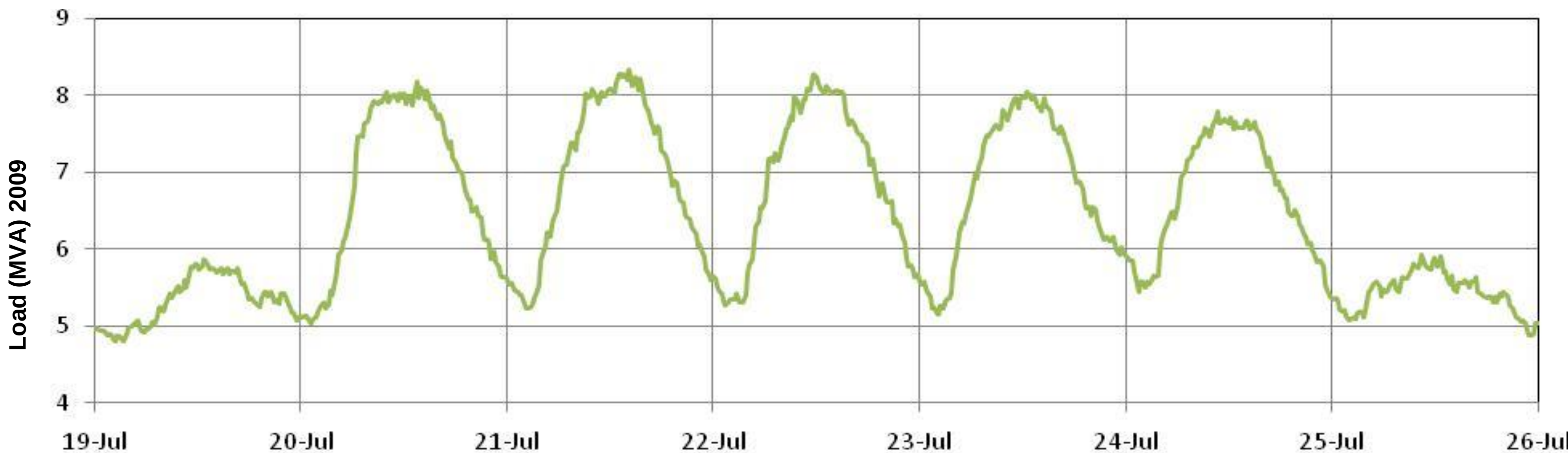
Residential Load (Kensington)





Commercial Load (Grow 15/18)





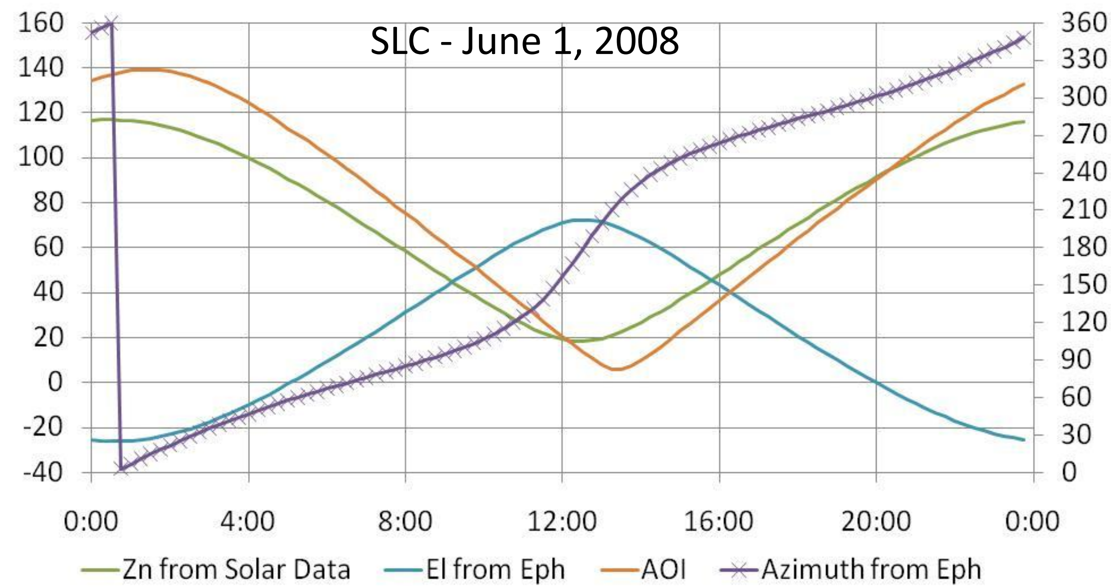
Solar Data and Simulation of PV Output Data

Options for Solar Radiation Data

- Ground-based data (NOAA-ISIS)
  - Integrated Surface Irradiance Study Network
  - The ISIS station in Salt Lake City
    - Located at National Weather Service site near airport
    - Data available from 2002 through 2009, 3-minute intervals
    - http://www.srrb.noaa.gov/isis/
  - Needs conversion to Plane-of-Array (POA)
- Satellite-based estimates data
  - Hourly resolution only
  - Tools exist to convert data directly to PV production
  - http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005

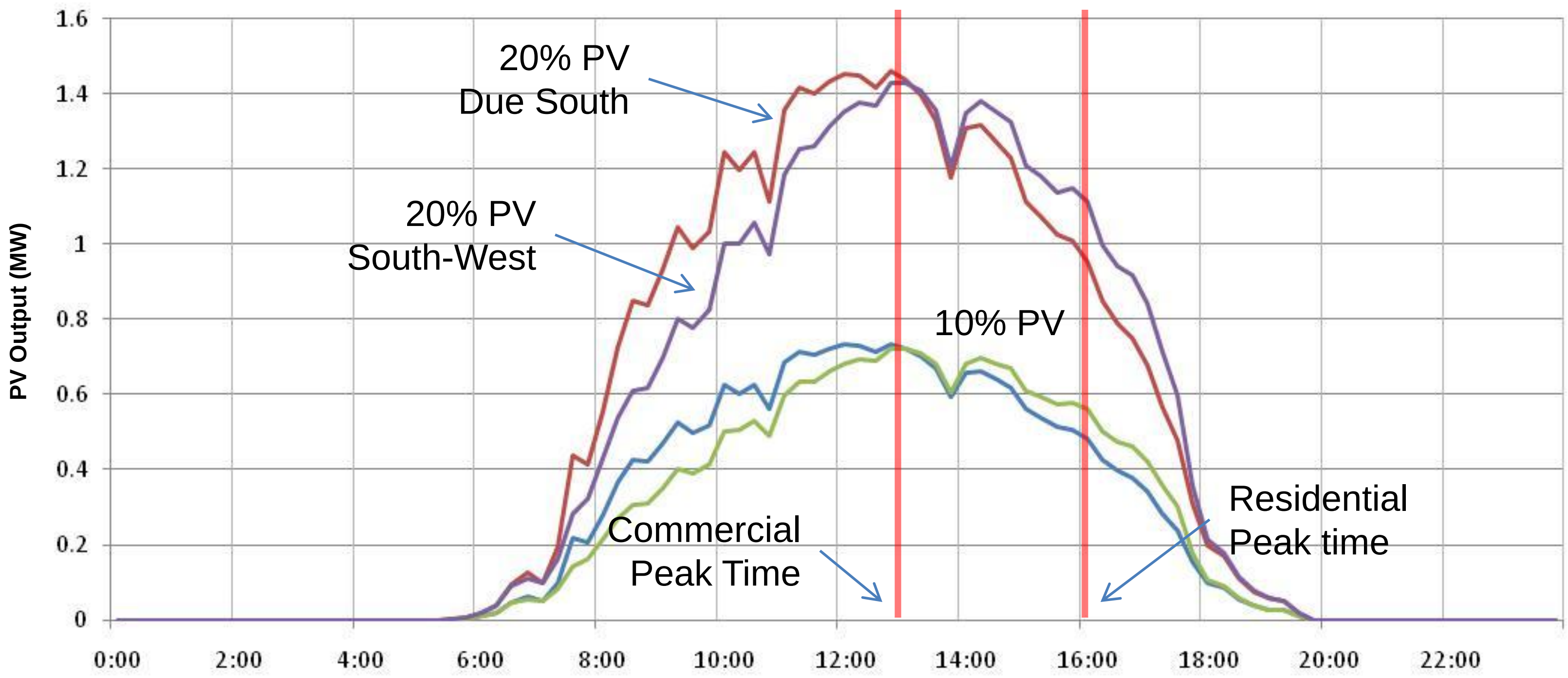
Basic Procedure for Solar Data

- What we did
  - Given global horizontal (GH) irradiance
  - Calculate POI for the desired array tilt and orientation
  - Average 3 min data to obtain 15 min data (captures some of geographical diversity effect)
  - Use POA data and ambient temperature to estimate PV output
- There are more precise computer models available



Solar Data

- Effect of PV array fixed orientation
  - Due South (maximum energy) and South-West
  - Shift is noticeable, but net effect on net load is very small
  - Chart below is for latitude tilt, residential case (6.25 MVA)

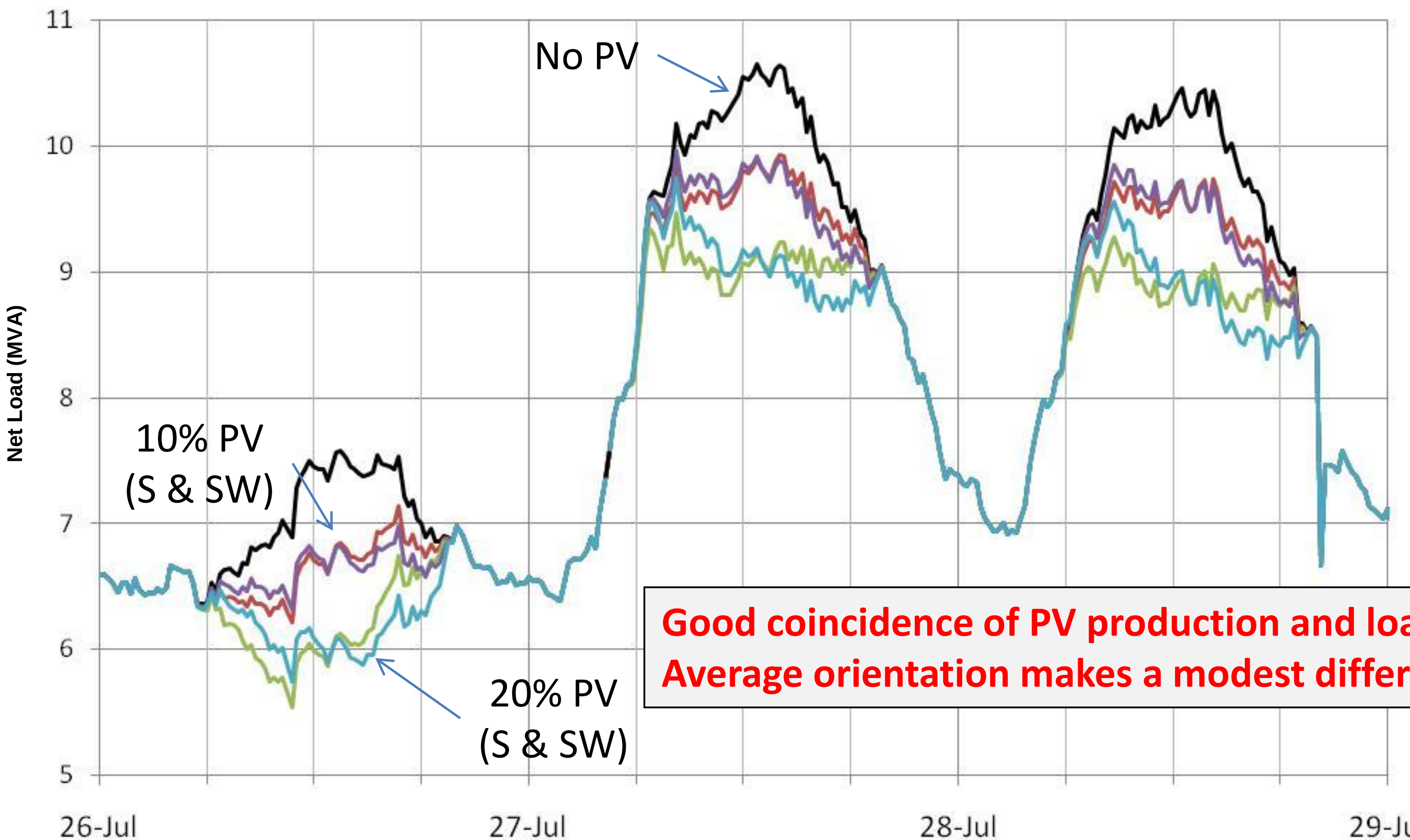


T&D Deferral Value of PV
(Distribution Station Overload)

Analysis of Deferral Value of PV

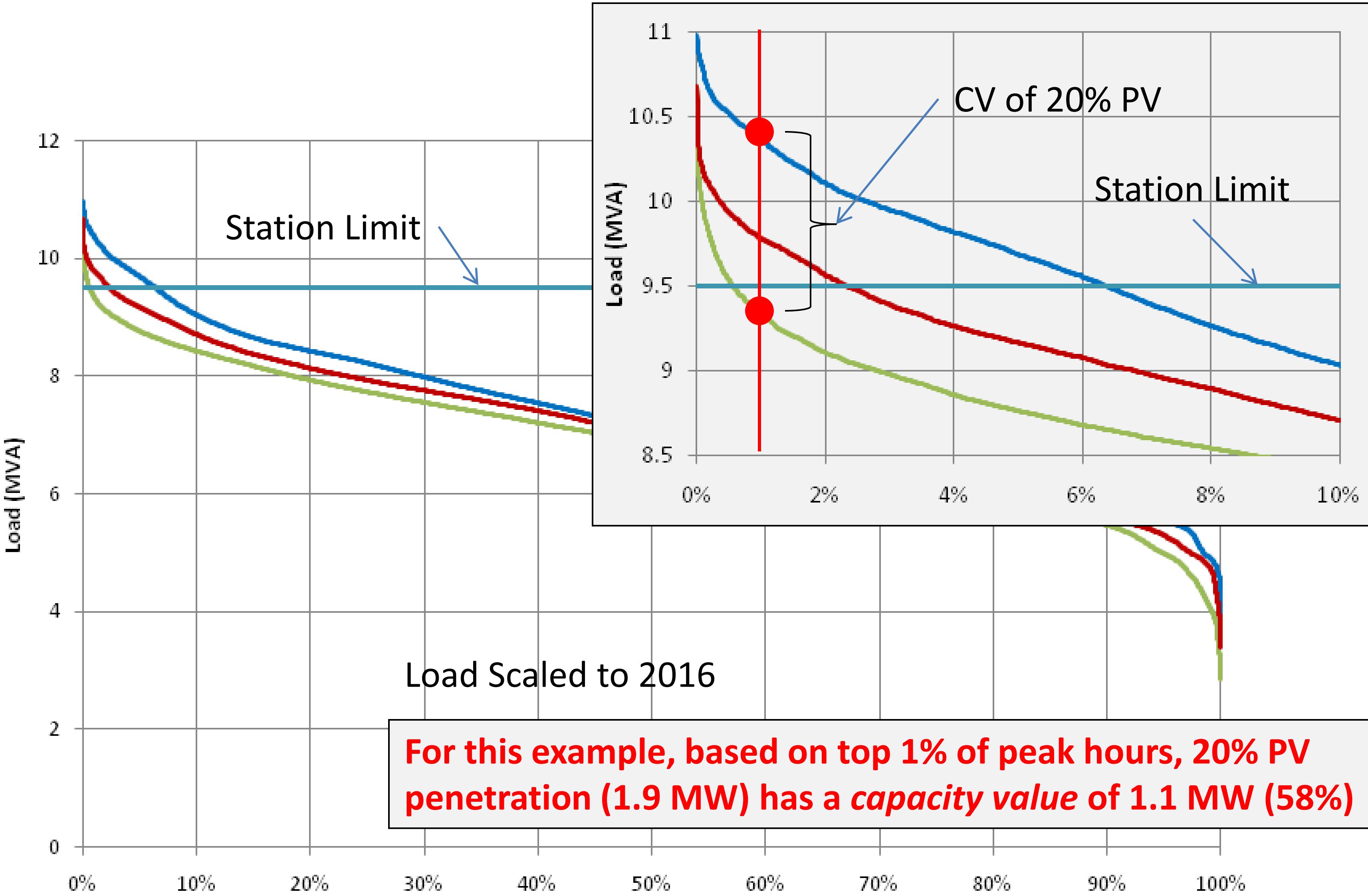
- Procedure
  - Obtain time-and-location-coincident load and solar data
  - Analyze scenarios of interest
    - Load year(s)
    - PV penetration level (No PV, 10% & 20% PV penetration)
  - Establish “capacity value” (CV) of PV
    - Based on peak load, or…
    - …better yet, based on some acceptable risk of overload (e.g., 1%)
      - See discussion of transformer rating/loading at the end of presentation
  - Estimate deferral value
    - This is based on avoided cost of capital upgrade only
    - Does not attempt to compare cost-effectiveness of alternatives

Results for Commercial Load



Good coincidence of PV production and load. Average orientation makes a modest difference

Results for Commercial Load



For this example, based on top 1% of peak hours, 20% PV penetration (1.9 MW) has a *capacity value* of 1.1 MW (58%)

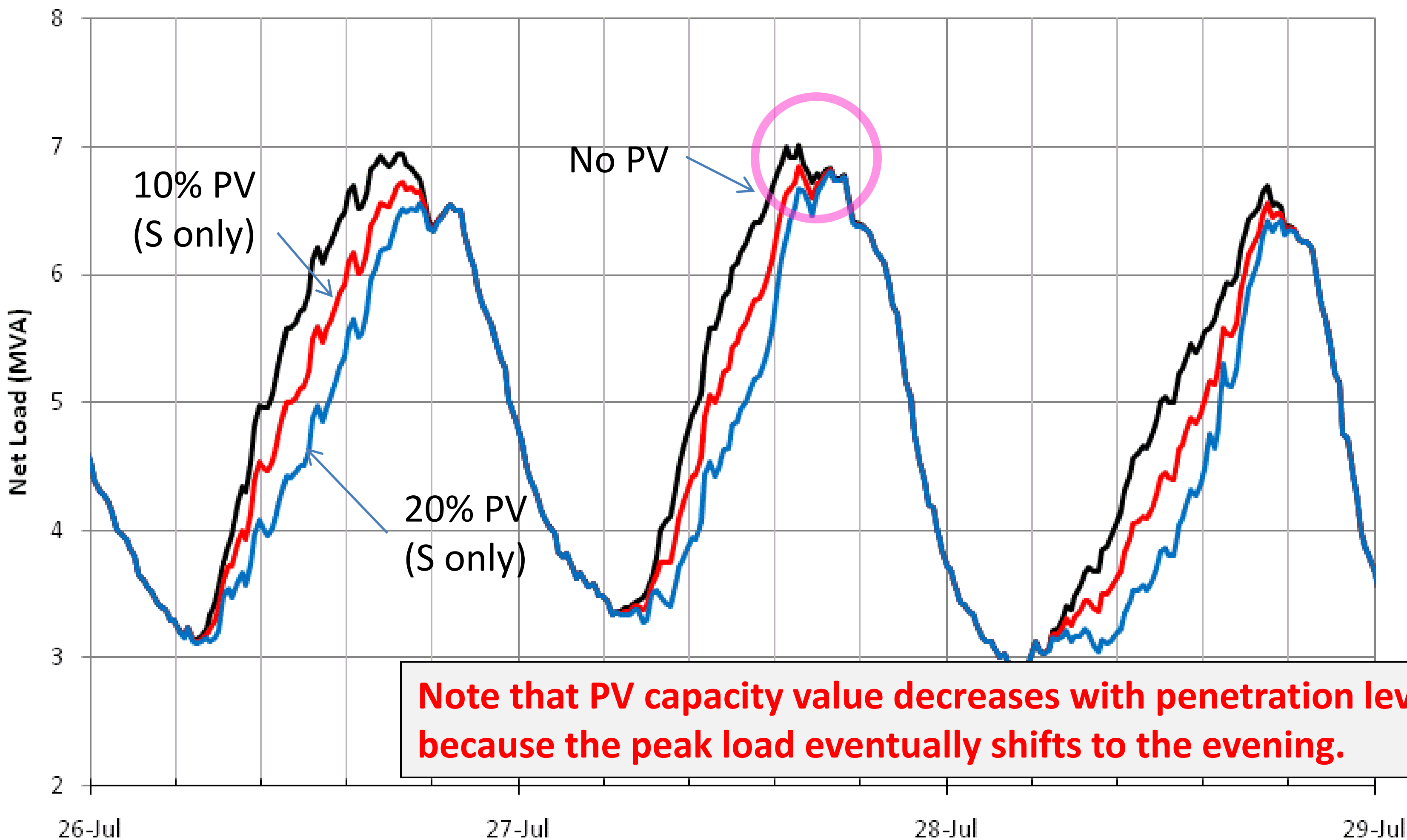
Results for Commercial Load

- Assumptions
  - Average PV array: 25 degrees, due South orientation
  - Station limit: 9.5 MVA (assumed for illustration)
  - Annual load growth: 4% (assumed for illustration)

Year	Scaling Factor	No PV		10% PV		20% PV	
		Hrs > Rating	Peak Load	Hrs > Rating	Peak Load	Hrs > Rating	Peak Load
2009	1.00	0.0	8.4	0.0	8.2	0.0	8.2
2010	1.04	0.0	8.7	0.0	8.5	0.0	8.5
2011	1.08	0.0	9.1	0.0	8.8	0.0	8.8
2012	1.12	0.0	9.4	0.0	9.1	0.0	9.1
2013	1.17	17.5	9.8	0.0	9.5	0.0	9.4
2014	1.22	135.0	10.2	3.8	9.9	0.3	9.9
2015	1.27	332.3	10.7	61.0	10.4	7.5	10.4
2016	1.30	510.8	11.0	179.5	10.7	34.8	10.7

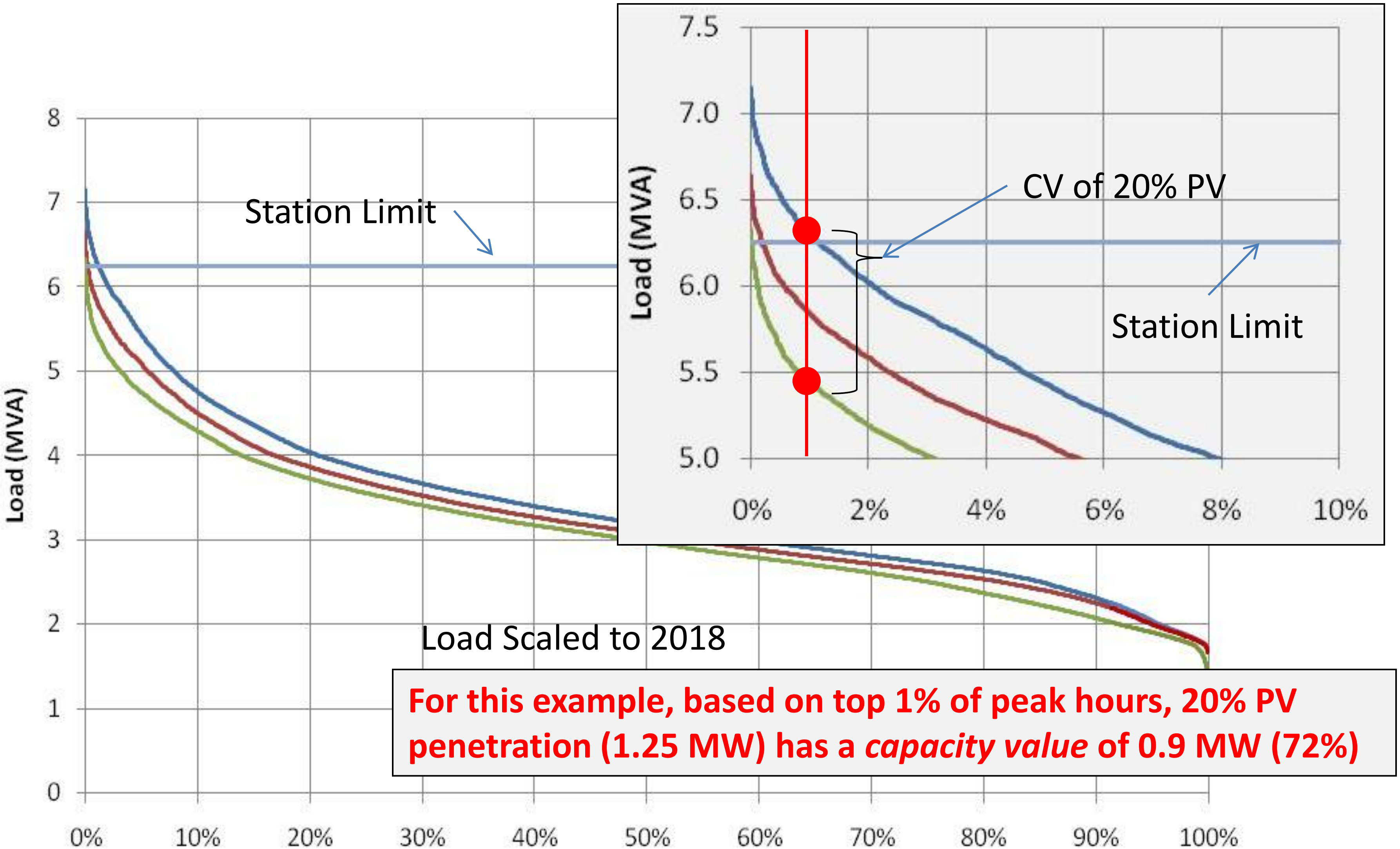
  - Based on 10% and 20% PV penetration could defer the station upgrade by 1-2 years and 2-3 years, respectively.

Results for Residential Load



Note that PV capacity value decreases with penetration level because the peak load eventually shifts to the evening.

Results for Residential Load



For this example, based on top 1% of peak hours, 20% PV penetration (1.25 MW) has a *capacity value* of 0.9 MW (72%)

Results for Residential Load

- Assumptions
  - Average PV array: 25 degree tilt, due South orientation
  - Station limit: 6.25 MVA; Annual load growth: 2.5%

Year	Scaling Factor	No PV		10% PV		20% PV	
		Hrs > Rating	Peak Load	Hrs > Rating	Peak Load	Hrs > Rating	Peak Load
2008	1.00	0.0	5.7	0.0	5.2	0.0	5.0
2009	1.02	0.0	5.8	0.0	5.3	0.0	5.1
2010	1.05	0.0	5.9	0.0	5.4	0.0	5.2
2011	1.08	0.0	6.1	0.0	5.6	0.0	5.4
2012	1.10	0.0	6.2	0.0	5.7	0.0	5.5
2013	1.13	2.8	6.4	0.0	5.9	0.0	5.7
2014	1.16	11.0	6.5	2.0	6.0	1.0	5.8
2015	1.18	23.0	6.7	11.3	6.2	7.0	5.9
2016	1.21	43.3	7.0	21.5	6.3	14.0	6.1
2017	1.24	66.5	7.0	43.3	6.5	29.0	6.2
2018	1.3	100.8	7.1	72.5	6.6	54.8	6.3

Some Conclusions of Study

- The value of PV decreases with penetration level
  - Net peak load shifts toward the evening (low or no sunlight)
- T&D Capacity Value of PV can be measured in different ways
  - Reduction of absolute annual peak load (i.e., based on zero overload risk)
  - Reduction in load at some acceptable (small, but nonzero) overload risk
- Reduction of load at a small nonzero risk should be used to establish the T&D value of PV
  - Shifting peak load toward periods with lower temperature and direct sun exposure tends to reduce thermal stress on transformers
  - Transformers can withstand temporary overloads without loss of life, based on the cyclical nature of the load
    - Operating transformers above nameplate rating is a complex issue, but there are prudent guidelines (see information at the end)
  - A suitable risk level (e.g., ½ % or 1%) can be selected based on the above

Estimating Deferral Value

- Example based on Commercial case
  - The current plan to upgrade the 9.5 MVA station transformer would cost $720,000. The new transformer would have a rating of 14 MVA. The annual fixed charge of 11%, and there would be no residual value for replaced station equipment.
  - Based on analysis, it is determined that 950 kW of PV (10% penetration) would defer the need for upgrade by 1 to 2 years
  - The *deferral value* for 1 year is

    $0.11 \times \$720{,}000 = \$79{,}200$
  - In this case, the *marginal cost* of the T&D upgrade is

    $\$720{,}000 \,/\, 4.5\ MVA = \$160{,}000\ per\ MVA$

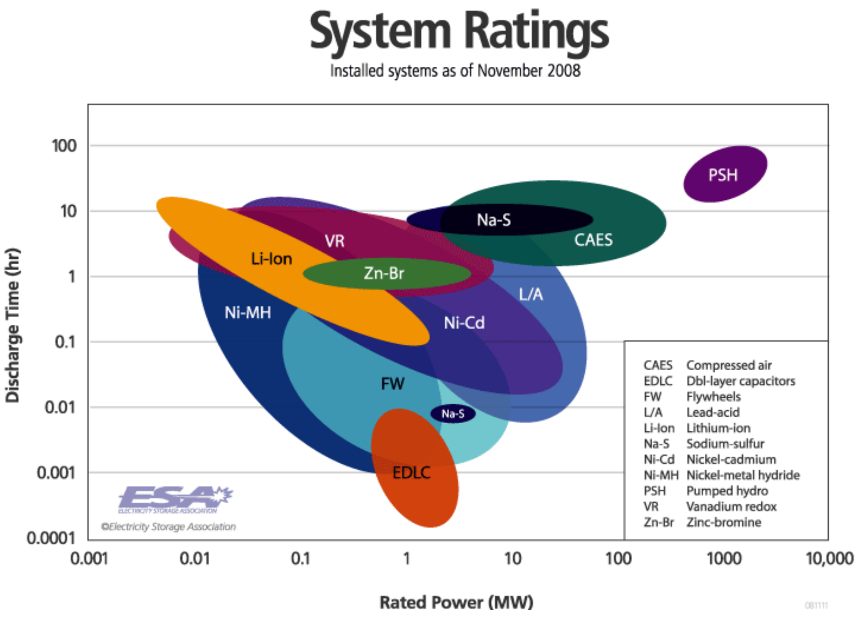
T&D Deferral with Energy Storage and PV
(Distribution Station Overload)

Deferral Value of PV & Storage

- Procedure
  - Obtain pertinent data
  - Analyze scenarios of interest to determine reasonable battery size
  - Evaluation of deferral value or cost-effectiveness
    - This is based on avoided cost of capital upgrade only
    - Energy storage is likely to be a utility-owned asset; thus, it could be treated as an option among other alternatives
    - Other value opportunities should be considered in a full evaluation (voltage support, etc)

Technical Considerations

- Sizing
  - Capacity (kW interface)
  - Energy (kWh useful storage)
- Technology
- Portability
- Other



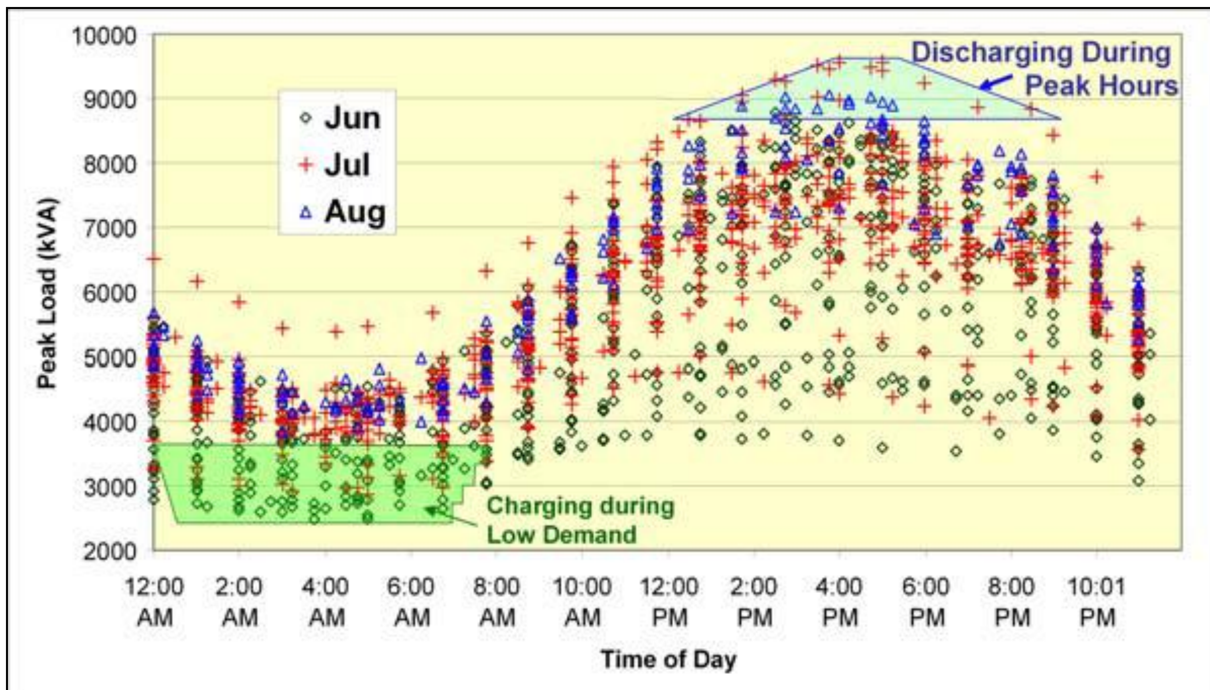
Energy Storage (kWh)

PCS (kW)

Grid

Technical Considerations

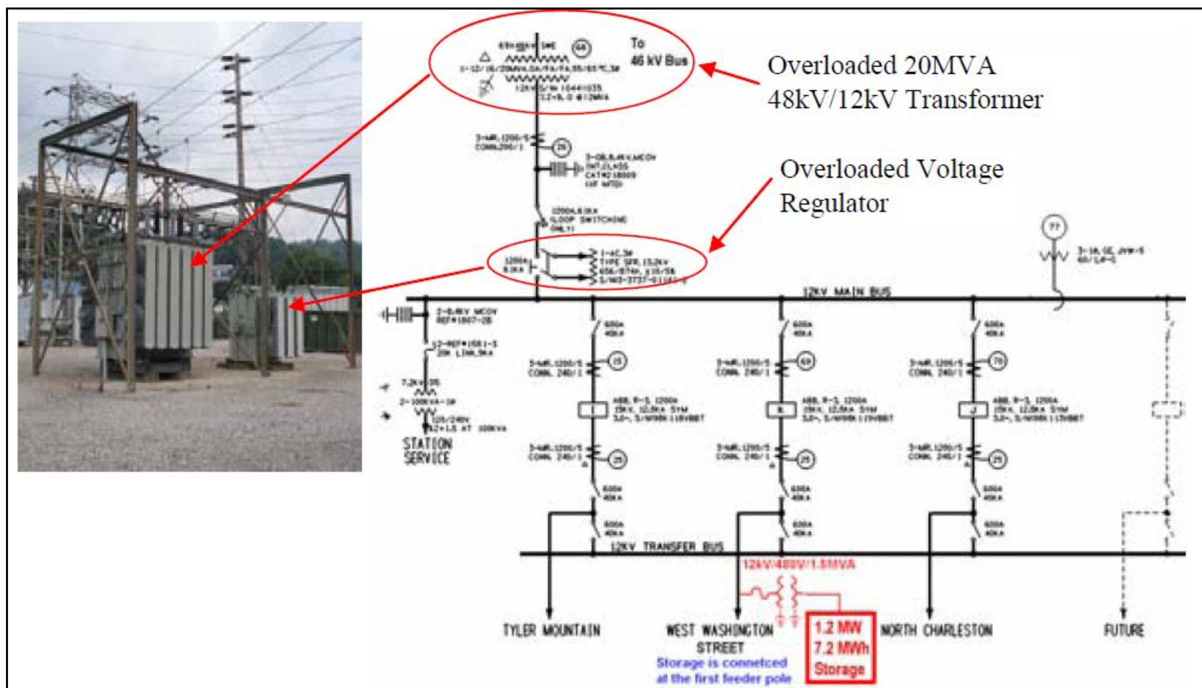
- Operating strategy
  - Discharge on peak, charge off peak
  - Details are site/situation/technology specific



Source: Installation of first Distributed Energy Storage System at American Electric Power (AEP) SAND2007-3580

Technical Considerations

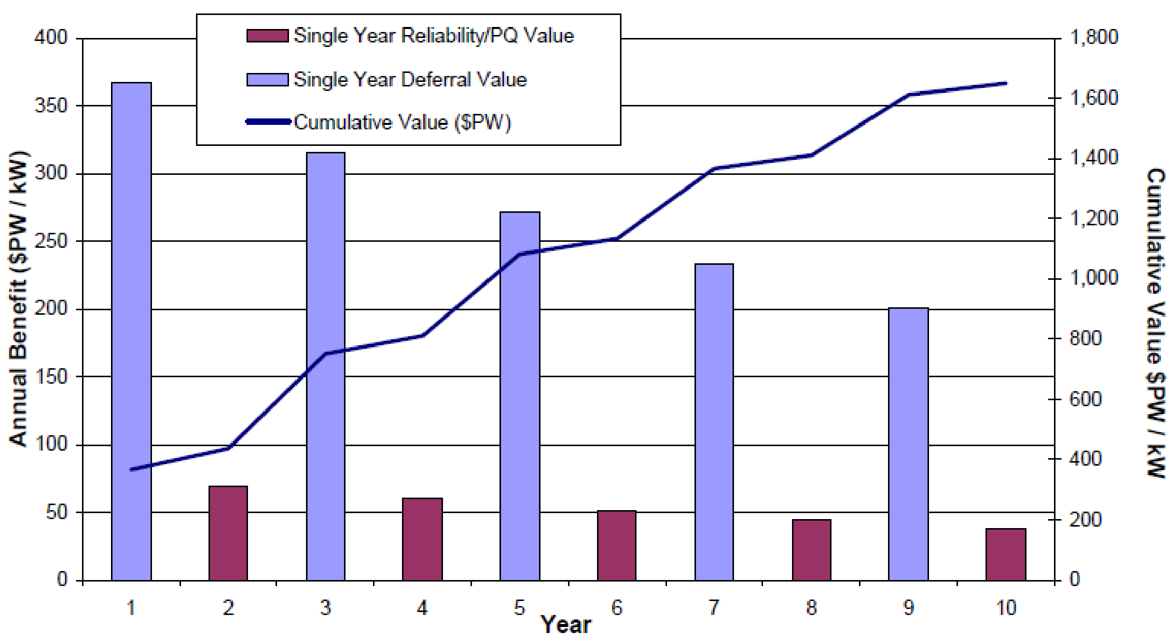
- Location of Energy Storage
  - Downstream from system constraint
  - Substation (easiest) or elsewhere on the feeder



Source: Installation of first Distributed Energy Storage System at American Electric Power (AEP) SAND2007-3580

Deferral Horizon

- Value proposition of energy storage is optimal for a 1-2 year deferral horizon
  - Avoids the need for underutilized capacity
  - This makes a strong case for mobile storage



Source: Energy Storage for the Electricity Grid, Benefits and Market Potential Assessment Guide SAND2010-0815

Technical Considerations

- Stationary Vs. Mobile storage application

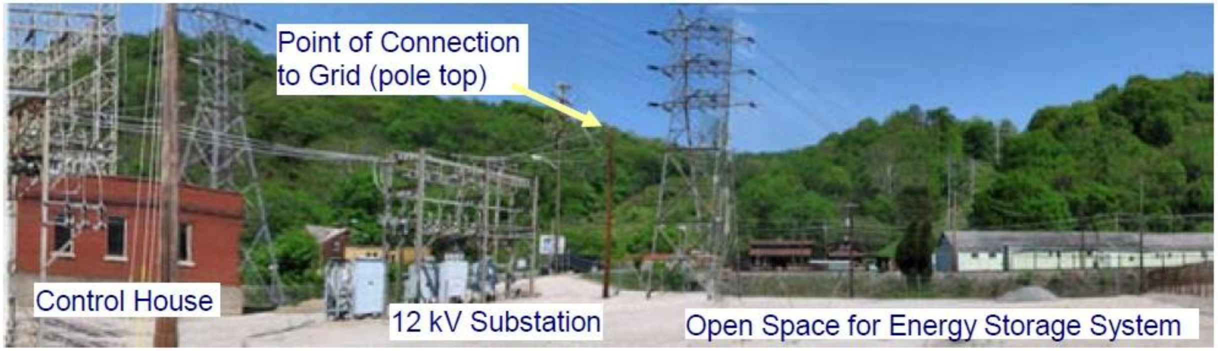
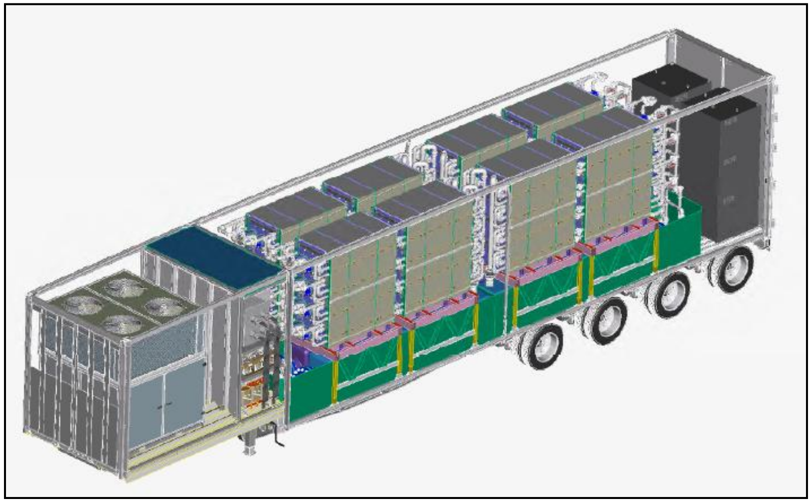


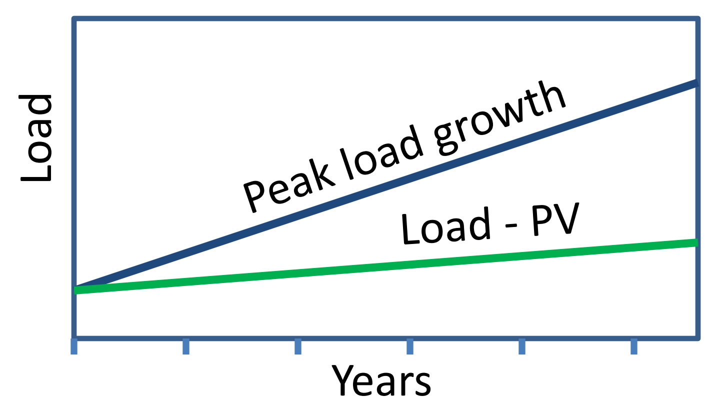
Photo courtesy of AEP



Source: http://www.premiumpower.com/product/transflow2000.php

Effect of PV Deployment

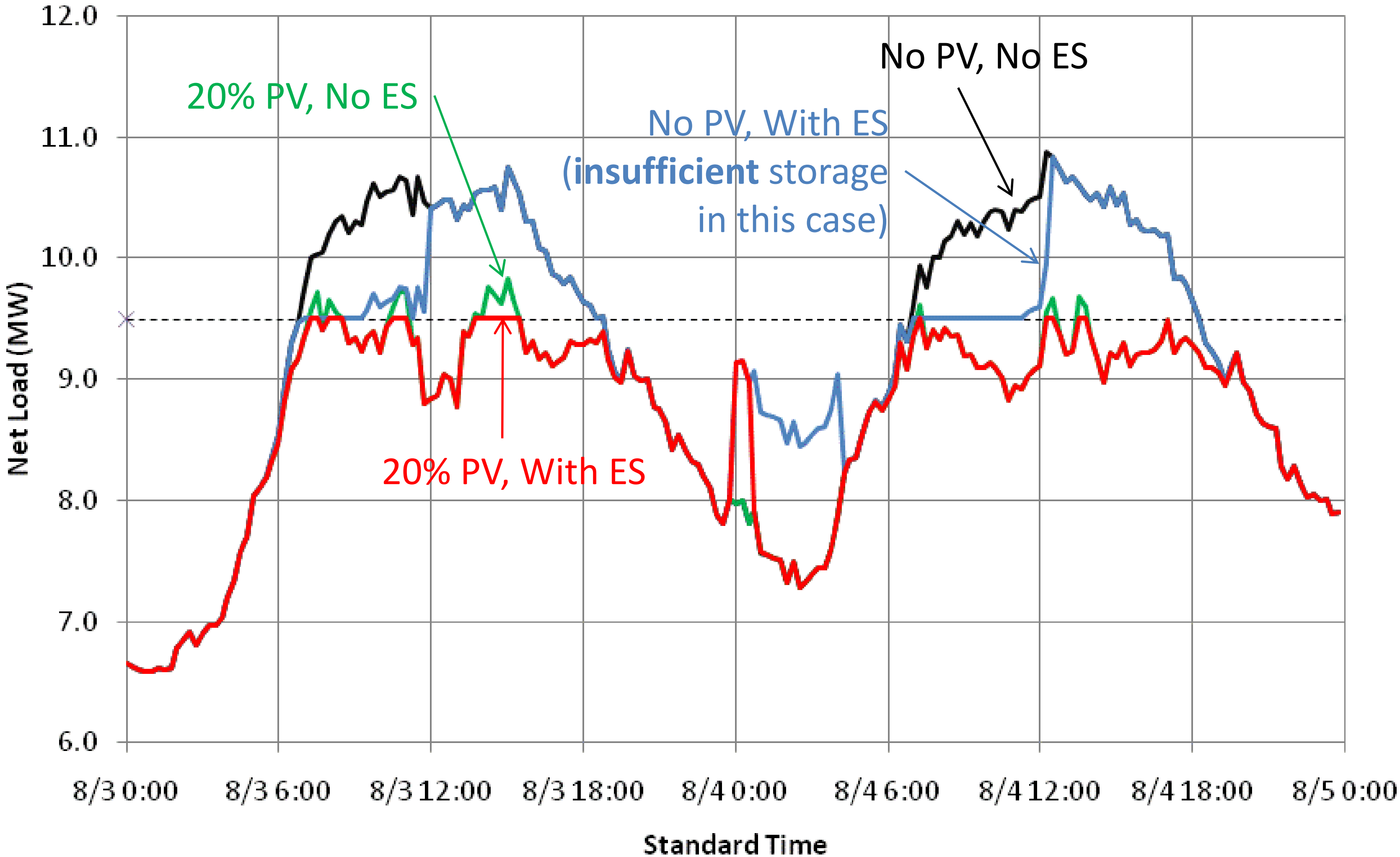
- PV reduces energy storage requirement
  - Discharge time (energy)
  - PCS size requirement (if it lowers peak load)
- Ideal synergy takes place when PV deployment offsets load growth
  - Energy storage could cost-effectively defer upgrade over multiple years



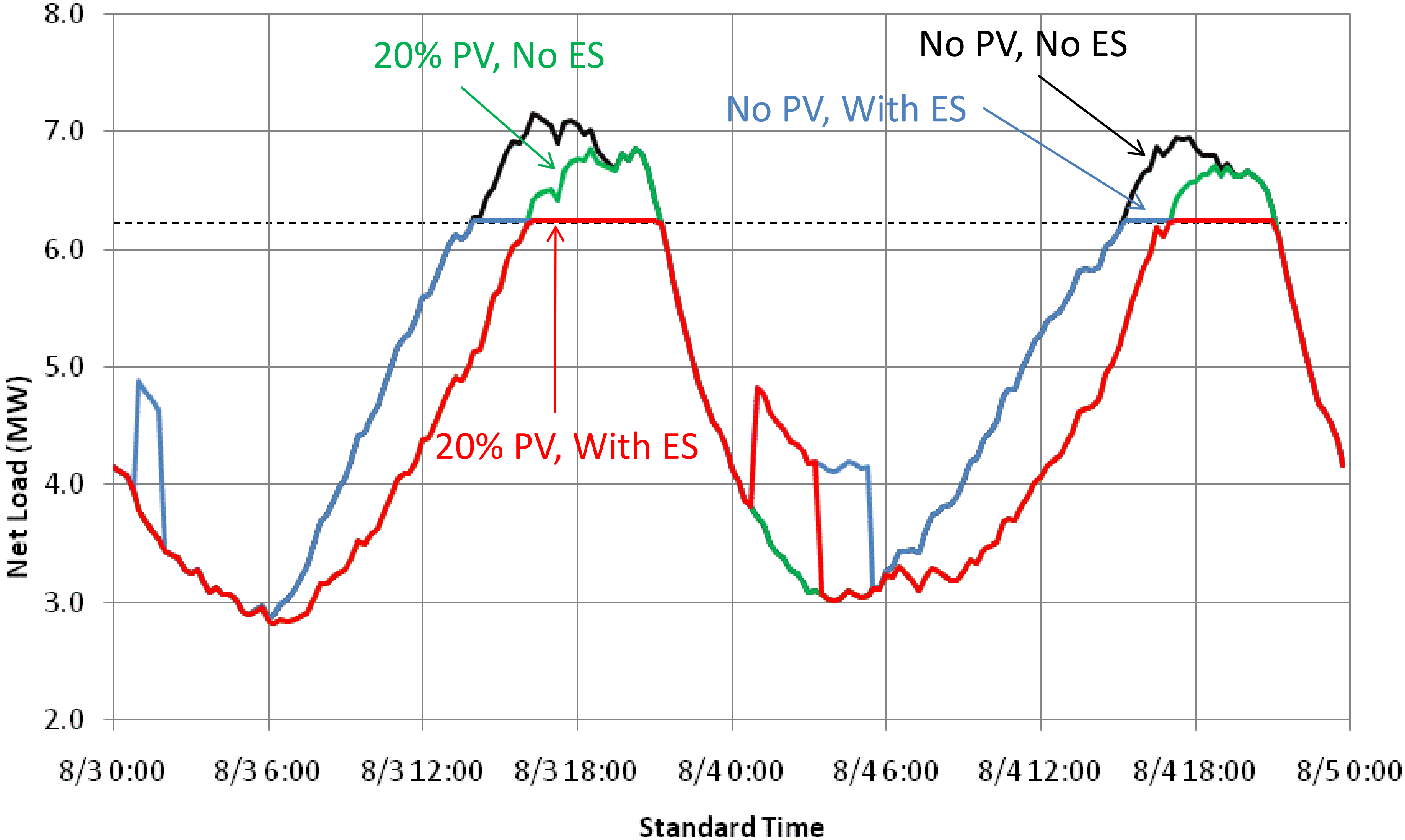
Energy Storage Operation Model

- Defining battery characteristics
  - Inverter Rating kW (sets maximum discharge rate)
  - Battery Capacity MWh
  - Maximum Depth of Discharge – DOD
    - Depends on battery type
    - Lead acid batteries should not be discharged completely
- Defining battery operation
  - Discharge energy daily with fixed start/stop times
  - Discharge when triggered by load exceeding a set level
    - Could reduce energy losses and increase useful life of battery

Example With Commercial Load



Example With Residential Load



Energy Storage and PV

- Based on the sample data analyzed, PV deployment in the 10-20% range **greatly improves** value proposition for station deferral using energy storage
  - Both battery capacity and PCS rating are greatly reduced

Case	Energy (MW-h)*		PCS Rating (MW) **	
	No PV	20% PV	No PV	20% PV
Commercial	12.0	2.0	1.2	0.3
Residential	4.5	2.5	1.0	0.6

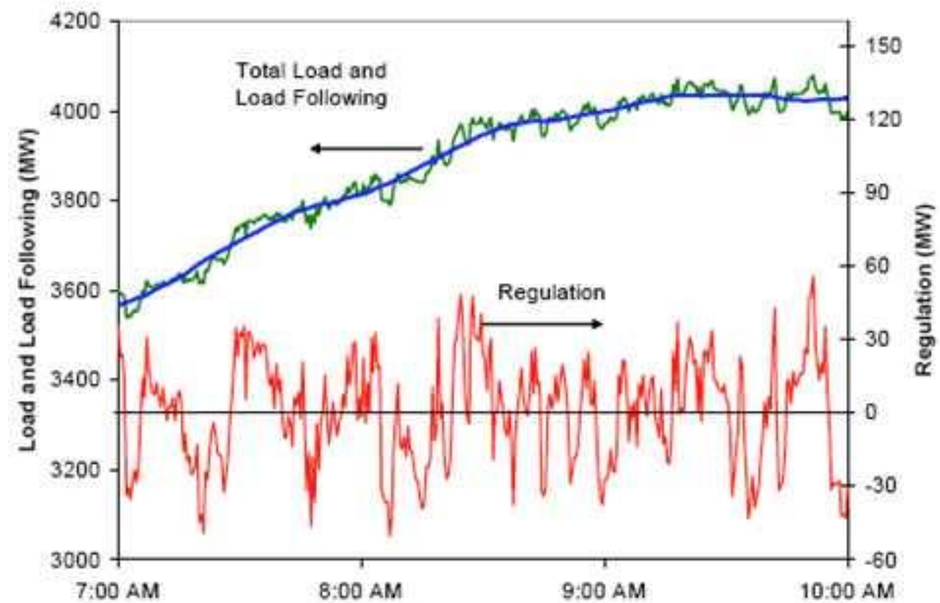
* Energy requirements shown are for a one-year deferral. Actual size of battery depends on allowable depth of discharge (DOD) and deferral years

** PCS rating is based on peak load for the study year

  - Storage provides multiple other values (besides deferral)

Additional Energy Storage Benefits

- Energy storage has value beyond station deferral
  - Voltage support
  - Power quality
  - Transmission congestion relief
  - Participation in load balancing
  - Customer demand management



Conclusions

- The value of PV and energy storage with respect to T&D deferral is situation-specific
  - Need good data to perform a useful analysis
- Energy storage could be a cost-effective alternative to manage station overloads
  - Value proposition is best for a 1-2 year deferral
  - PV deployment (10% to 20% penetration) can greatly improve the value proposition for deferral
- Analysis shows methodology & basic concepts
- SAND Report forthcoming

Discussion of Transformer Rating and Loadability

Transformer Rating and Loading

- Definition of Transformer Rating
  - The MVA rating of a power transformer is the continuous load that results in the following temperature limits:

Standard limits for transformer temperature raise above ambient	
Average winding temperature raise	65°C
Winding "hot spot" temperature raise	80°C

  - Assumes ambient average ambient temperature of 30°C (86 F) and maximum temperature of 40°C (104 F)
  - Transformers can typically be loaded well above their rating without impacting operating life (30 to 50 years)
    - Based on the fact that load is cyclical
    - Based on ambient temperature or oil temperature (if available)

Transformer Rating and Loading

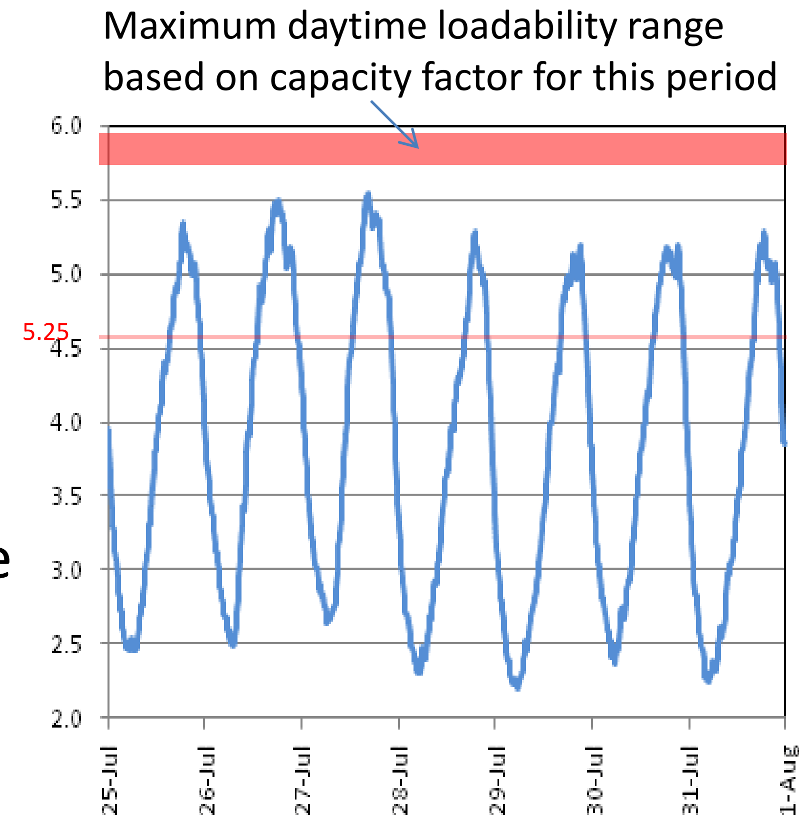
- Reasonable adjustment based on load capacity factor
  – A transformer can be loaded 0.4% to 0.5% percent above its nameplate rating for each percent by which capacity factor (load/transformer rating) averaged over any 24 hr period is below 100%, up to a maximum adjustment of 25%.

References:

1. *Transmission and Distribution Reference Book, Section 5 – Power Transformers and Reactors, Pages 113-114.*
2. *The Electric Power Engineering Handbook, CRC Press and IEEE Press, Section 3.11 – Loading Power Transformers by Robert F. Tillman Jr.*

Transformer Rating and Loading

- Example:
  - A transformer has nameplate rating of 5.25 MVA, load as shown on the right
  - By 5 PM on July 26, the load reached 5.25 MVA, rising
  - Capacity factor is 78% over the previous 24 hrs
  - Based on this, the operator could allow up to 5.75 MVA loading (9% above nameplate rating) without transformer loss of life.

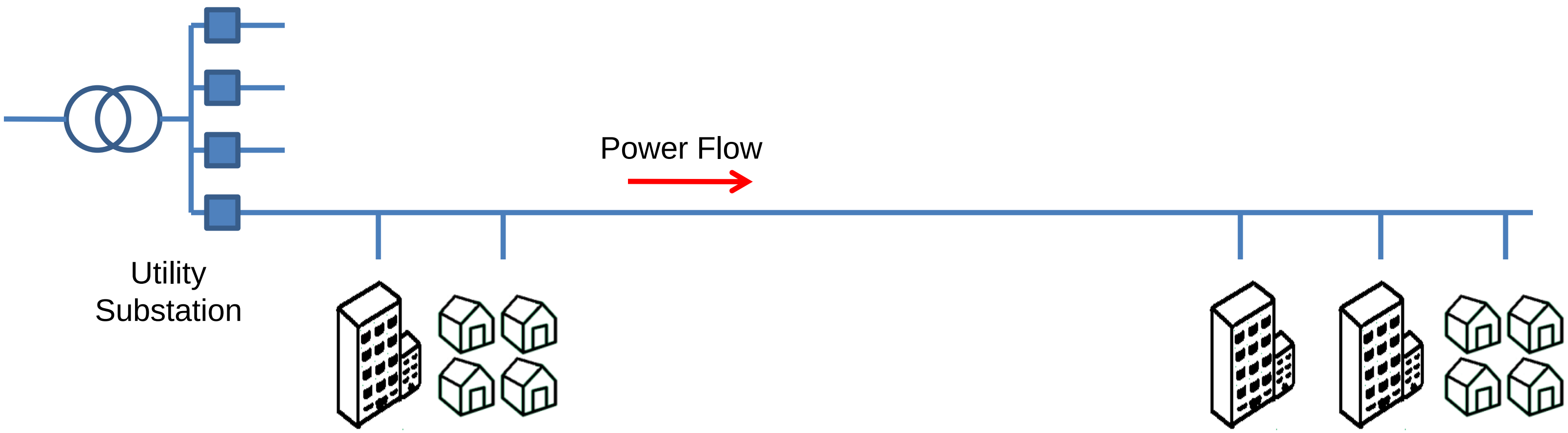


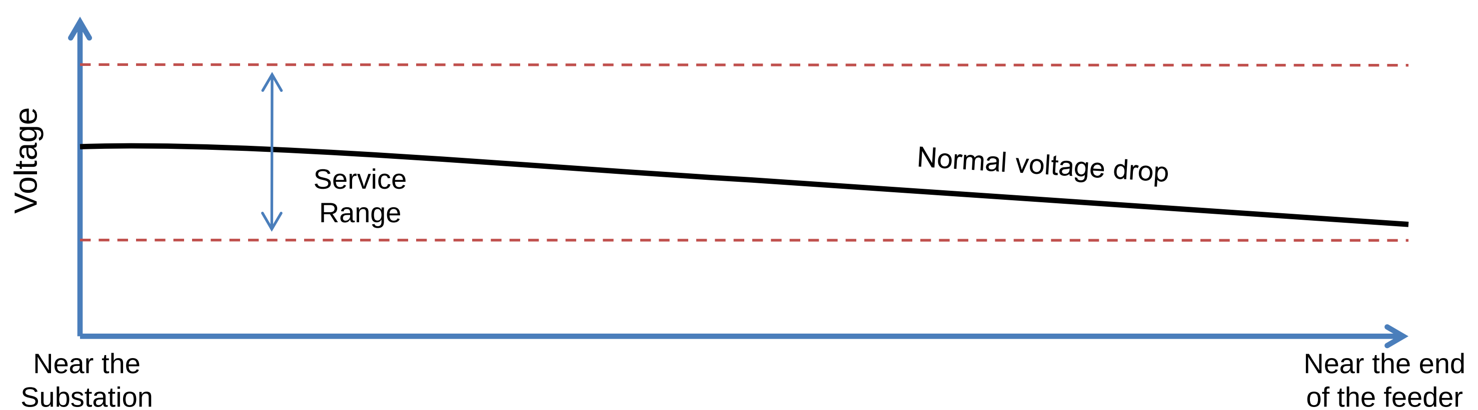
For the sample data above, average ambient temperature was 27℃, and peak temperature is 38℃. Loadability adjustment based on ambient temperature would be small.

Discussion Voltage Regulation with High Penetration PV

Voltage Raise Issue

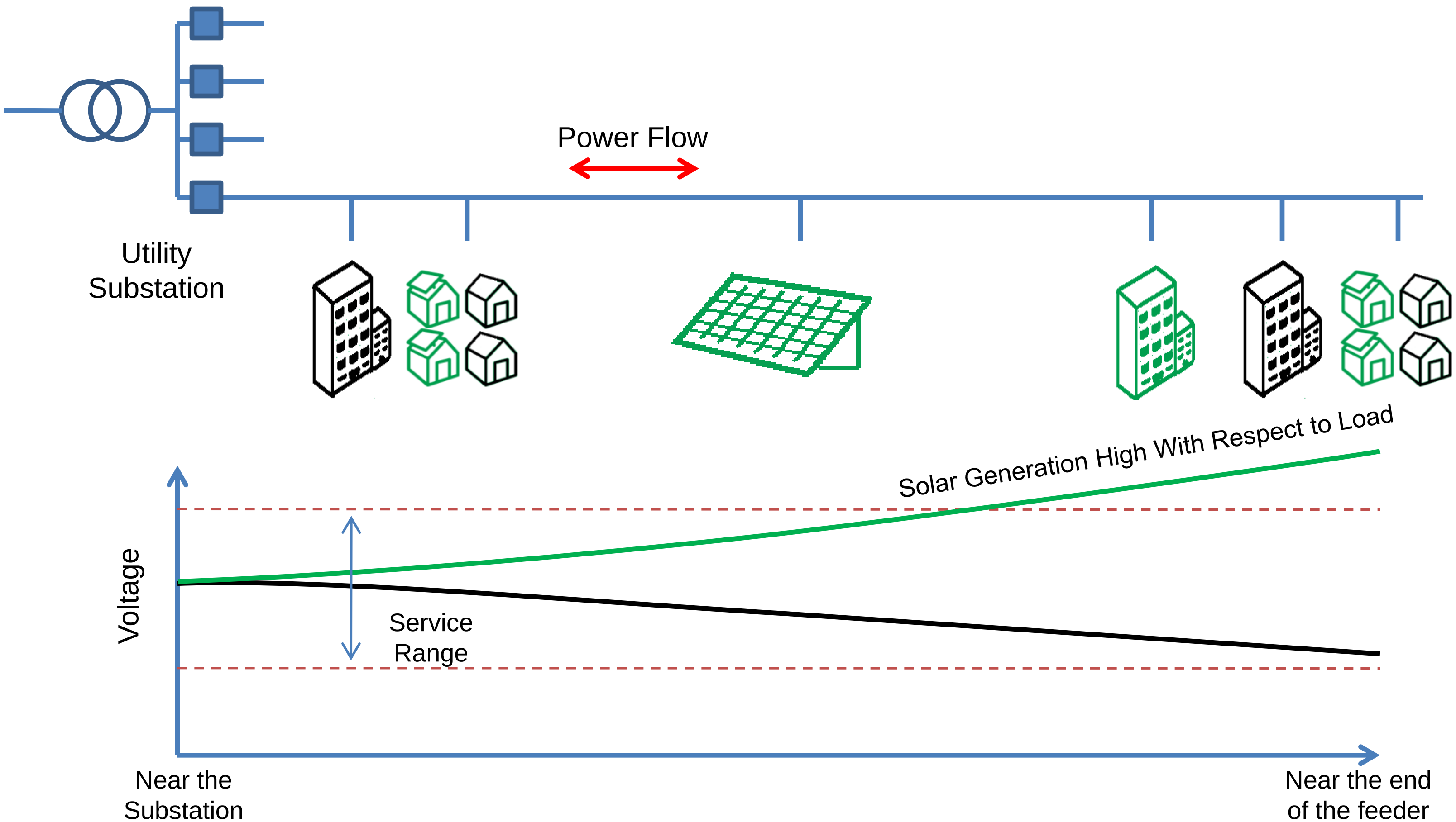
- Voltage along the feeder must be maintained within service limits (ANSI standard)





Voltage Raise Issue

- Depending on the feeder, high amounts of PV (or other DG) could cause high voltage or poor voltage regulation



Voltage Control Issue

- There are technical solutions to deal with feeder voltage control, some may be cost-effective, some not
- Possible technical solutions
  - Locate large solar generation closer to substation or connect directly to station with dedicated feeder
  - Operate voltage regulators in "DG mode"
  - Allow PV inverters to adjust power factor
- More expensive alternatives
  - Dedicated feeder (for utility-scale systems)
  - Upgrade feeder circuit, voltage regulator
  - Disconnect or reduce solar output when feeder or customer voltage is too high
  - Apply energy storage