Methods of Integrating a High Penetration Photovoltaic Power Plant into a Micro Grid

SUNPOWER™

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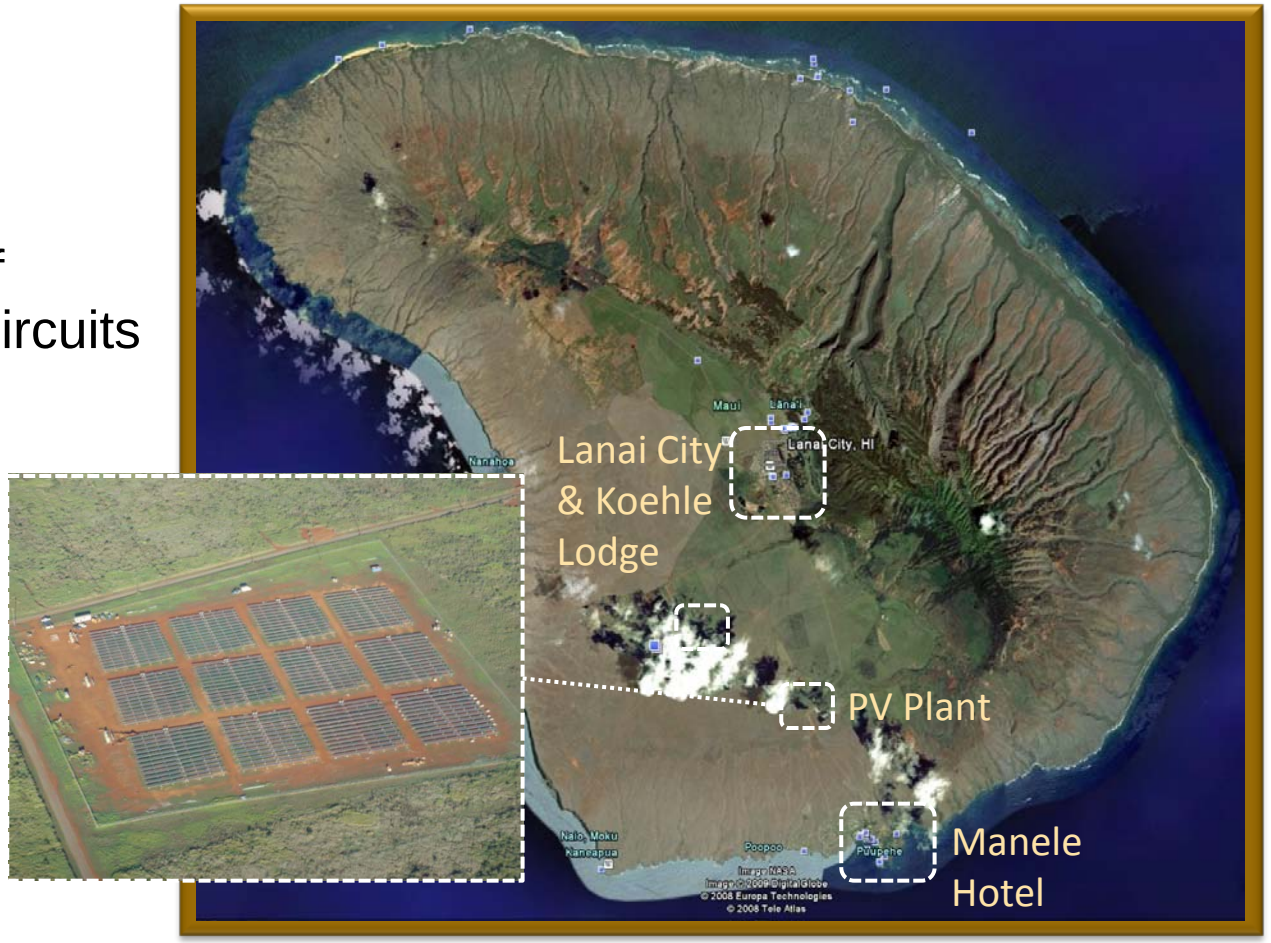
System Overview

- 1.2 MW_{AC} PV plant; Lanai peak net load is 4.7 MW
- Single-axis T0 trackers
- 12 Satcon PowerGate® inverters
- Interconnected to one of Lanai's three 12.47 kV circuits



Performance Requirements

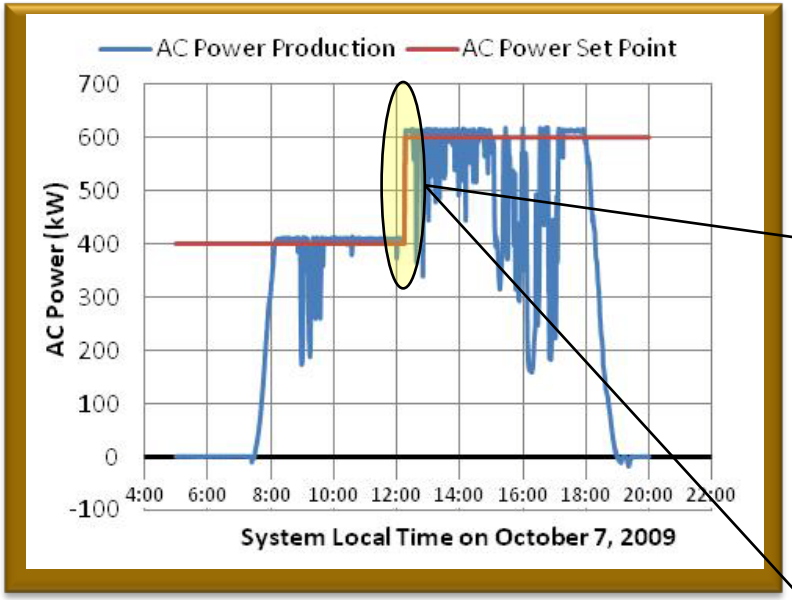
- **Curtailment Control:** Utility provides maximum output between 0-1200kW
- **Power Factor Control:** Utility provides inverter set point between 0.95 lagging to 0.98 leading
- **Ramp-Rate Limiting**
  - Plant ramp rate limited to 360 kW/min during beginning/end of day and startup/shutdown periods
  - Plant output fluctuations limited to 40-60 kW/s at all times
- **Voltage and Frequency Event Ride Through (see tables)**

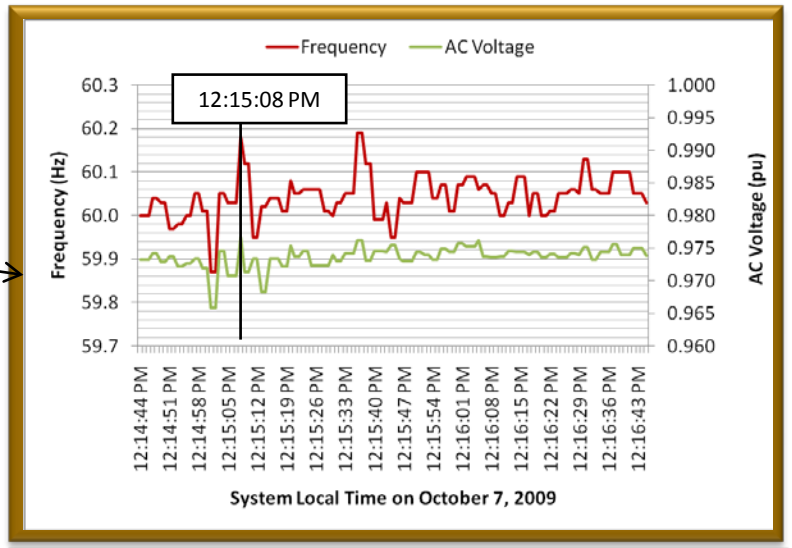
SunPower and Satcon collaborated to implement controls

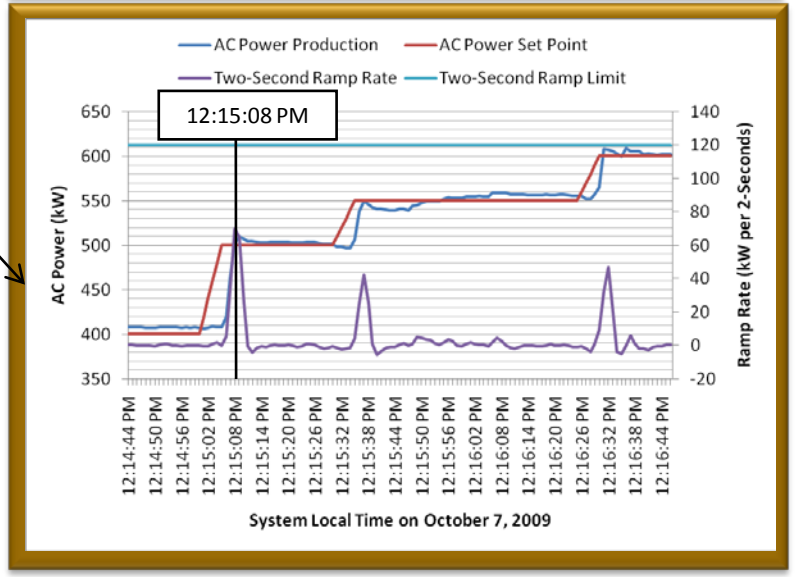
Lower Limit (pu)	Upper Limit (pu)	Action
1.20	--	May disconnect if in this range for more than 160 milliseconds
1.10	1.20	May disconnect if in this range for more than 3 seconds
0.90	1.10	Remains connected
0.70	0.90	May disconnect if in this range for more than 2 seconds
0.05	0.70	May disconnect if in this range for more than 600 milliseconds
--	0.05	May disconnect if in this range for more than 150 milliseconds

Lower Limit (Hz)	Upper Limit (Hz)	Action
65.0	--	Must disconnect if in this range for more than 160 milliseconds
62.0	65.0	May disconnect if in this range for more than 2 seconds
61.0	62.0	May disconnect if in this range for more than 6 seconds
57.0	61.0	Remains connected
55.0	57.0	Remains connected within the extended ride-through range
--	55.0	May disconnect if in this range for more than 160 milliseconds

Curtailment Control



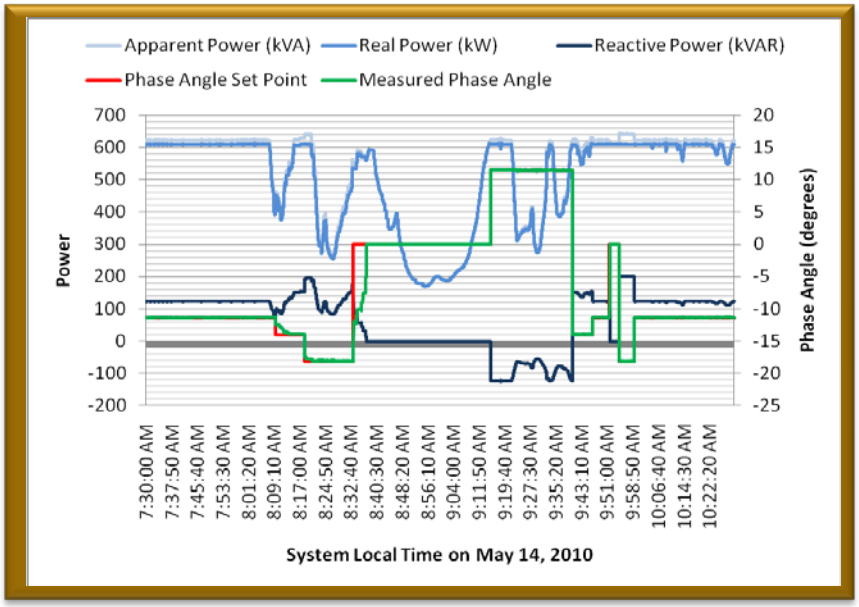


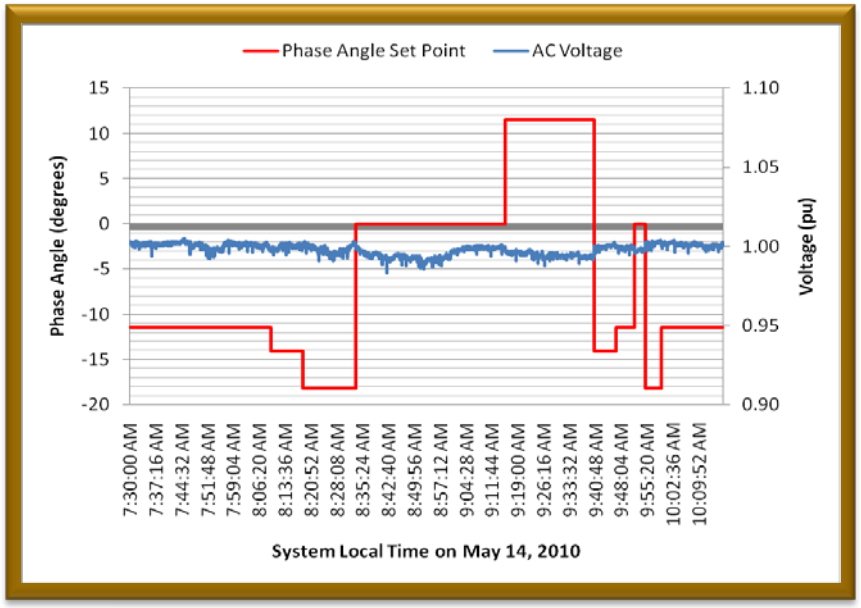


- Curtailment set point increased from 400 kW to 600 kW
- 70 kW/ 2 seconds max ramp accompanied by 0.12 Hz increase in frequency (0.15 Hz predicted by KEMA model)
- Similar fluctuations occur independently of PV ramps: +/- 0.2 Hz common, prior to PV system. An example is seen just prior to set point change.

Power Factor Control

- Inverters successfully respond to changes in PF set point.
- Faster inverter response during stable power production
- Change in PF set point may induce small changes in grid voltage that are well within specified normal operating range



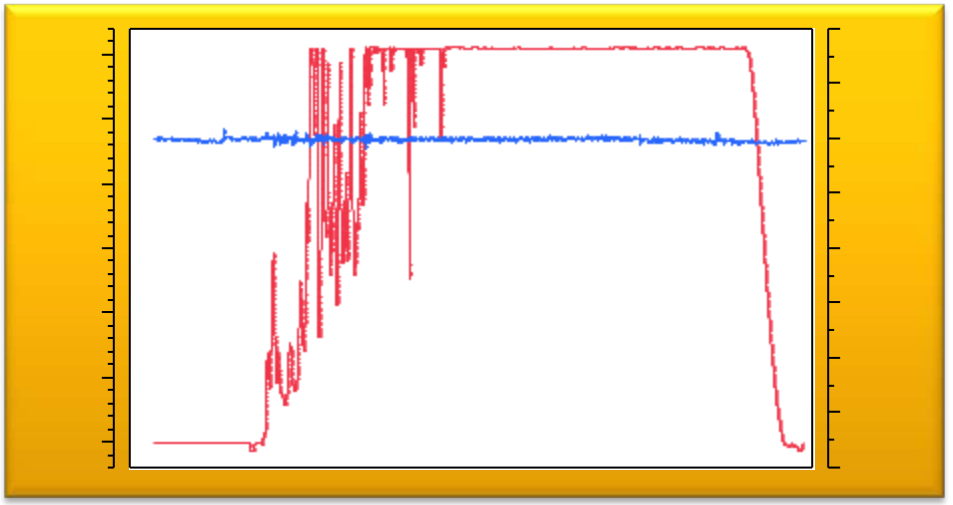


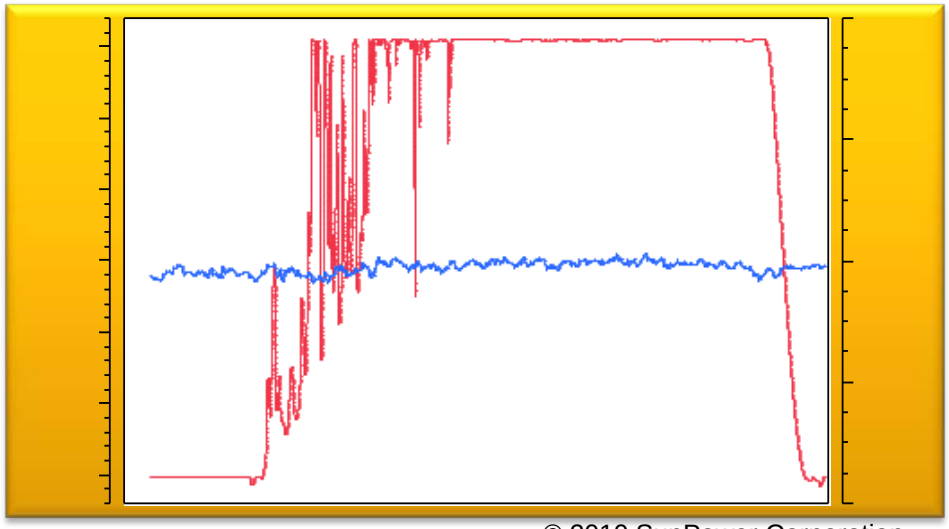
PV Plant Effect on Grid Voltage and Frequency

For the single day examined:

- No significant changes in grid frequency or voltage during both variable and stable PV power production
- Limited correlation between average magnitude and standard deviation of changes of power with voltage and frequency

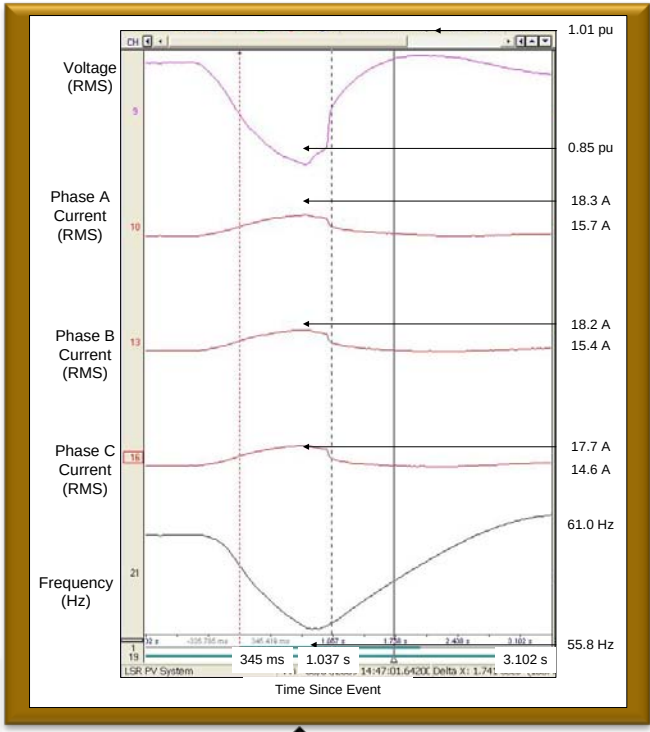
	Voltage with Power		Frequency with Power	
Comparative Statistic \ Time Scale	1-Minute	15-Minute	1-Minute	15-Minute
Average	0.58	0.65	0.06	0.12
Standard Deviation	0.12	0.35	0.15	0.36



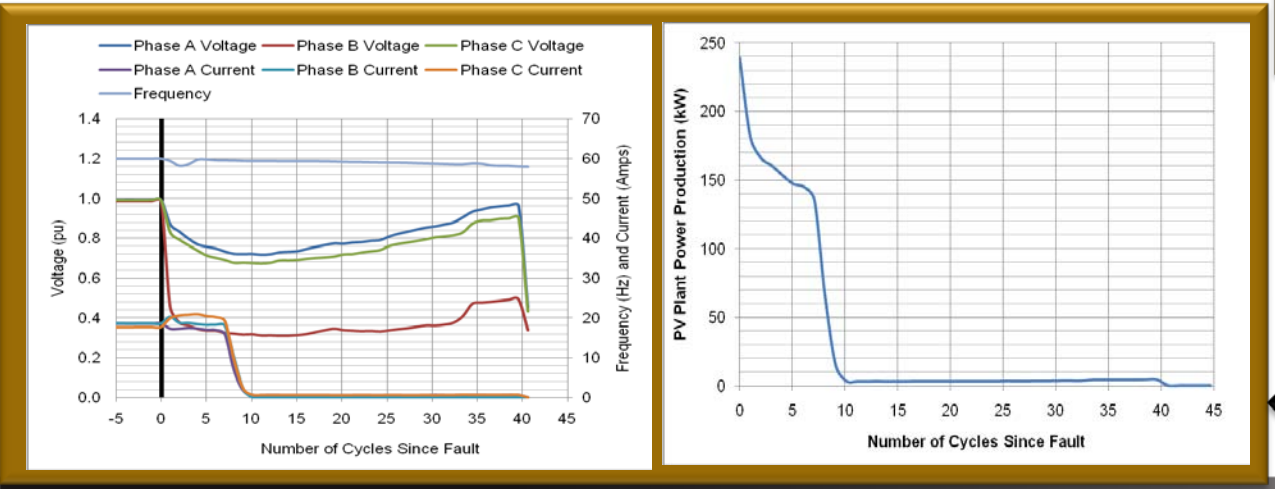


Voltage and Frequency Ride Through

- An example of a successful inverter ride through of a low frequency event plotted to the right
- An example of a successful inverter ride through of a low voltage event plotted below
  - Output is reduced to < 5 kW, but inverters remain online for at least 600 milliseconds
  - Intertie breaker opens after 41 cycles, eliminating the possibility of the inverters coming back online



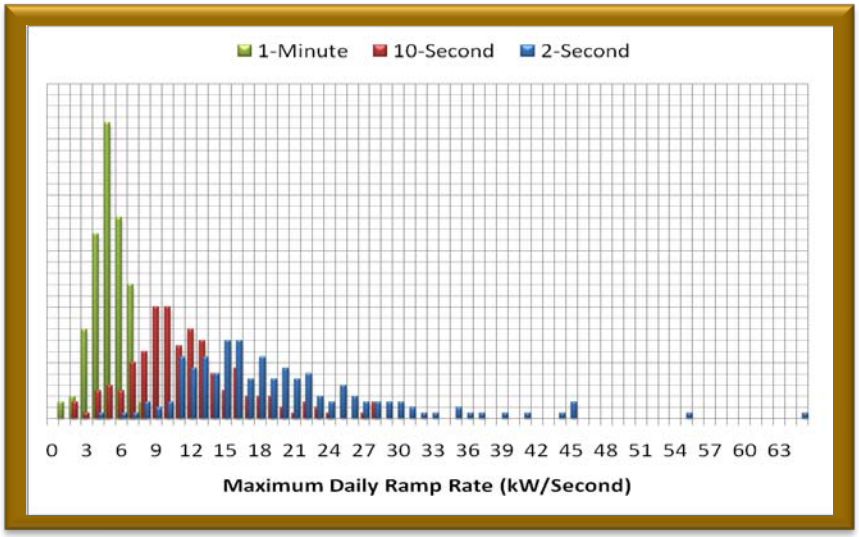
Underfrequency Event

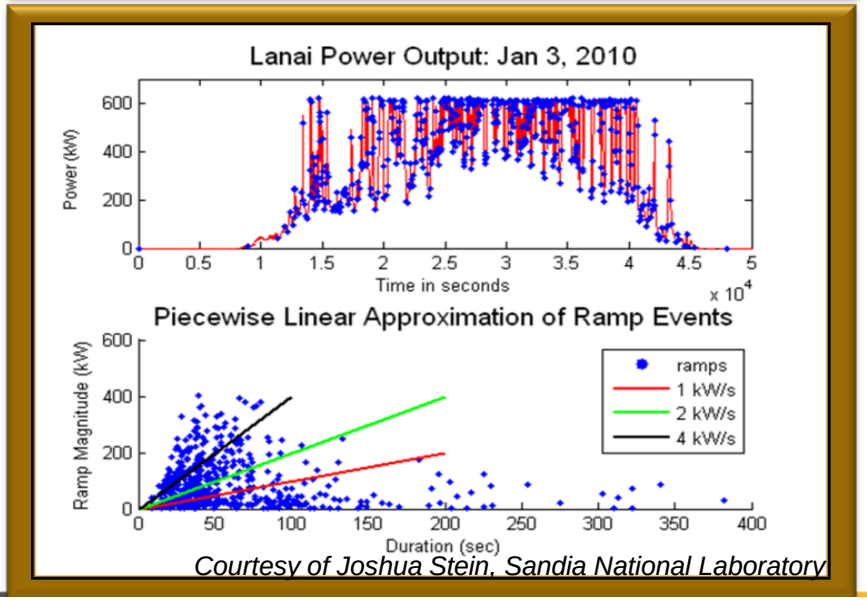


Low Voltage Event

Sustained versus Instantaneous Ramp Rates

- Two methods of comparing instantaneous and sustained ramps
  - Maximum daily ramp rates calculated between September 2009 and May 2010
  - Sandia's application of piecewise linear approximation (PLA) method gives ramp magnitude and duration for a highly variable day
- Short duration ramps are not sustained over longer time intervals – i.e. 600 kW/min is not equivalent to 10 kW/sec.
- Ramp rates must be defined correctly relative to the system impacts of concern – for instance regulation vs. load following.





Courtesy of Joshua Stein, Sandia National Laboratory

Note: Outside of micro grids such as Lanai, variability is almost always more practically and cost effectively managed at the system level, not at individual plants.

Conclusions

- Inverter controls have been shown to be successfully implemented
  - Curtailment control
  - Power factor control
  - Voltage and frequency event ride through
- PV plant performance does not significantly affect grid performance
- High instantaneous ramp rates are not sustained over longer time intervals

- Special thanks to:
  - Satcon Corporation
  - Maui Electric Company
  - Castle and Cooke / Lanai Sustainability Research
- Questions