PV System Reliability:
An Operator's Perspective

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Solar O&M Maturation

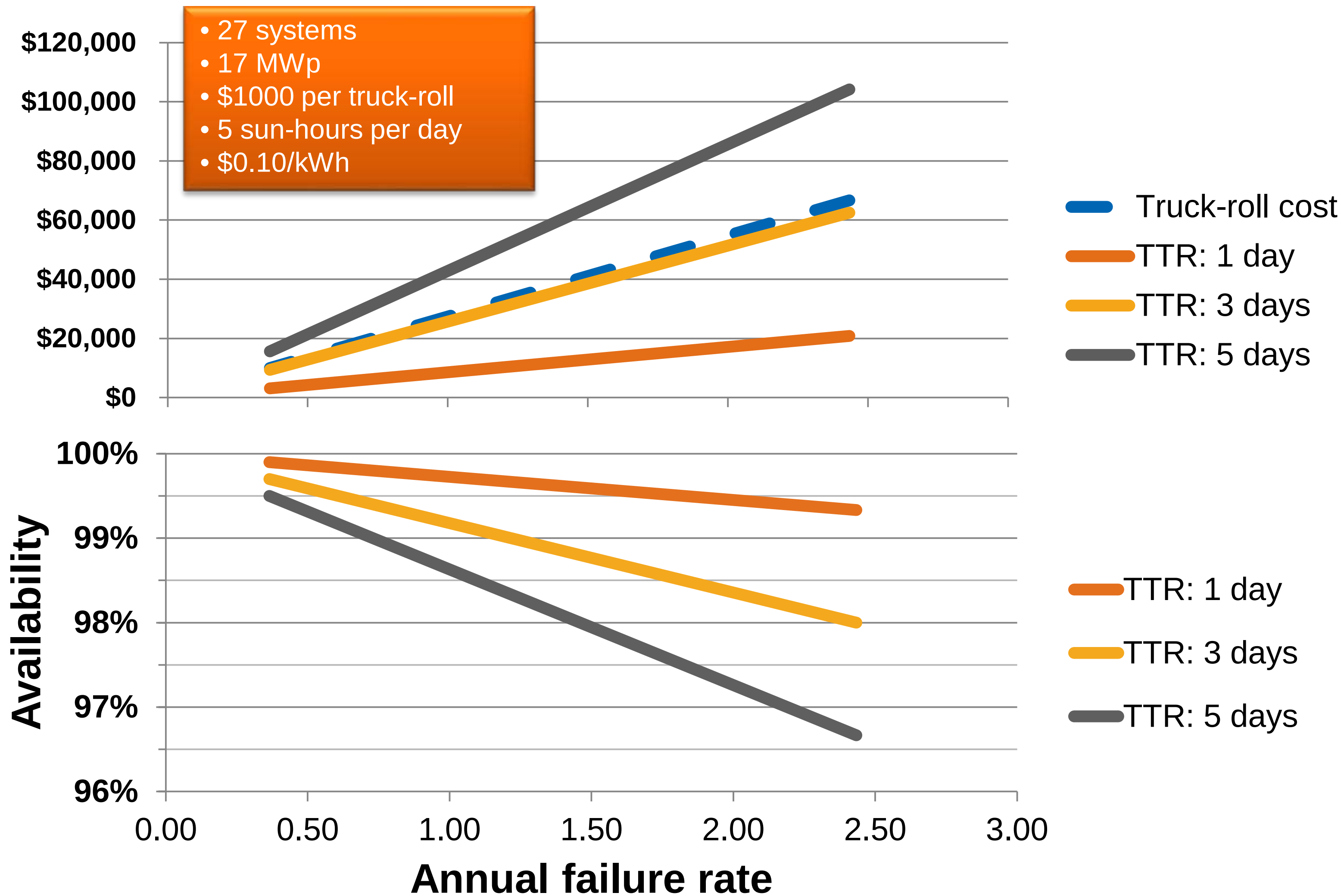
Before 2000	2000-2010	Future
• Direct Sales ($/W) • DIY O&M	• FIT, PBI, PPAs • Professional Maintenance	• Expansion to Operations • Power vs. Energy

The Importance of Reliability to an Operator

- Low-reliability systems:
  - Need attention → drive up service costs
  - Are less productive than expected → drive down revenue

- Collateral issues:
  - Increased monitoring needs (and capital/service costs)
  - Reputation cost (with customer and/or investor)
  - Lengthier procurement process
  - Increased risk of safety-related incidents

The Cost of Reliability and Time-To-Repair



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- 750 plants with over 700 MW across 3 continents:

- North America: US (15 states), Canada, Puerto Rico
- Europe: Spain, Italy, Bulgaria
- Asia: South Korea, India, Thailand

- 3 Renewable Operations Centers (ROC):
  - North America: Belmont, CA
  - Europe: Madrid, Spain
  - Asia: Chennai, India

Geographical distribution

Diversity of systems

- 15+ inverter vendors
- 30+ PV module vendors
  - x-Si (>80% of units)
  - CdTe
  - a-Si
- Structure types
  - Rooftop, fixed (ballasted and mounted)
  - Ground, fixed
  - Ground, tracking (single axis, dual axis)
- Climates
  - Tropical, Desert, Coastal, High Desert, etc
- Age
  - Up to 7 years

Tickets, Outages, and Impairments

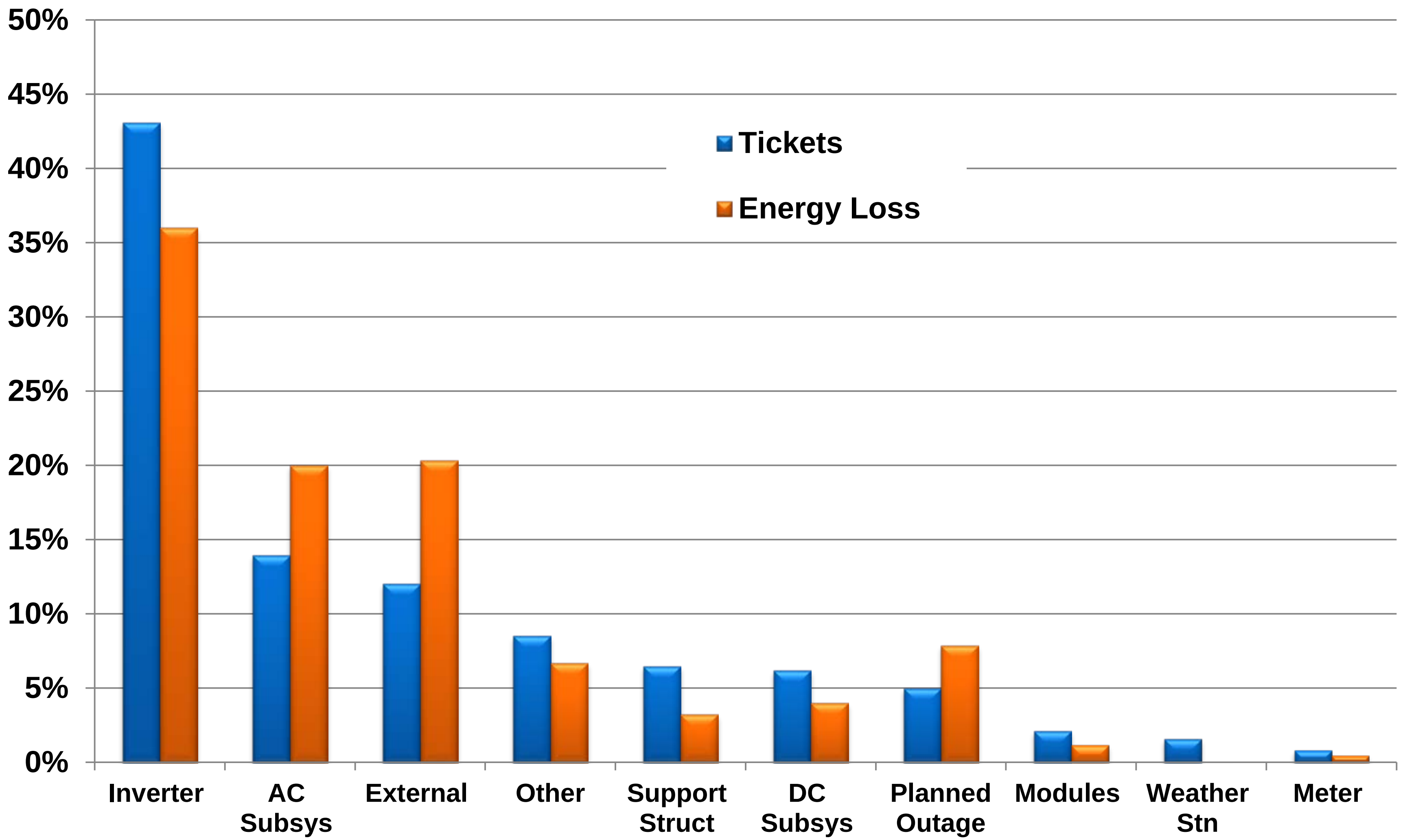
- Service ticket:
  - A record of an issue affecting the PV system
    - May impact energy output, or not
    - Failure Area (**Where** did the issue manifest?)
      - Subsystem and Component level
    - Root Cause (**Why** did the issue manifest?)
      - General and Specific
- Outage:
  - An issue affecting a critical subsystem
  - Visible immediately
  - To be addressed urgently
- Impairment:
  - An issue affecting a non-critical subsystem
  - Visible with advanced analytics or high-granularity monitoring
  - Can be addressed in opportune timing
- Sensor or communications issue:
  - Not affecting production
  - Usually visible immediately
  - To be addressed immediately

Analyzed Dataset

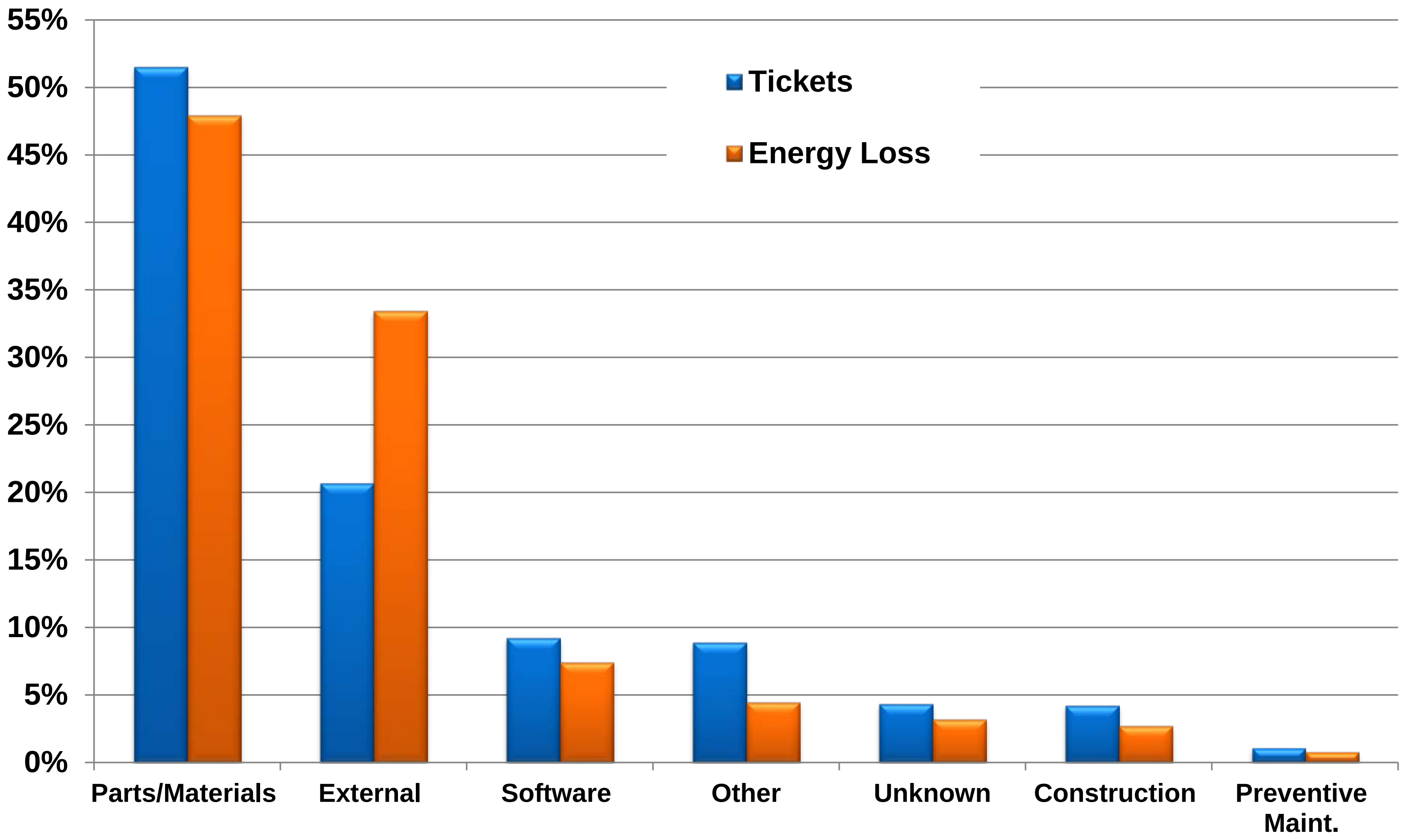
- 3600 service tickets for 450 systems in 27 months
  - January 2010 – March 2012

- Unrealized energy generation:
  - ~1% of total production in 27 months

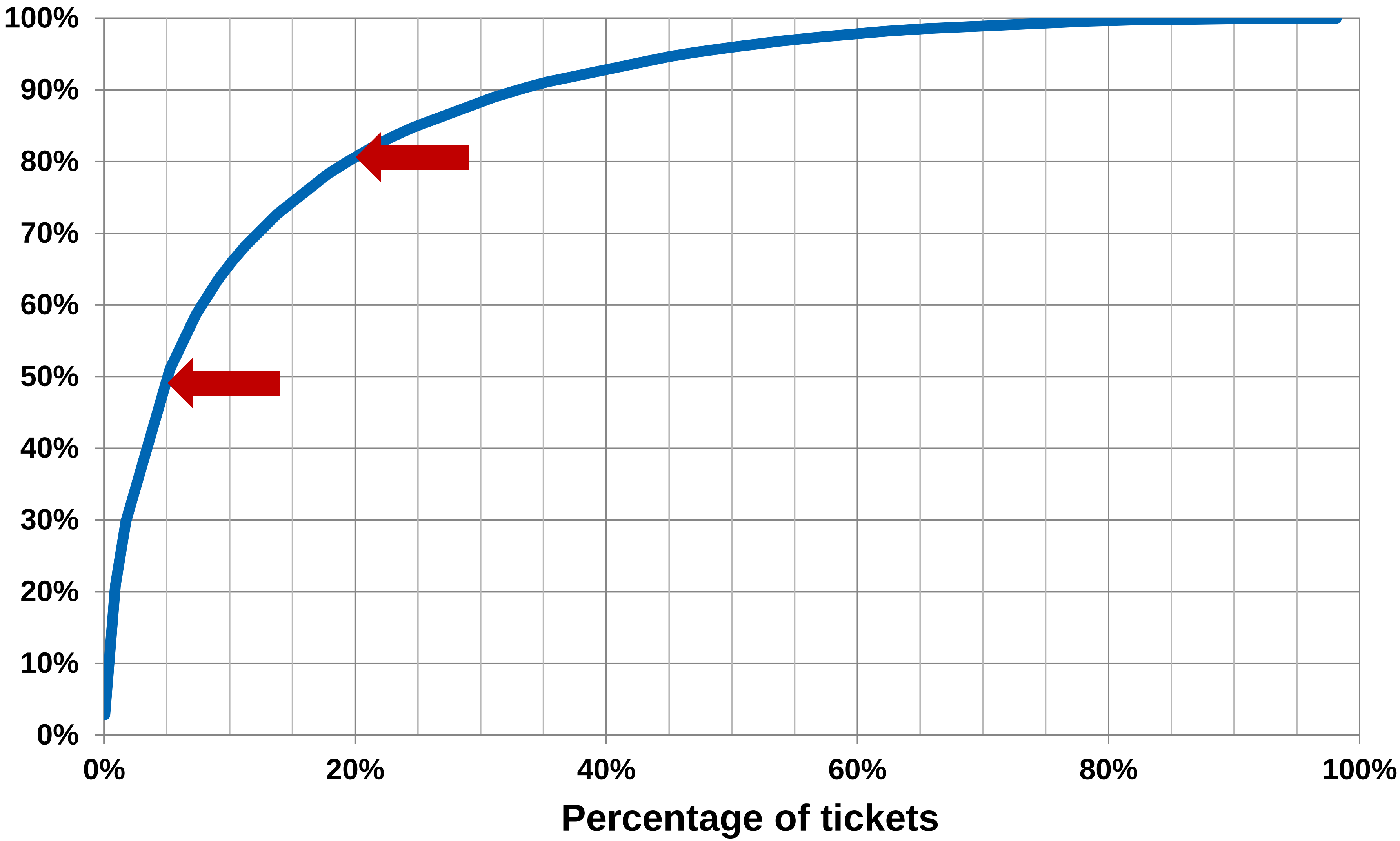
Failure Areas: Frequency and Energy Impact



Root Causes: Frequency and Energy Impact



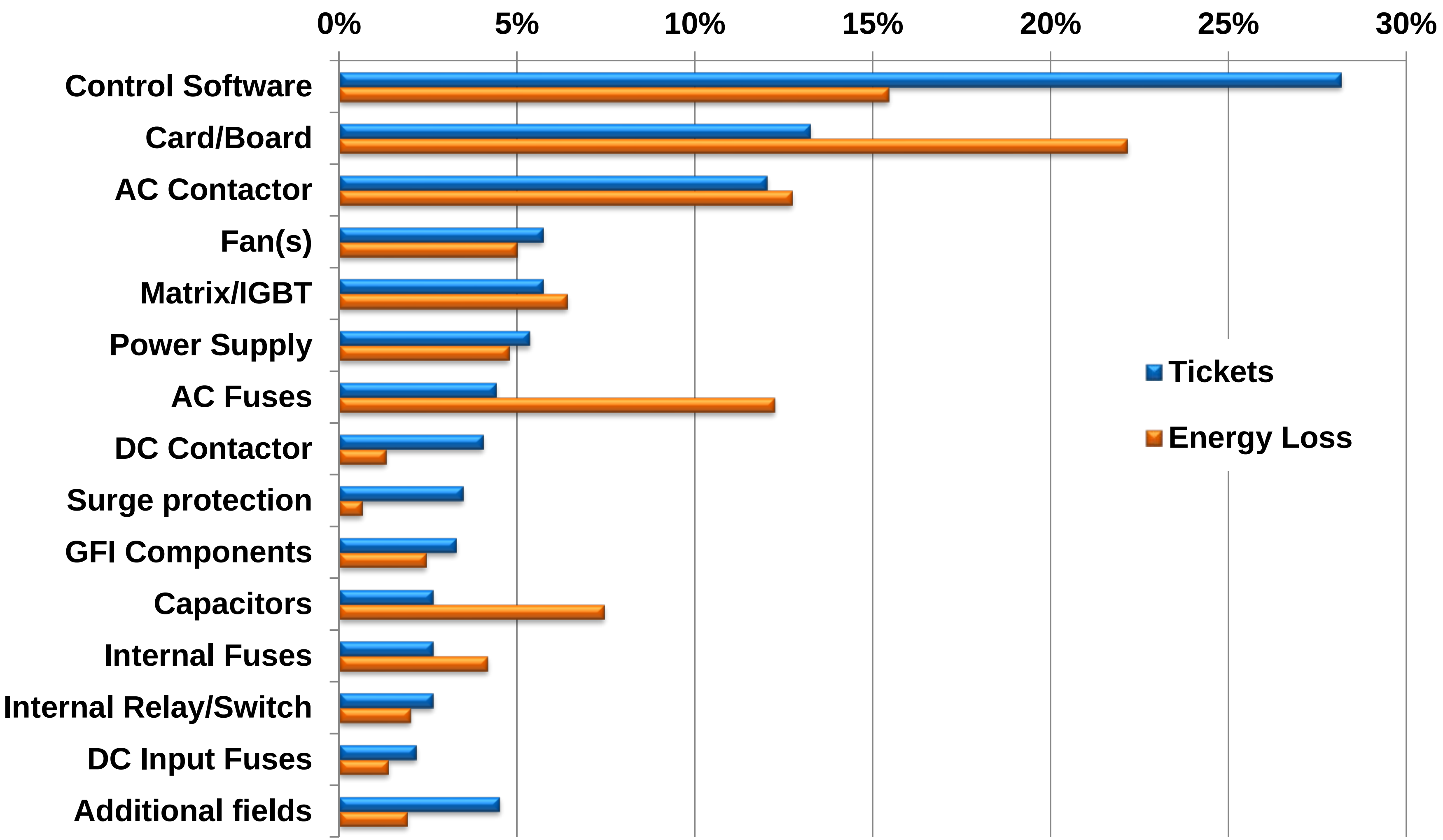
Cumulative Energy Loss: the 80/20 rule



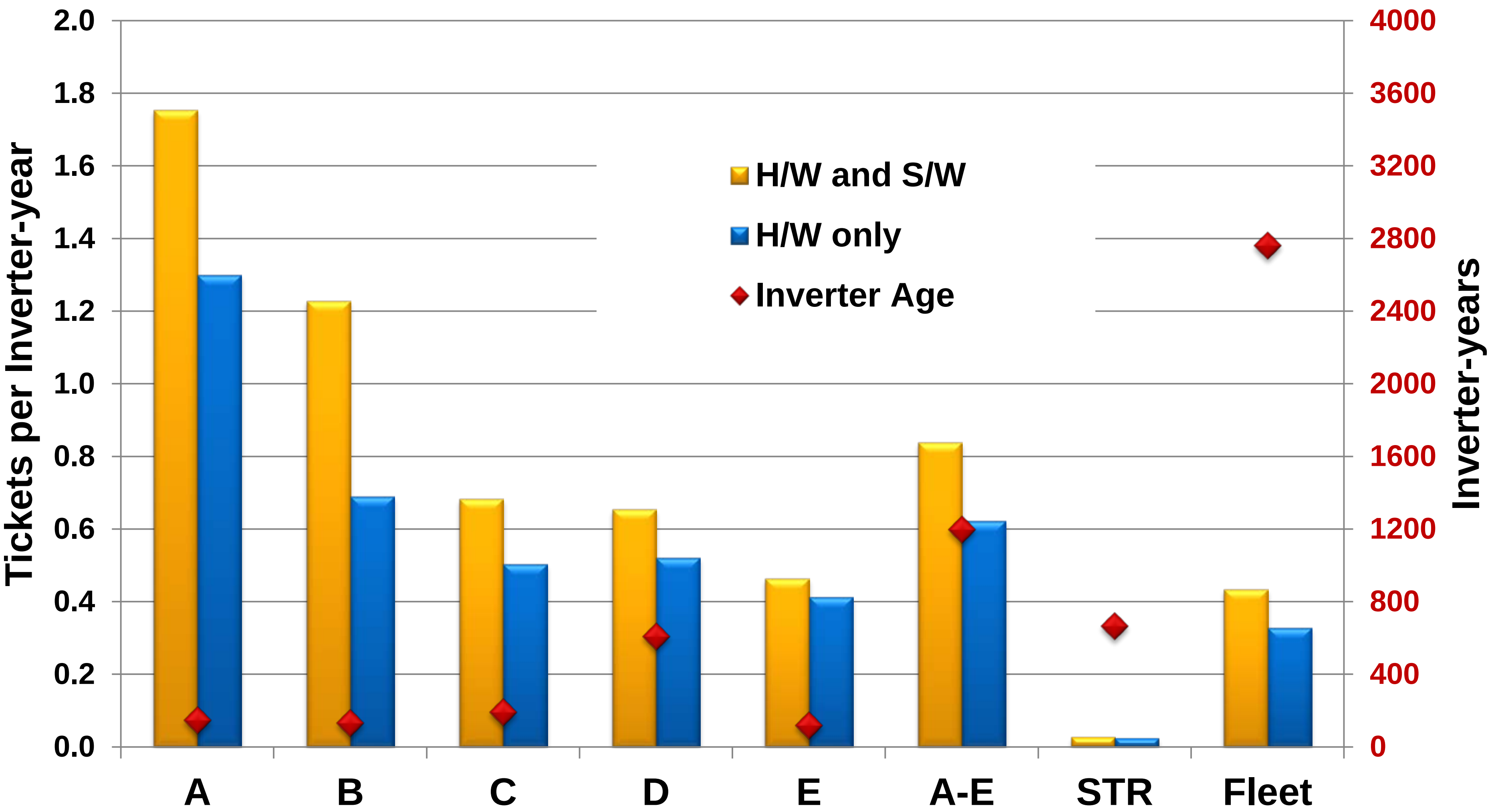
Conclusions - I

- Inverters
  - Highest frequency of issues
  - Largest share of energy loss
- 75% of energy losses manifest at mission critical nodes
  - Inverter
  - AC subsystem
  - External subsystems (Interconnection, Grid)
- 50% of tickets and energy loss due to component failures
- 33% of energy losses attributed to external agents
- 50% of energy loss caused by 5% of incidents
- Largest losses represent long outages

Inverter Components that Fail



Reliability of Central Inverters – 5 vendors



Tracking Inverter Reliability with Age: Cohorts

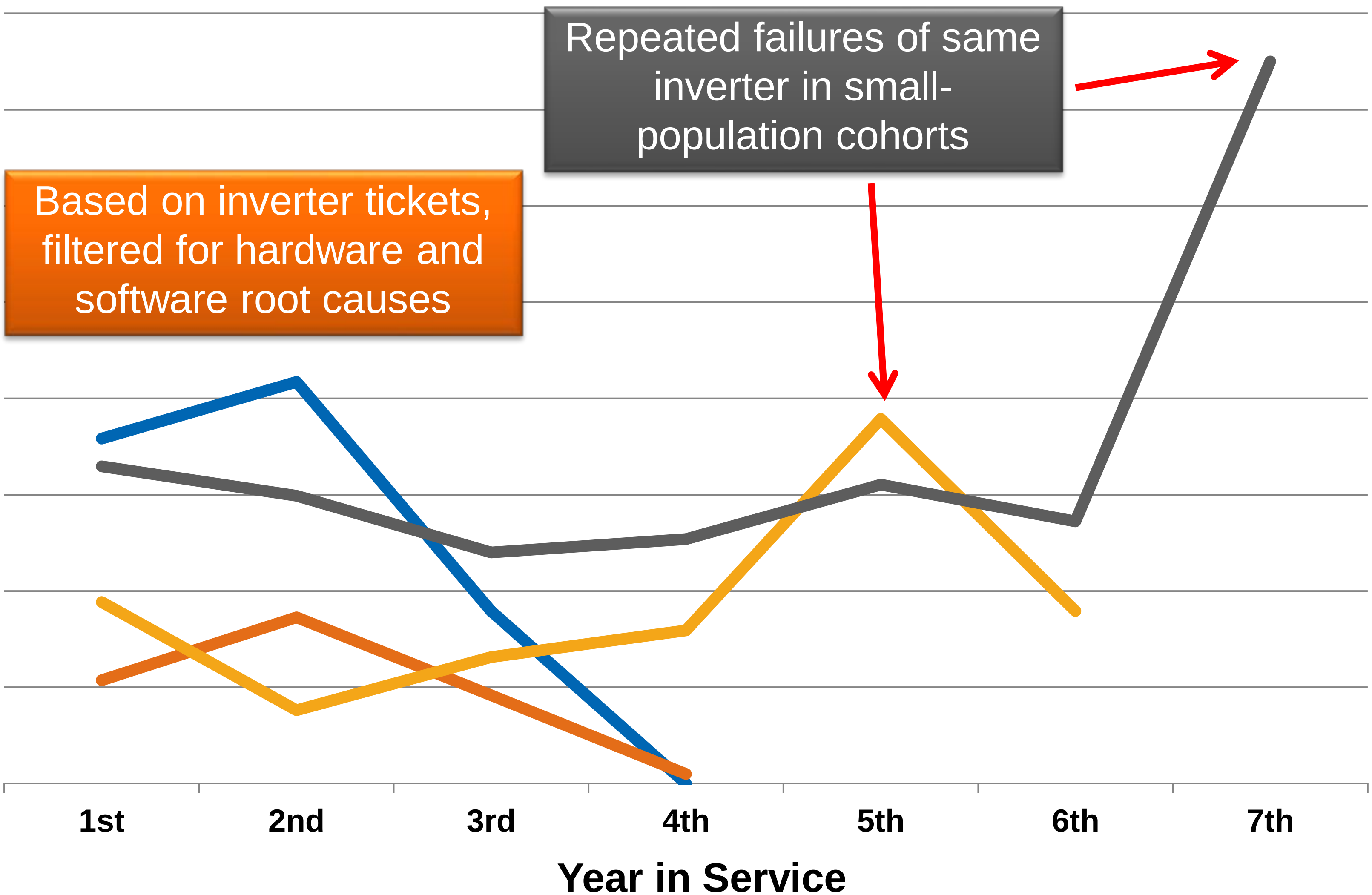
	Number of inverters (from a specific vendor)					
system age in months	**Jan 2010**	**Feb 2010**	**Mar 2010**	**Apr 2010**	**May 2010**	**Jun 2010**
1	22	3	1	6	3	
2		22	3	1	6	3
3			22	3	1	6
4	22			22	3	1
5	1	22			22	3
6	1	1	22			22
7	4	1				
8		4				
9	1					
10	9	1				
11	4	9				
12		4				

	Number of inverter tickets (for a specific vendor)					
system age in months	**Jan 2010**	**Feb 2010**	**Mar 2010**	**Apr 2010**	**May 2010**	**Jun 2010**
1	4	1	1		2	
2		2	3			1
3			1			
4				2		
5					3	
6			2			2
7				1		
8						
9						1
10						
11			1		1	
12			1	2		

	Monthly failure rates (for a specific vendor)							
system age in months	**Jan 2010**	**Feb 2010**	**Mar 2010**	**Apr 2010**	**May 2010**	**Jun 2010**	**Mar 2012**	**Average**
1	0.18	0.33	1.00	0.00	0.67			0.12
2		0.09	1.00	0.00	0.00	0.33		0.12
3			0.05	0.00	0.00	0.00	0.00	0.04
4	0.00			0.09	0.00	0.00	0.00	0.07
5	0.00	0.00			0.14	0.00	0.00	0.05
6	0.00	0.00	0.09			0.09	0.00	0.18
7	0.00	0.00	0.00	0.05				0.08
8		0.00	0.00	0.00	0.00			0.02
9	0.00		0.00	0.00	0.00	0.05		0.01
10	0.00	0.00		0.00	0.00	0.00	0.00	0.07
11	0.00	0.11	1.00		0.25	0.00		0.07
12		0.00	0.11	2.00		0.00	0.00	0.11

Annual Failure Rate: **0.94**

Annual Failure Rate for 4 Inverter Vendors



Conclusions - II

- Most inverter failures manifest at
  - the control software
  - various PCBs
  - the AC contactors
- Failures attributed to control S/W may include failures triggered by upstream or downstream issues that cause inverter shutdown without error codes
- Typical bathtub behavior is not observed
  - Infant mortality issues manifest during installation (before launch)
  - Long-term statistics not yet reliable, but some old inverters exhibit repeated issues

Module Components that Fail

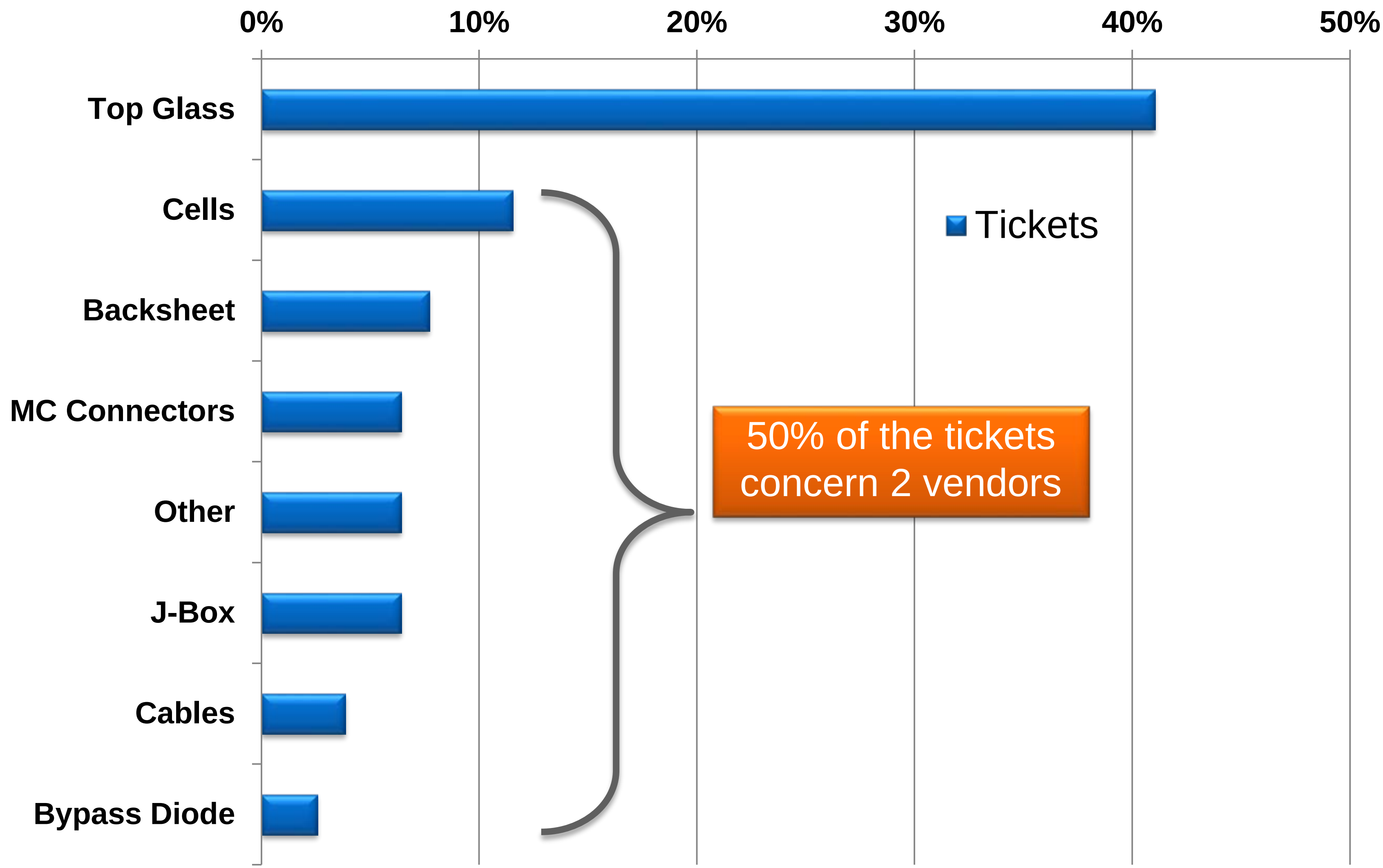
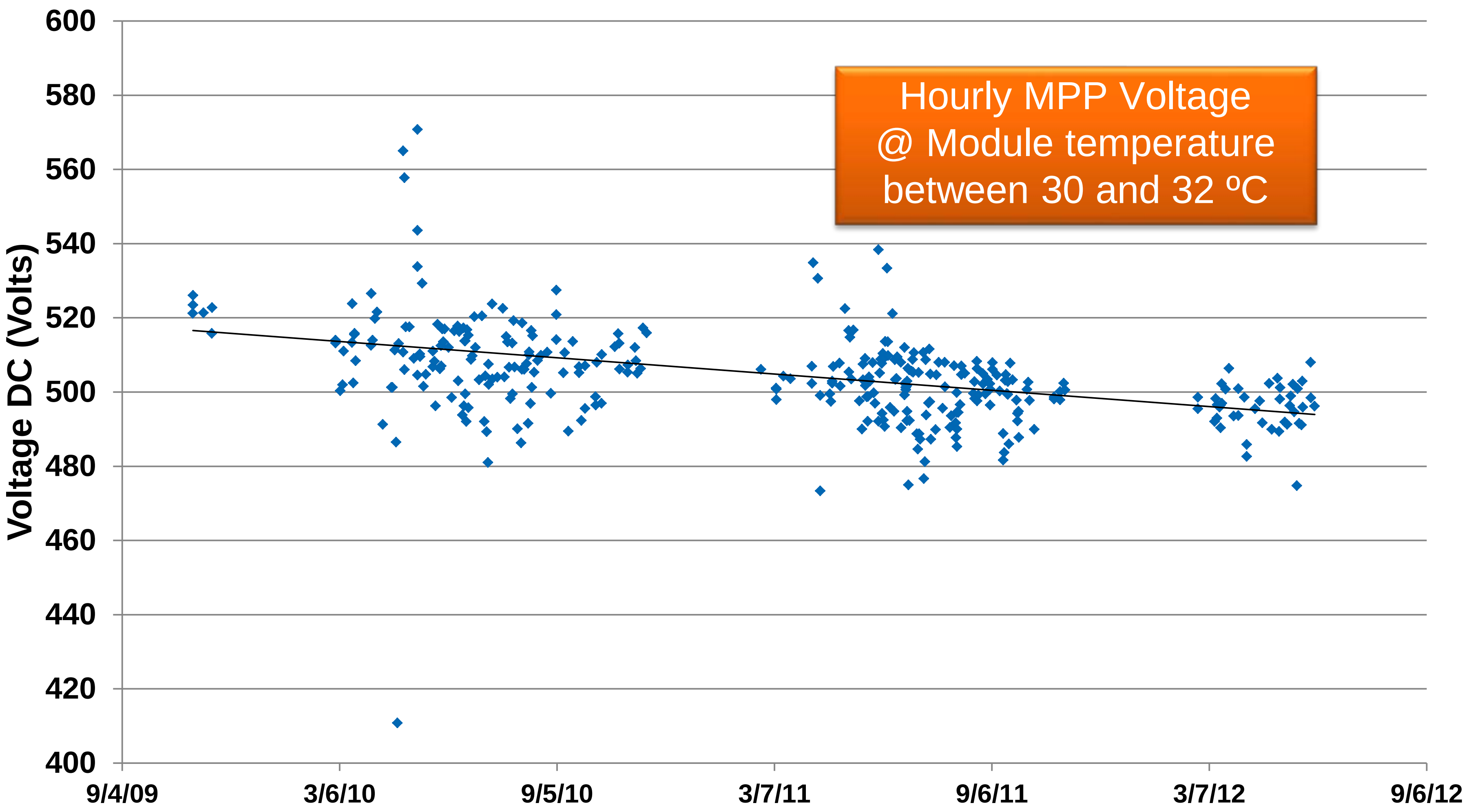



Photo by Morgan Smith

Systematic Underperformance

- Occasionally a system will underperform relative to expectations over an extended period without being affected by an outage
- During maintenance the field crews will check DC connectivity
- If all combiners and strings are connected and the underperformance persists, the field crews will take I-V curves from random strings and modules
- If the results show performance in breach of the power warranty, sampled modules are sent to an independent lab for flash testing

Example of Suspected Module Degradation



Conclusions - III

- Identified module failures represent a very small fraction of service tickets
- Vast majority of system data do not indicate that module failures are being overlooked
  - There are exceptions, which have led to closer investigation of module performance
- Most frequent failure is the breakage of the front glass, which is caused by an external agent

Challenges in Quest for Reliability

Operator

Data integrity

- Staff training
- Data entry platform
- Definition clarity

Uncontrolled environment

- Difficult to ID issue and cause

Issue complexity

- Lack of tools and product knowledge

Vendor

Data scarcity

- No contextual information

Uncontrolled environment

- Difficult to simulate and test

Issue complexity

- Lack of data and system operation knowledge

What Can Be Done About Reliability

- The PV system operator may <u>manage</u> reliability
  - Procurement
  - Standardization in design and construction
  - Service dispatch schedule
  - Performance monitoring and analytics
  - Inventory optimization
  - Supply chain QA
- The equipment vendor may <u>improve</u> reliability
  - Supply chain QA
  - Standardization in design and manufacturing
  - Continuous improvement

From Maintenance to O&M

- High penetration levels will make passive interconnections for PV unsustainable.
- What does it take for PV to be a better citizen of the grid?
  - Ability to manage Power as opposed to Energy;
  - Response times dramatically reduced;
  - More robust solutions;

  - **Ability to “Say what you’ll do and do what you say.”**

PV Power Forecasting: An example

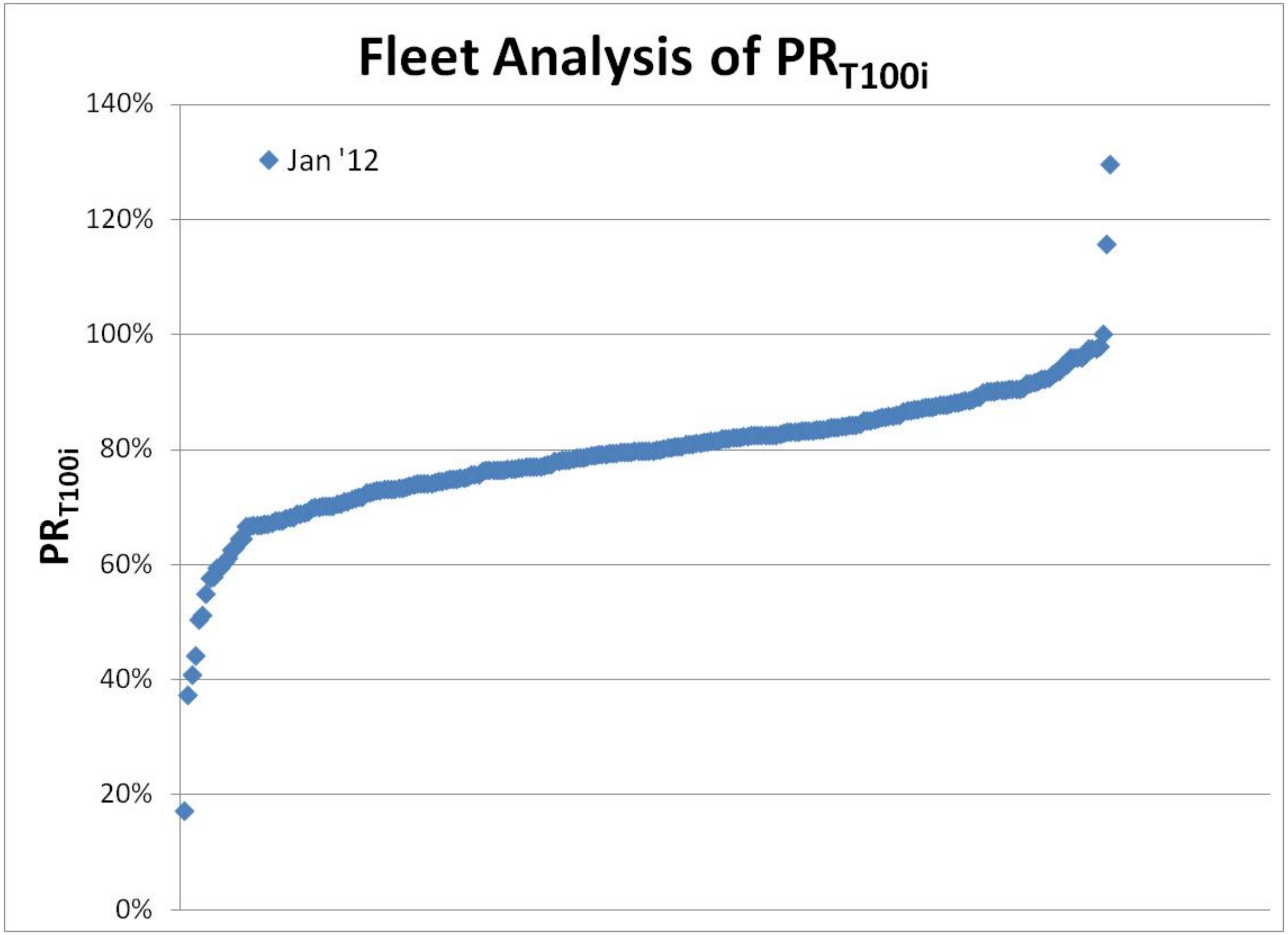
- The primary challenge today remains sufficiently accurate meteorological forecast;

- Second order challenges include:
  - Accurate and timely power conversion models;
  - Accurate, real-time Availability reporting.

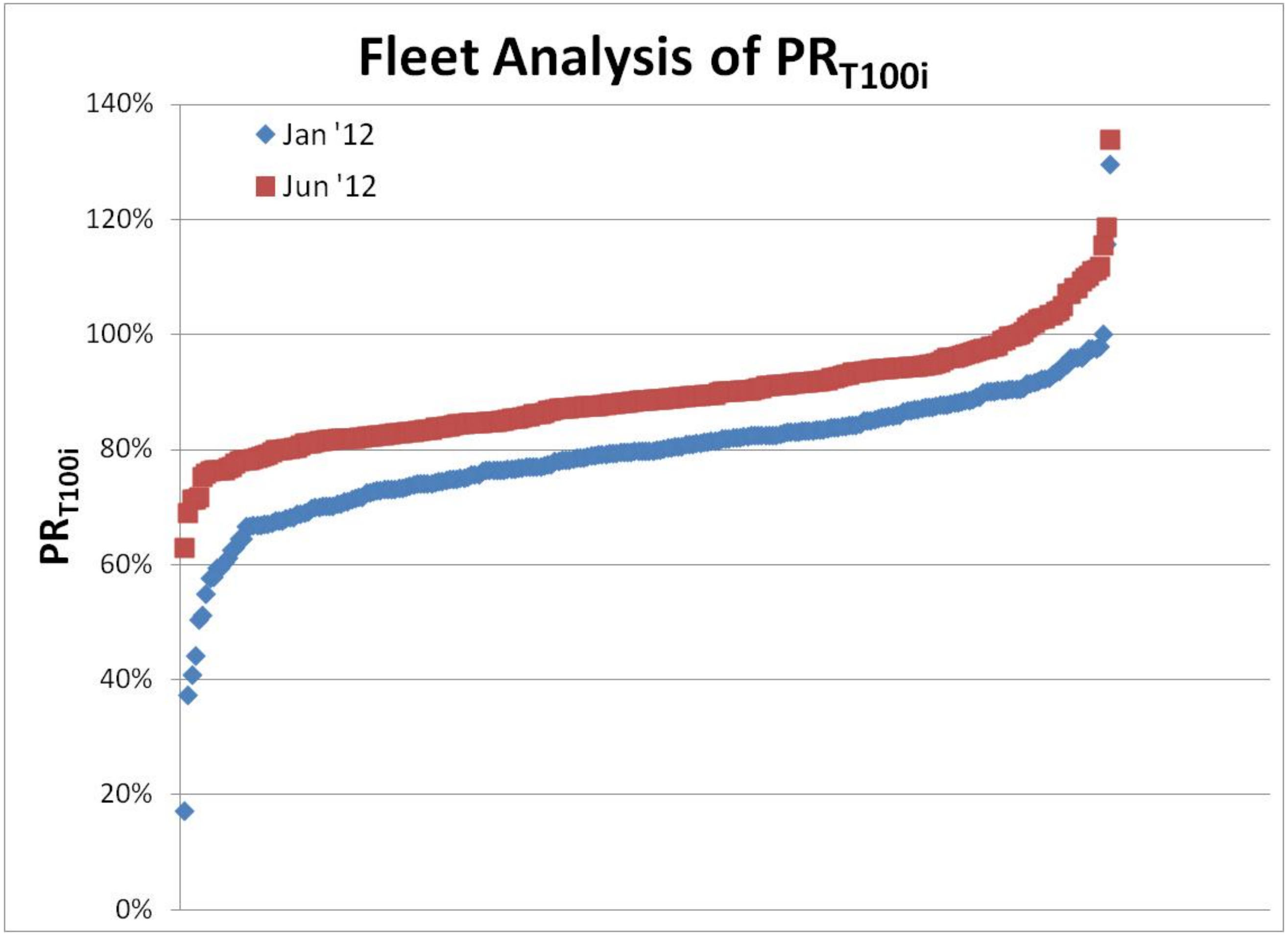
Performance Ratio

- PR_{T100i}
- Temperature Corrected Performance Ratio for hours with 100% inverter availability

"Big Data" for PV



“Big Data” for PV, continued



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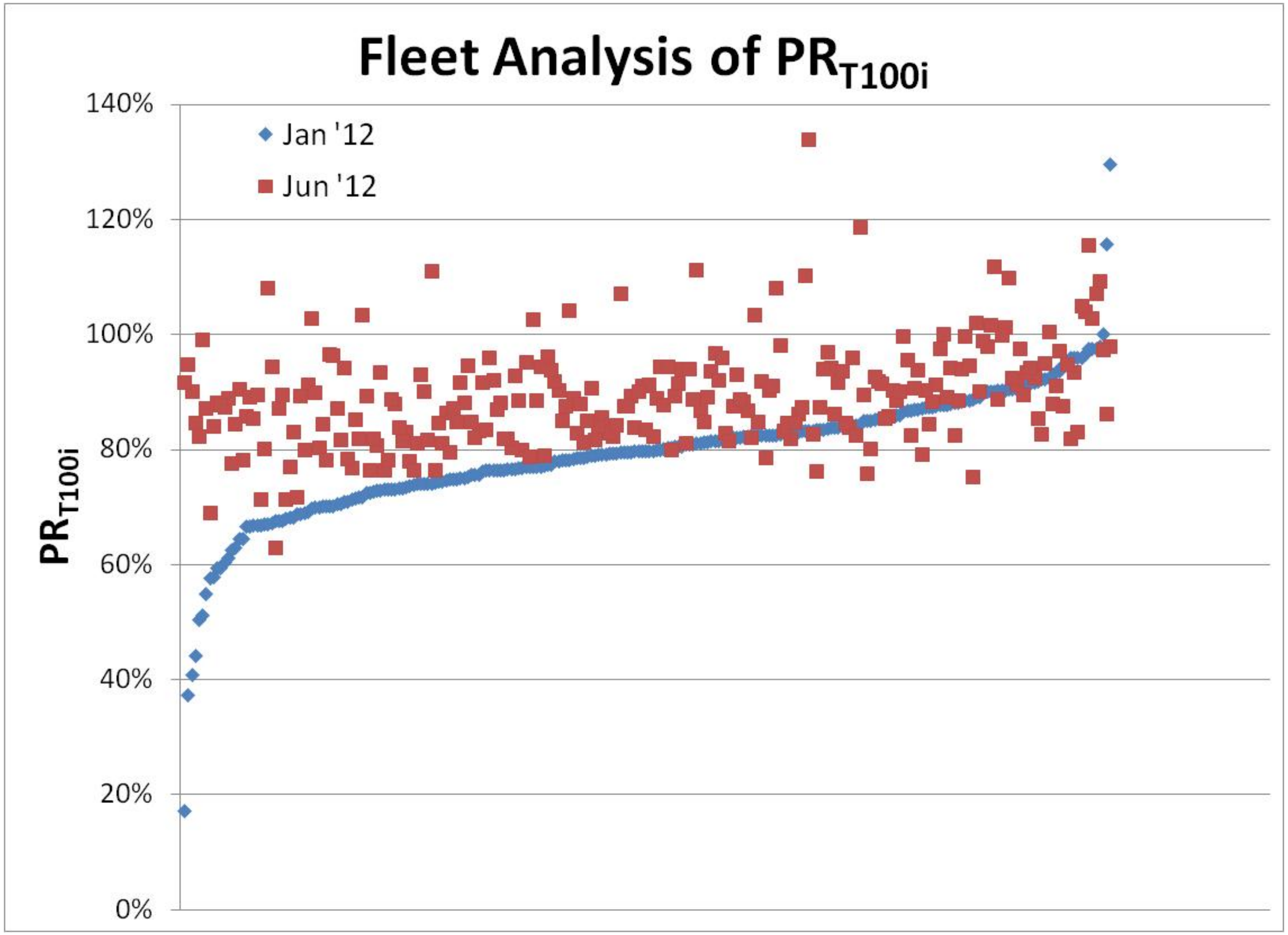
“Big Data” for PV, continued



Conclusion

- Continuous improvement of Maintenance practices and system reliability are needed;
- The transition from Maintenance to Operations and Maintenance has begun;
- Under high penetration scenarios, robust O&M of distributed assets will be critical to cost effective integration;
- Robust O&M requires: data quality, sophisticated modeling and data handling, automation and credibility.

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