PV Reliability Workshop – Lakewood, CO

February 27, 2020

Welcome to the 2020 Photovoltaic Reliability Workshop! This year's PVRW continues in the tradition of attendee participation. Attendees (and one guest) should present on the reliability of PV, either giving an oral or poster presentation. The workshop provides a unique opportunity for learning, discussion, and leadership relative to the present issues in PV-module and -system reliability.

Topics of interest during the PVRW include failure modes and degradation rates of fielded systems, module degradation modes (for materials and components), modeling of degradation, extreme weather events, collaborative research, PV standards and accelerated testing, extending system life, power electronics, trackers, and fires.

Chair:

David MILLER

Committee:

Teresa BARNES

Mike BOLEN

Dan BRAKE

Evelyn BUTLER

Chris DELINE

James ELSWORTH

Jack FLICKER

Tassos GOLNAS

Margaret GORDON

Greg KIMBALL

Inna KOZINSKY

Sarah KURTZ

Sumanth LOKANATH

Jenya MEYDBRAY

Matt MULLER

Dana OLSON

Nancy PHILLIPS

Jon PREVITALI

Ingrid REPINS

Laura SCHELHAS

Tim SILVERMAN

Josh STEIN

Scott STEPHENS

Mani G. TAMIZHMANI

Andy WALKER

Kent WHITFIELD

AGENDA – Thursday, 27 February 2020

7:30 - 8:00	**Continental Breakfast**
8:00 - 9:50	**Session K: Extending system life** *Session Chairs: Tristan ERION-LORICO (PVEL) and Jon PREVITALI (Wells Fargo)* **8:00** – Trends in accelerated testing – Henry HIESLMAIR (DNV GL) **8:20** – Correlation between financial yield improvements, extending system life, standardization, risk mitigation, and rating – Thomas SAUER (Exxergy) **8:40** – Assessing existing solar arrays for storm vulnerabilities; assessing risks by location and retrofit measure – Gerald ROBINSON (LBNL) **9:00** – Perspectives on the useful life of module – Henry HIESLMAIR (DNV GL) **9:20** – Questions/Discussion – led by Session Chairs and Slido Team
9:50 - 10:10	**Coffee Break**
10:10 - 11:40	**Session L: Inverters and power electronics** *Session Chairs: Michael BOLEN (EPRI) and Jens MOSCHNER (KU Leuven)* **10:10** – Inverter faults & failures: common modes and patterns – Thushara GUNDA (SNL) ~~**10:25** – Inverter reliability data – Phil STILES (Leidos)~~ *(Speaker was sick so no presentation was actually given, but the slides will be included in the proceedings)* **10:40** – Inverter reliability: An EPC contractor's perspective – Beth COPANAS (RES) **10:55** – Inverter AFCI: challenges and real-world performance – Jenya MEYDBRAY (PVEL) **11:10** – Questions/Discussion – led by Session Chairs and Slido Team
11:40 - 12:40	**Lunch** (poster viewing/discussion encouraged)
12:40 - 14:10	**Poster Session M -** posters associated with Sessions K, L, N, and O
14:10 - 15:40	**Session N: Trackers** *Session Chairs: Sumanth LOKANATH (First Solar) and Matt MULLER (NREL)* **14:10** – Wind standards, plant lifetime, and aeroelasticity of PV trackers – Alex ROEDEL (NEXTracker) **14:30** – Torsional response of single-axis tracker with passive load mitigation – Todd ANDERSEN (Array Technologies) **14:50** – Aeroelastic modeling and full-scale loads measurements for investigation of wind-driven dynamic instabilities in single-axis PV trackers – Scott DANA (NREL) **15:10** – Questions/Discussion – led by Session Chairs and Slido Team
15:40 - 16:00	**Coffee Break**
16:00 - 17:35	**Session O: PV Fires and contributing components** *Session Chairs: Colleen O'BRIEN (UL) and Timothy SILVERMAN (NREL)* **16:00** – The good, the bad and the fugly – Dean SOLON (Shoals Technology) **16:20** – Measured DC arc-flash incident energy in PV plants – Bijaya PAUDYAL (EPRI) **16:40** – PV fires experiences in Italy: from forensic activities to fire risk assessment of existing and new PV plants – ~~Luca FIORENTINI~~ (TECSA S.p.A.) *(Presented by Colleen O'Brien on Luca's behalf due to travel restrictions)* **17:00** – Questions/Discussion – led by Session Chairs and Slido Team **17:30** – Today's Poster Awards – David MILLER (NREL)
17:35	**Adjourn** – REMOVE POSTERS

POSTER SESSION M: Thursday, 27 February 2020

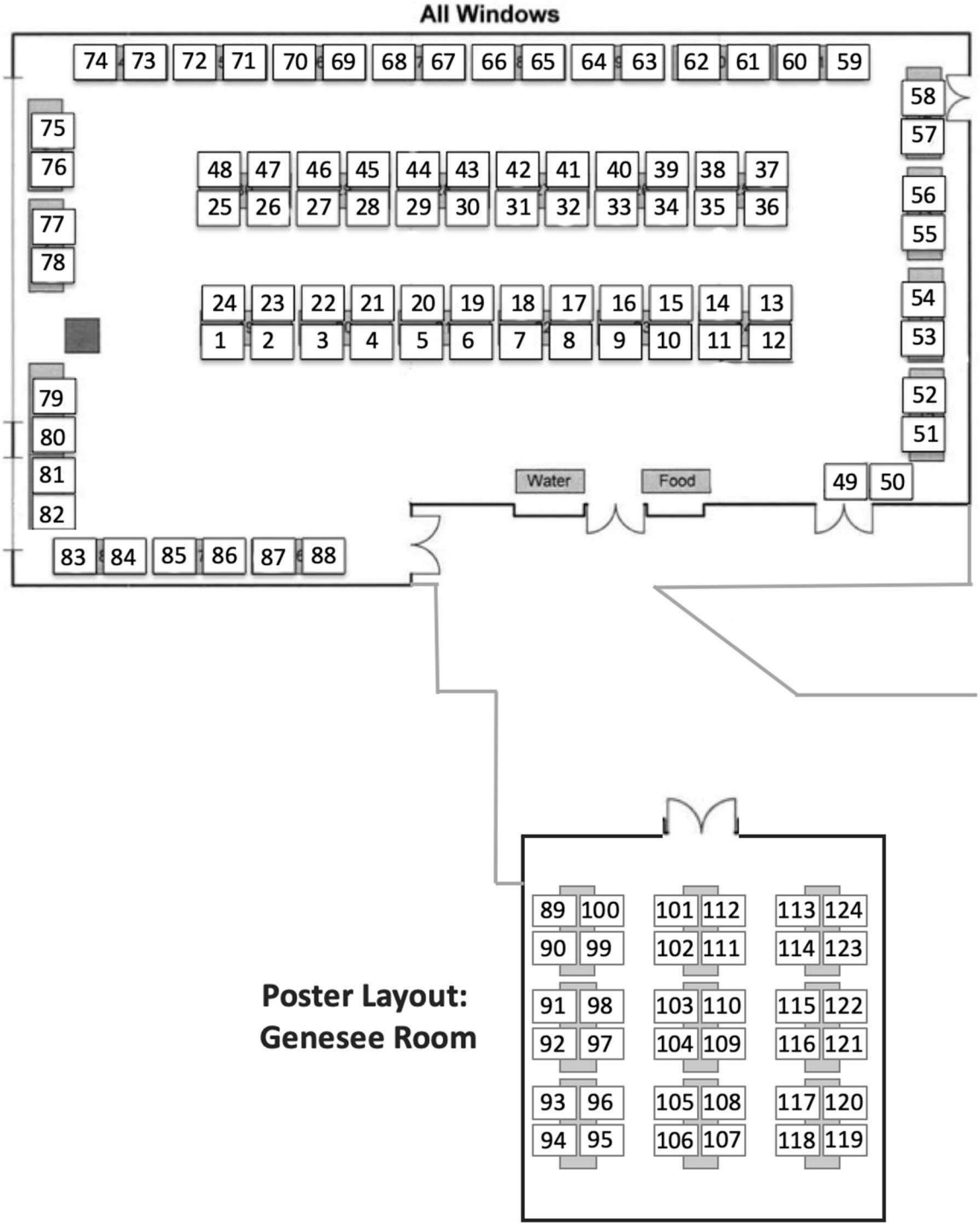
*Session M posters are associated with Sessions **K**, **L**, **N**, **or** **O***

2.	*A.M. Gabor, A. Sanghvi, A. Anselmo, R. Janoch, R. Lockhart, A. Elrefaiy,* "Pre-installation EL & I-V solar panel testing in a mobile test lab"
50.	*S. Johnston, D.B. Sulas-Kern, D. Jordan,* "Module imaging for hail damage assessment and two-year follow-up"
56.	*R.R. Hill,* "Progress in IEC PV availablity and reliability standards"
64.	*M.A. Green, Y. Jiang, Z. Zhou, S. Pillai, M. Keevers, J. Bilbao Bernales, J. Guo, N.J. Ekins-Daukes,* **"**Reduced operating temperature to improve durability and efficiency of solar modules"
72.	*M.B. Köentopp, T. Gittermann, W. Engler,* **"**A new manufacturing quality control program based on IEC 63209"
79.	*A.S. Edun, C. LaFlamme, M.U. Saleh, S. Kingston, E. Benoit, H. Ellis, J. Mismash, M.A. Scarpulla, C.M. Furse, J.B. Harley*, "Spread spectrum time domain reflectometry to detect and locate disconnects in large-scale PV arrays"
80.	*C. LaFlamme, A.S. Edun, E. Benoit, M.A. Scarpulla, C.M. Furse, J.B. Harley,* "Quantifying impact of environment on spread spectrum time domain reflectometry signatures of PV arrays and implications for fault detection"
92.	*K.G. Bedrich, Y. Wang, J. Chai, Y.S. Khoo,* **"**Quantitative electroluminescence imaging of PV modules: quality enhancement through multi-frame super resolution"
96.	*J.D. Moschner, S. Ravyts, W. Van de Sande, M. Daenen, J. Driesen***,** **"**Module-level inverters and converters for BIPV ñ performance limitations and reliability aspects"
100.	*G. Touloupas***,** **"**Benchmarking PV module quality in the factory: quality risk statistics over GWs of projects in a very dynamic sector"
104.	*J. Walzberg, A. Carpenter, G. Heath,* "Closing the loops on solar photovoltaics"
115.	*S. Ayala Pelaez, H. Mirletz, T. Silverman, A. Carpenter, T. Barnes,* "De-fluffing circular economy metrics with open-source calculator for PV"

*Please remember to **take your posters with you** at the end of the workshop*

POSTER LAYOUT – CITY LIGHTS BALLROOM

Poster Layout: City Lights Ballroom



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February 2020

DNV·GL

Trends observed from testing of PV modules at PV Evolution Labs (PVEL)

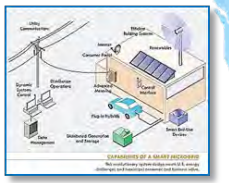
Henry Hieslmair

February 2020

About DNV GL

DNV·GL

- Energy
- Maritime
- Oil & Gas
- Software
- Business Assurance



151
Year History

Wind

Solar

Storage

Transmission

Certification

DNV GL is the world's largest independent energy & renewable advisory firm.

DNV GL >12,000 employees in 100+countries

We have over 1000 experts focused on renewables.

PVEL is the Independent Lab for the Downstream Solar Market

Global

300+ downstream partners worldwide with 30+GW of annual buying power

Comprehensive

Testing for every aspect of a PV project from procurement to O&M

Experienced

Pioneered bankability testing for PV products nearly a decade ago

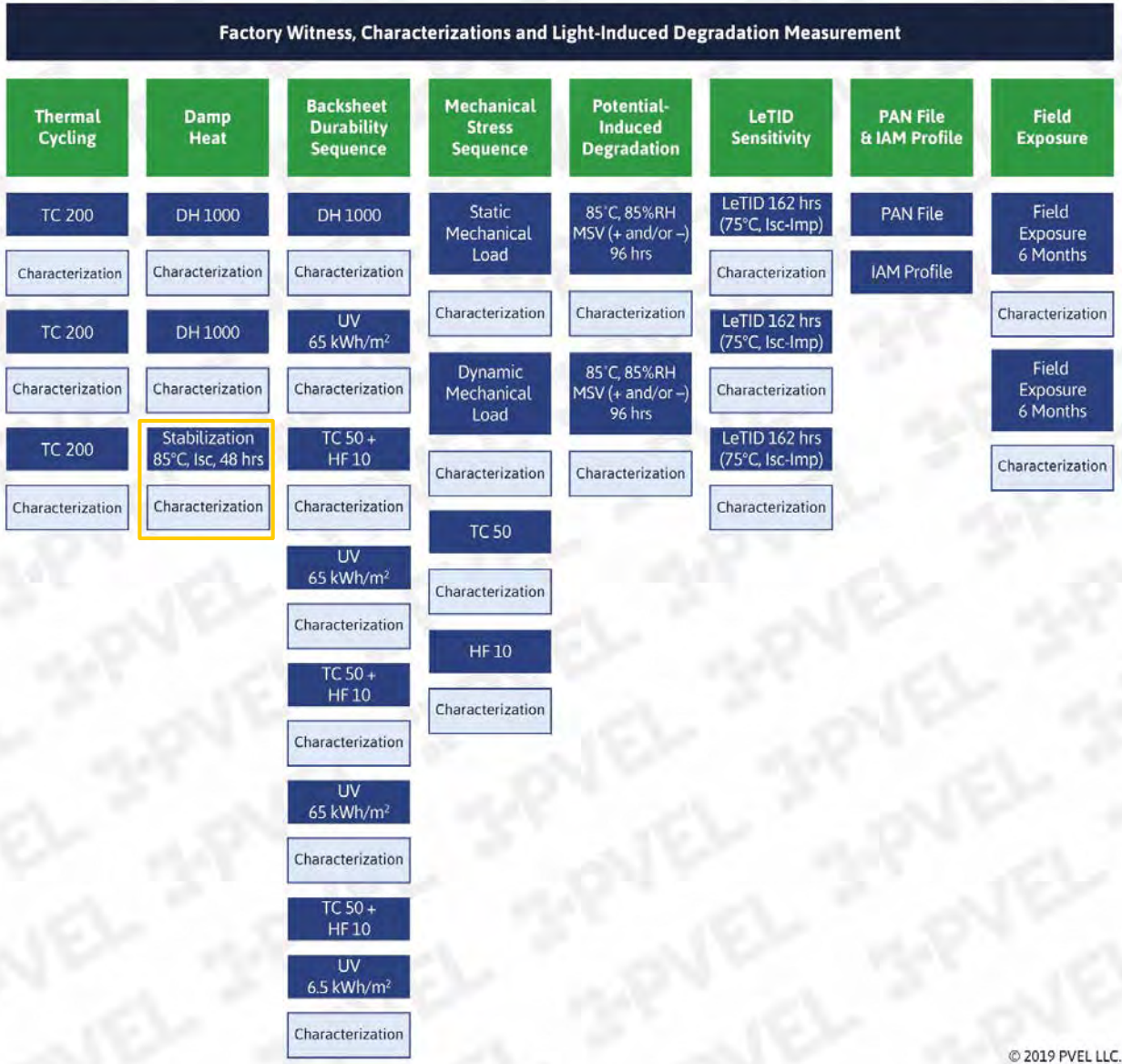
Market-driven

Continuously refining test programs to meet partner needs

PVEL's Module Product Qualification Program (PQP)

The PQP is updated annually based on feedback from the industry.

2020 Test Sequences is the biggest update yet.



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About the anonymized test data

Inputs: Module info & BOM specifications

Over 40 manufacturers and 300 BOMs

From 2014 to 2019

Tests explored*	Description
TC600	Thermal Cycling between -40°C and 85°C for 600 cycles
DH2000	Damp Heat: 85°C & 85% relative humidity for 2000 hours.
DML+TC50+HF10	Dynamic Mechanical Load: 1000 cycles of ±1000Pa + TC50 + HF10
PID	DH96 or DH100 with -1000V or -1500V bias

*These tests were chosen because they had the highest population

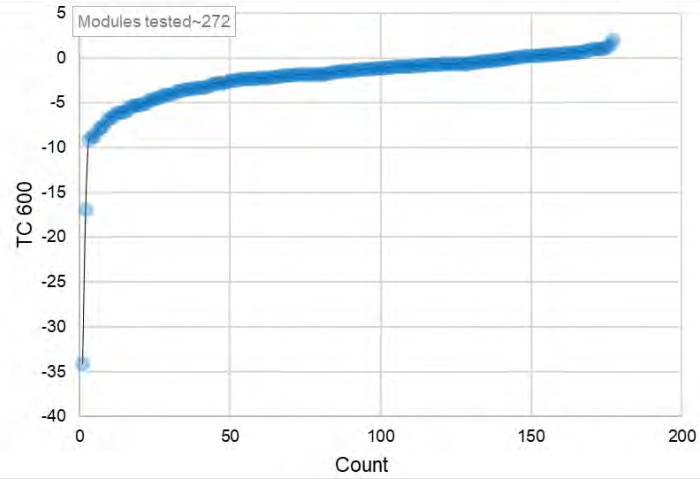
Outcomes: ΔP_{max}

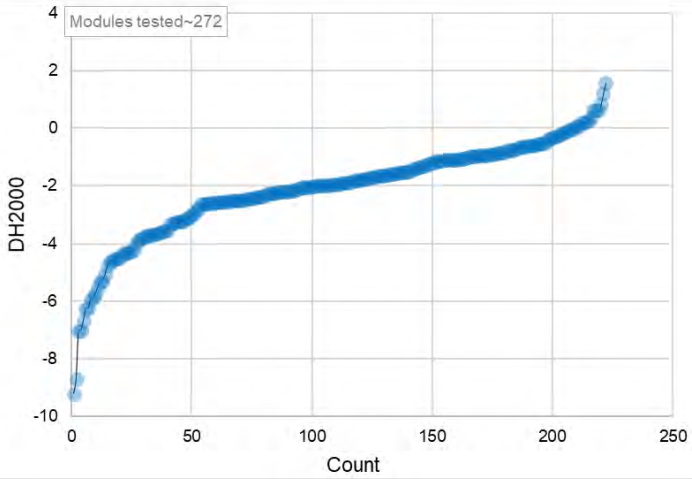
Anonymized information

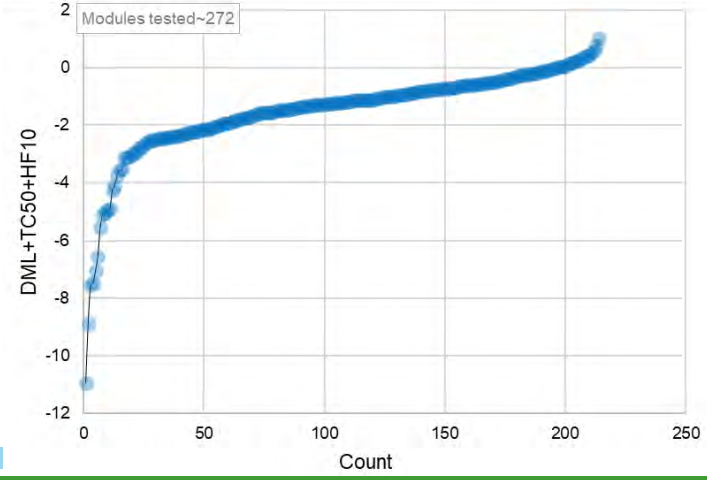
Manufacturer	Country	Model	Pmax				
Cells	Supplier	Model	Type	Year	# BBs	#/module	
Front Encapsulant	Supplier	Model	Type	Thickness			
Rear Encapsulant	Supplier	Model	Type	Thickness			
Glass	Supplier	Coating	Type	Thickness			
Backsheet	Supplier	Model	Type	Thickness	Inner	Core	Outer
Insulation sheet	Supplier	Model	Type	Thickness			
Frame	Supplier	Material	Thickness				
Ribbon	Supplier	Model	Width	Thickness			
Flux	Supplier	Model					
J-box adhesive	Supplier	Model					
J-box pottant	Supplier	Model					

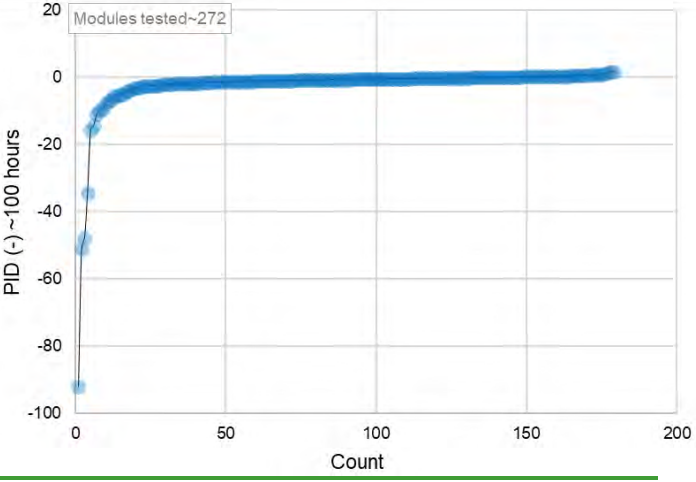
Observations about the tests

Thresholds

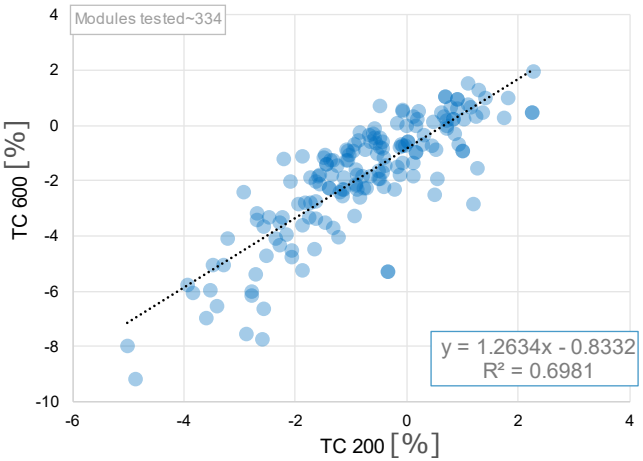

Modules tested~272
TC 600
Count
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0
50
100
150
200

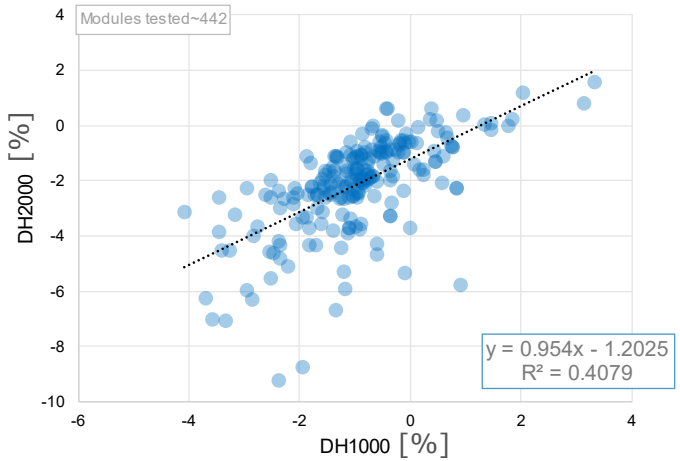

Modules tested~272
DH2000
Count
4
2
0
-2
-4
-6
-8
-10
0
50
100
150
200
250

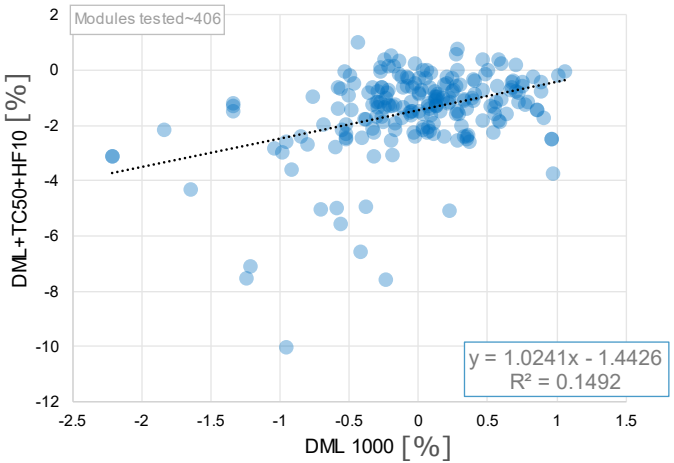

Modules tested~272
DML+TC50+HF10
Count
2
0
-2
-4
-6
-8
-10
-12
0
50
100
150
200
250

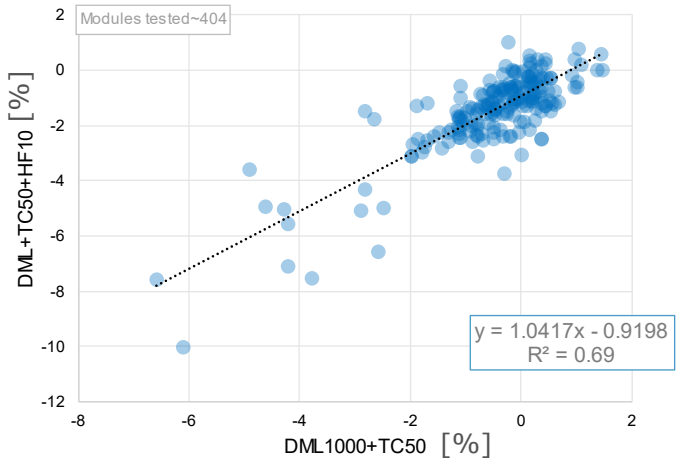

Modules tested~272
PID (-) ~100 hours
Count
20
0
-20
-40
-60
-80
-100
0
50
100
150
200

Intra-test correlations

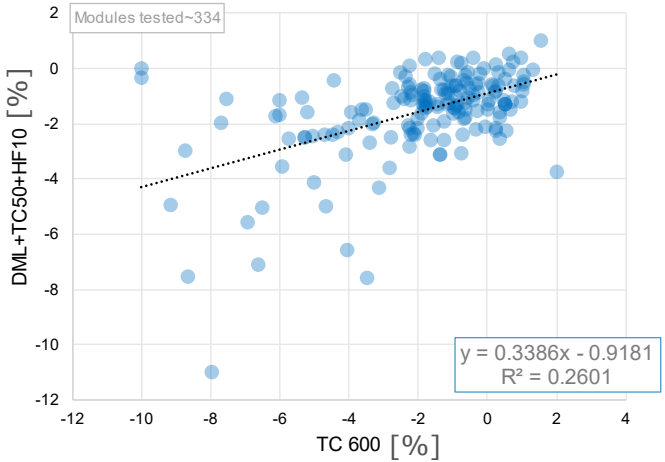


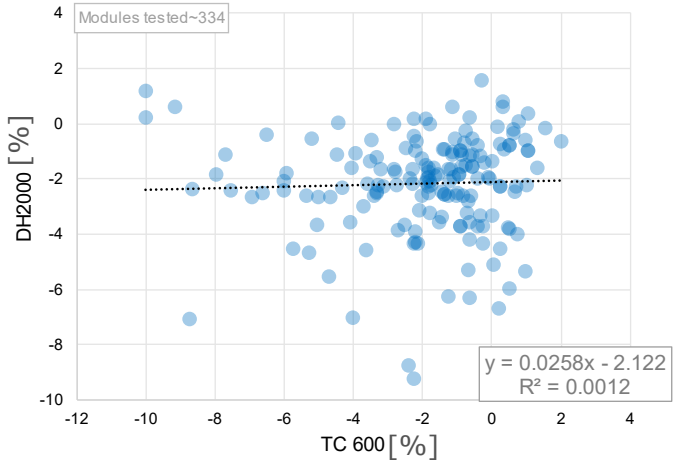


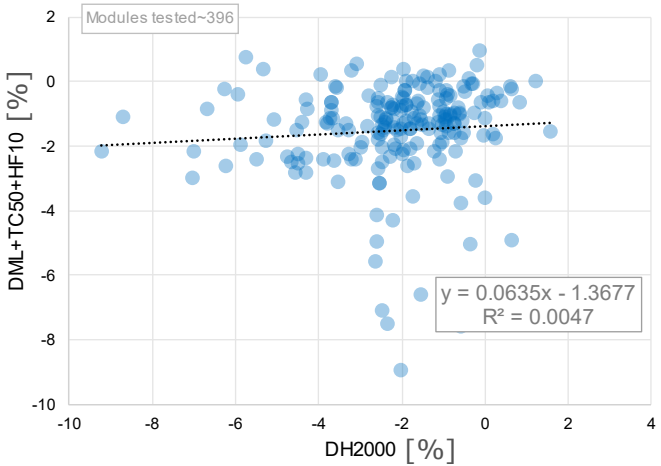


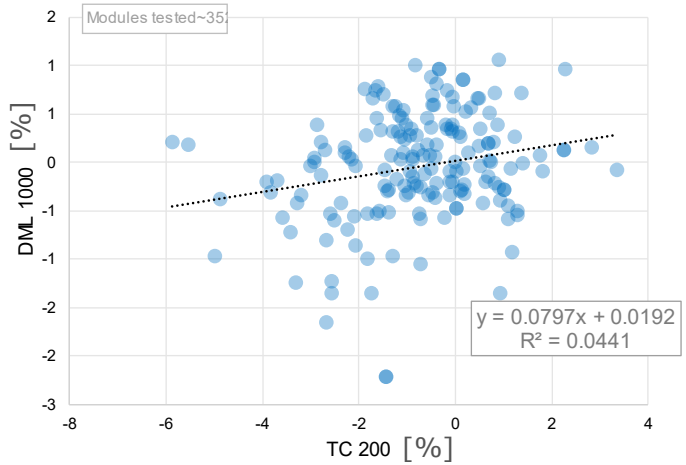


Inter-test correlations



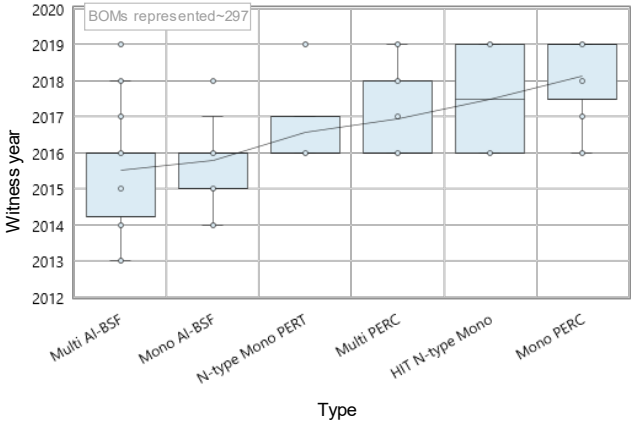


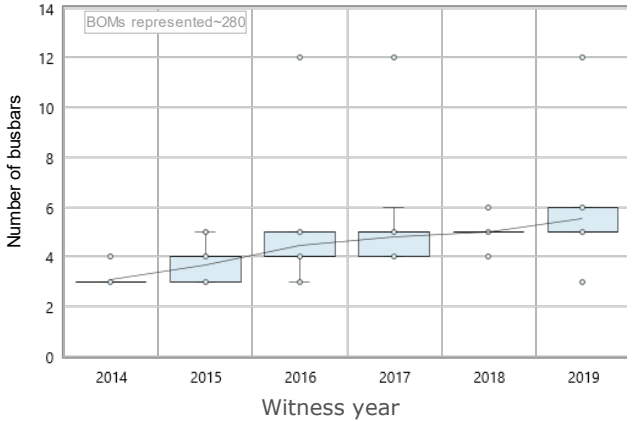


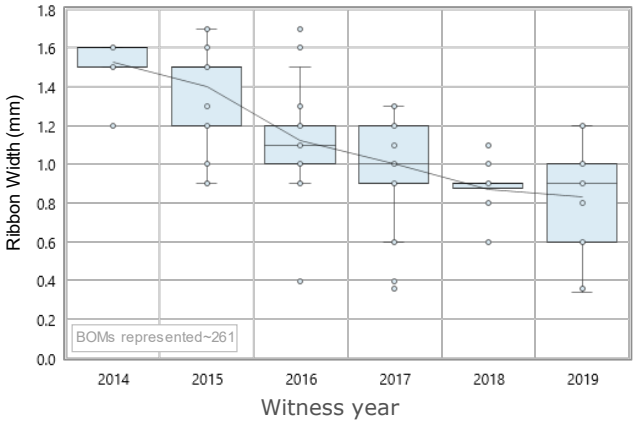


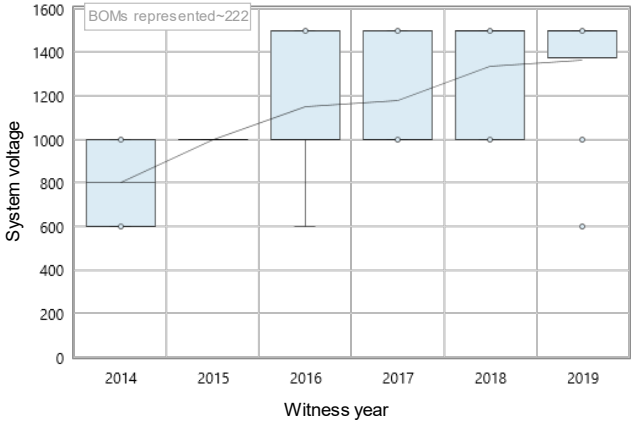
BOM trends over time

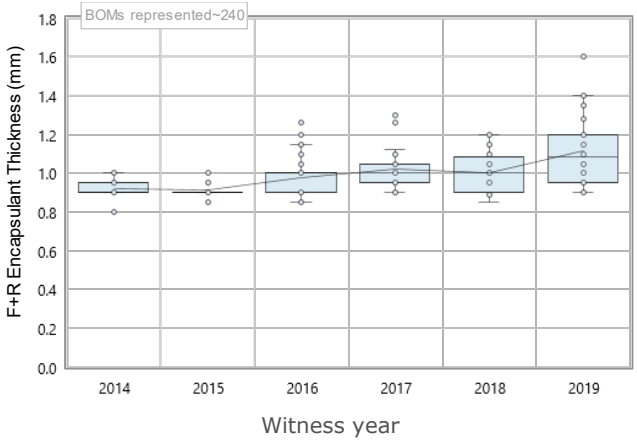
Trends in module BOM

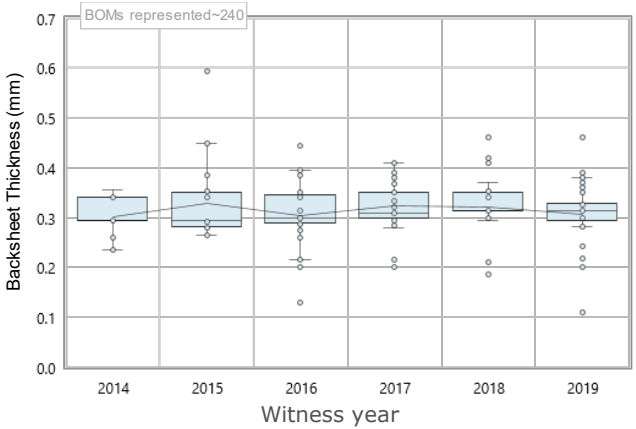




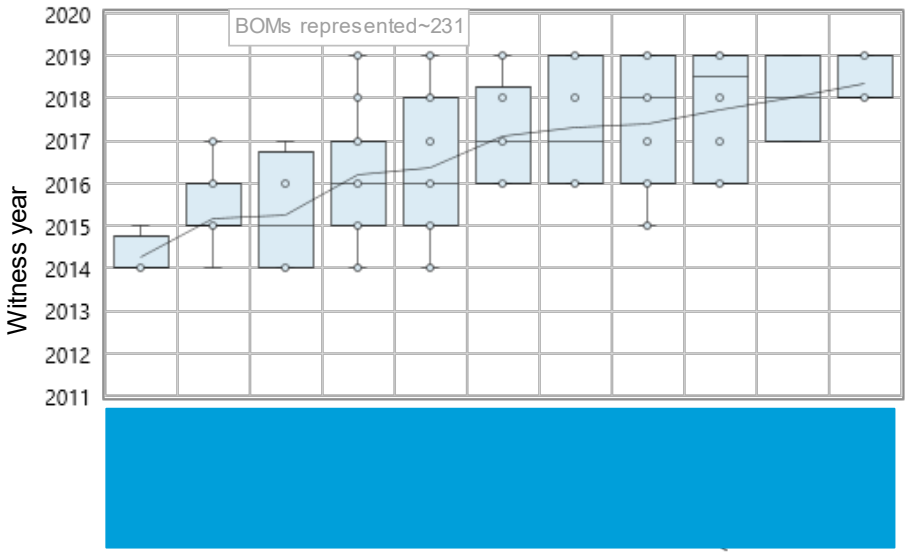




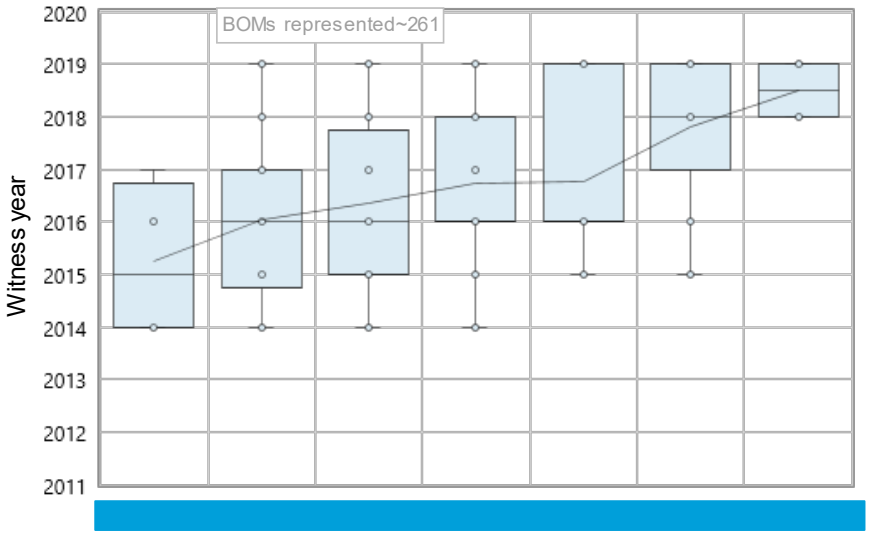




Trends in module BOM: Materials are changing



Backsheet inner layer

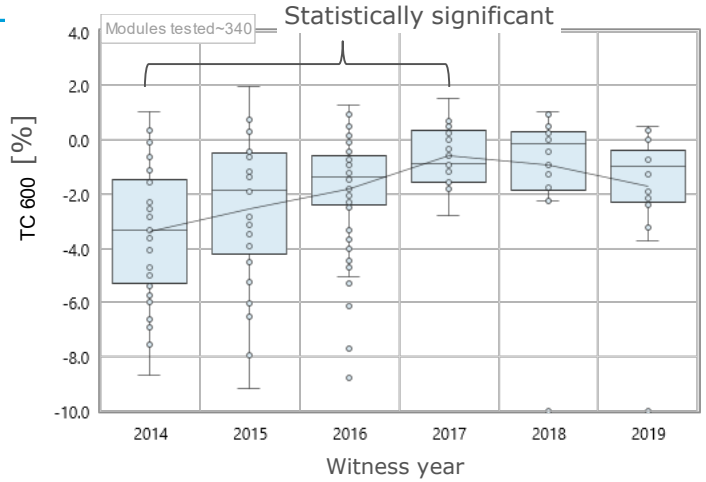


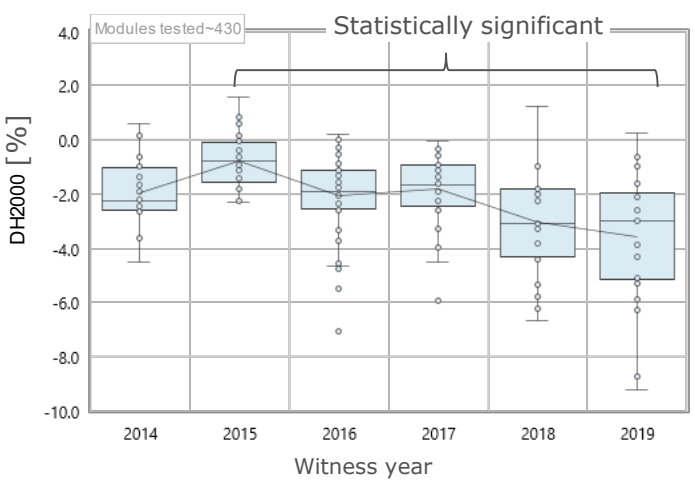
Backsheet outer layer

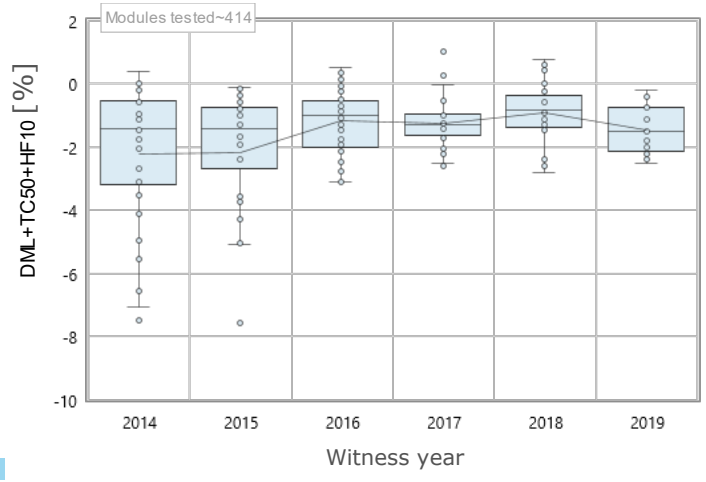
Testing trends

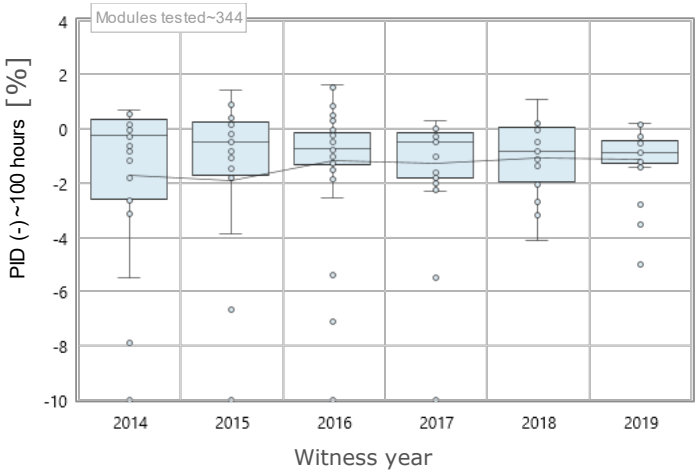
Trends in test results

Some trends are statistically significant ($p<0.05$).









Trends by type: Al-BSF vs PERC

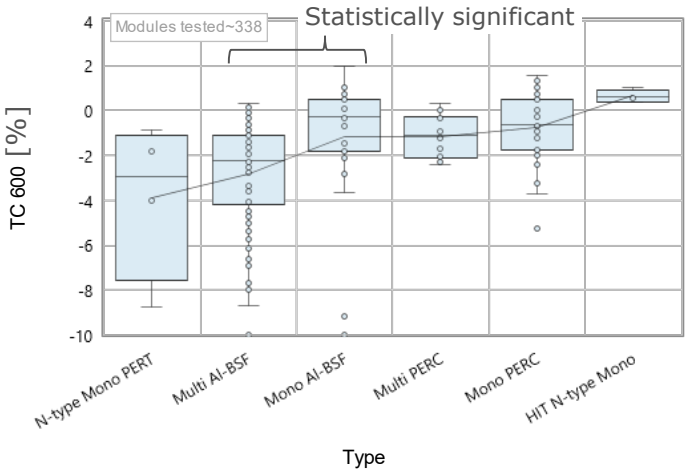
Few trends

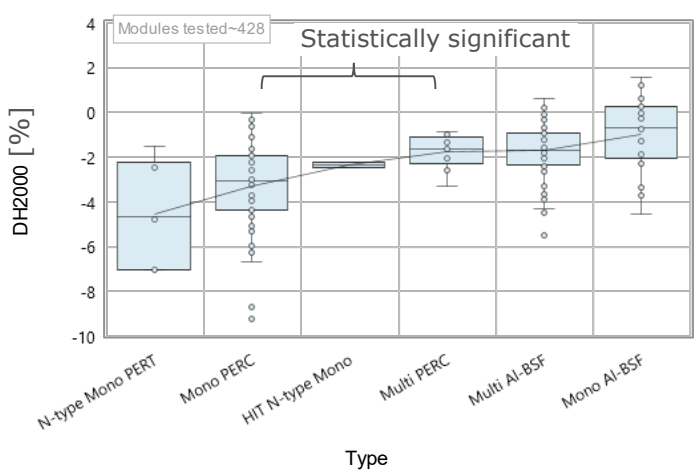
Population size differs

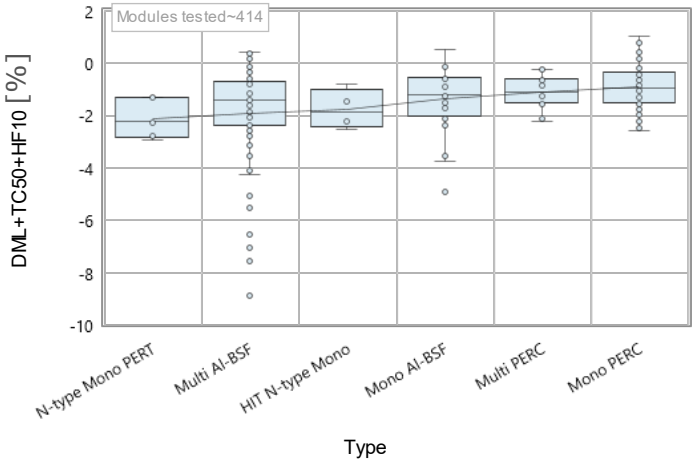
(N-PERT small)

Other factors exist

Al-BSF~4BB; PERC ~5

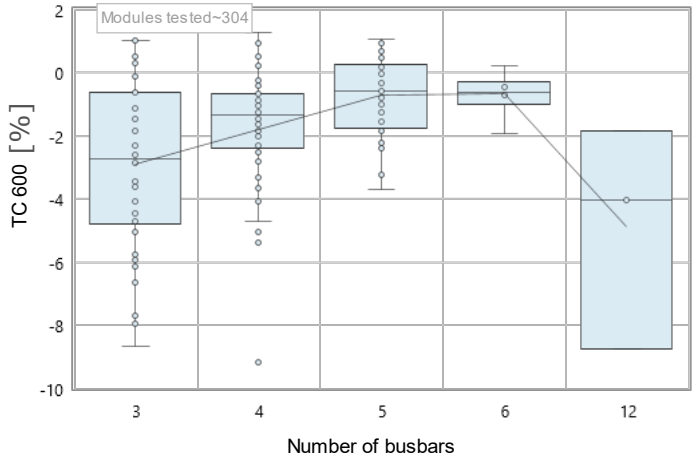


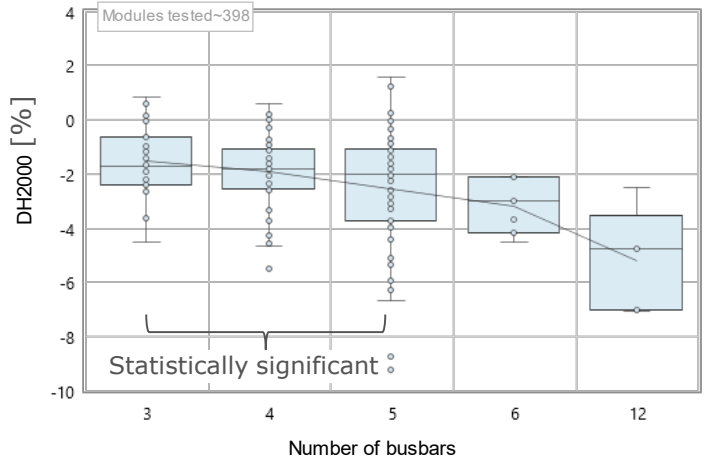




Test correlations

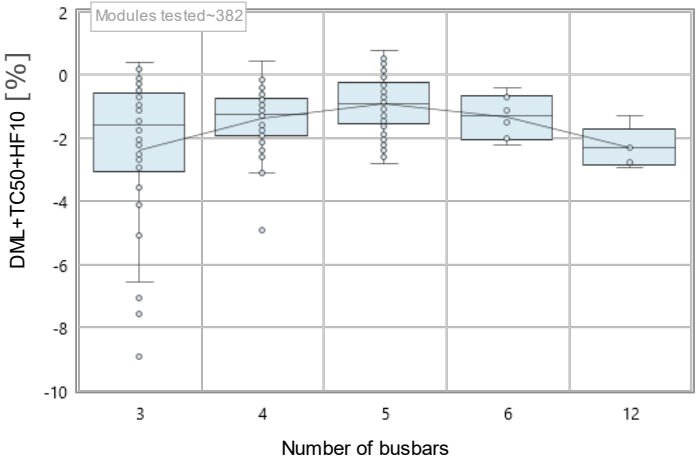
Statistically significant



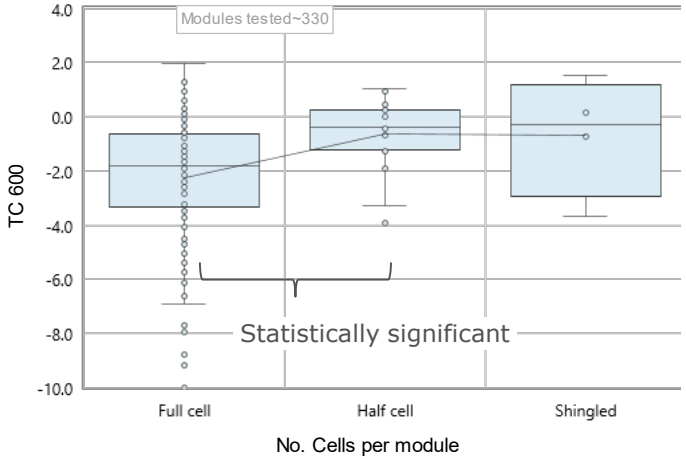


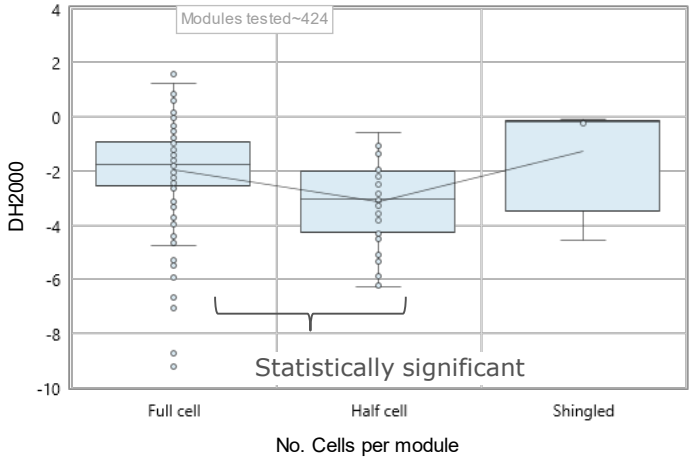
Other effects

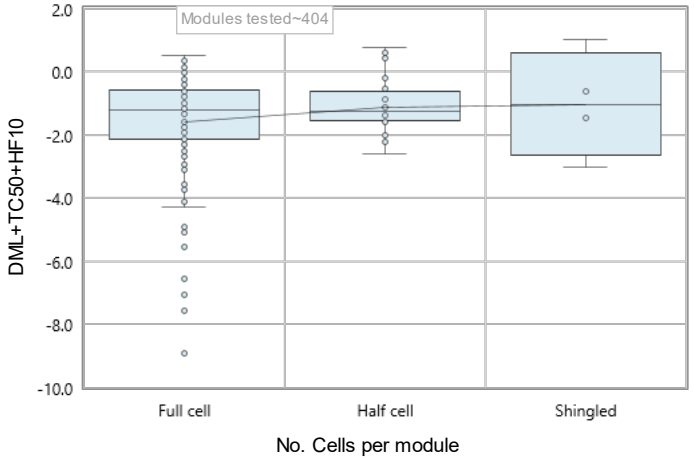
Population size differs



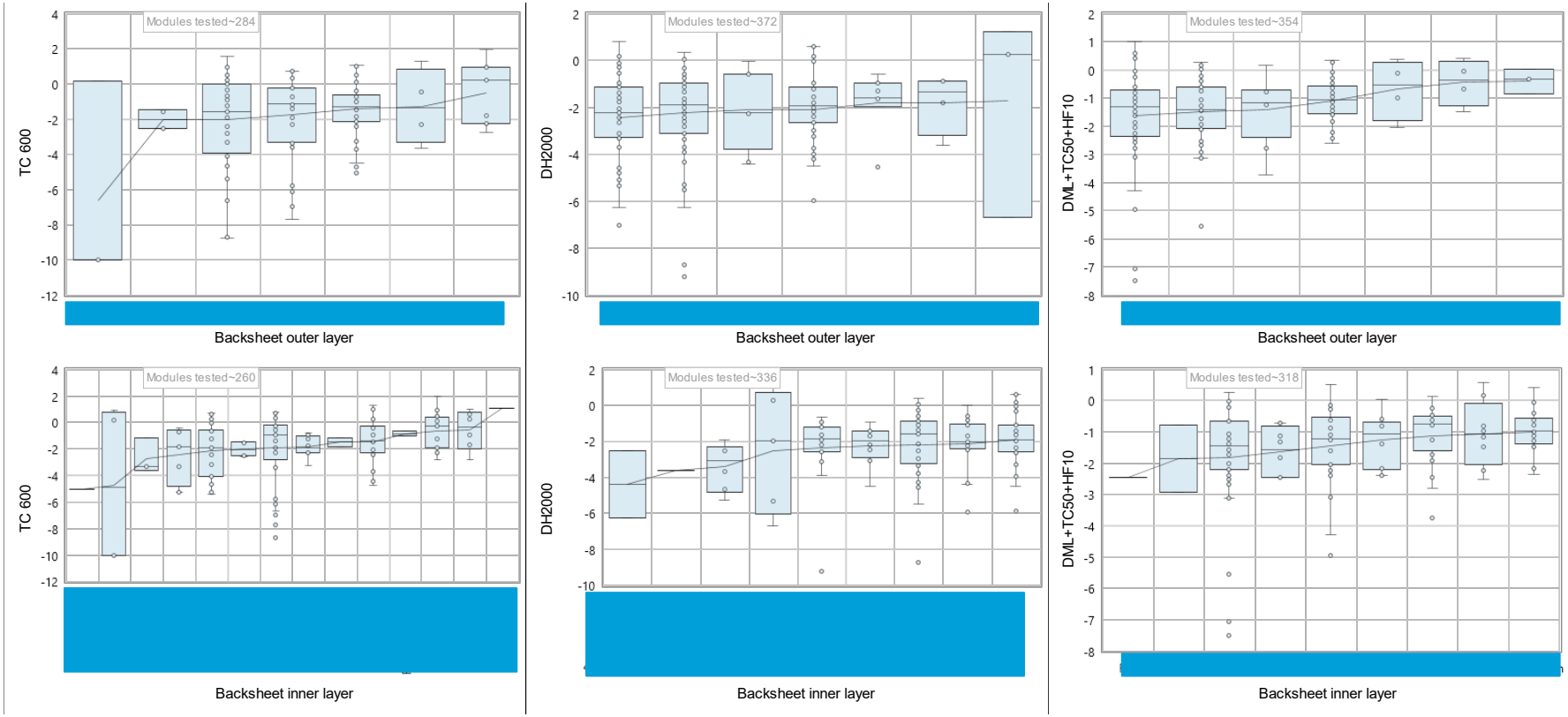
Test correlations: Full cells, half cells, and shingled







No smoking gun

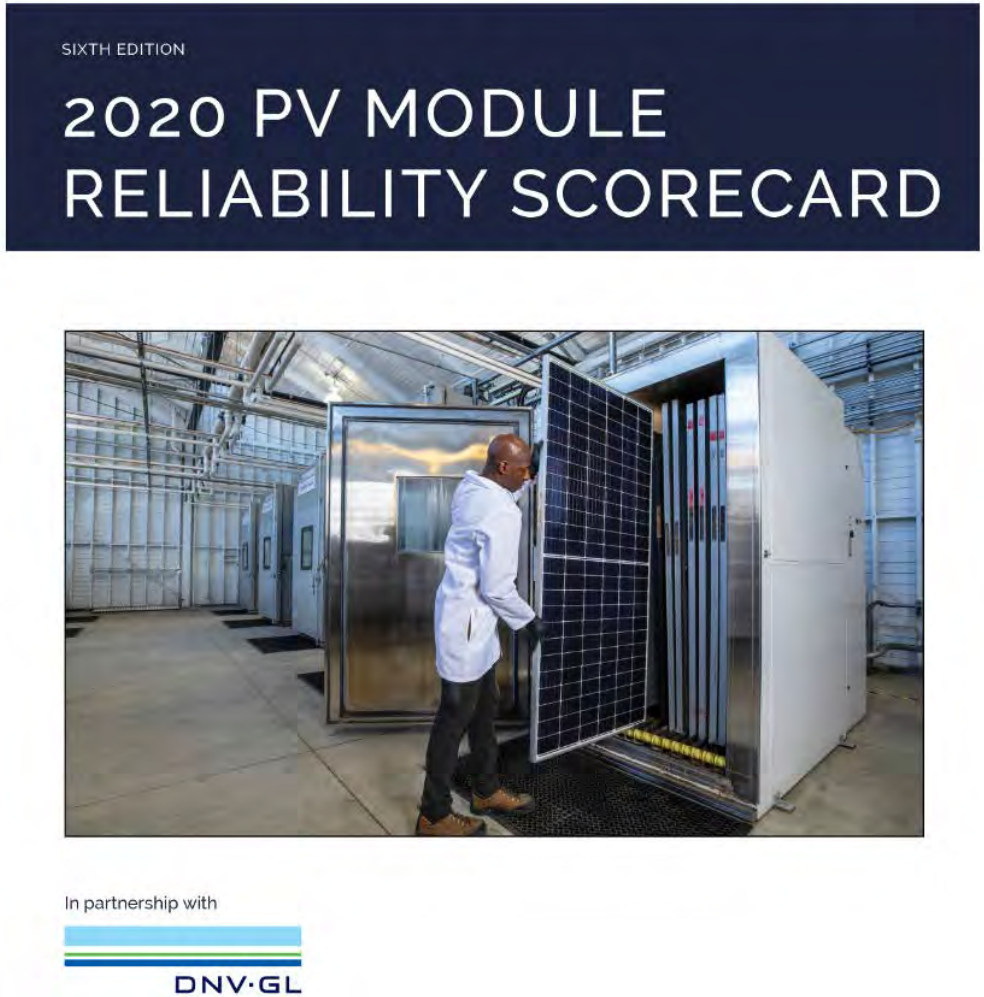


Observations Summary

- Evidence of testing thresholds
- Inter- and intra-test correlations suggest current testing is not duplicative nor prolonged
- ↑Encapsulant thickness & number BB; ↓Ribbon width; ↔backsheet thickness
- Backsheet materials have changed over time
- Not seeing a strong trend toward better test results
- Some trends were statistically significant

Acknowledgements

Thank you to PVEL



TEXXECURE Rating Foundation

EXXERGY Focusing on the flow of energy

How to draw a correlation between financial yield improvements, extending system life, standardization, risk mitigation, and rating

NREL Transforming ENERGY

Lakewood, CO • February 27, 2020

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Story line and acknowledgements

EXXERGY
Focusing on the flow of energy

- Who is EXXERGY ?
- Does the general perception correlate to reality?
- Results from insurance claim case study
- Case study I: Financial consequence from deteriorating performance
- Talking about risks and risk mitigation
- Proposed solution: IECRE rating standard
- Case study II: Examplary financial benefit from rating
- Conclusions

Acknowledgements
- George Kelly (ARESCA)
- Roger Taylor (EXXERGY)
- Masaaki Yamamichi (RTS)
- …and all supporters from the PV sector, SolarPower Europe, IEC, and several banks and surety/insurance companies

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EXXERGY is a consulting firm offering a wide range of comprehensive services

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Solar power | Power storage | Glass and specialty chemicals | Industrial and specialty gases

Corporate Strategy	• Marketing and sales strategy • M&A: Buy Side / Sell Side advisory • Organizational development and structuring • Business due diligence
Markets	• Market research and analysis • Product development • Sales effectiveness optimization • Operational market entry support • Operational procurement support
Finance	• Project bankability • Business planning • Financing structures & fund raising • Business assessment • Performance warranty insurance
Human Resources	• Management assessment • Performance management • Training programs • Recruitment
Technology Processes	• Manufacturer audits / technical DD • Technology transfer • Product development • Process optimization • Technical feasibility assessments

EXXERGY …

… supports / cooperates with several NGO / non-profit organizations

IECRE™ | SolarPower Europe | TEXXECURE Rating Foundation

ARESCA American Renewable Energy Standards and Certification Association | DKE VDE DIN

… etc.

… is active in:

- Europe
- North America
- China
- Japan
- APAC

…soon, also in the Middle East, and…

…later in Central Asia and in Latin America

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On the way from ~2% to 20+%*, questions on value generation, consolidation pressure and the resulting sustainability continue

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- For the past 20 years, the PV sector has enjoyed tremendous volume growth…
- While the first decade (2000 – 2010) showed quality growth, critical undesirable developments have taken place since 2008

Financial crisis 2008
with default of businesses → Effects remain within the PV industry

Massive risk aversion by all
businesses on all levels → Continuously increasing
control over cash flows

Bad reputation of renewable
industry as “cash burner” → The profitability of most players falls significantly short of expectations
Cash is burnt on several levels throughout the value chain

Extremely cyclical markets
Unsustainable price declines
Unexpected performance gaps
Business insolvencies
Risk of fading PV-project bankability

SOLUTION ???

* Of worldwide electricity production

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Do stakeholders share a common perception of their part of the overall deal?

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Possible perception of (some) PV park investors

- PV is a blue chip investment delivering “automatic”, reliable, long term returns
- Quality meets industrial standards
- Business plans are “a sure thing”
- Deal flow is of the essence
- The project will be “flipped” soon, anyway
- …

Possible perception of (some) banks

- Typical non-recourse financing structure is non-investment grade
- Risk exposure is mitigated by
  - warranties
  - contingency reserve requirement
  - leverage limits
  - …

Low risk exposure ?

Any missing links ?

Low risk exposure ?

Possible self-perception of (some) manufacturers

- Price matters, and so does size
- The quality level that the customer accepts is sufficient
- Certificates, warranties, and insurance covers are essentially a marketing tool
- …

Possible perception of (some) insurance companies

- Cover may be avoided, e. g.
  - Exclusion clauses (e. g. conforming components)
  - Delayed start of coverage
- Risk mitigation by principle of large policy numbers vs. quality control
- …

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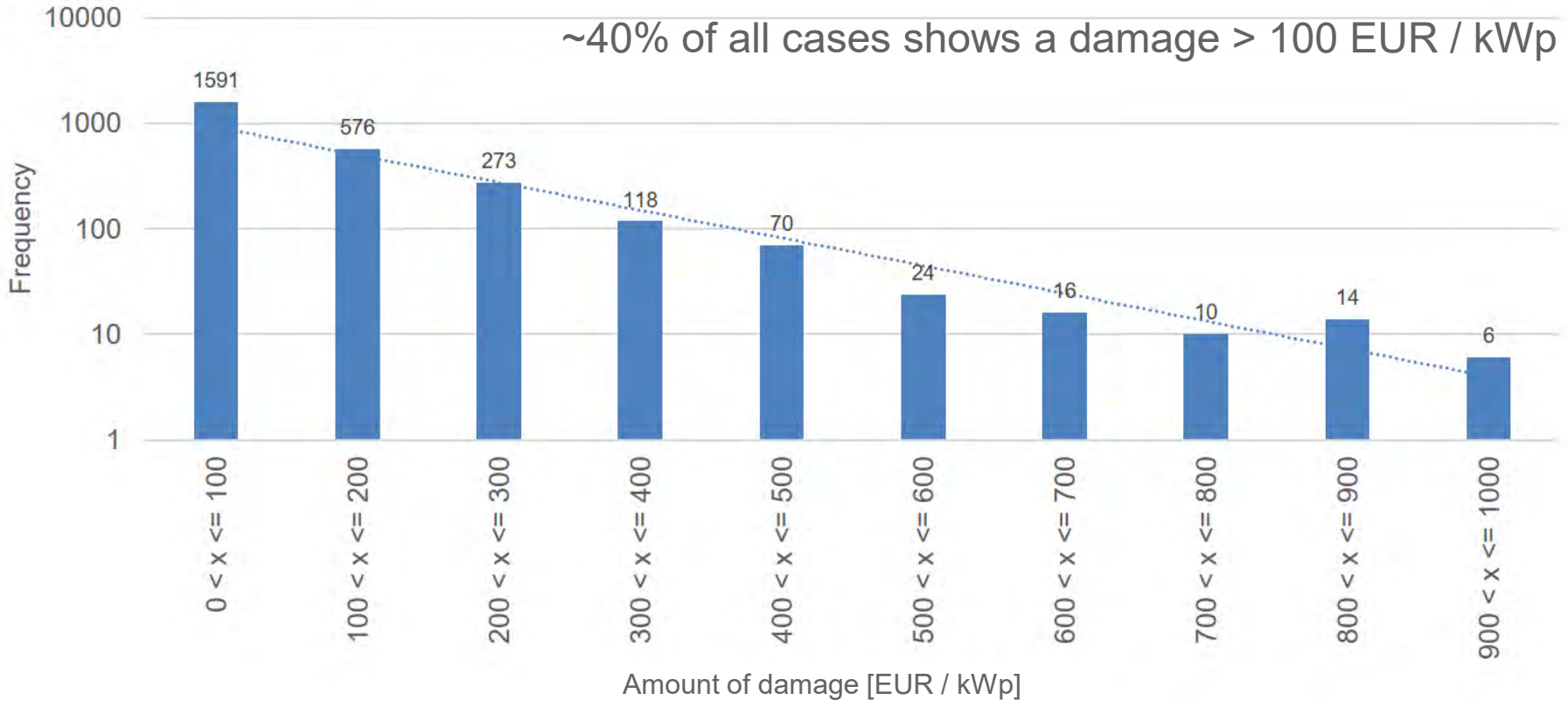
An insurance claim cases study identifies damage amounts that can be more significant than calculated for…

- More than 3.600 insurance claim cases have been analyzed in total
- Generally, the relative amount of loss trends to decline with increasing system size
- The mainstream amounts of loss spreads over 2 orders of magnitude
- Outliers range up to 3.500 EUR / kWp (incl. consequential damage)



All claim cases Jan 2012 through June 2017 for which amounts of damage have been available

Source: EXXERGY analysis on >3.600 insurance claim cases 2012 - 2017

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…and for the ~20% of claim cases associated with internal failures, a rising trend correlated to service life seems to be evident

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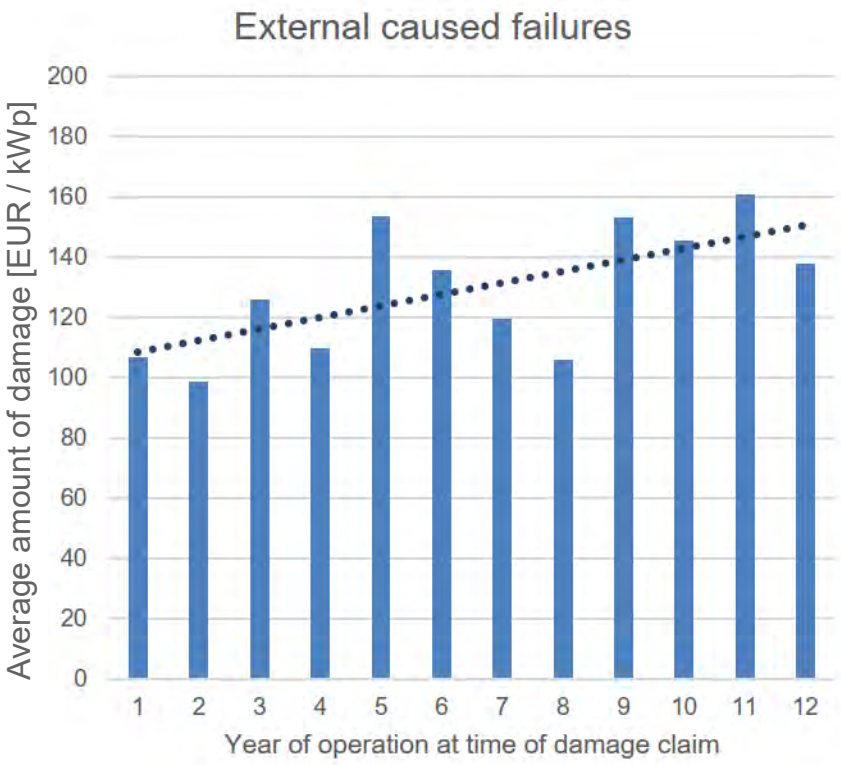
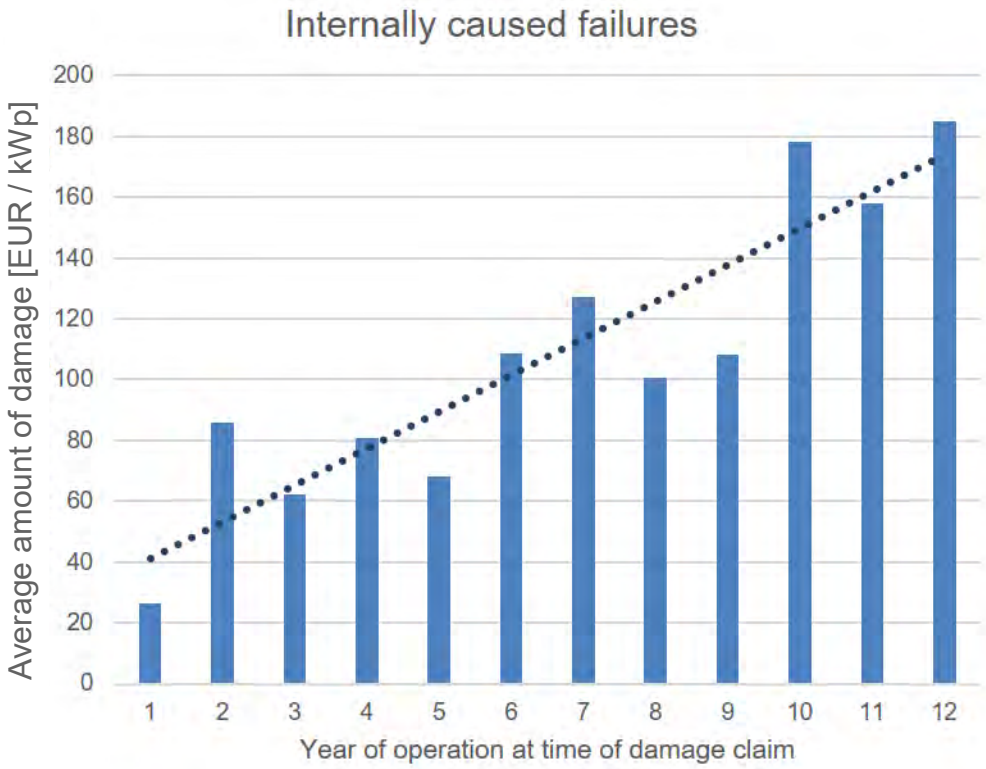
Average amount of damage over service lifetime





- Externally caused failure: Damage is caused by external factors (hail, lightning strikes, snow loads, theft, marten bites etc.)
- Internally caused failure: Damage is caused by the PV system (20.13% of all cases)

The graphs only reflect such claim cases for which
(1) the service age of the PV power plant was known at the date of claim and max 12 years and
(2) the amount of damage covered was >0.
PV power plants with a service life >12 years have not been listed because the data pool did not offer a statistically relevant number of cases.

Source: EXXERGY analysis on >3.600 insurance claim cases 2012 - 2017

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As PV cost reductions have slowed down, any equity cash drain caused by corrective actions can no longer be compensated for by lower prices

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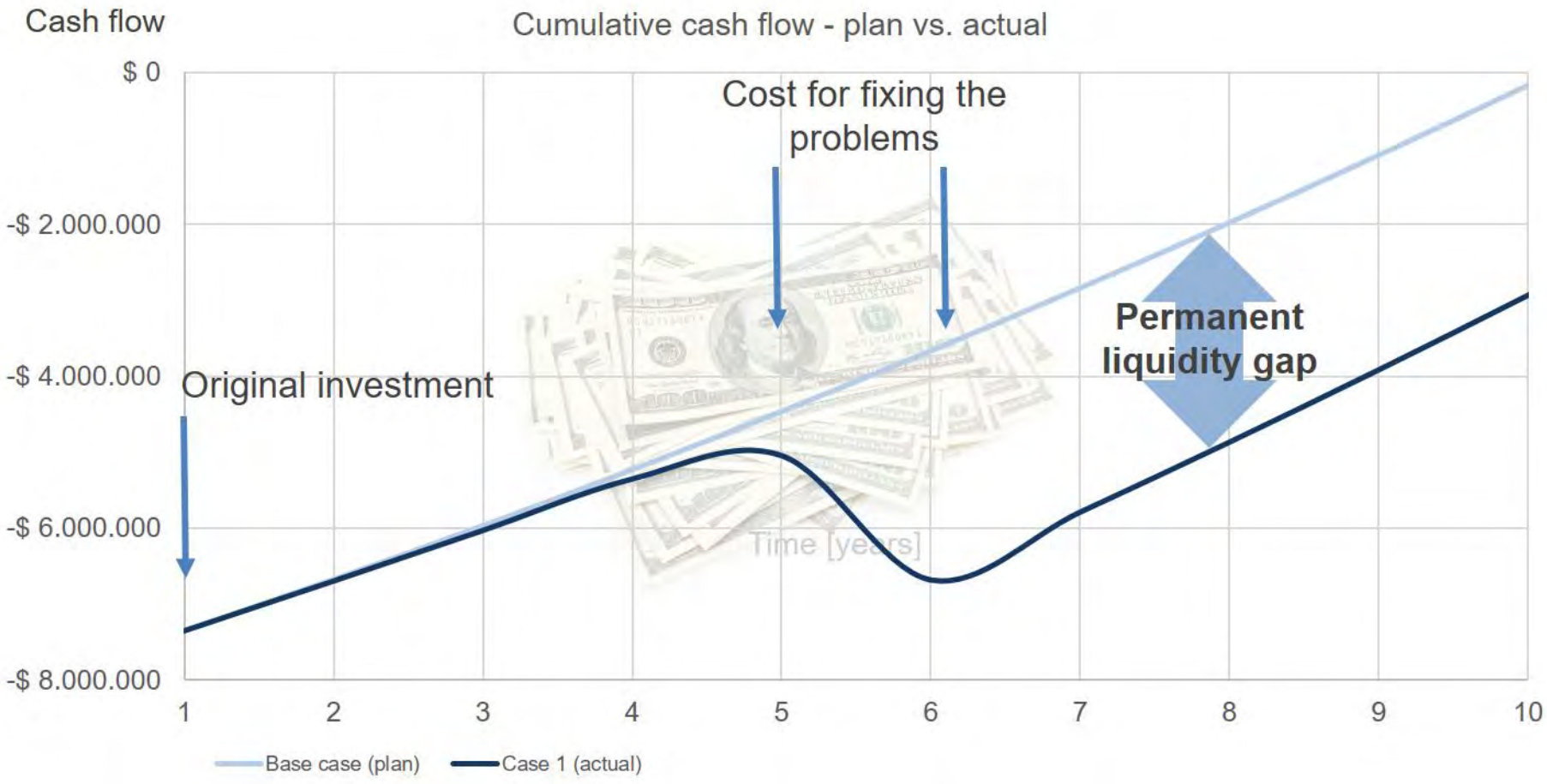
PV-park investment:

Case study I:

- Investment (Capex) 750 US$/kWp (EPC share, only)
- Power purchase price: 0,125 US$/kWh
- Assumption on cost for repair reflects estimate on future price reduction of components that is significantly lower than in the past.



Sources: TÜV Rheinland, EXXERGY financial model

Chart data is illustrative based on a real case

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All this begs a fundamental question: Does the solar sector (and/or the financial sector) need to shift paradigms…?

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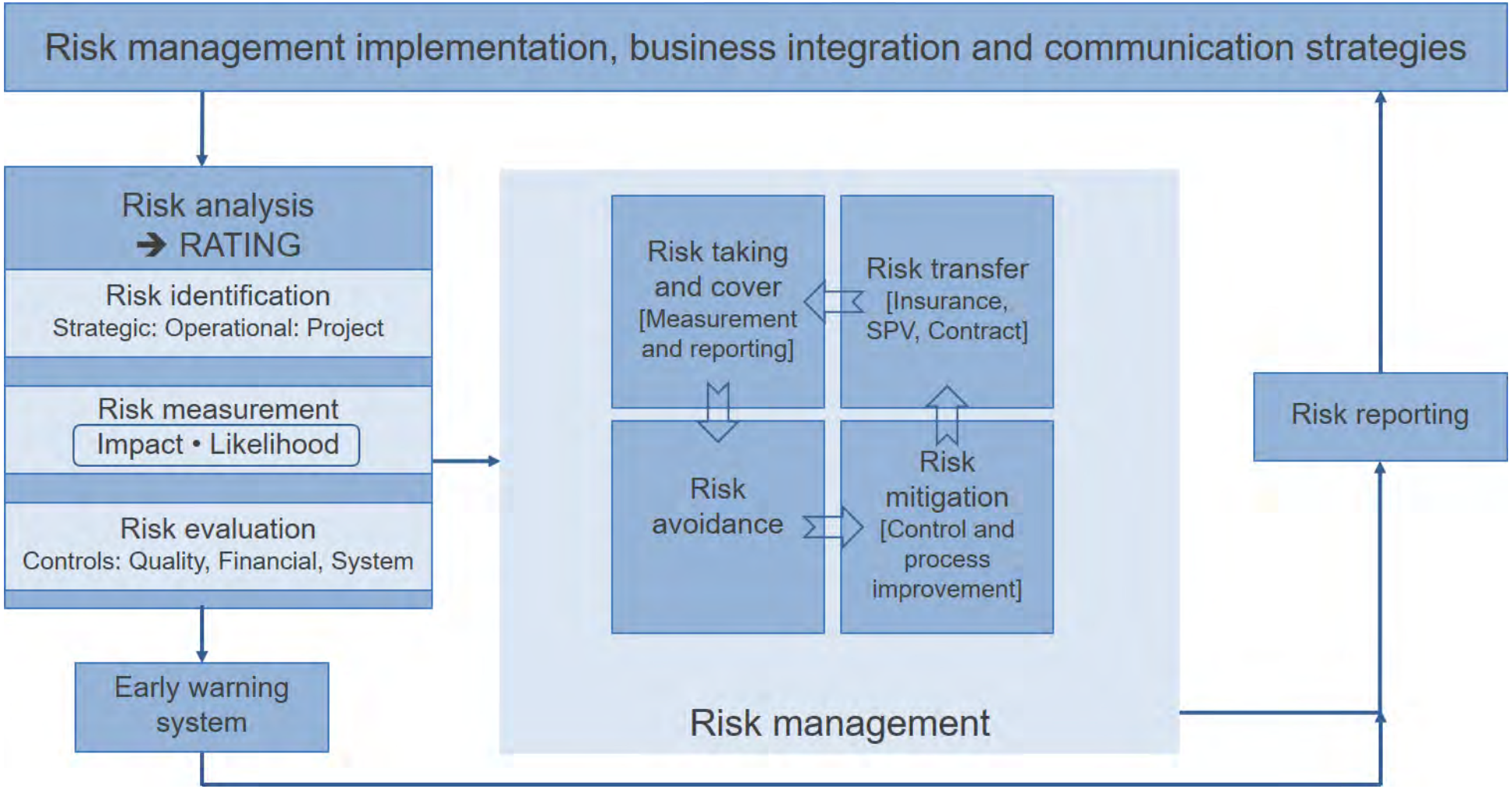
A solid risk management strategy requires a viable toolset for risk analysis and a basis for common understanding



International standard for conformity assessment and rating supports

- Common interpretation
- Mutual trust and recognition
- Performance
- Trade
- Etc.

IECRE

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Responding to quality issues in the field, IECRE was formed to develop and establish an international standard conformity assessment system

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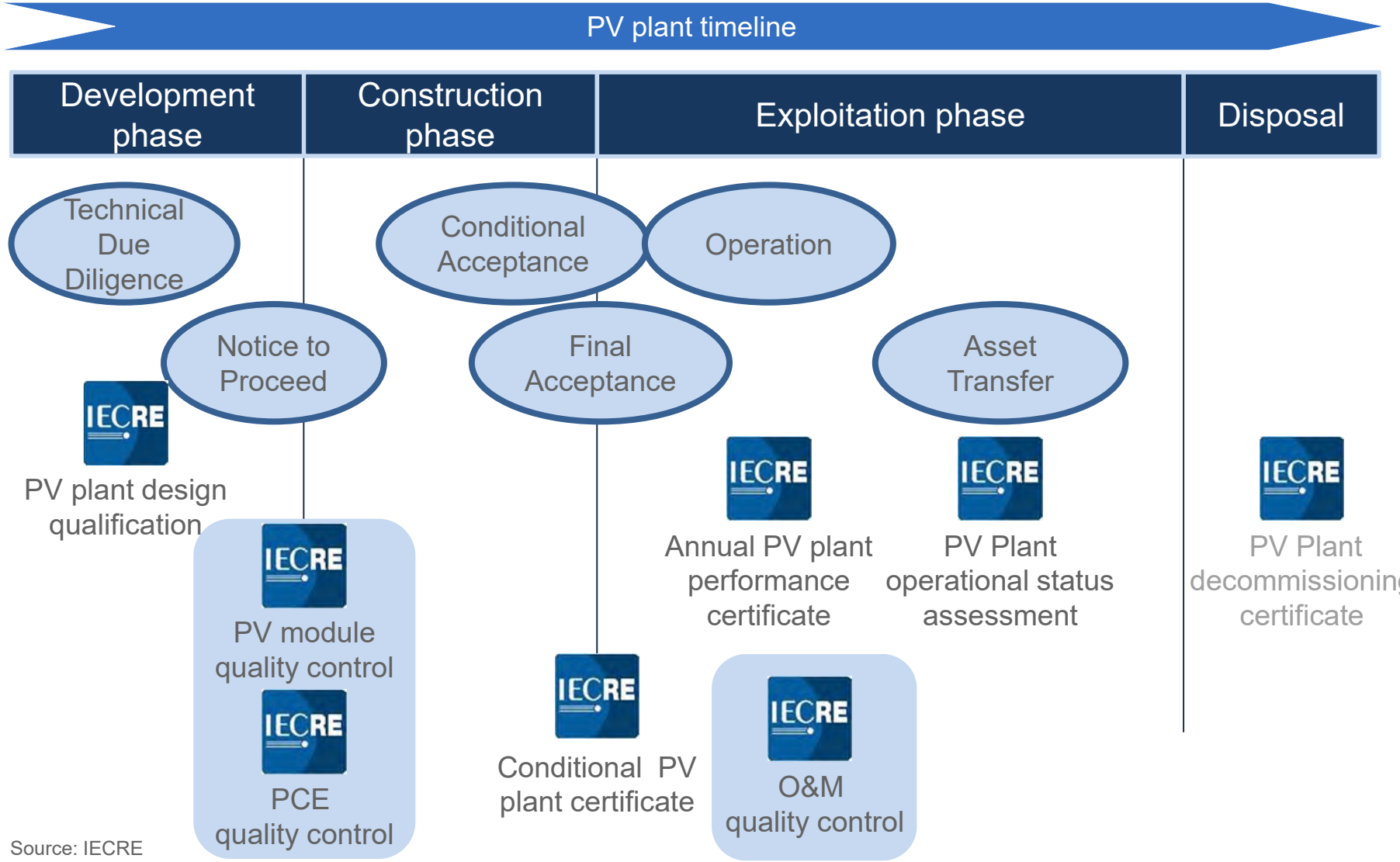

Source: IECRE

- The concept is to offer certification throughout the lifetime of a PV power plant
- Operational documents (ODs) offer a full range of certifications under the IECRE scheme
- IECRE itself does not certify, but administers the system
- Qualified registered IECRE participants are competent to assess RE equipment and projects

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To effectively enable managing risks, TEXXECURE is currently developing a rating system within the framework of IECRE

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Result: Project rating

Nexus of module results (algorithm)

Execution level

3.1. Production:
Production supervision and assessment scoring

3.2. General plant construction:
Construction supervision and assessment scoring, documentation check

3.3. Operations and maintenance:
Assessment of O&M standard operating procedures / manuals

Process level

2.1. Manufacturers:
Audit and rating of manufacturers, specifically per production site / fab

2.2. EPC contractors:
Audit and rating specifically per EPC contractor

2.3. O&M service provider:
Audit and rating of O&M service providers

Product level

1.1. Modules:
Rating of specific material combinations, the nominal power rate, the durability, recyclability etc.

1.2. Inverters:
Rating performance characteristic data, design parameters, durability, recyclability etc.

1.3. Connectors / cables
Rating connectivity, (el. resistance), durability, recyclability etc.

IECRE™

TEXXECURE
Rating Foundation

Proposal to EU Commission:

➔ Min. BBB-

- Ecodesign
- Energy label

➔ Min. AA-

- Ecolabel
- GPP

➔ IECRE is referenced in recent EU commission reports

➔ Provisional assignment: IECRE OD-411 series

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The rating points are transformed into a risk exposure which may trigger the calculation of financing and/or insurance premium conditions

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Currently discussed rating ranges, subject to possible adjustments

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Rating Foundation

Rating		Point range		Short description (proposal)
		From	To	
AAA		981	1000	Benchmark standard
AA	AA+ AA AA-	921	980	Meets high quality standards
A	A+ A A-	861	920	Meets essential quality standards
BBB	BBB+ BBB BBB-	801	860	Meets standards to an acceptable level
BB	BB+ BB BB-	741	800	Meets standards to a moderate level
B	B+ B B-	681	740	Meet standards to a minimum pass level
C		621	680	Fails to meet standards to a major extent
D		≤	620	Completely fails to meet standards

FICTIVE EXAMPLE

Attracts low risk investors (Investment grade) →
Attracts medium risk investors →
Attracts high risk investors (Non-investment grade) →
No certificate issued (report, only)

AAA	981	–	1000		Risk low →
AA	921	–	980	"Pass"	
A	861	–	920		
BBB	801	–	860		Risk medium →
BB	741	–	800	"Conditional pass"	
B	681	–	740		Risk high →
C	621	–	680	"Fail"	No acceptance
D	≤ 620				Risk too high →

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Besides just costs, conducting a thorough rating project during the inception phase can result in significant yield improvements

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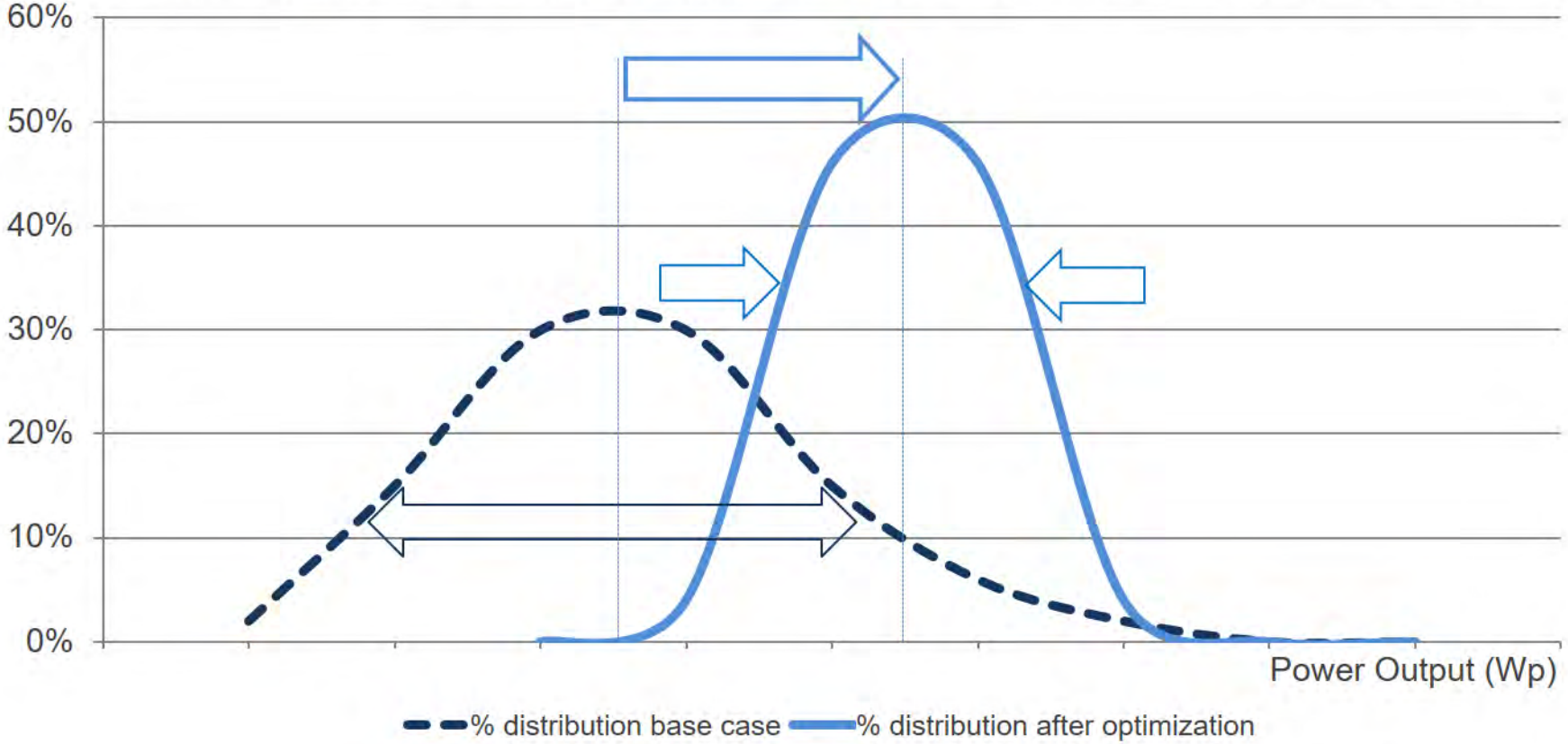
- Rating round 1: BB+ ➔ Shortfall identification during unbiased production / construction situation and lower rating
- Rating cycle 2: Work process improvements resulted in better system performance and in improved rating ➔ A

Case study II:

PV module power output distribution in % before and after corrective actions following a rating and re-rating project



Results:
- ~ 550,000 modules measured (~160 MWp)
- Rating improved from BB+ to A
- Productivity improved by >5%!
- Enhanced project bankability

Chart data is illustrative based on a real case

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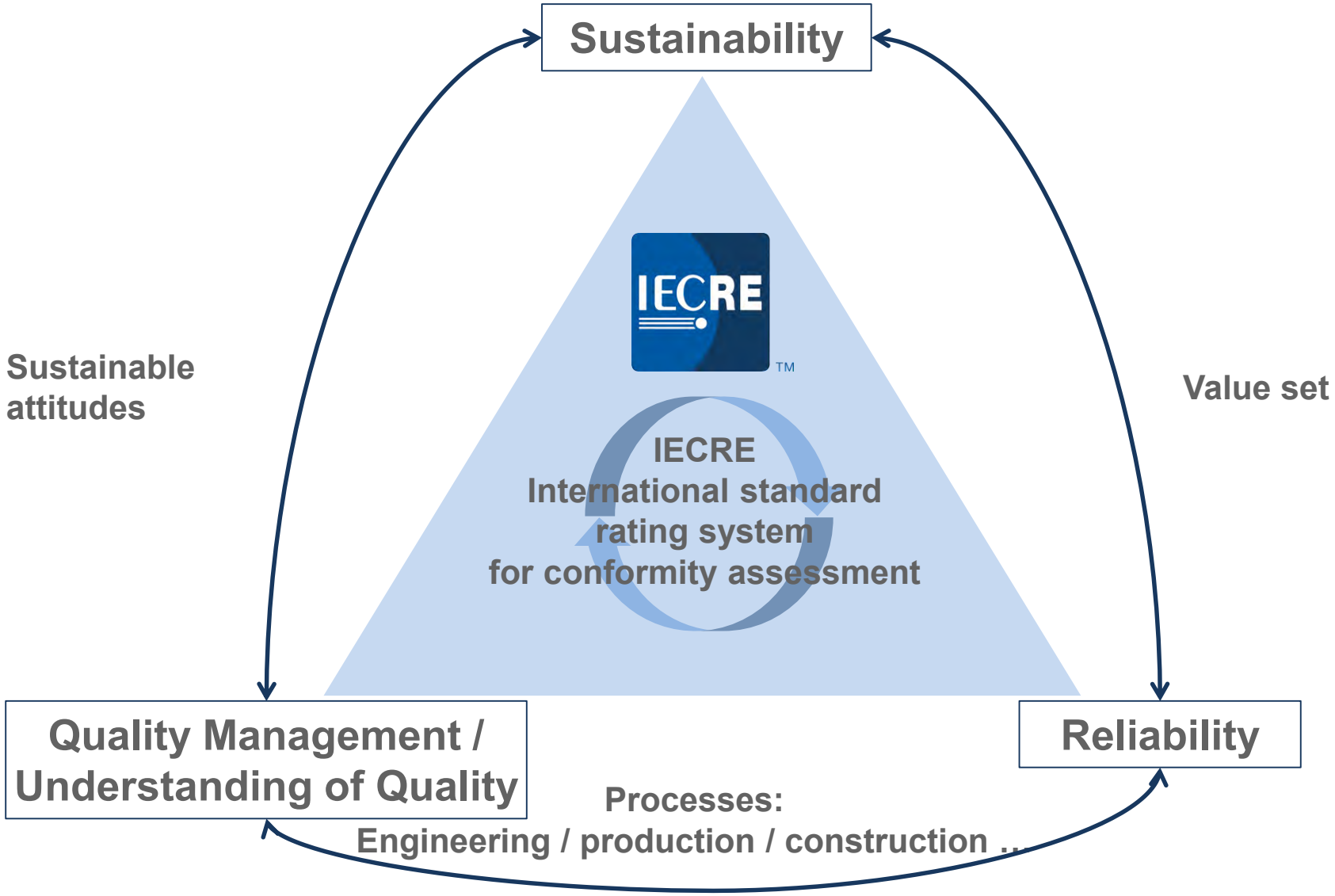
In a nutshell, the rating system will become an integral component to the “magic triangle”



Changing to a quality and value paradigm will enable the PV sector to pave the way in pursuit to grow towards the next order of magnitude

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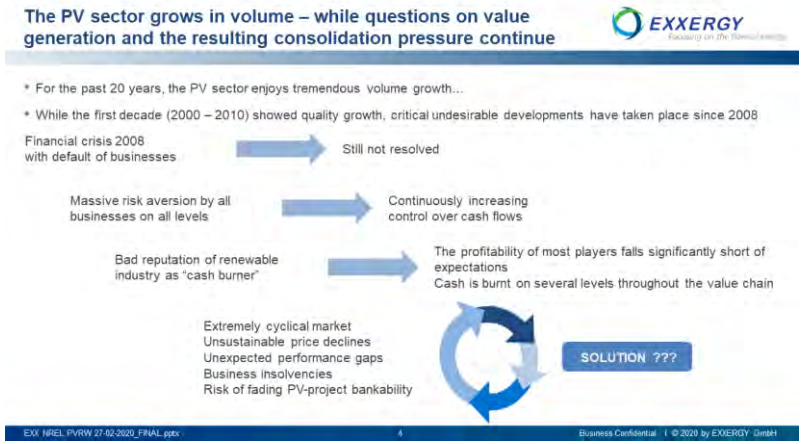
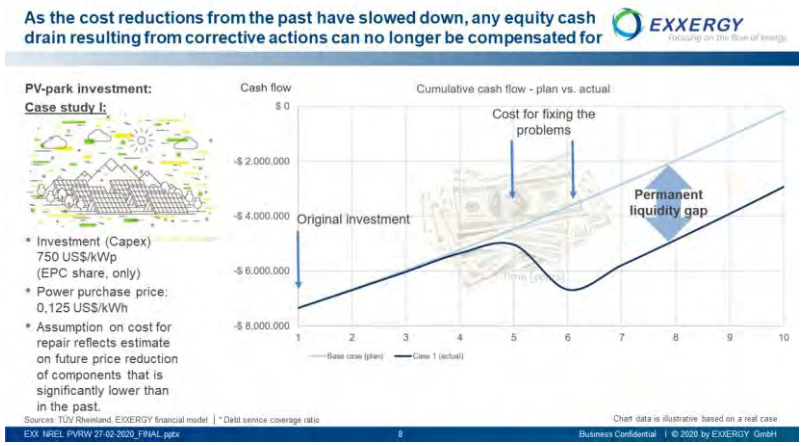
- The PV sector is facing constant, recurring, critical pressure points
  - Market cycles
  - Price races to the bottom and resulting cost cutting on projects
  - Constant dashes to meet critical timelines
  - Resulting quality issues
  - Etc. …



Reality check

- Plan is never actual – however,
  increasing performance gaps in PV threaten the viability of the sector
  …as well as the success of the energy transition towards affordable power
- LCOE is already lower than for thermal power plants or for wind turbines
  ➔ Tapping real cost reduction potential is generally good
  ➔ Business health is vital
  ➔ **There is no real need for a continued price race to the bottom at the expense of reliability and sustainability**



Risk mitigation by applying a thorough rating system and yield optimization turn out to be two sides of the same coin

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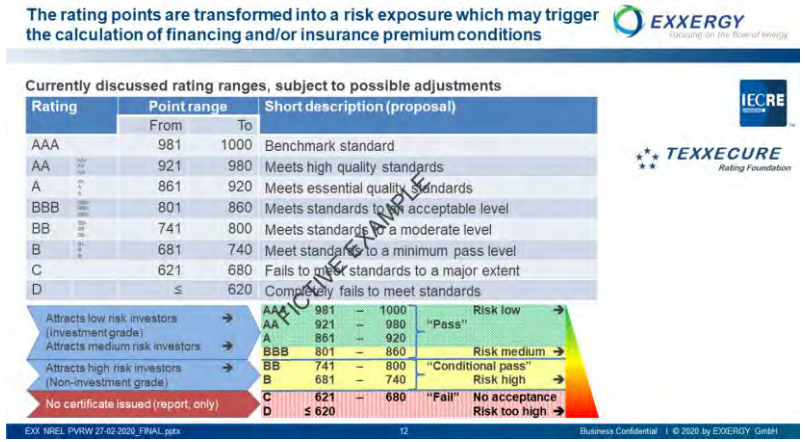

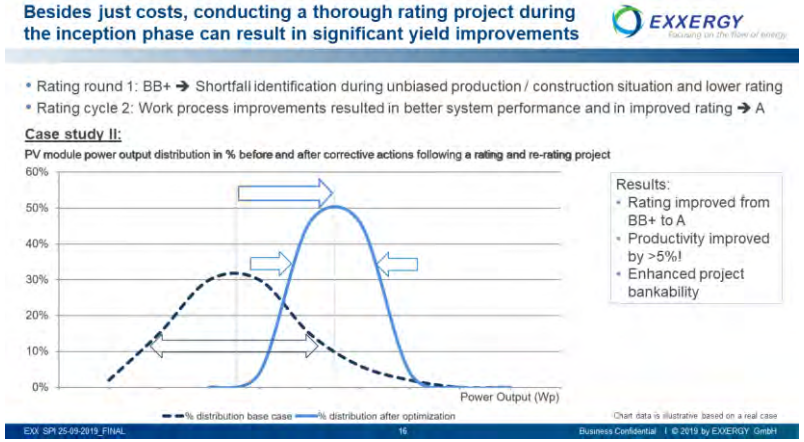

Solution

- **Consistent, quantifiable classification** of the risk exposure and the expected performance of a PV power plant
- The costs of **thorough quality control** easily pays back through improved lifetime performance
- Improvements resulting from applying the rating system approach can result in **significant yield improvements**
- Current status of the rating system development status:
  - TEXXECURE Rating Foundation continues to raise funds and the development process has started
    → **Sponsors are welcome**
  - Expected timeframe for market introduction of first elements: Q1/2021

Risk mitigation by applying a thorough rating system and yield optimization turn out to be two sides of the same coin

TEXXECURE Rating Foundation

IECRE™

Solid rating enables high quality oriented investors to leverage their competitive advantage because it is predictive…as opposed to finding out problems later

- Alignment of the technical assessment quality:
  - Clearly defined requirements, policies, and procedures for certification bodies (CB) and inspection bodies (IB)
    - ➔ Consistency and comparability ➔ Mutual recognition
    - ➔ Credibility of the standardization effort

- Acceptance by the financial sector:
  - Selected players are involved in the rating system development process
  - Increased confidence
    - ➔ Better access to capital and to viable insurance solutions
  - Investor groups with different risk appetites may be addressed
    - ➔ Rating will allow differentiation as it provides risk assessment guidance
  - Rating system supports investors focusing on the secondary market
    - ➔ Clear guideline towards the (technical and financial) performance and risk profile

- High quality stakeholders can leverage part of the net present value advantage to demand better selling prices
  - ➔ Healthy business
  - ➔ **Healthy and sustainable development for the solar PV sector**

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Thank you for your attention !

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Funds & contributions welcome:

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Rating Foundation

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Questions… ?

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Investors are naturally assessing risks involved in any financial engagement – are these sufficient to ensure solid investment returns?

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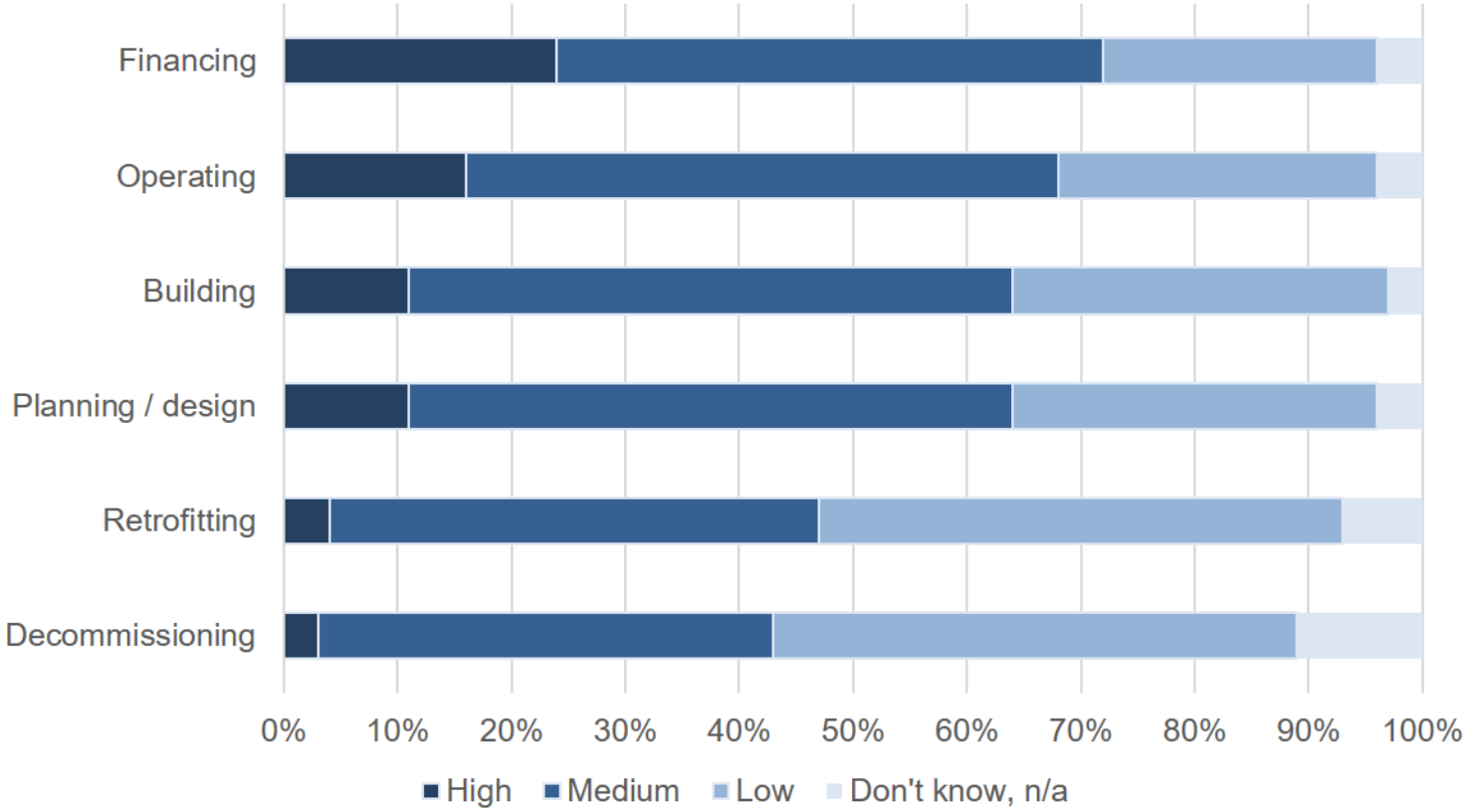
Question:
As a general matter, how would you assess the overall degree of risk associated with each of the following stages of building and operating a RE power plant?



Not specifically mentioned:

- **Procurement**
- **Supply chain management**
- **Quality assurance**

Source: The Economist Intelligence Unit, sponsored by SwissRe

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Does a correlation between the complex challenges in the PV sector and the observations of deteriorating performance exist?

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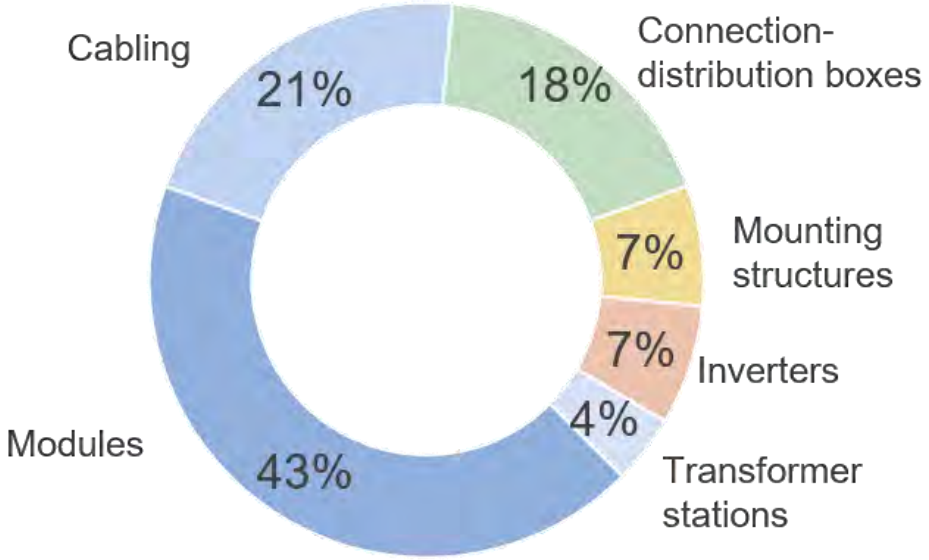
Type of mistake	Description	Yield reduction
Planning mistake	Important design criteria are disregarded or have not been appreciated	≤ 40%
Component mistakes / problems	Components don‘t meet name plate functionality	≤ 60%
Mounting errors and mistakes	Quality issues during mounting and construction	≤ 20%
Lack of monitoring	Inoperative situation or performance issues are not detected at all or detected too late	≤ 70%

- 30% of inspected operating PV power plants show serious defects requiring immediate corrective action
- Most prevalent causes for defects are related to production of components and installation

Extent of performance assessments:
More than 1,5 GWp inspected

Sources of poor performance



Sources: Analysis Fraunhofer Institute, Voigt & Collegen, TÜV Rheinland, EXXERGY estimates

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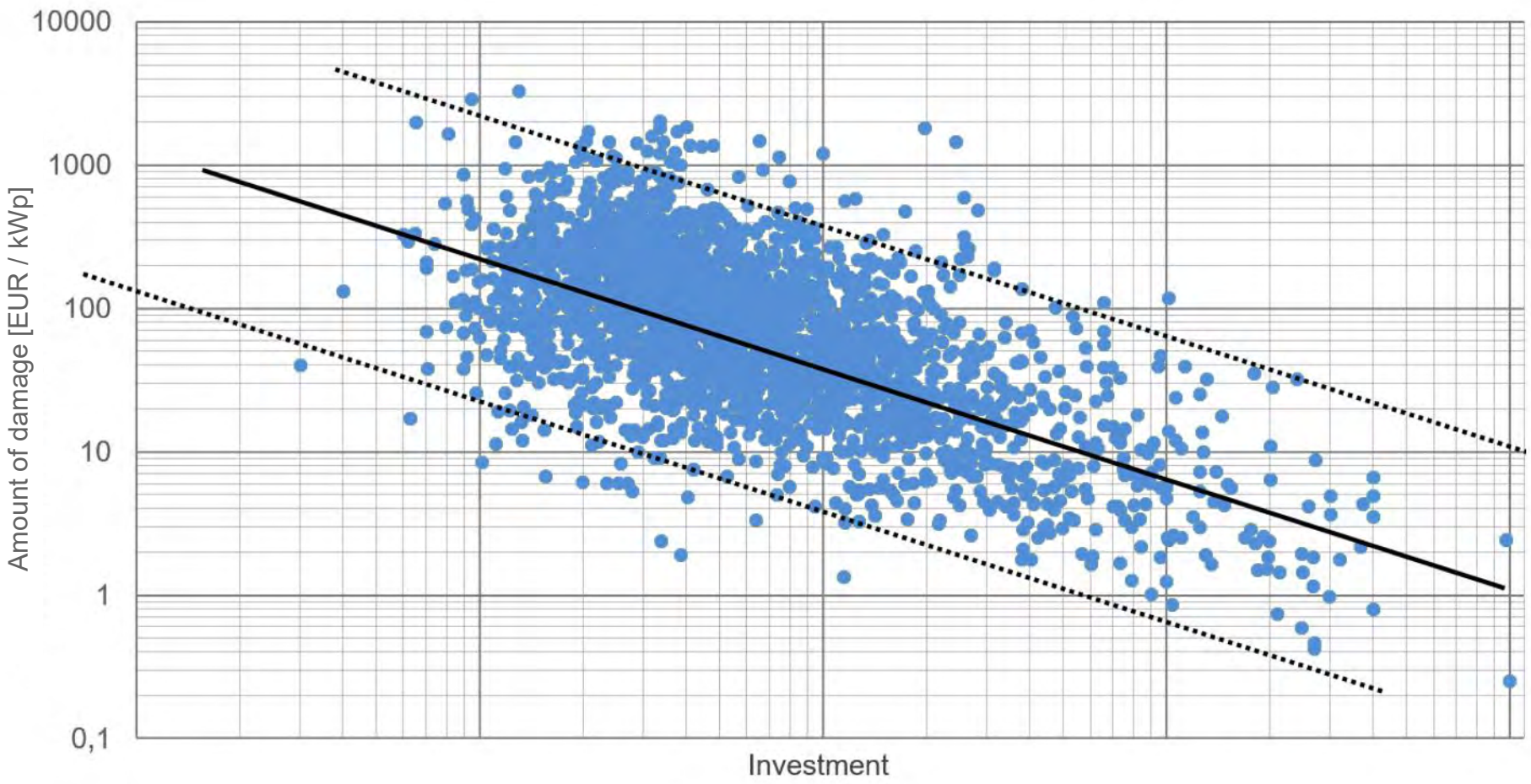
An insurance claim cases assessment suggests that amounts of damage can be more significant than calculated for…

- More than 3.600 insurance claim cases have been analyzed in total
- Generally, the relative amount of loss trends to decline with increasing system size
- The main stream amounts of loss spreads over 2 orders of magnitude
- Outliers range up to 3.500 US $ / kWp (incl. consequential damage)



3503 claim cases Jan 2012 through June 2017 for which amounts of investment and of damage have been available

Source: EXXERGY analysis on >3.600 insurance claim cases 2012 - 2017

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Clustered by manufacturer reveals an interesting correlation, however, the ratio between damages on inverters vs. modules may be misleading

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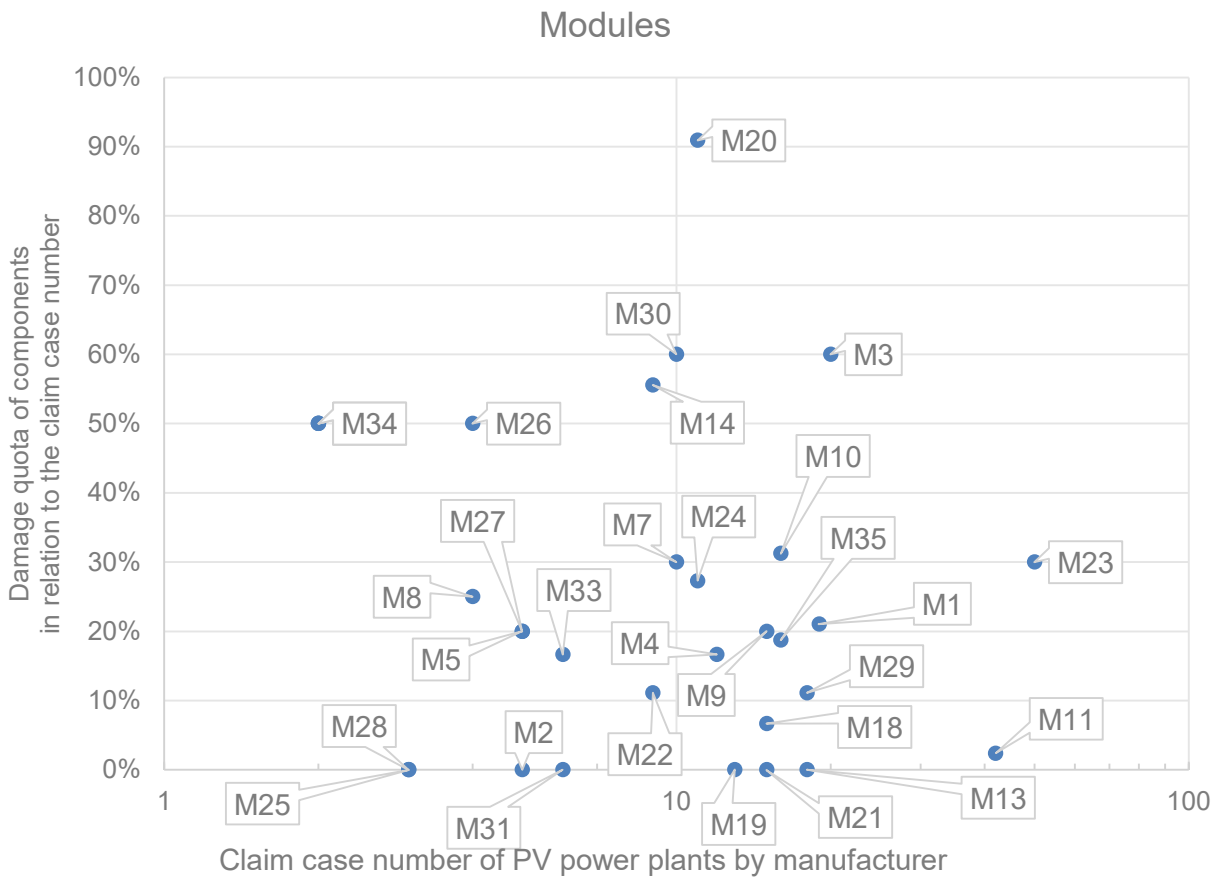
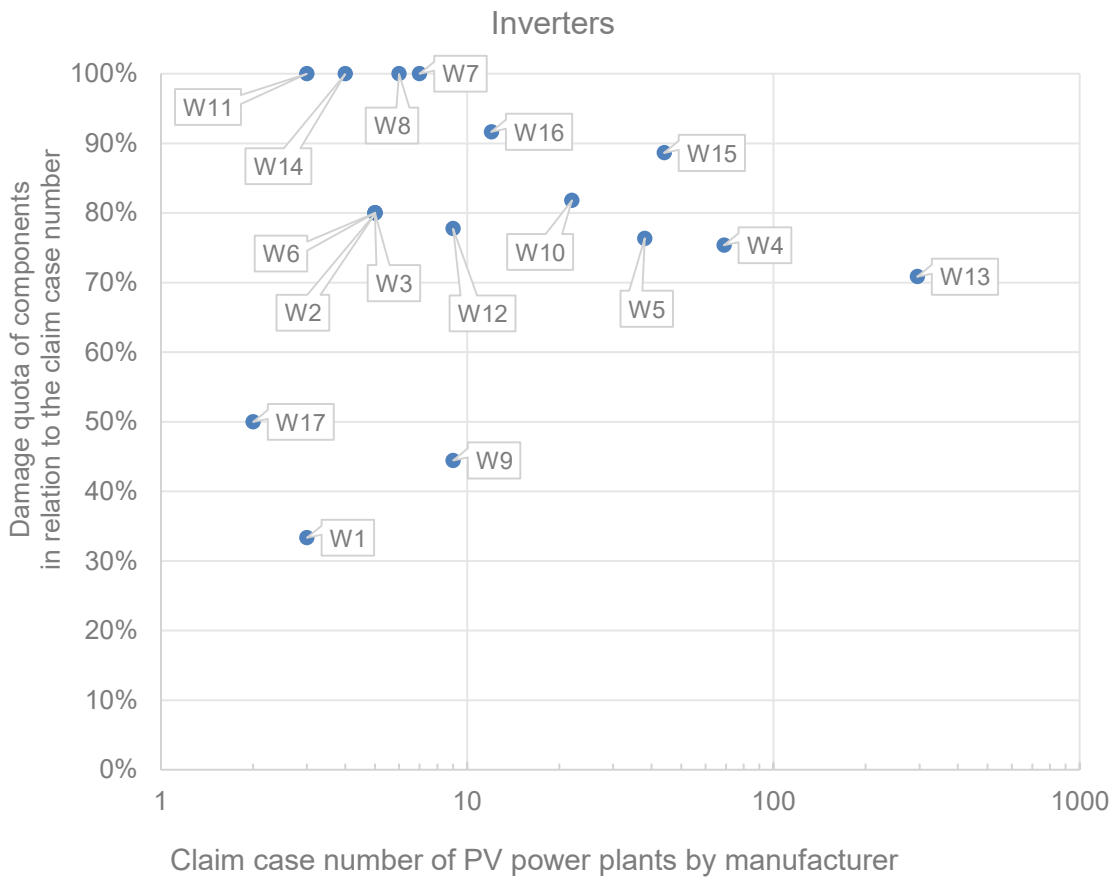
Ratio of internal damages by manufacturer in relation to total number of damages





Source: EXXERGY analysis on >3.600 insurance claim cases 2012 - 2017

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Many investors take financial performance from PV power plants for granted – a realistic assumption?

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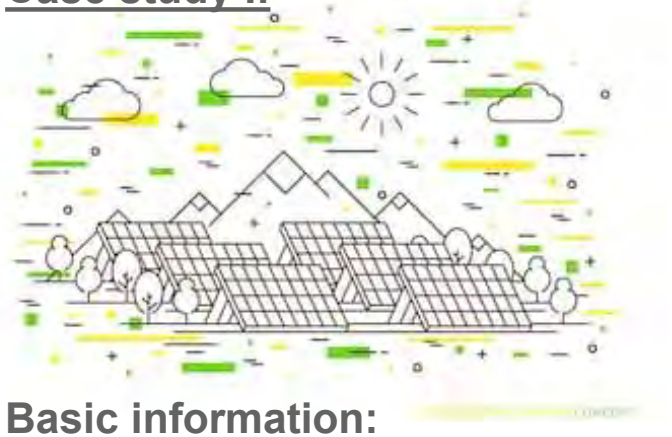
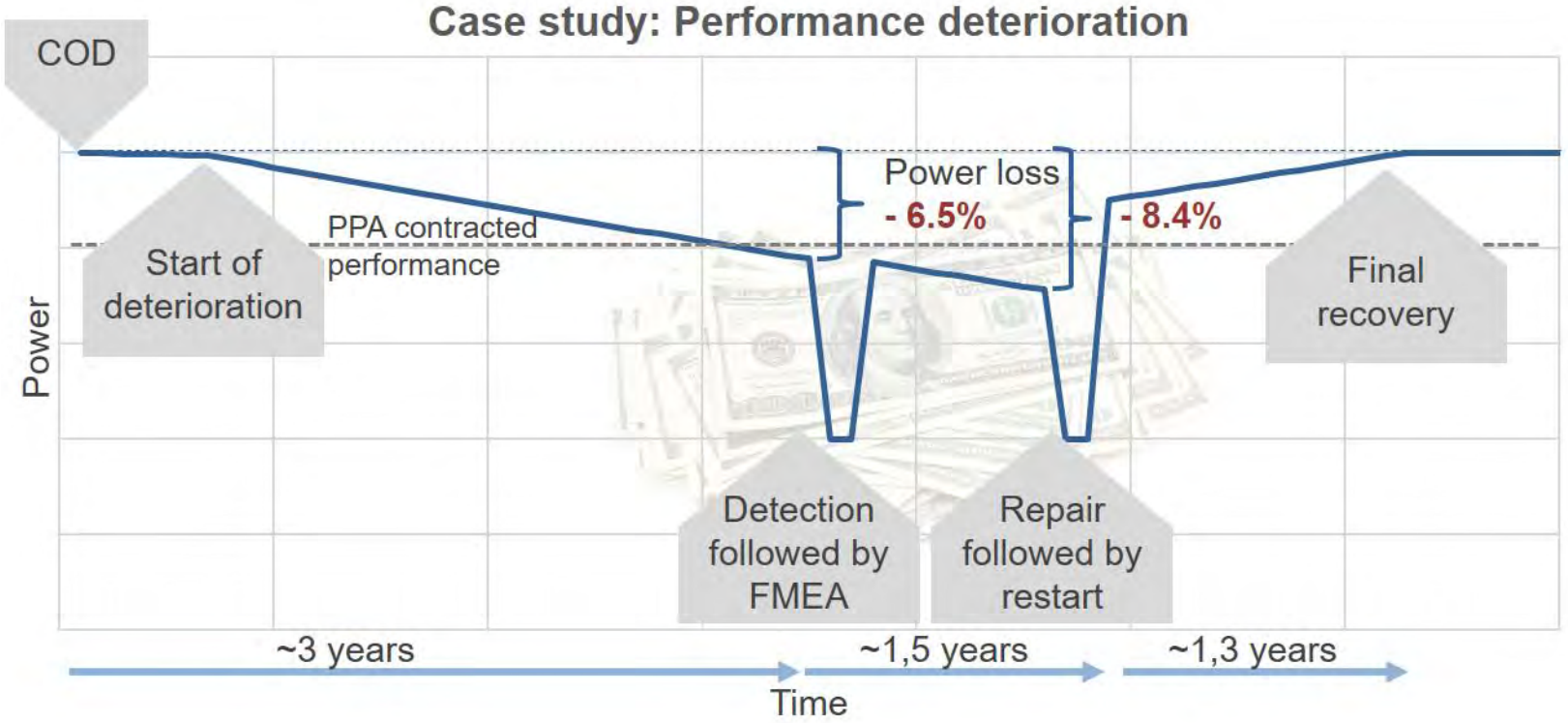
PV-park investment:

Case study I:



Basic information:

- PV power plant approx. 10 MWp
- Ground mount
- Investment (Capex) approx. 750 US$/kWp
- Power purchase price: 0,125 US$/kWh



Impact on financials and other resources (excerpt)

- Reduced revenue streams
- Costs for detection (FMEA) and definition of corrective action
- Cost for repair
- Penalties from bank
- Liquidated damages for non-performance on PPA
- Human resources for fixing issues
- Material resources (replacements)
- …

Sources: TÜV Rheinland, EXXERGY financial model

Chart data is illustrative based on a real case

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The previous case was financially a challenge but not a disaster… What if the PIRR reduces to below 11%...?

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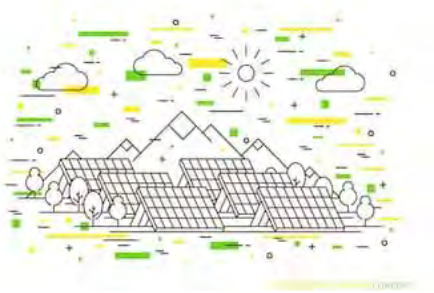
PV-park investment case



Basic changes on "today projection":

- Investment (Capex) 750 US$/kWp
- Power purchase price: 0,125 US$/kWh
- Assumption on cost for repair reflects estimate on future price degression for modules

Today projection @ <11% PIRR	Plan (base) case	Case 1: Actual performance case	Case 2: Investment to match case 1 PIRR	Case 3: Solid quality investment case
Total Capex initial investment [kUS$]	7.350	7.350	+38,5% 10.180	+10% **8.090**
Cost for FMEA[1] [kUS$]	-	+38,2% 260	-	**-**
Cost for repair [kUS$]	-	(activated) 2.400	-	**-**
Compensation for electricity supply [kUS$]	-	150	-	**-**
Cumulative EBIT[2] 20 years lifetime [kUS$]	25.150	22.120	22.320	**24.410**
Project DCF[3] 20 years [kUS$]	7.580	6.200	7.830	**7.640**
PIRR[4] (unlevered)	10,6%	4,6%	4,6%	**8,7%**
20 years equity IRR[4] @60% leverage for 12 years, 9,5% interest	23,7%	14,3%	12,9%	**20,2%**
DSCR[5] range	1,65..3,08	Fatal default **1,13**..3,24	Requires ≥55% equity 1,23..2,30	**1,51..2,83**
Payback year	5,7	10,0	7,7	**6,2**

US$ numbers commercially rounded to 10 kUS$

Sources: TÜV Rheinland, EXXERGY financial model | [1] Failure mode and effect analysis | [2] Earnings before interest and taxes | [3] Discounted cash flow | [4] (Project) internal rate of return | [5] Debt service coverage ratio

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Well…what happens when planned PIRR further drops to 7% - a number that is increasingly seen in the region

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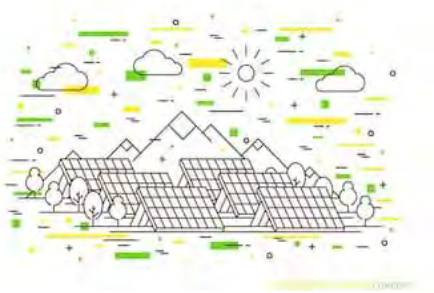
PV-park investment case



Basic changes on "today projection":

- Investment (Capex) 750 US$/kWp
- Power purchase price: 0,106 US$/kWh
- Assumption on cost for repair reflects estimate on future price degression for modules

Today projection @ 7% PIRR	Plan (base) case	Case 1: Actual performance case	Case 2: Investment to match case 1 PIRR	Case 3: Solid quality investment case
Total Capex initial investment [kUS$]	7.350	7.350	+38% 10.140	+10% **8.090**
Cost for FMEA[1] [kUS$]	-	+38,2% 260	-	-
Cost for repair [kUS$]	-	(activated) 2.400	-	-
Compensation for electricity supply [kUS$]	-	150	-	-
Cumulative EBIT[2] 20 years lifetime [kUS$]	19.610	16.640	16.820	**18.880**
Project DCF[3] 20 years [kUS$]	6.400	5.060	6.650	**6.470**
PIRR[4] (unlevered)	7,0%	1,5%	1,5%	**5,3%**
20 years equity IRR[4] @60% leverage for 12 years, 9,5% interest	17,2%	8,5%	7,9%	**14,2%**
DSCR[5] range	1,39..2,60	Fatal default **0,92**..2,76	Requires ≥60% equity 1,05..1,96	**1,28..2,39**
Payback year	6,8	11,7	9,0	**7,4**

US$ numbers commercially rounded to 10 kUS$

Sources: TÜV Rheinland, EXXERGY financial model | [1] Failure mode and effect analysis | [2] Earnings before interest and taxes | [3] Discounted cash flow | [4] (Project) internal rate of return | [5] Debt service coverage ratio

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…that will allow an individual rating for each category and the aggregation of these category results into a final project rating

EXXERGY
Focusing on the flow of energy

IECRE™

TEXXECURE
Rating Foundation

Result: 863 points ➔ Project rating A-

Nexus of individual modular results (algorithm)

Execution level

3.1. Production (fulfilment):
Modules: 980/1000
Inverters: 995/1000
Connectors: 995/1000

3.2. General plant construction(fulfilment):
900/1000

3.3. Operations and maintenance manual (fulfilment):
945/1000

Process level

2.1. Manufacturers:
Modules: 910 points ➔ A+
Inverters: 975 points ➔ AA+
Connectors: 990 points ➔ AAA

2.2. EPC contractors:
870 points ➔ A-

2.3. O&M service provider:
855 points ➔ BBB+

Product level

1.1. Modules:
930 points ➔ AA-

1.2. Inverters:
970 points ➔ AA+

1.3. Connectors / cables
990 points ➔ AAA

FICTIVE EXAMPLE

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Applying artificial intelligence will amplify the usefulness of the TEXXECURE / IECRE rating system

EXXERGY
Focusing on the flow of energy

IECRE™

TEXXECURE
Rating Foundation

1.1. Primary research
- Expert interviews
- Data acquisition of material and component manufacturers and from EPCs
- Description of degradation mechanisms
- Etc.

1.2. Secondary research
- Desktop research (public and private data bases)
  - Best Practices
  - Norms and regulations
  - Formulas of degradation mechanisms
- Field data acquisition

2. Analysis, evaluation, concluding nexuses etc.

3. Release of rating system version 1.0, 1.X, X.X

4.1. Issuance of certificates with rating

4.2. Field data acquisition of rated PV power plants

4.3. Reconciliation of actual vs. planned performance

4.4. Deviation analysis actual rating vs. current certificate

BC

Deviation greater than y%?

Y

N

5. Continuous monitoring, possibly refinement of GUI, functionalities etc.

Feedback loops to stakeholders: Analysis and continuous improvements

AI

* Abbreviations:
BC: Blockchain
AI: Artificial intelligence

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The triangle of standardization, conformity assessment, and rating system enables furthering healthy LCOE reductions

EXXERGY
Focusing on the flow of energy

- **Several initiatives are crucial to further the reduction of LCOE**
  - PV is on a continuing trajectory reducing LCOE significantly
  - The trajectory for LCOE reduction for wind is relatively marginal
  - **Quality concerns can jeopardize LCOE projections**
- **Crucial initiatives are about standardization**
  - **IECRE issues standards for RE power plants**
  - **The "Orange Button" initiative is about data taxonomies**
    - **for financial reporting (historical data) → XBRL data system**
    - **To manage larger technical performance data volumes, a more efficient taxonomy is required**

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Risk mitigation by applying a thorough rating system and yield optimization turn out to be two sides of the same coin

TEXXECURE Rating Foundation

Cooperation level	Platinum	Gold	Silver
Contribution USD	**300,000**	**120,000**	**60,000**
One (1) advisory committee position	X		
Personalized free copy of the EXXERGY insurance claim case report (pitch see attached document "PVS Insurance Report Pitch EUWW 01-03-2019.pdf") *	X	X	
Participation in IECRE or TEXXECURE end user group (first annual fee (either for 2019 or 2020, depending on when the end user group is set up) waived, thereafter annual fee)	X	X	
Participation in IECRE or TEXXECURE end user group (for additional annual fee)			X
Participation in selected project work groups sessions	X	X	X
Consortium partner to TEXXECURE: Provision of neutralized information, data, and knowledge deemed essential to the PV Rating System 1.0 development	X	X	X
TEXXECURE to consortium partner: Specific provision of neutralized information, data, and knowledge deemed necessary to the PV Rating System 1.0 development	X	X	X
Provision of progress reports	X	X	X

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BERKELEY LAB

Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY

UNIVERSITY OF CALIFORNIA

BERKELEY LAB

LAWRENCE BERKELEY NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Existing Array Storm Vulnerabilities & Risks
Sub-Frame Deflection, Fastener & Module Damage

Gerald Robinson

Program Manager

PV High Wind User Test Facility

Otto Van Geet, Jeroen van Dam, Scott Dana, James Elsworth
National Renewable Energy Laboratory

Gerald Robinson, Lawrence Berkeley National Laboratory

WE WANT YOUR INPUT!

Photo from UTMSI

The Challenge

Wind loading, such as that experienced during hurricanes Irma and Maria, has caused catastrophic damage to solar fields. This significantly reduces the potential value of solar as a resilient power solution. In many locations, there is a need and demand for stronger PV systems.

Photo from Above Photography Photo from Andy Walker, NREL

Impact

There can be a tendency to race to the bottom cutting capital costs, devaluing robust design features and technologies. This project seeks to enable testing of various designs for PV systems in high wind or storm prone regions, with the goal of helping industry identify effective ways of hardening PV arrays in the face of high wind loads and protecting solar modules exposed to extreme or repetitive stresses. There is some indication that cost-effective, storm hardened design elements exist that could benefit from further evaluation and validation.

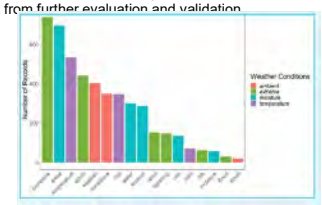


Figure from Gunda, 2019

The PVROM database documents common words featured in PV O&M tickets. The figure above shows that 'hurricane',' 'storm,' and 'wind' are the most common extreme weather events causing damage to the PV systems included in this analysis. The figure below shows that hurricanes were the top source of PV insurance claims, as well.

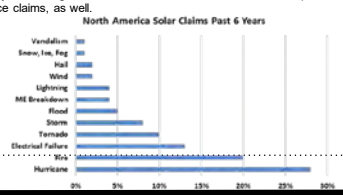


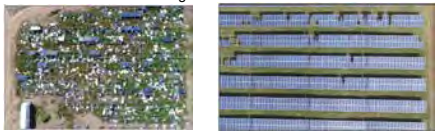
Figure from G-Sole, 2018

Proposed Project

The creation of a PV high wind test facility at the NREL Flatirons Campus that will enable private and public research efforts aimed at storm hardening PV systems. The facility will be instrumented to monitor effects of high wind conditions on modules and other array components. These in-field tests will coordinate with flow models, wind tunnel testing, validation of PV aeroelastic design codes, and post-testing module and system component analysis.

Initial Concept

Creation of an L-shaped testbed with a "strong floor" – a poured concrete slab with embedded threated inserts on a grid to which we could attach various system configurations for in-field testing. In-field testing will validate flow models and wind



Two images showing various impacts from the same storm in Puerto Rico. Humacao installation (left) suffered near total damage while Oriana array (right) needed replacement of only ~10% of modules, largely because of superior structural design

Potential Projects:

Fasteners and Bolted Joints: Testing of various bolted joint or clamping configurations such as through bolting, locking fasteners, clamp position, number, length

Array shapes and layouts: Testing of various tilt angles, heights, row spacing

Tracker systems: testing locking trackers, stow angles, racking designs

Racking systems: Various materials, shapes, and designs that can maintain structural integrity in the face of high winds and other severe weather

Wind-calming fence: Installing a fence around an array to reduce loads on perimeter rows.

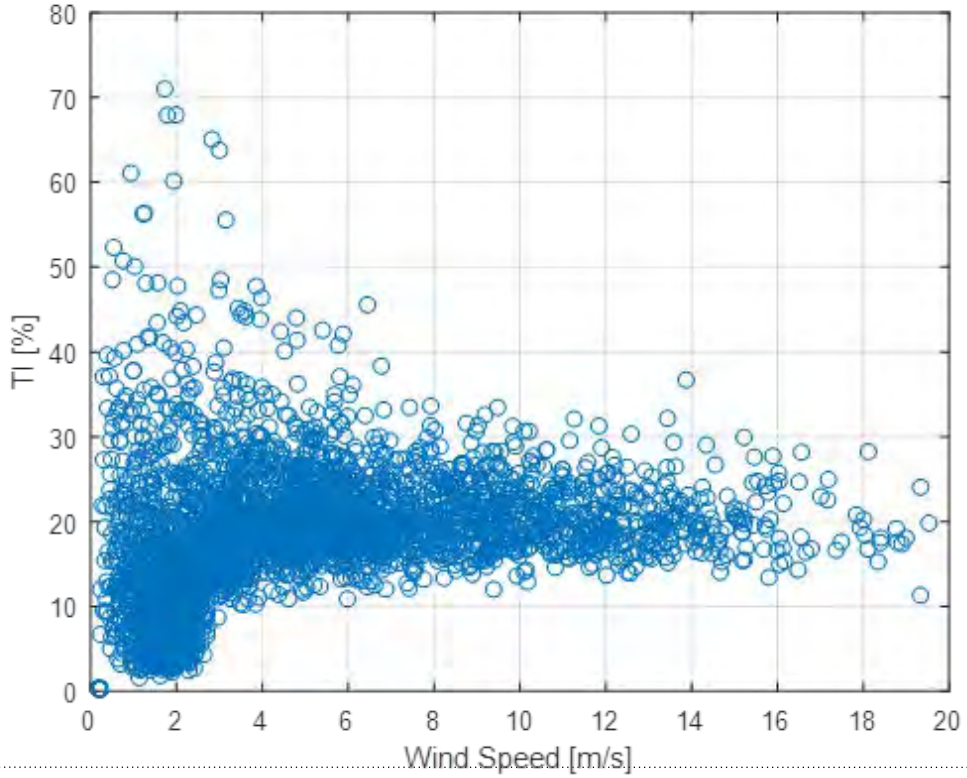
(left) A solar PV tracker wind loading experimental setup showing instrumentation

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Federal Energy Management Program. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

PV Reliability Workshop
Lakewood, CO
February 25-27, 2020
NREL/PO-7A40-76046

NREL Wind Test Center – Flatiron Campus

High winds of 100 MPH are common.



Key Points

1. Common purlins choices leading to high deflection and torsional instability = fastener failures and module damage.

2. Retrofit and reinforcement of existing arrays.

3. Relationship between fastener specifications and module protection in wind events.

Information Sources

Direct Field Observation

Observation From Operators

Fastener Engineers

Racking+ Module Manufacturers

Reports + Guides

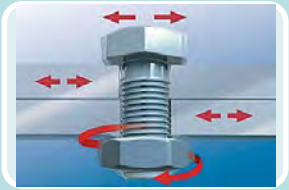
1. RMI Under The Storm 1+ 2
2. FEMA Report – 2018

High Wind Events Aside....

- Losses that underpin conclusions presented here occurred on arrays less than 100 MPH with two at 70 MPH.

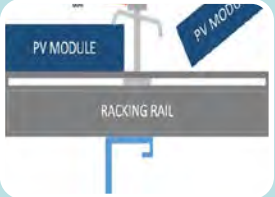
- Sources contacted for these slides report losses occurring during routine weather events.

Example Module Fastener Failure Modes



Vibration induced fastener loosening

- Loss of pre-load
- Complete disassembly



Row loss – shared fastener schemes

- “Row Domino”

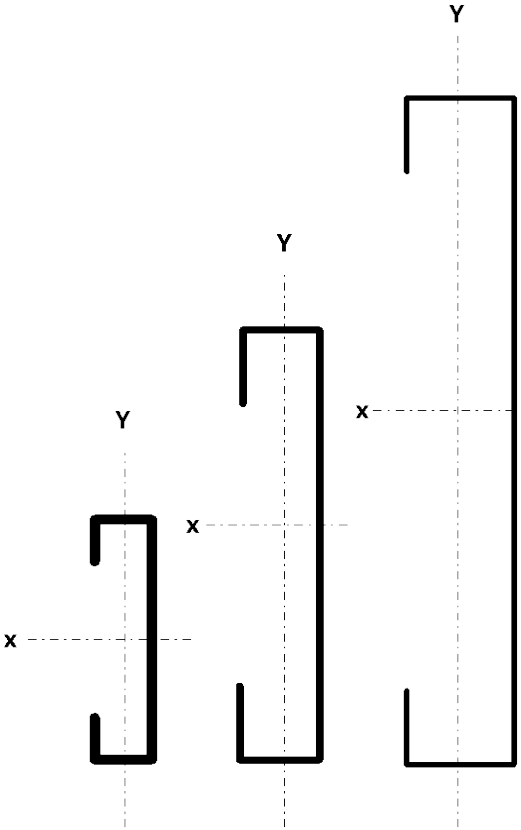
Top-down clamp fatigue

- Wind back pressure on module
- Thermal expansion not accommodated

New fastener products

- UL 2703 6.5 not followed
- Use tensile strength of metal as “rating”

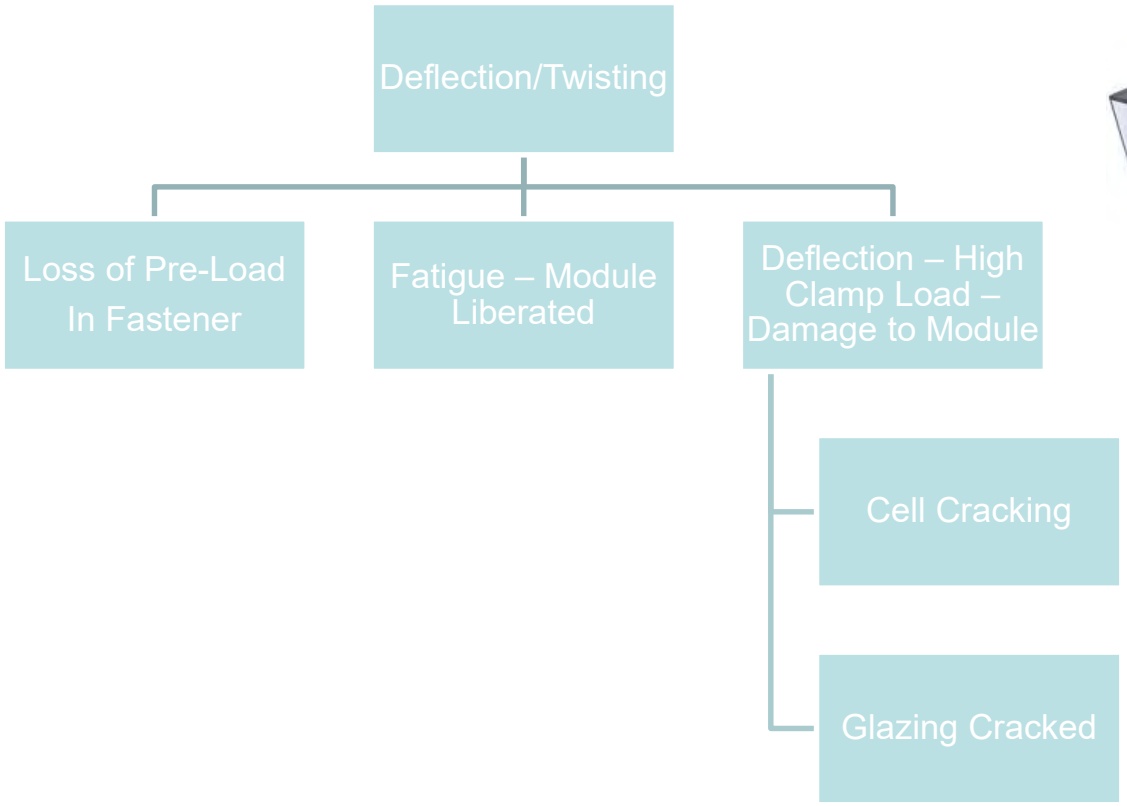
Sub-Framing Stability

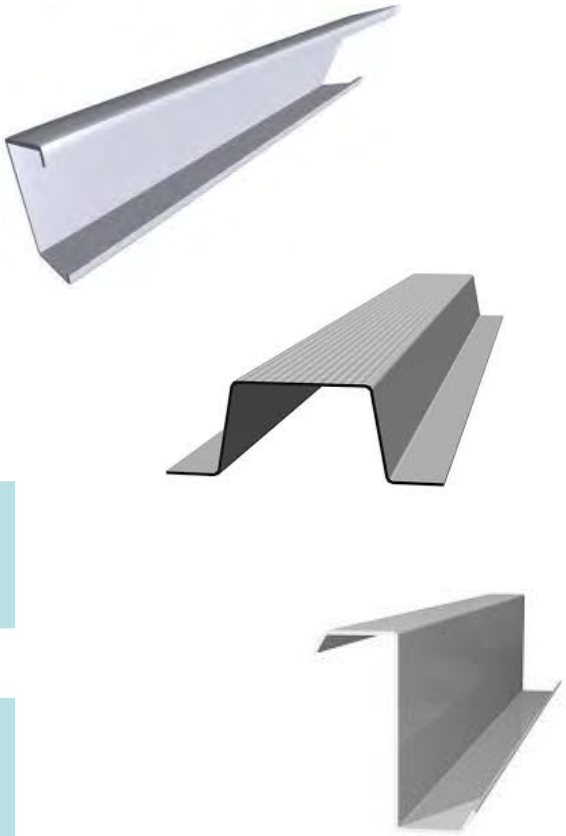


1. Larger – lighter gauge achieves desired strength along x and y axis.

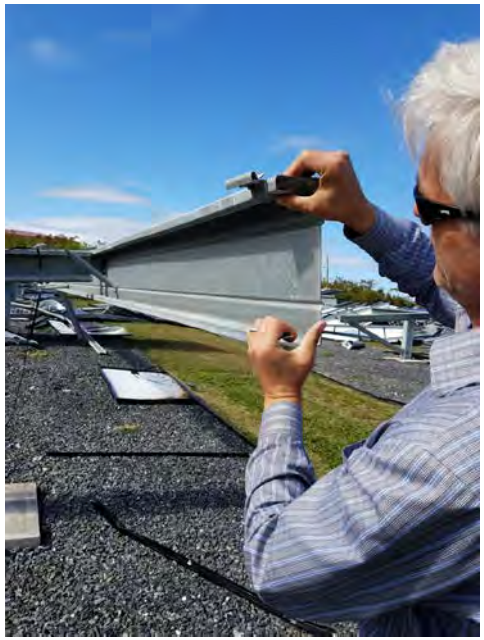
2. Introduces instability (e. g. torsional) and requires bracing and reinforcement.

Unstable Frame Elements – Cascading Effects





Example Sub-Frame Instabilities



Photos by Gerald Robinson

Deflection/twisting leading to “over-clamping”

Retrofitting sub-framing

1. Reinforcing framing:

✓ Bracing, stiffening, strapping.

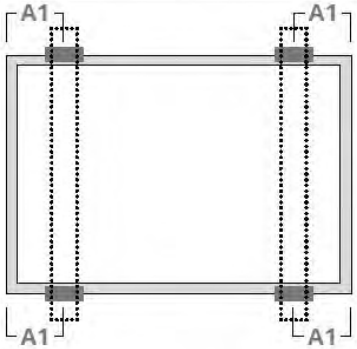
✓ Preventing whole table movement.

2. Fastener Upgrades:

✓ Module manufacturer's recommendations for greatest protection – fastener contact surface area, position and quantity.

✓ Full accounting of dynamic wind forces using actual module.

Gaining Full Module Rated Strength

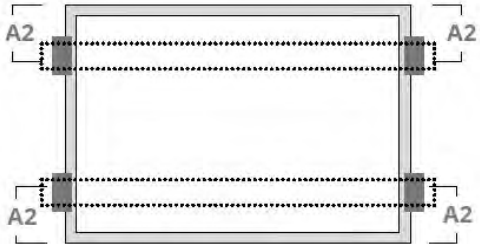


Use four clamps on the long side. Mounting rails run perpendicularly to the long side frame.

A1 range = (0 – 239) mm
Maximum Load:
Uplift load ≤ 2000 Pa
Downforce load ≤ 2000 Pa

A1 range = (240 – 330) mm
Maximum Load:
Uplift load ≤ 3600 Pa
Downforce load ≤ 5400 Pa

A1 range = (331 – 550) mm
Maximum Load:
Uplift load ≤ 2400 Pa
Downforce load ≤ 2400 Pa



Use four clamps on the short side. Mounting rails run parallel to the long side frame.

A2 range = (200 – 250) mm
Maximum Load:
Uplift load ≤ 2000 Pa
Downforce load ≤ 2000 Pa

Questions

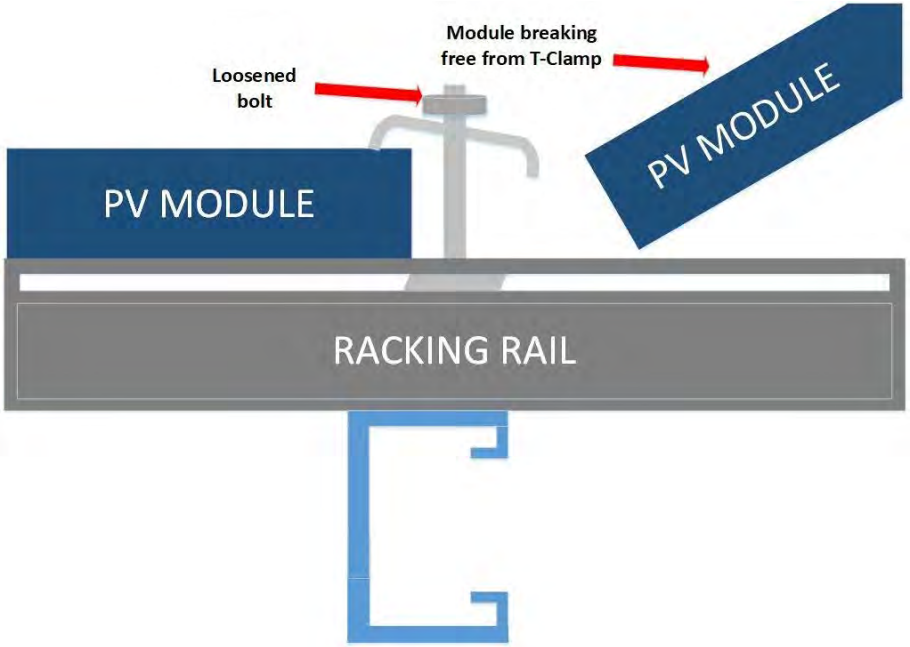
1. How many asset owners or operators in audience?

2. What module fastener failure modes have you experienced?

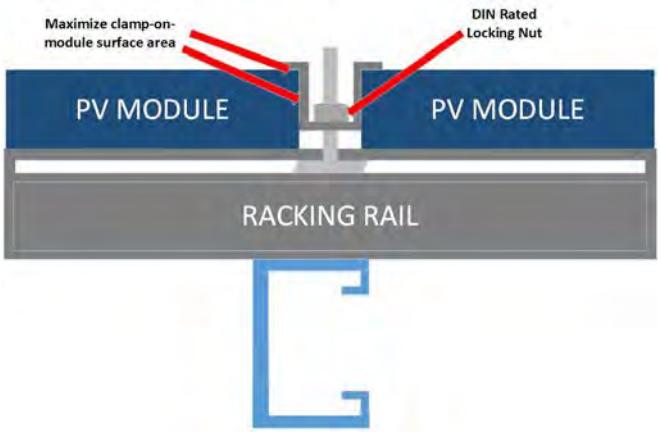
3. Have you reinforced existing arrays with high deflection?

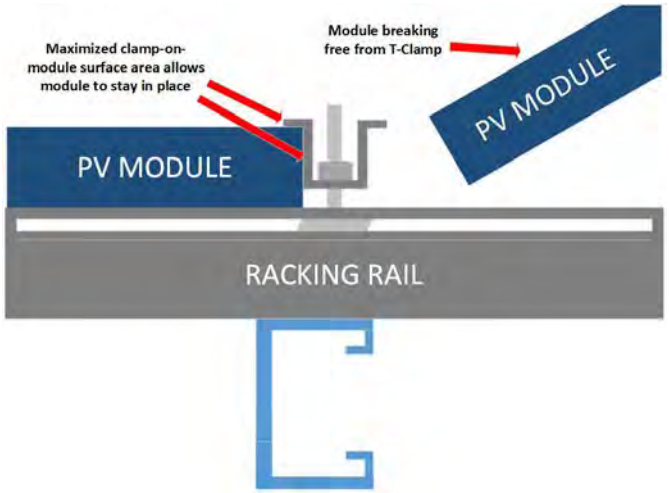
Appendix Slides

”Row Domino” Phenomena

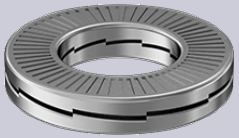
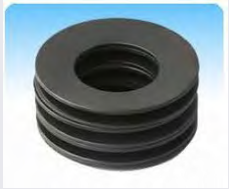


Preventing Row Domino





DIN 65151 Rated Locking Fasteners

Fastener		Adjustable	Specialized Tools + Training	Pre-Load Scatter (%)	Retail Cost ($) – ¼" Fastener*	Notes
Lock Bolts (Huck Bolts)		No – replace fastener	Yes – but simple process	Low < 5%	$.80/Each	
Thread locking pre-applied		No – replace fastener	Torque Wrench	10-15%	$.75/Each	Exposure to heat, humidity and UV
Wedge Lock Washers		Yes	Torque Wrench	10-15%	$1.10/Set of Two	Need two sets
Belleville Washers		Yes	Torque Wrench	10-15%	$1.25/Each	Combine with other locking fastener

Junker Test (DIN 65151) – Pictures from McMaster Carr + Fastener Engineering

DNV·GL

Perspectives on the Useful Life of Modules

Henry Hieslmair henry.hieslmair@dnvgl.com

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Introduction

- What is presented here is not what DNV GL practices… yet…
- The intent is to show my thinking on how IE’s might tackle extended useful life.
- Clients are interesting in extended useful life... 35, 40, and more years.

DNV GL © 2020

Why extend the useful life of a PV system to 40 years?

- Improve asset value
- Lower LCOE ~16% to 20%
- Utility plants have >25 year useful life i.e. hydropower, nuclear, coal,…
- Postpone the decommissioning costs
- Reduce waste with longer life components
- Amortize the carbon foot print of the system over a longer life
- Better energy returned on energy invested (EROI)

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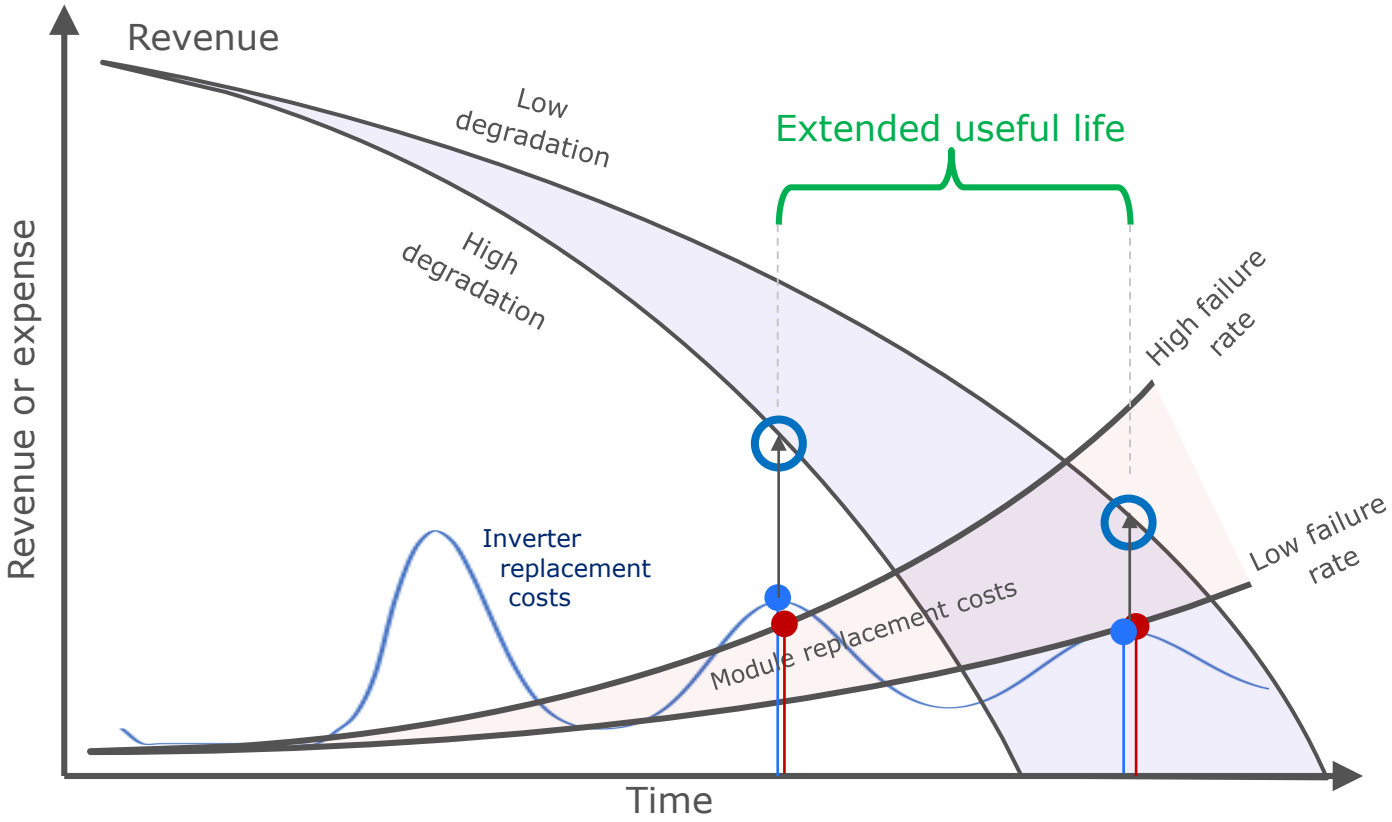
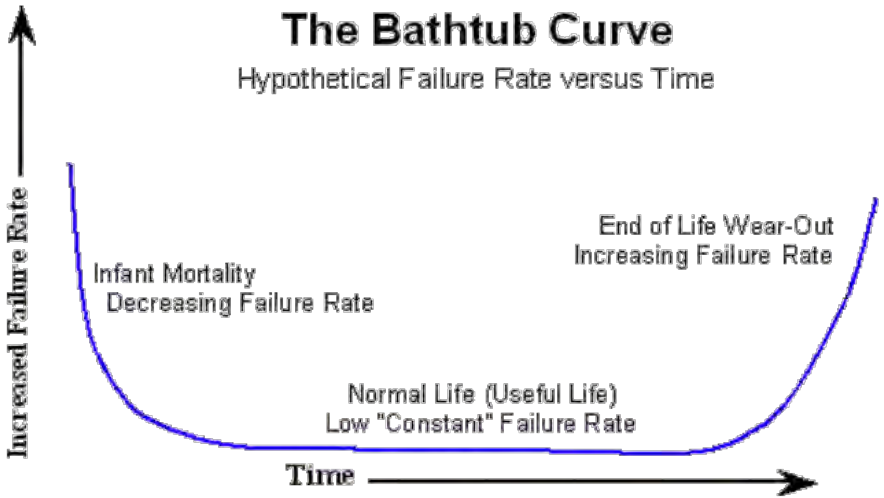
Useful Life of a PV system

Expenses = Revenues



Module Useful Life Example 1



Failures

↓

Functional

↓

Module quality

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Module Useful Life Example 2

SunPower 'Useful Life' is 40 years:

- 99% of modules functioning
- at ≥70% of nameplate power.

Failures → Functional → Module quality

Degradation → Economic → Module & project

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Two main references for degradation and failure rates.

Compendium of photovoltaic degradation rates.

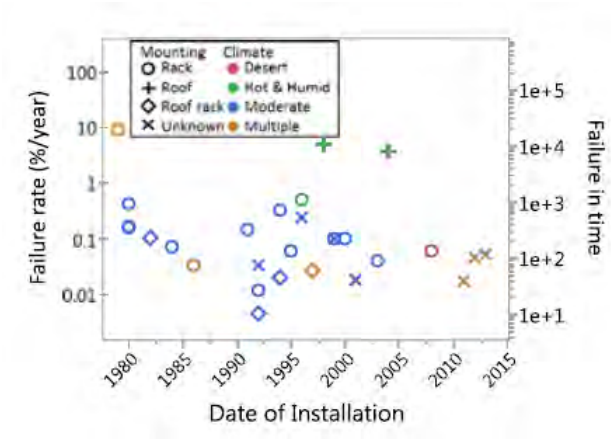
Jordan DC, Kurtz SR, VanSant K, Newmiller J. Progress in Photovoltaics: Research and Applications. 2016 Jul;24(7):978-89.

Module degradation rate is 0.5%/year, system 0.64%/year

Photovoltaic failure and degradation modes.

Jordan DC, Silverman TJ, Wohlgemuth JH, Kurtz SR, VanSant KT. Progress in Photovoltaics: Research and Applications. 2017 Apr;25(4):318-26.

Module failure rate is 0.05%/year



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How can we reconcile such low failure rates with…

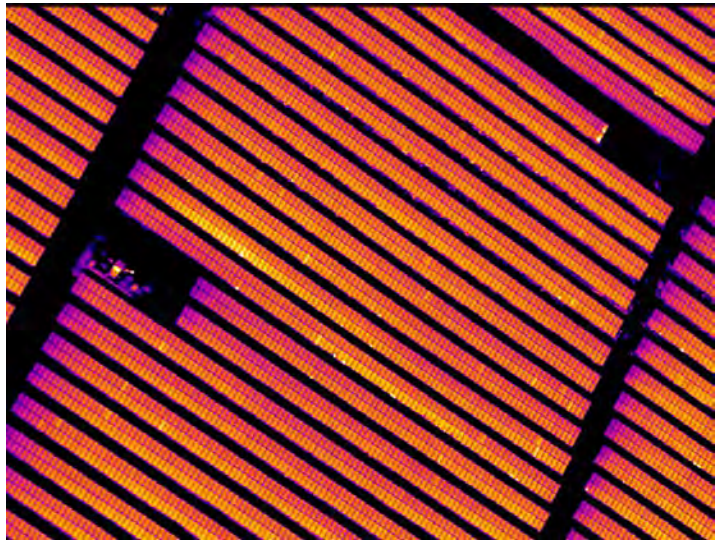
DuPont Global Field Reliability Program

2019 Study

With 1.8 GW of fields inspected, the following observations were made:

- Total module defects: 34%
- Total backsheet defects: 14%
- Backsheet defects increased 47% from 2018
- Cracking comprises 66% of all backsheet defects

Heliolytics
Aerial inspections for solar asset optimization



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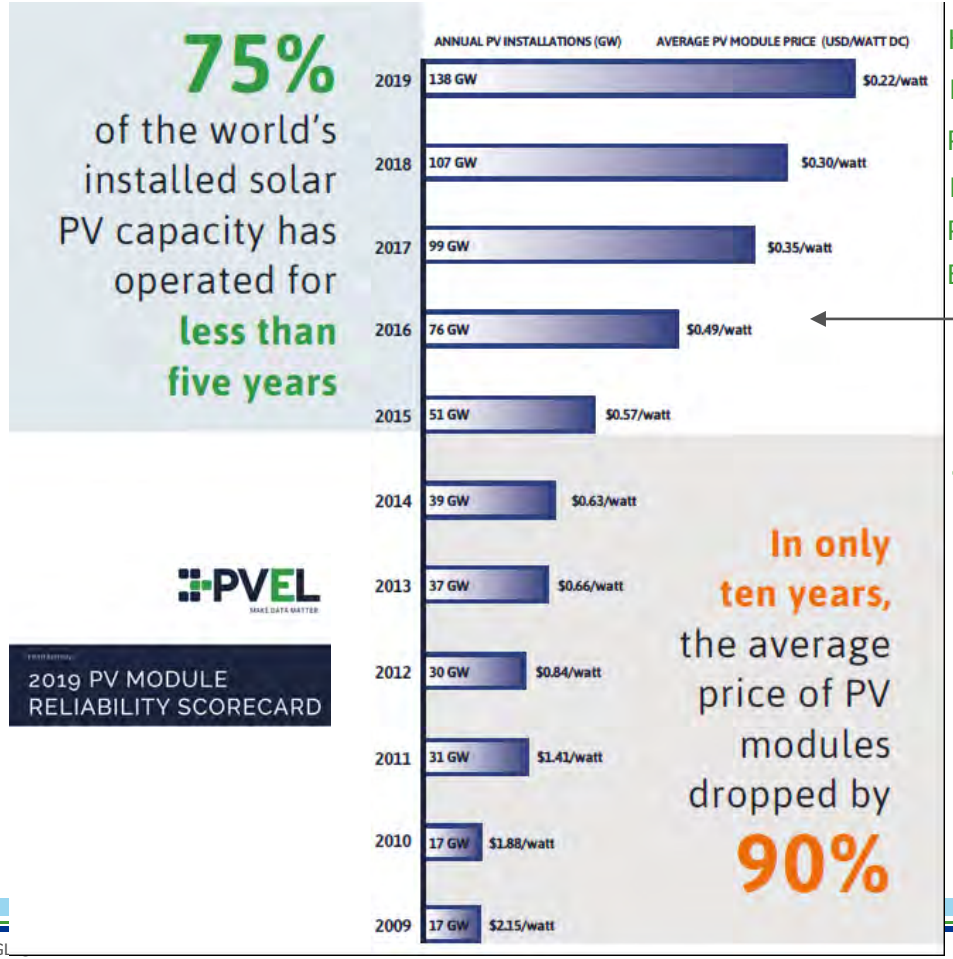
Rate of change



HJT, Tiling ribbon

Half-cell, MBB

PERC bifacial, shingled, 6 busbar

Mono ~ Multi by volume

PERC adoption

B-O LID mitigation, 5 busbar

"Compendium" published July 2016

4 busbar

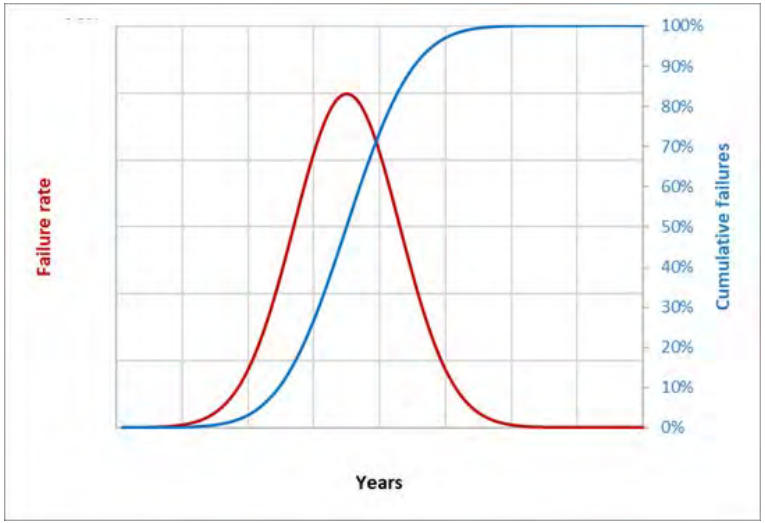
Manufacture date of modules

3 busbar

How to move forward on module useful life?

a) Module useful life based on failure

b) Adopt a model for failure rates



c) Define 3 module classes

Standard

- Little experience,
- Limited field history,
- Questionable warranty

Quality

- Experienced,
- Extended testing,

High Durability

- BOM review,
- Rigorous accelerated testing,
- Factory audits,…

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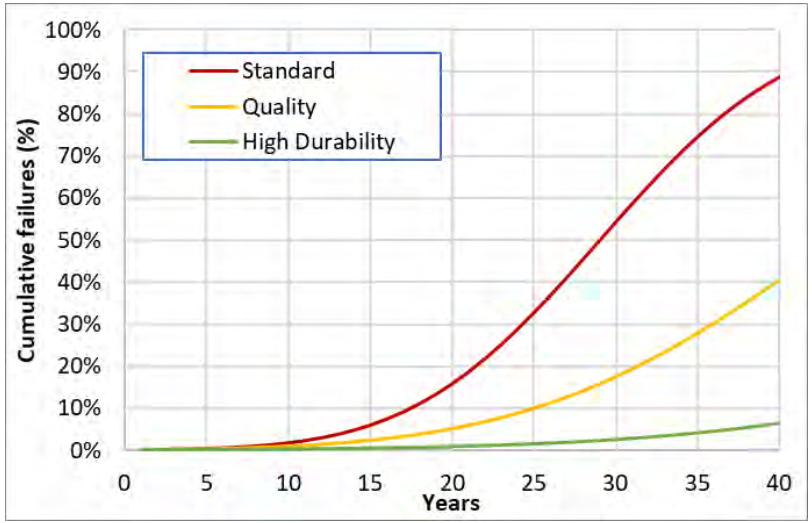
How to move forward on module useful life? #2

d) Create failure profile for each module class



0.1%/year

Cumulative failures %			
Year	**Standard**	**Quality**	**High Durability**
10	1.7%	1.0%	0.2%
25	33%	10%	1.5%
30	54%	18%	2.5%
35	75%	28%	4%
40	89%	41%	6%

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Costs analysis: a) Strategies

- **Option 1:**
  - Purchase extra modules today to cover post-warranty,
  - Set aside cash for
    - Estimated labor costs
    - Warranty enforcement costs up to year 25

- **Option 2:**
  - Set aside cash for:
    - Purchase cheaper replacement modules post-warranty
    - Estimated labor costs
    - Warranty enforcement costs up to year 25
    - Estimate repowering costs?

- **Option 3:** Utilize higher grade modules

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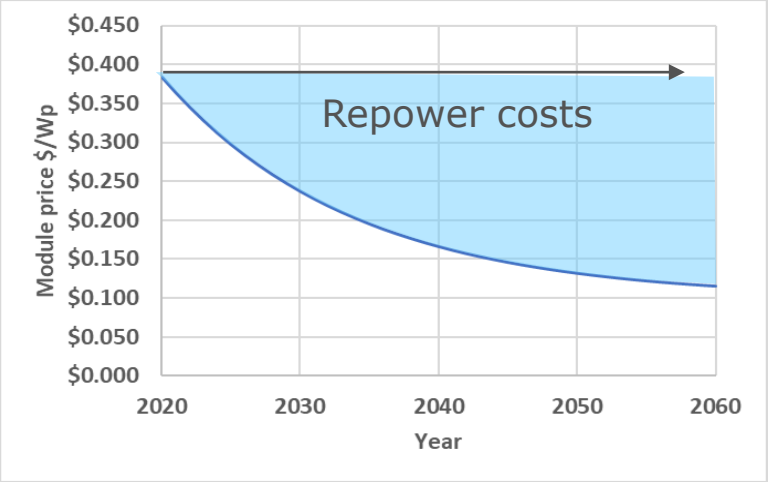
Costs analysis: b) Modelling assumptions

Future module costs will decline (Option 2)

Costs of repowering?



Other model inputs

Current module cost	0.38/Wp all classes
Real discount rate	3.0%
Labor (replace module)	$30.00 per module
Warranty enforcement	$0.04 $/Wp

Depending on the warranty and the company, warranty enforcement costs includes: transportation, module disposal, lawyers, laboratory testing, and lost production.

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Costs analysis: c) Increase in module Cap Ex

Required increase in module Cap Ex to cover future failures

	Standard No warranty	Standard 3rd party warranty	Quality Good warranty	High Durability Good warranty
Option 1: pre-purchase modules, cash set aside for labor & warranty enforcement				
25 year	46%	22%	4.4% (Δ17.6%)	0.6% (Δ3%)
40 year	123%	100%	50% (Δ50%)	8% (Δ42%)
Option 2: Cash set aside for future modules, labor, repower, & warranty enforcement				
25 year	16%	12%	2.5% (Δ9.5%)	0.4% (Δ2.1%)
40 year	56%	42%	19% (Δ23%)	3.0% (Δ16%)

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How to classify modules?

	Standard	Quality	High Durability
Experience & financials **(Use PV Tech Bankability)**	Recently founded	<10 years experience, B or A status	>10 years A status
Manufacturing quality	No information	Audit report A or B rating	Recent audit report with A rating
Module testing	Minimal	Extended-duration testing (similar PQP) <5% degradation	Very extended-duration testing <2% degradation + sequential tests
BOM	No information	BOM disclosed BOM controlled	BOM disclosed BOM controlled **Special construction**

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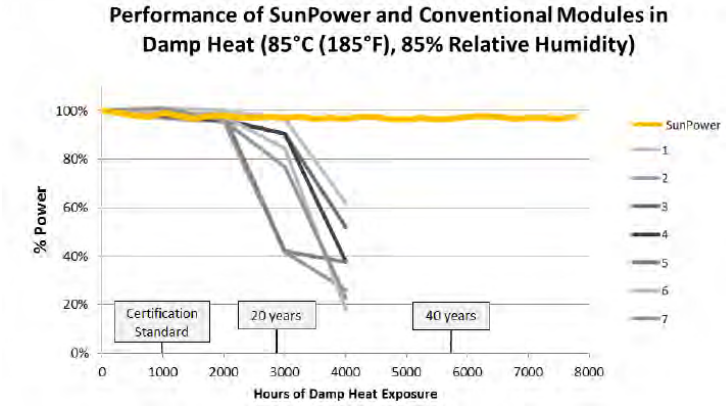
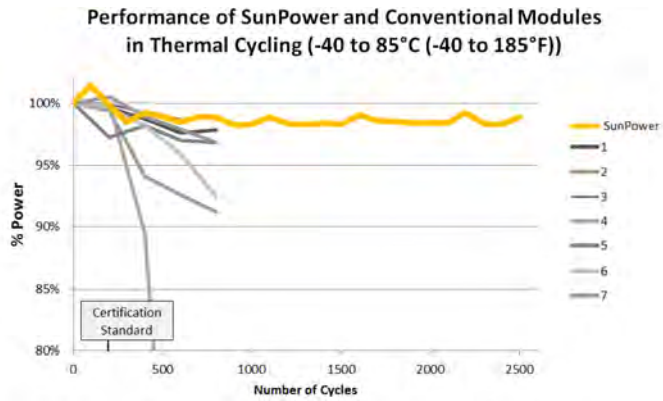
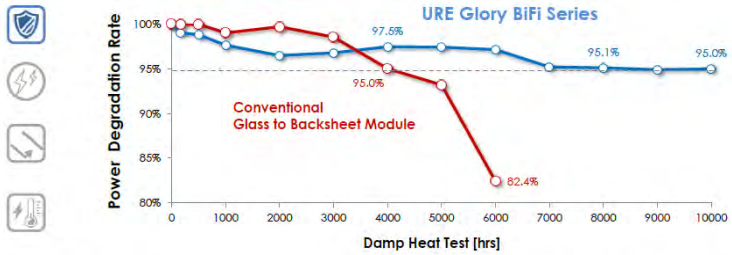
Testing 1: Very extended-testing

SunPower based their 40 year Useful Life in part on very extended-testing

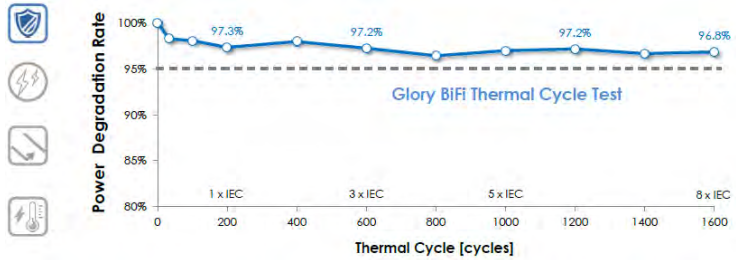




"Design of Glass-Glass Bifacial Module in Severe Coastal Condition in Taiwan" URE Presented at PV Module-Tech conference 2019

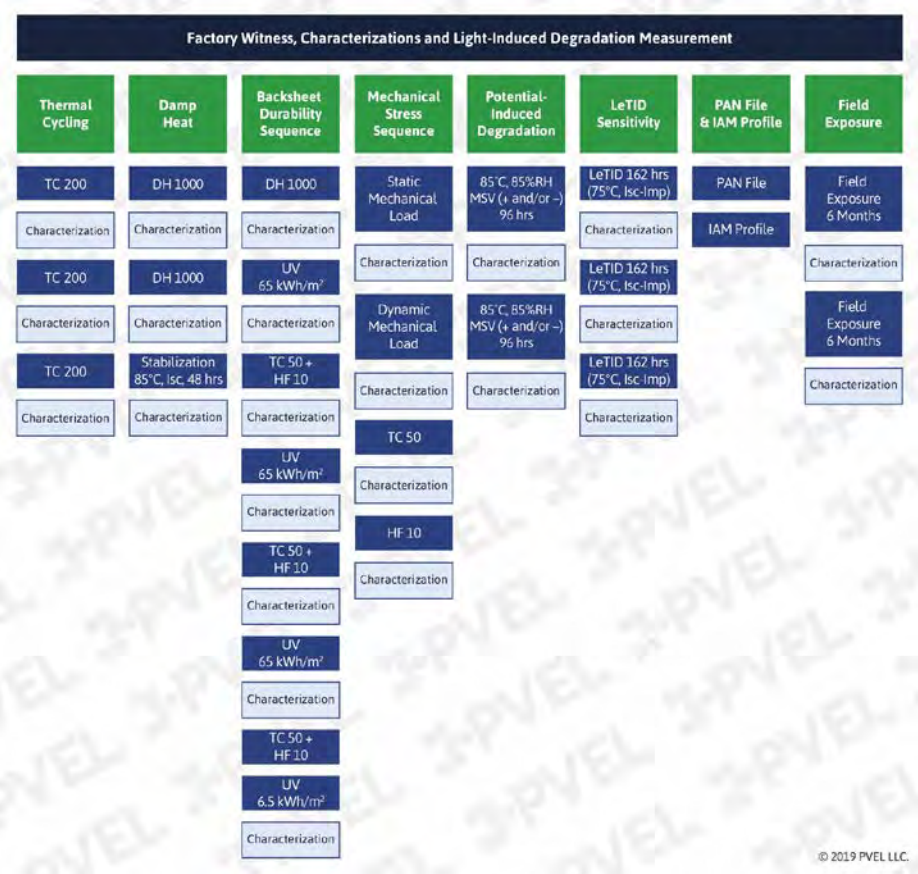


- G2G BiFi PV module can pass 10 x IEC damp heat (DH 10000 hours) test.



- G2G BiFi PV module can pass 8 x IEC thermal cycle test (TC 1600 cycles) test.

Testing 2: Sequential testing



BOM specifications for classifying modules (WIP)

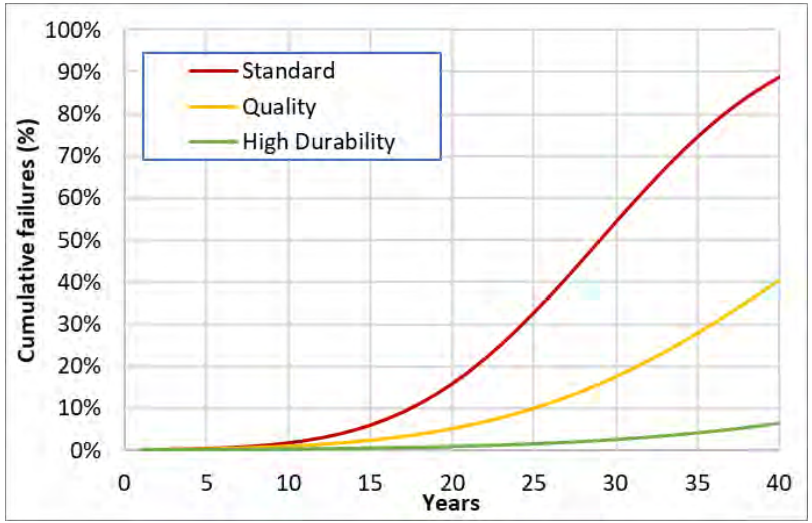
- BOM control

- More thought for ‘High Durability’?
  - What makes a J-Box ‘High Durability’?
  - What frame specifications are needed for ‘High Durability’?
  - Can EVA be ‘High Durability’?

 DNV GL © 2020

Summary of Perspectives on Module Useful Life

- Focused on failures not degradation
- Assume three classes of modules:
  - Standard
  - Quality
  - High Durability
- Explored cost implications 25 and 40 year
- Propose to classify a module with:
  - Manufacturing quality audit reports
  - Experience and financials
  - Extended-duration testing
  - BOM
- Provides motive to purchase a higher quality modules
- Provides boundary on premium price of higher quality modules



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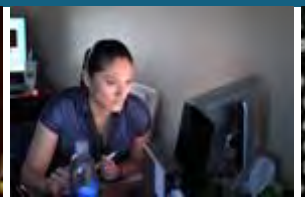
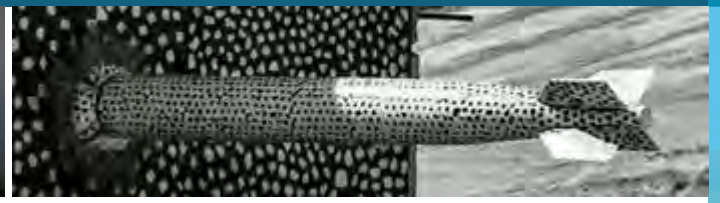
Inverter Faults & Failures: Common modes & patterns





Thushara Gunda

Photovoltaics Reliability Workshop

February 27, 2020

SAND2020-2323 C

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Yang Hu (GE Renewable Energy)

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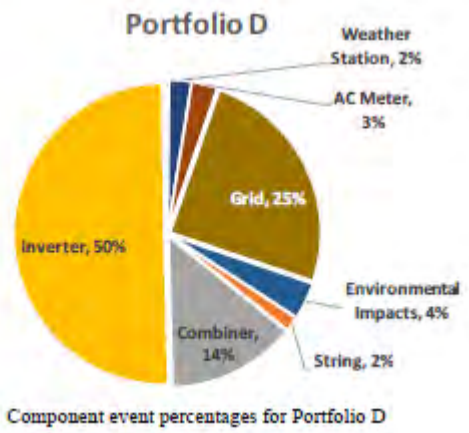
Inverters dominate failures



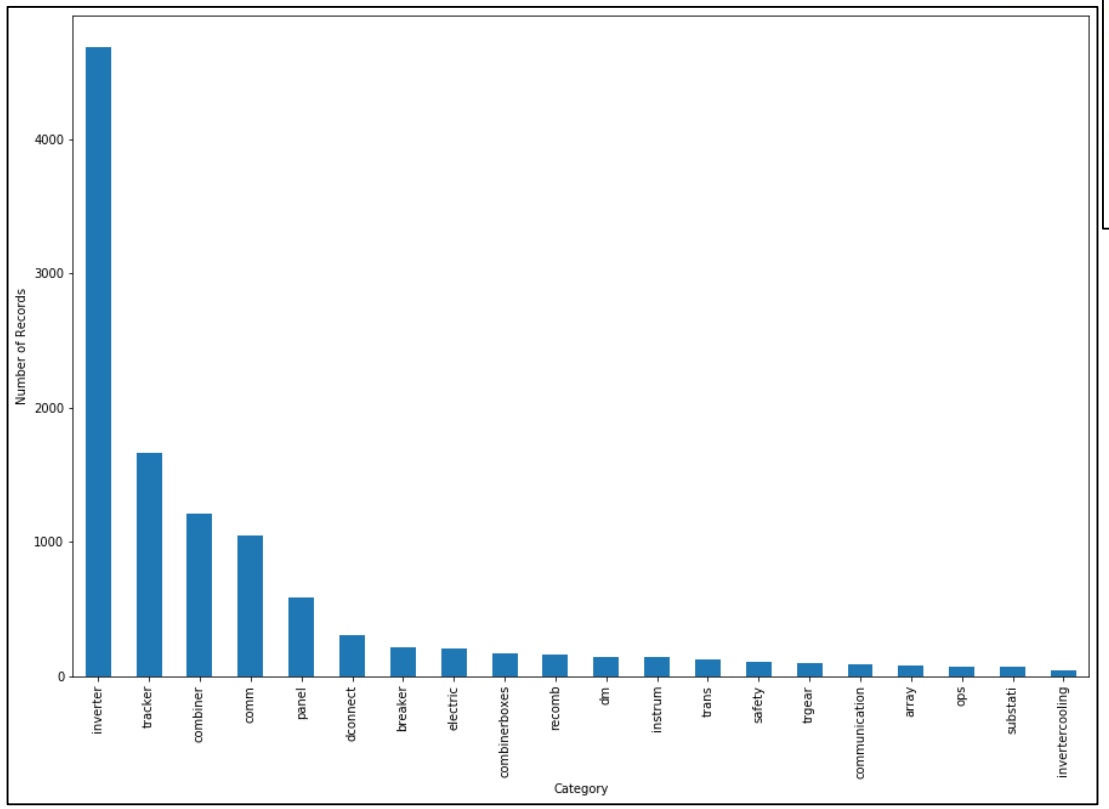
Component event percentages for Portfolio D

Freeman et al (2018)

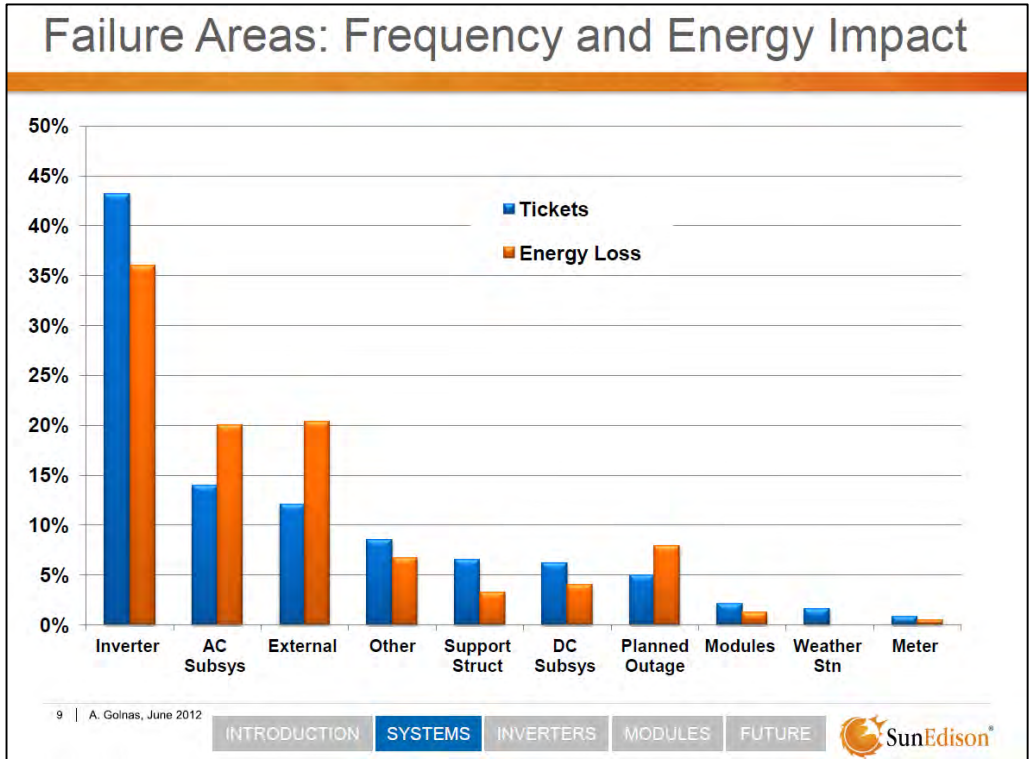
Table 1
Failures frequency [9].

#	Failure subsystem	Frequency, %
1	Inverter	43
2	AC subsystem	14
3	External	12
4	Support structure	6
5	DC subsystem	6
6	Modules	2

Cristaldi et al (2015)



EPRI (2019)



Golnas (2012)

Cost Implications

PV O&M BUDGET COMPONENTS AND COSTS

Based on PV system O&M estimates published by the Electric Power Research Institute, a utility-scale project O&M budget, excluding system monitoring plan, may cost between $10 to $45/kW per year.

Even though this list of budget items is not exhaustive, it demonstrates how O&M costs may vary widely. For example, "panel washing" is listed as "per event" occurrence, meaning that budget item can easily double or triple per year to ensure output performance if the PV plant is located in a rural, arid environment. One of the most varying cost is "spares". Asset owners expecting high reliability from system performance will require more stringent spare parts management, such as keeping the most critical equipment like inverters and transformers available at all times.

TABLE 1. ESTIMATED PV O&M BUDGET COMPONENTS AND COSTS.

BUDGET ITEM	BUDGET RANGE ($/KW-YR)	NOTES
Overall Budget	$10.00-45.00/ kW-yr*	Variable based on whether cost plus, extended warranty, and other items are included. Also, some O&M activities are non-linear which can affect overall outlays.
General Site Maintenance	$0.20-$3.00/ kW-yr	Variable based on system size, location. (e.g., desert environments are less expensive than snowy locales that require snow removal from critical areas), and frequency of activity.
Wiring/Electrical Inspection	$1.40-$5.00/ kW-yr†	Includes inspection of wires, junctions boxes, combiner boxes, AC/DC disconnects, service panel, etc.; string testing. Prices will differ, among other things, based on whether inspection covers 10% or 100% of the plant.
Panel Washing	$0.80-$1.30/ kW-yr†	Variable based on technology (different form factors), cleaning regimen, prevailing wages, and other factors. As a result, some stakeholders provide cost metrics on a $/module basis.
Vegetation Management	$0.50-1.80/kW-yr†	Variable based on site characteristics and acreage. Often a "cost-plus" contingency item.
Inverter Maintenance	$3.00-7.50/kW-yr†	Activity typically encompasses cleaning of filters, torqueing, thermal imaging of internal components, minor equipment repair, etc.
Inverter Replacement	$6.00-10.00/kW**	Typically, plant owners only budget for one inverter replacement activity after the initial warranty period. Price ranges encompass different utility-scale inverter sizes and models.
Racking / Tracker Maintenance	Insufficient data	Racking maintenance is negligible, however tracker maintenance is more costly. Specific data points for the latter activity are insufficiently available.
Spares	$2.00-$20.00/ kW-yr***	Most critical spares to have on hand include fuses, contacts, wiring, inverter parts (circuit boards, filters, fans, etc.), disconnect switches, and modules.

Source: EPRI, 2015 December, "Budgeting for Solar PV Plant Operations & Maintenance: Practices and Pricing"

Notes: Budget numbers exclusively for utility-scale plants; they encompass an entire range of baseline, cost-plus, and warranty terms.
* Constituent components of the O&M budget are non-linear and will not necessarily add up to the overall budget on a $/kW-yr basis.
** Inverter replacement metrics are based on a $/kW, and cover a one-time equipment replacement and installation activity over the course of a plant's lifetime.
*** Budget range for spares primarily encompasses equipment procurement and storage costs.
† Price points based on a 1x annual frequency (i.e., per event)

6

SEPA (2019)

Study Objective

- Analysis of maintenance logs to identify most common failures modes within inverters
- Identification of variabilities across climate, equipment, and other factors

Dataset

6 industry partners

650+ sites (2008-2019 COD)

80% utility-scale

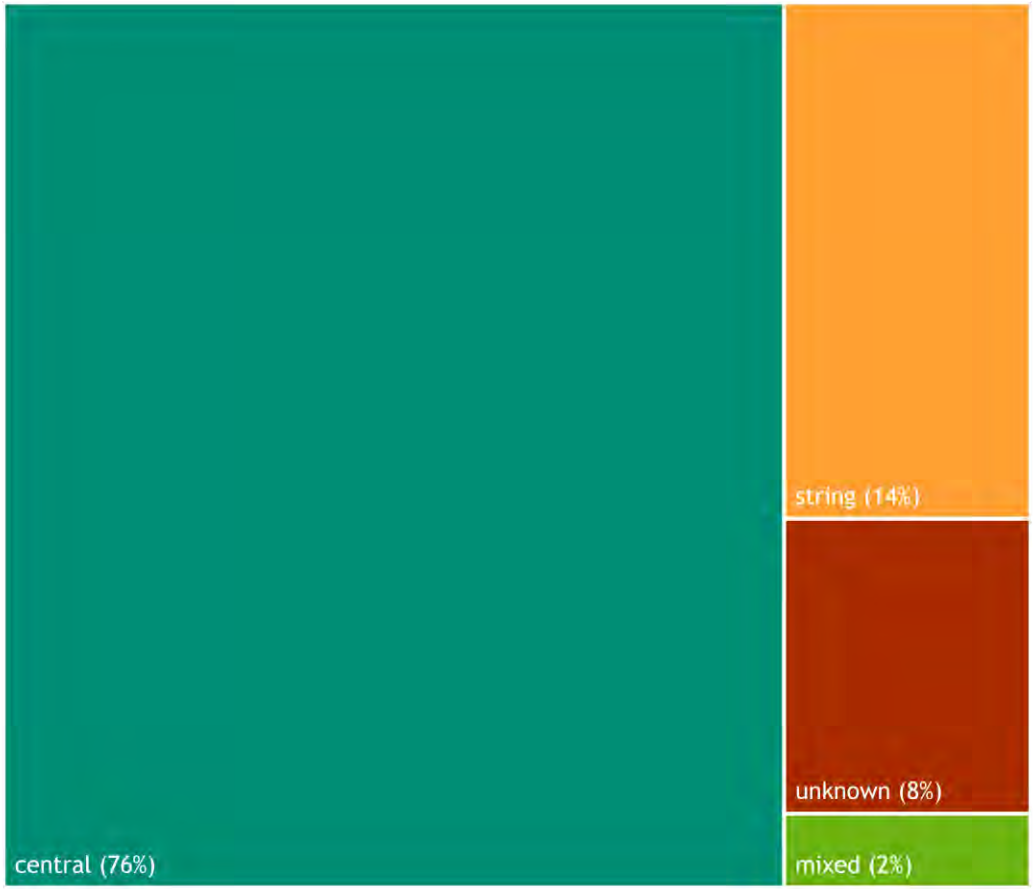
5.2 GW in DC Capacity (4.0 AC_{GW})

26 U.S. states

13 climate zones

Central inverter-type dominated

20K records (97% CM)

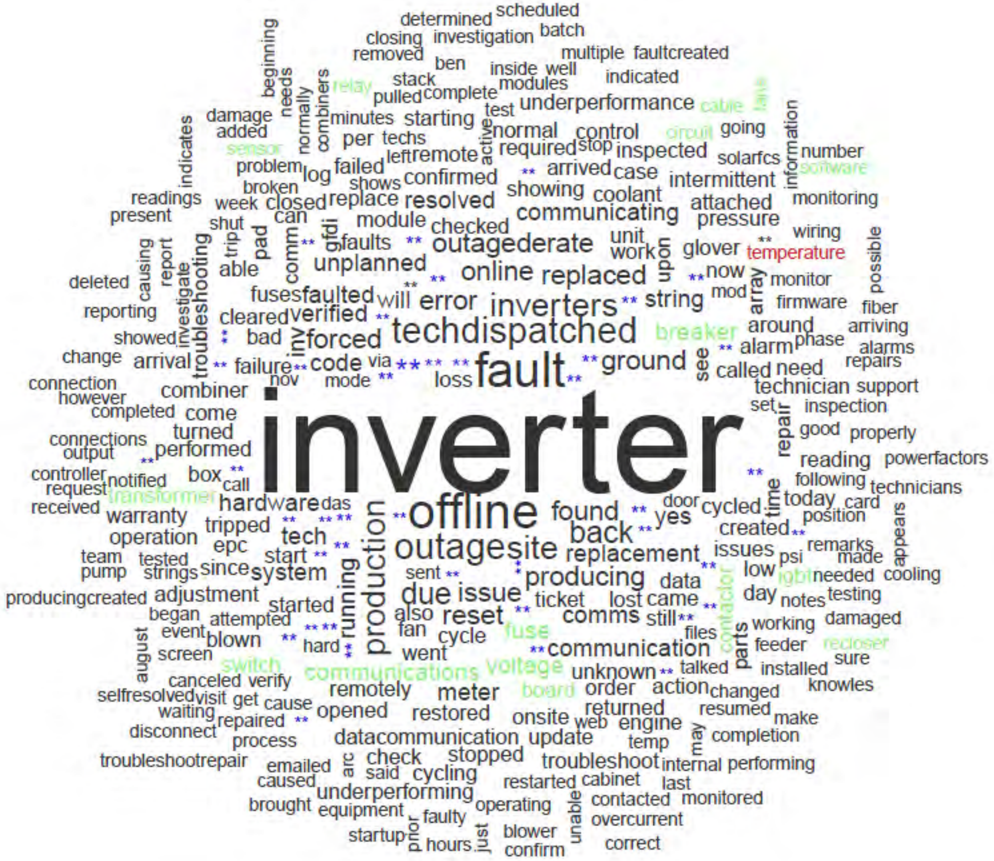


What do the tickets contain?

Varying level of detail

Common elements include site location, time, and description

Used text analytics + machine learning to develop a consistent “asset” label across the logs



Common terms in tickets
Component/subsystems
Weather terms

Failure Modes

Failure Modes: Literature Review

Common modes include:

- Subsystems: storage capacitors, power stage drivers, cooling, isolation transformers
- Functional aspects: controller, interlock, internal, matrix, design
- Stages: manufacturing and inadequate design, control, and electrical components
- Root cause: parts/materials, external, software, other, unknown, construction, preventative maintenance

Common components include: fan motor, air filters, control software, power supply, AC contactor, DC contactor, capacitors, fuses, GFI components, IGBT matrix/driver control board, inductors, …

- ➢ In this work, failure modes focus on replacement (i.e., components that can be replaced/have individual part #s)

Inverter Subsystems

IGBTs

PCBs/Cards (control, communications, accessory, sensor, driver)

Capacitors

Contactors

Heat Mgmt. systems (fans, motors, pumps, liquid, filters)

Sensors

Fuses

Switches

Power supply

Reactor/inductor

Breakers

AC Output

Enclosures

Transducers

External to Inverter

- Cabling
- Recloser
- Transformer
- Relay

Systems-level

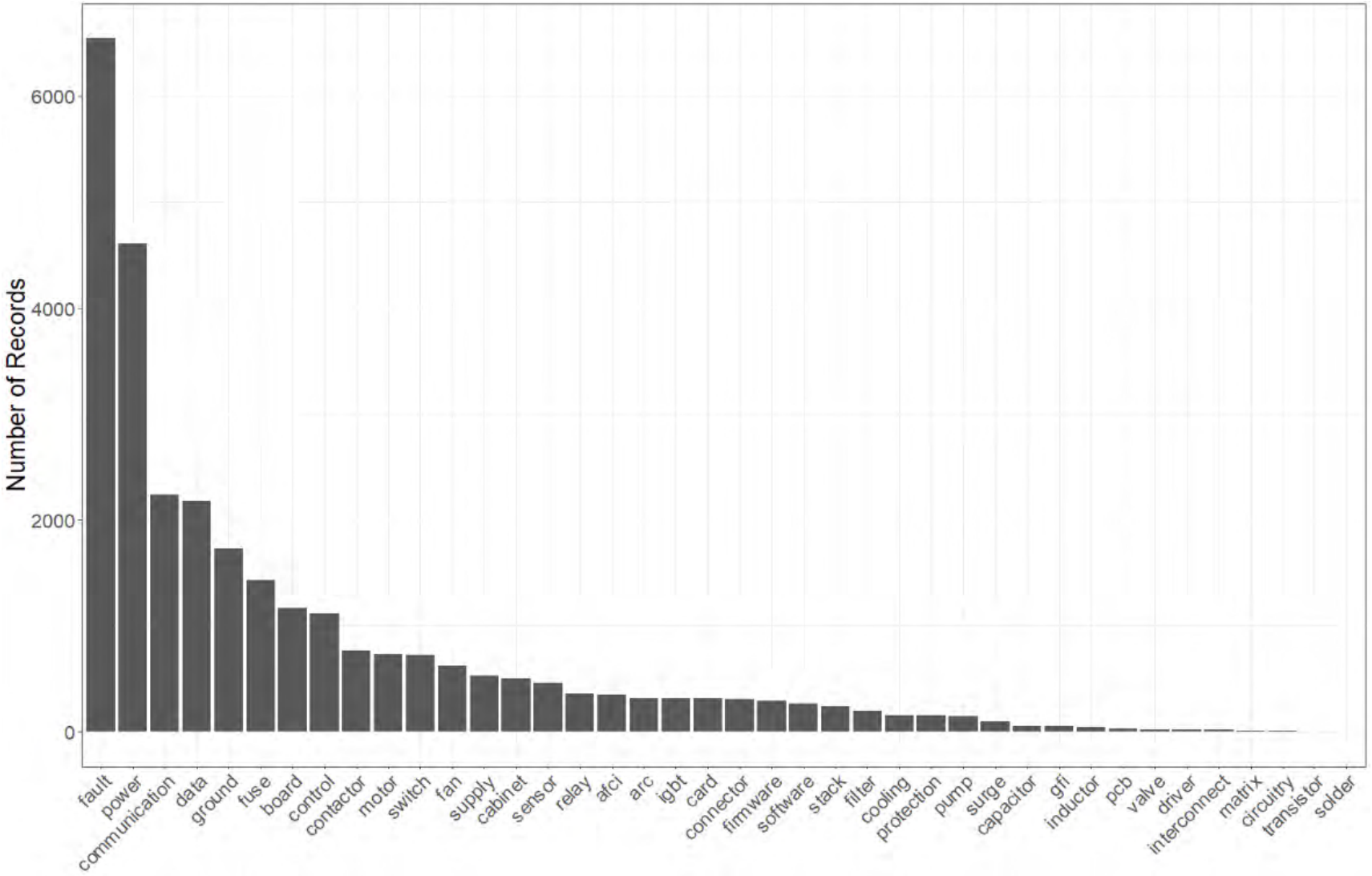
- Configuration (hardware)
- Software (settings, updates)
- Communications

Data Patterns

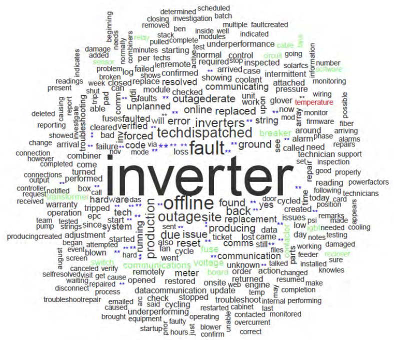
Key Terms in Data

Single term searches provide some insight

Combinations of words would be more informative



Topic Modeling



Collection of O&M tickets

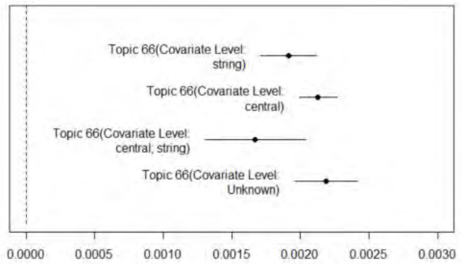
Latent Dirichlet Allocation

hardware replacement offline …	ground fault wiring …	power cycle supply …

Topics: Clusters of words

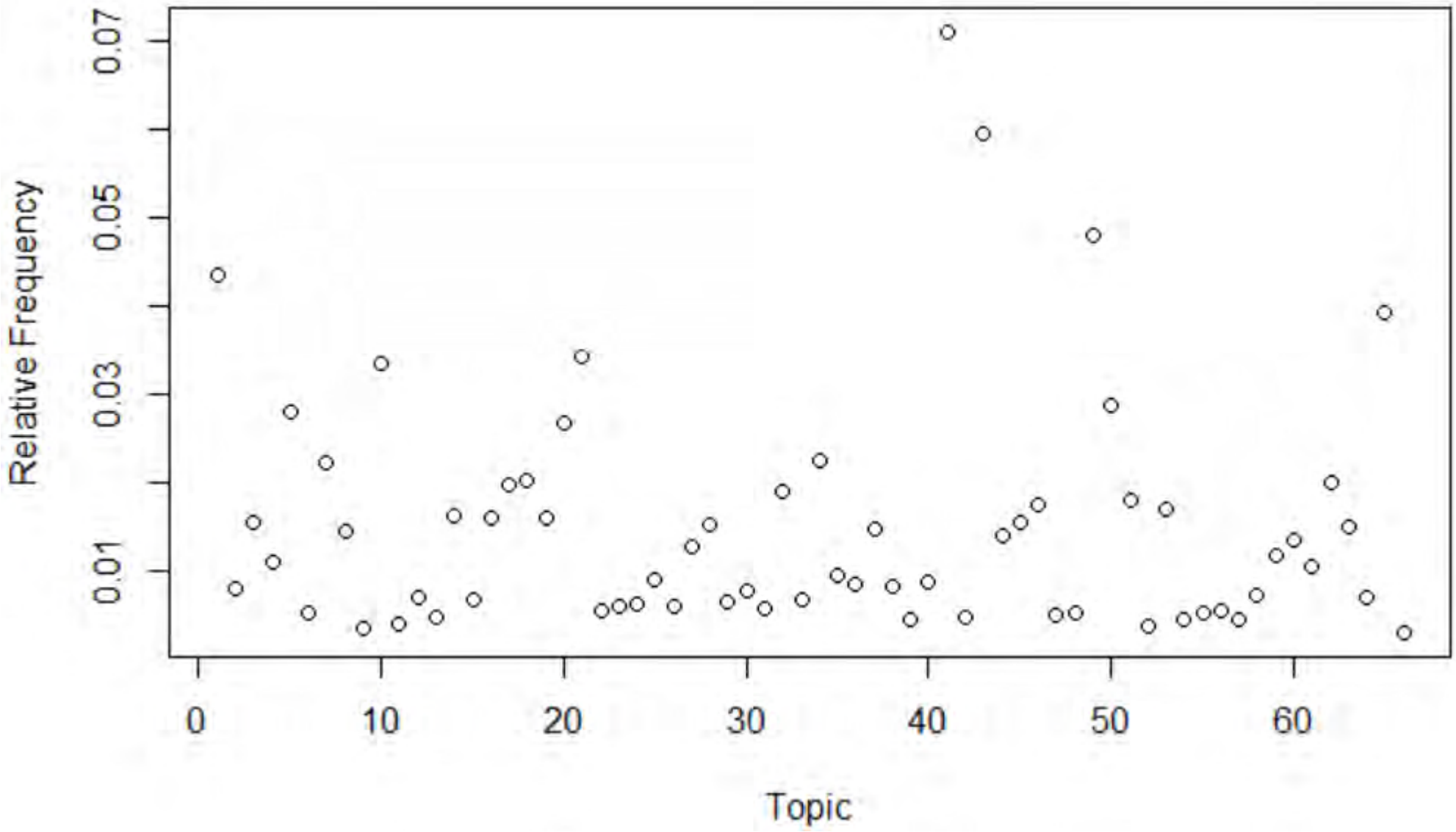
Document	Topics
Inverter cycling due to hardware malfunction. Power cycle.	hardware; power cycle
Inverter #4 down. AC fuse replaced. 24 volt power supply replaced.	fuse; power supply

Distribution of topics

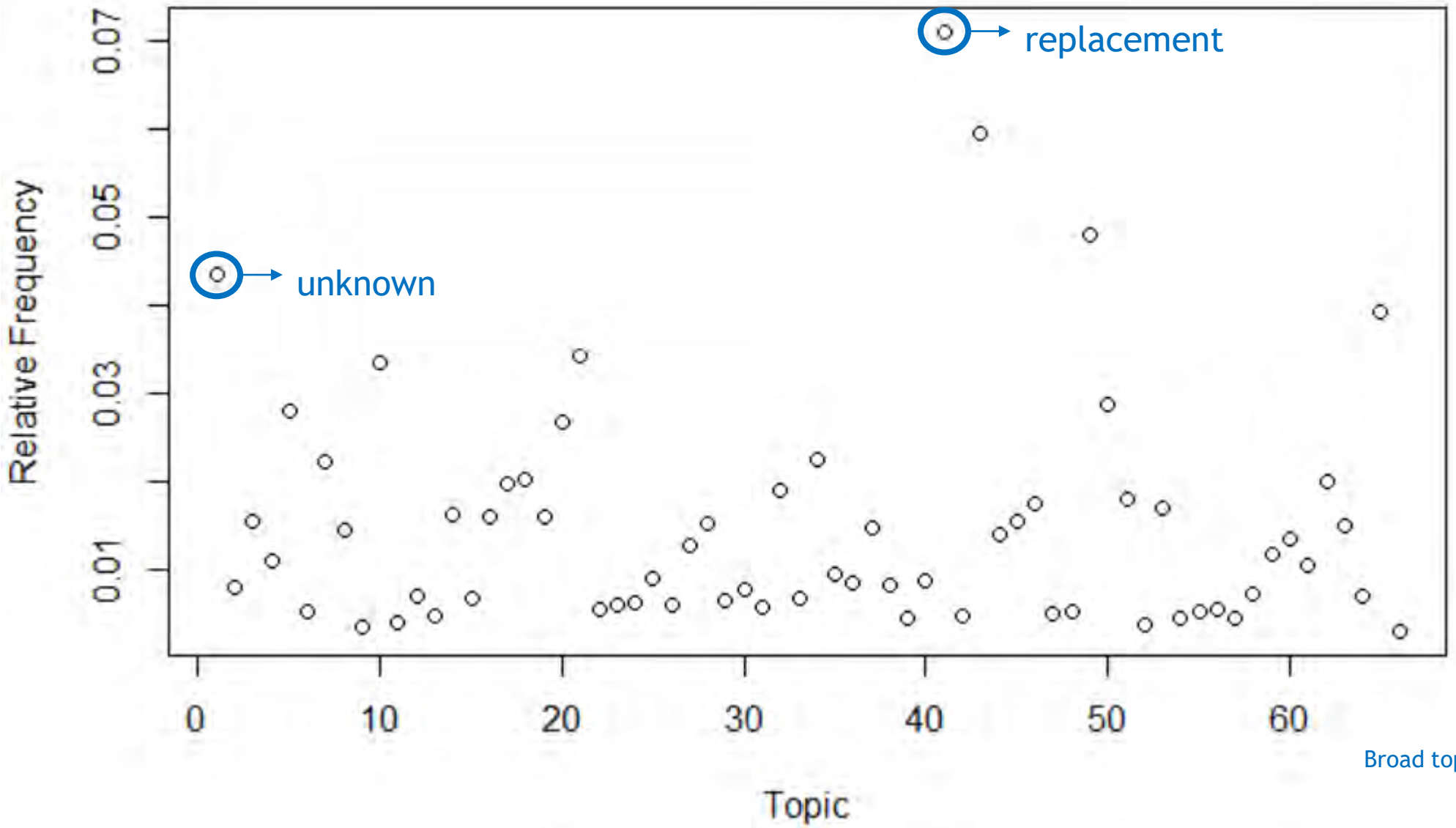


Differences across attributes

Topic Frequency

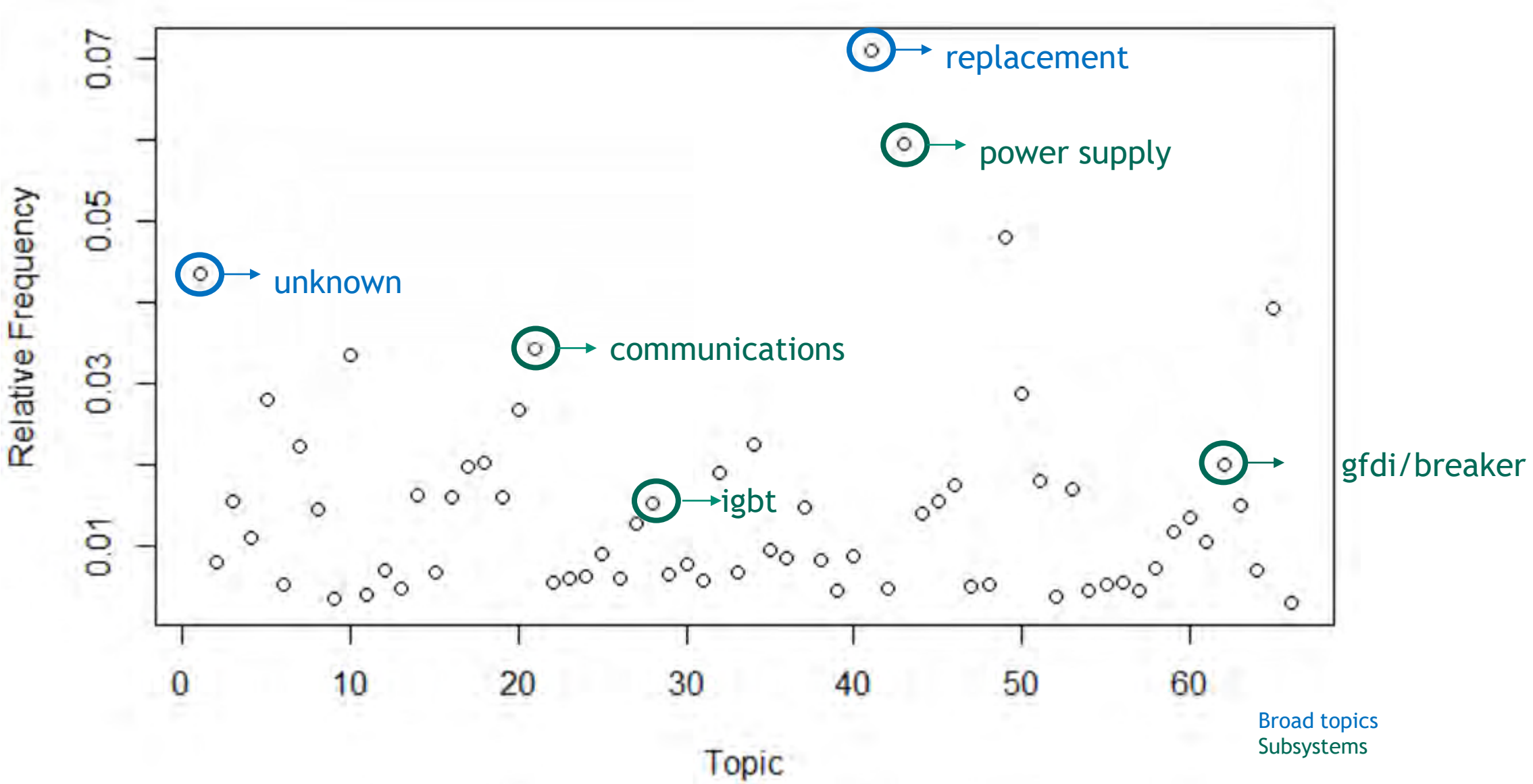


Topic Frequency



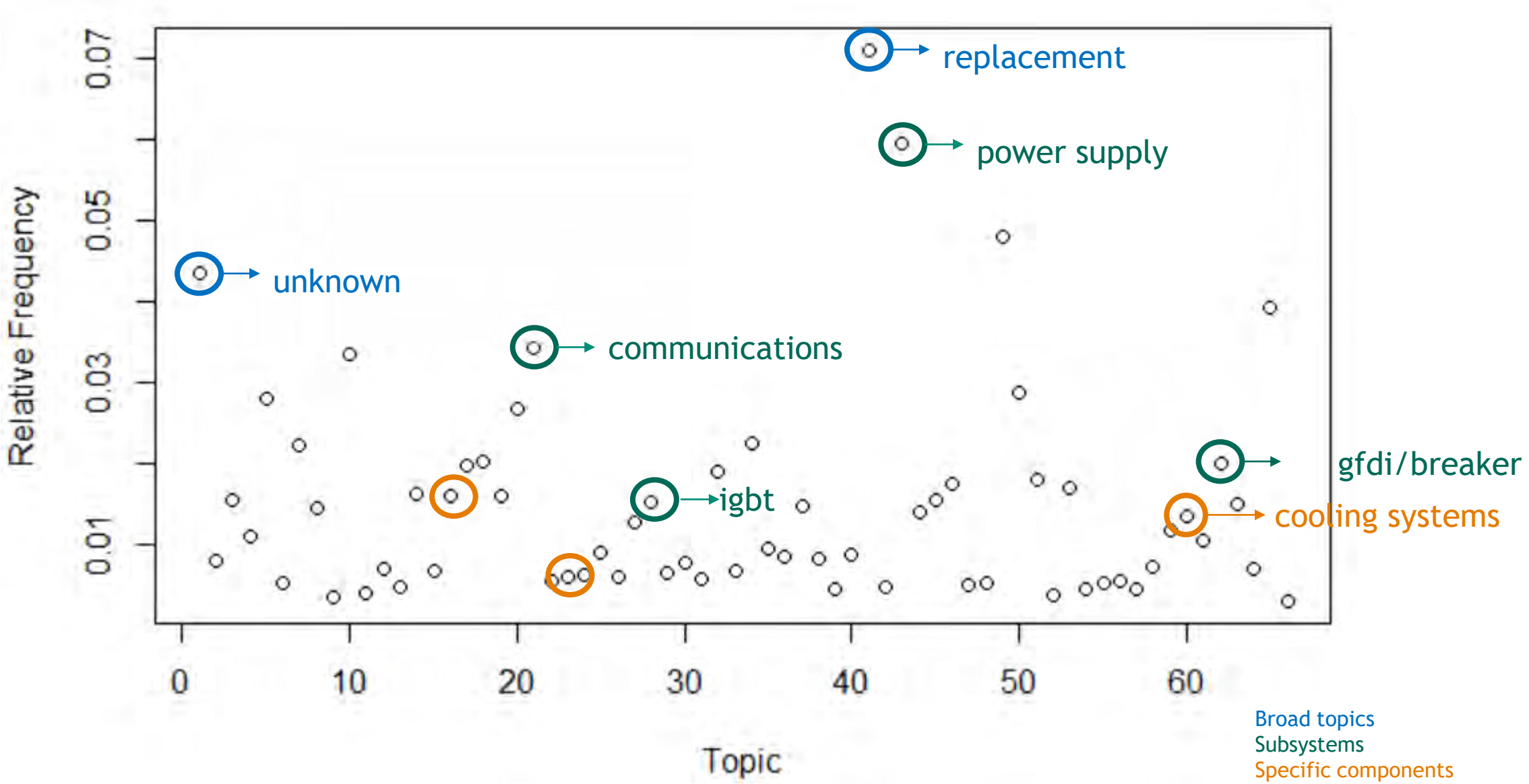
Broad topics

Topic Frequency



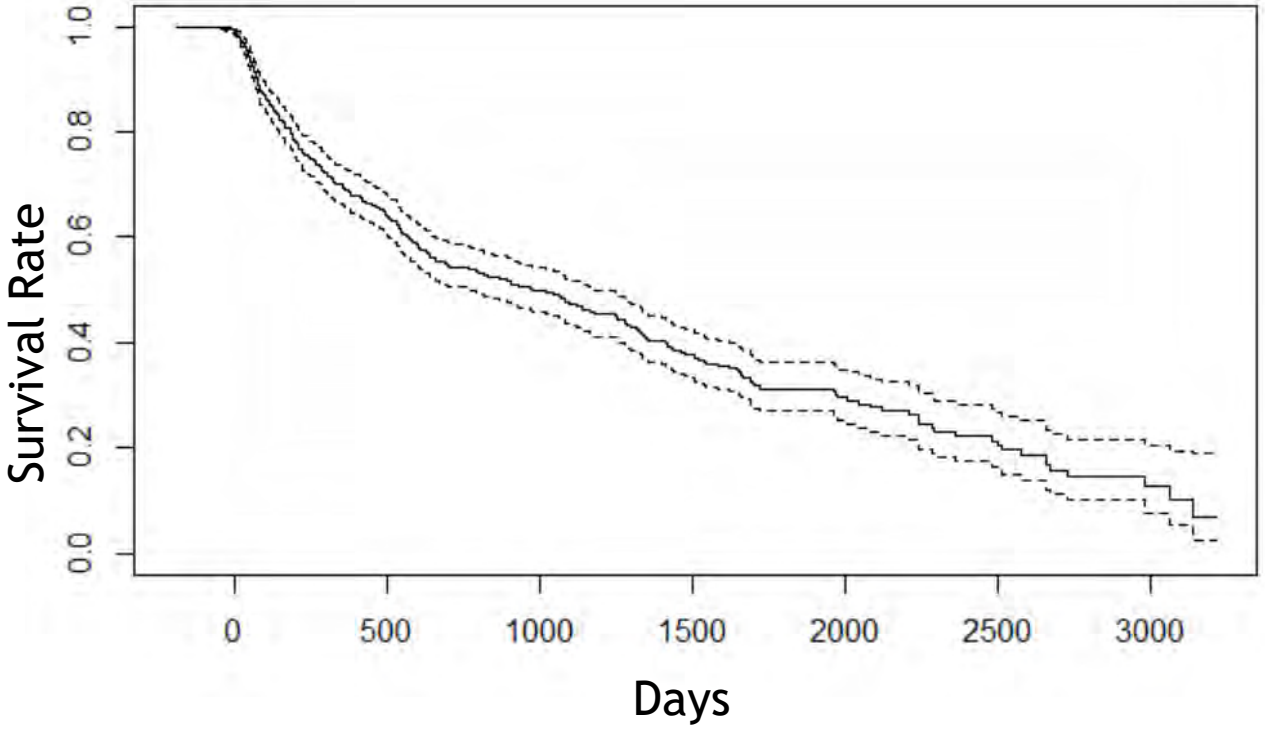
Broad topics
Subsystems

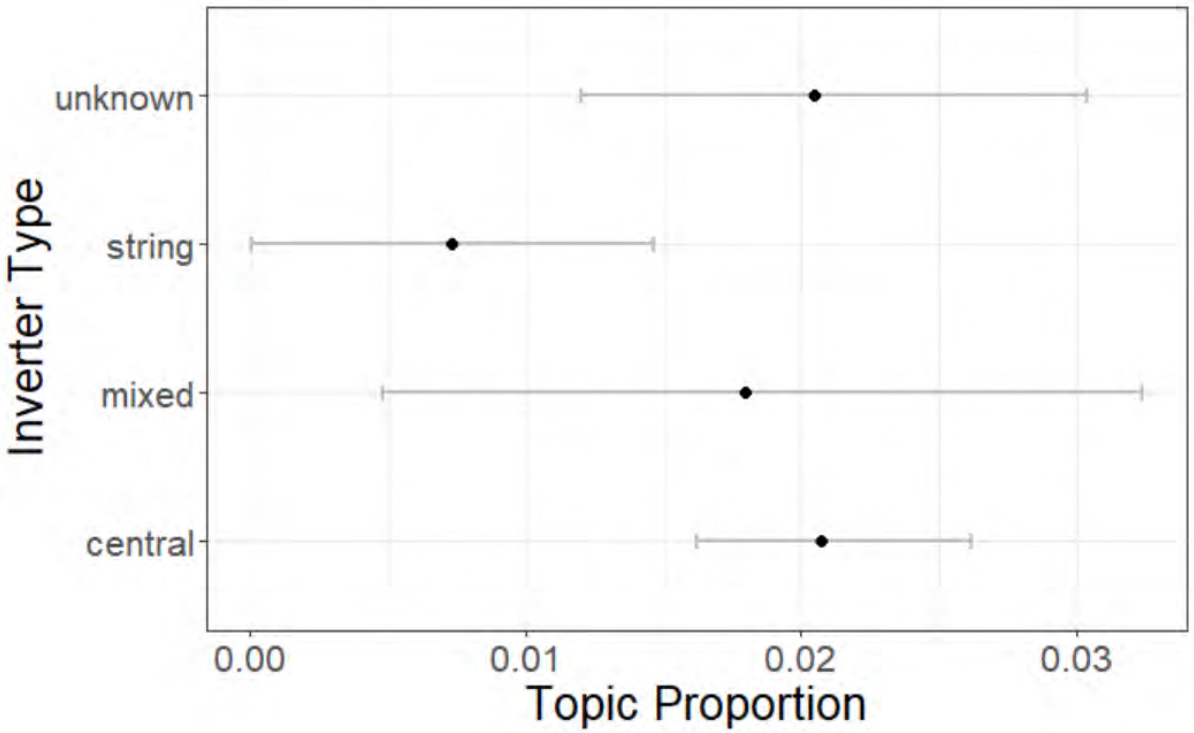
Topic Frequency



Broad topics
Subsystems
Specific components

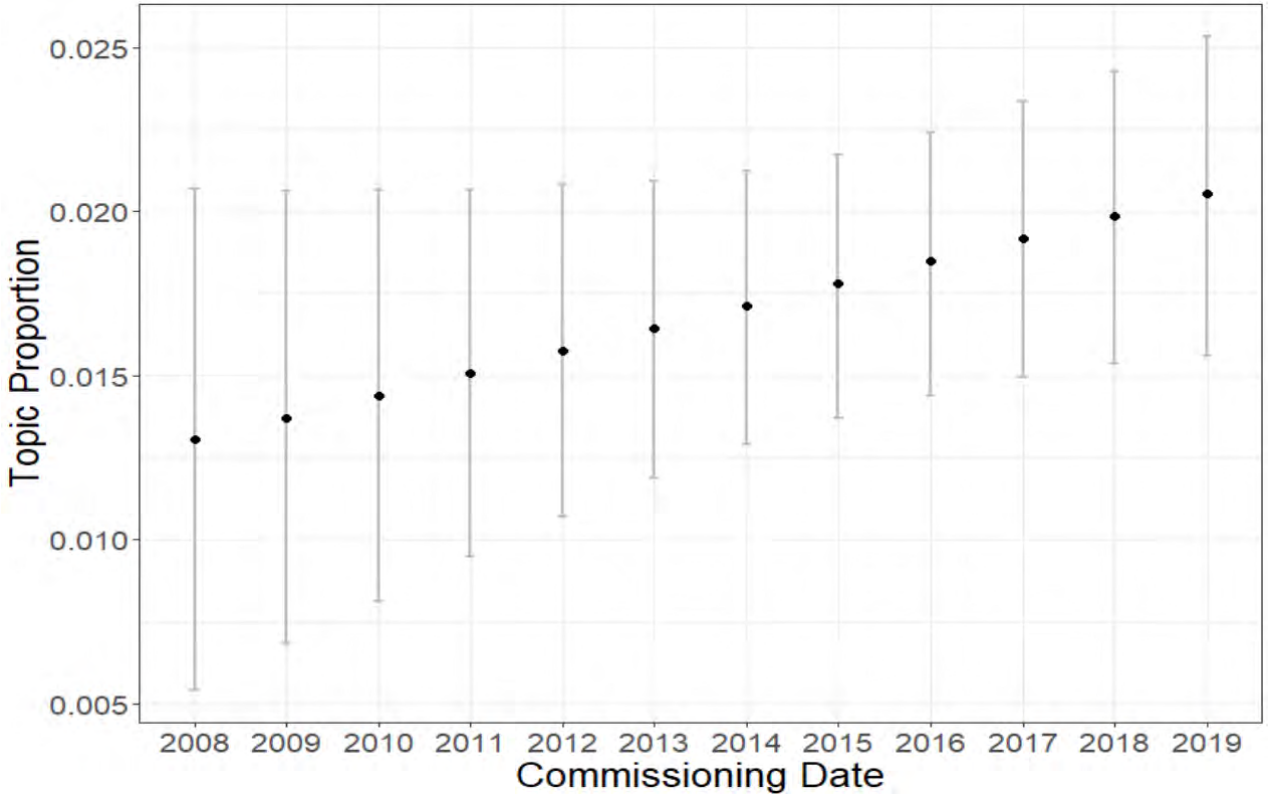
Failure Patterns: IGBTs

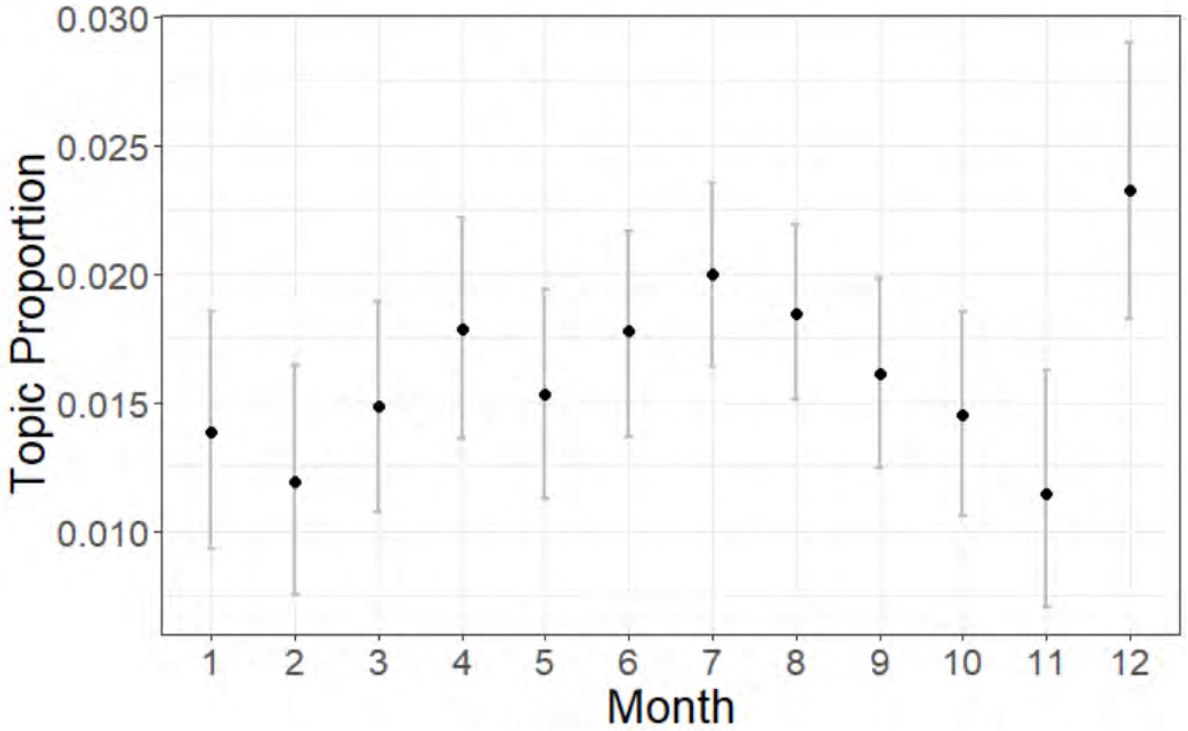




- Within 9 years, almost all sites experience an IGBT failure
- IGBT failures are less prevalent in string inverters than central inverters

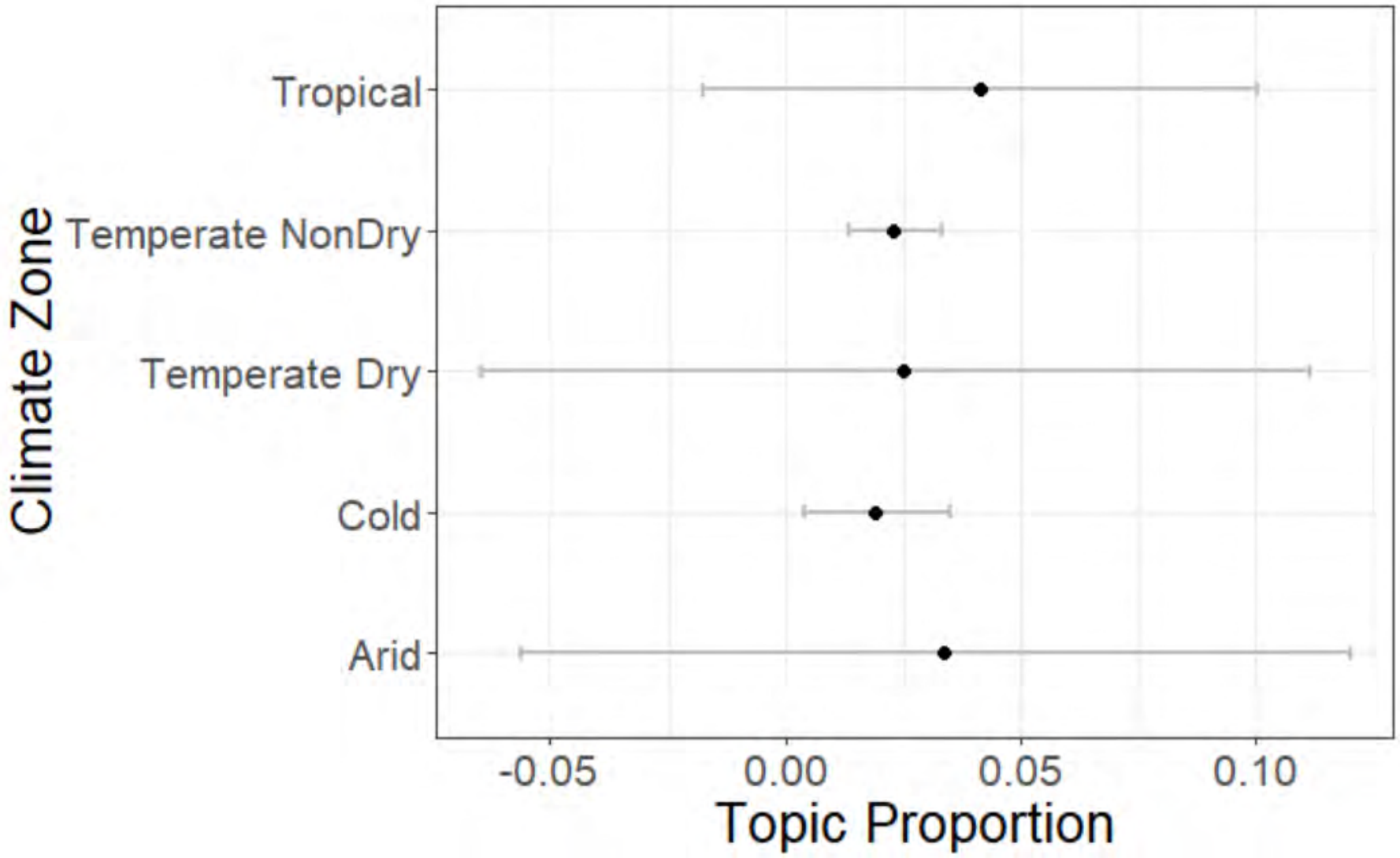
Temporal Variations: Ground Faults/Breaker Trips



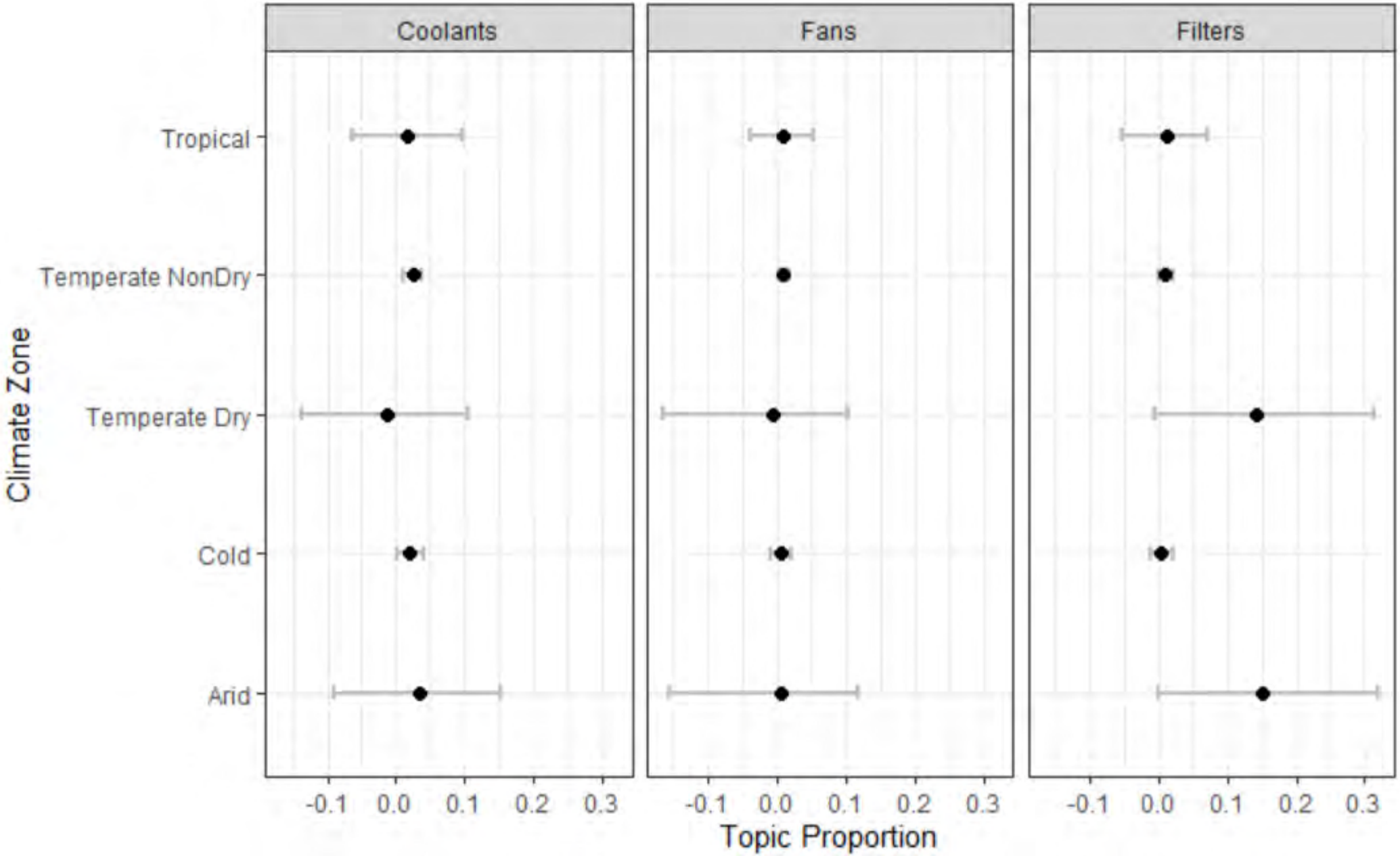


- Increasing prevalence of ground faults in recent years
- Seasonal variations present – financial considerations for Dec peaks?

Geographical Variations: Ground Faults/Breaker Trips



Geographical Variations: Cooling Systems



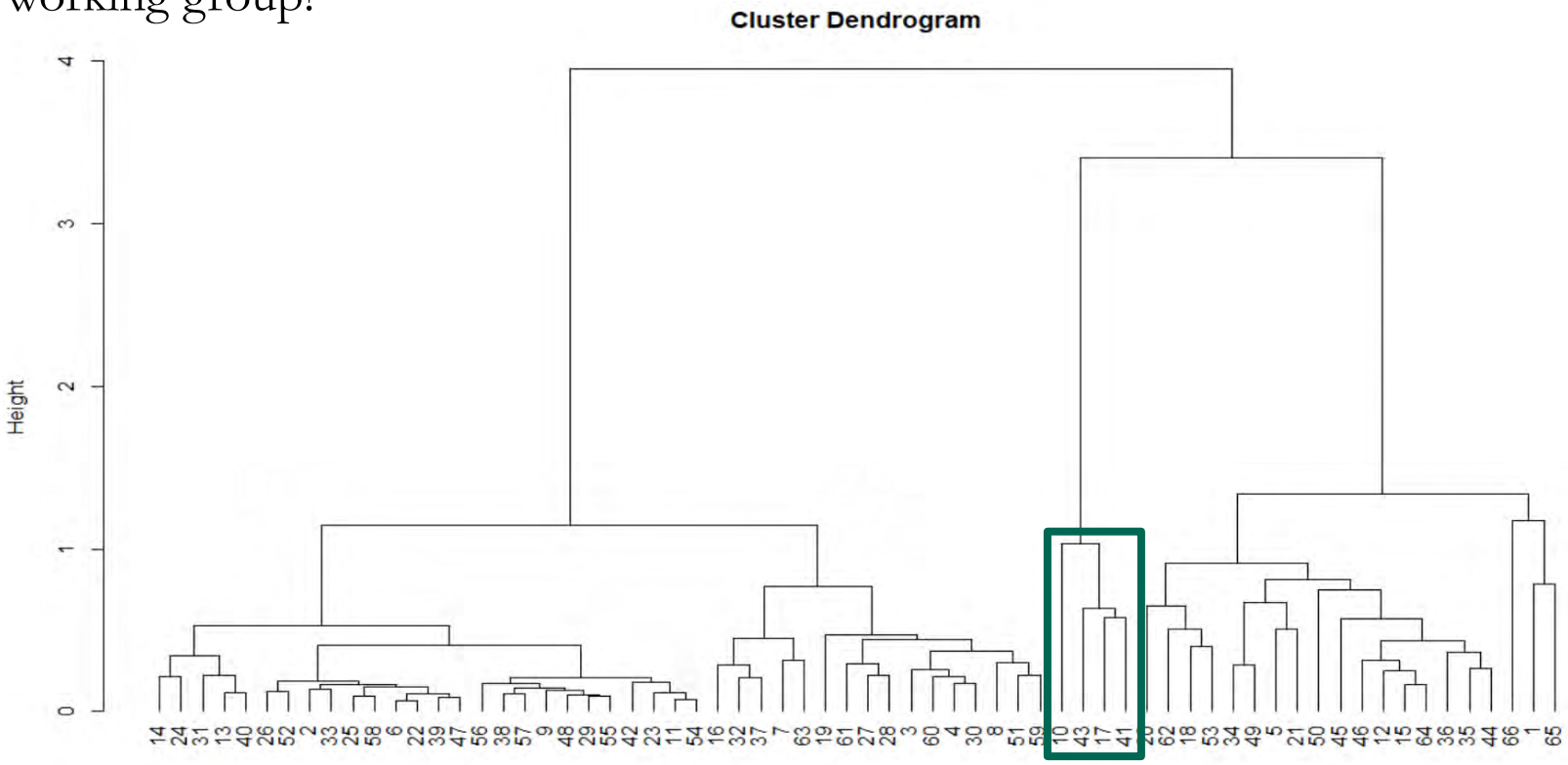
Ongoing work

Are these patterns consistent with your experiences?

Evaluate correlations between topics

Continued discussions standardization is needed (for analysis, for reporting)

Welcome to join our quarterly working group!



Power supply + replacement

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Thank you for your time!

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Inverter Reliability: An EPC Contractor's Perspective

Beth Copanas, Director Solar Energy

February 27, 2020

Agenda

- RES Overview
- RES Inverter Reliability Experience
  - Construction Phase
  - Operations and Maintenance Phase
- Next Steps

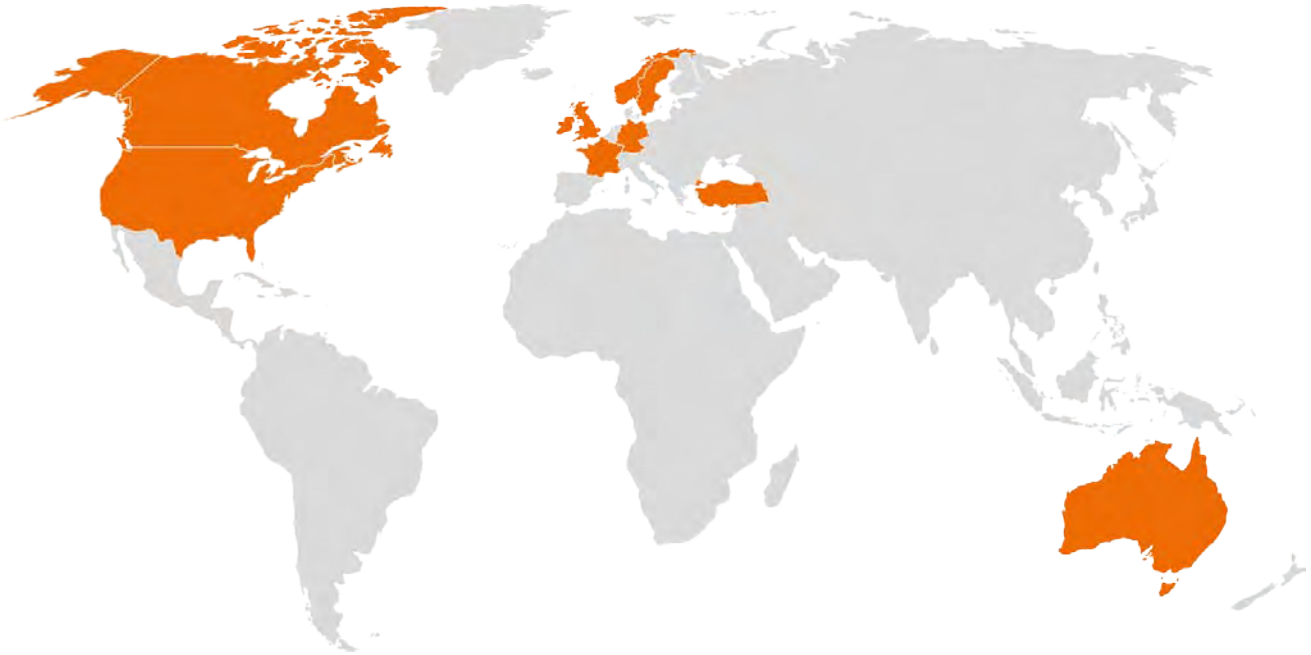
RES Overview

17 GW
PROJECT PORTFOLIO

37
YEARS OF EXPERIENCE

5.5 GW
OF OPERATIONAL ASSETS SUPPORTED

2500
EMPLOYEES



ACTIVITIES

DEVELOP

CONSTRUCT

OPERATE

TECHNOLOGIES

WIND

SOLAR

STORAGE

T&D

Presentation Today

RES would like to thank NREL and the PV Reliability Workshop Committee for the opportunity to present today.

Today's presentation is based on RES' Engineering, Procurement & Construction (EPC) experience in the US and UK Operations and Maintenance (O&M) experience.

Special thanks to:

- *Our Industry Partners*
- *James Willet – RES Engineer, Brian Darnell – RES Head of Solar O&M, UK*
- *RES EPC and O&M Colleagues*

While these slides present worst case issues RES has encountered, the challenges outlined in this presentation represent a small subset of projects.

RES values our industry partners and welcomes opportunities to collaborate to improve PV system design, construction and O&M / Asset management.

Inverter Reliability

The inverter is the critical engine of the utility scale plant starting with commissioning & testing during the construction phase all the way through the end of the 35 year project life cycle.

Construction (EPC)

- Performance Liquidated Damages Risk ($250,000 – $4,000,000 USD per project)
- Delay Liquidated Damage Risk ($30,000 – $140,000/day USD)
- Loss of Test Energy Revenue

Operations & Maintenance (O&M)

- Annual Performance Test Risk
- Overall Decrease in Operating Plant Revenue
- Increased OPEX as compared with expected OPEX

Increased Risk for EPC Contractors, O&M Providers, Owners and Investors

Can lead to Decreased Owner and Investor Confidence

RES US EPC Experience

RES projects in the Construction Utility and Performance Testing phases during 2019:

- EPC for about 500MWac
- 5 Different Inverter Suppliers across the projects
- All Projects utilized Central Inverter Solutions: a skid foundation with integrated inverter supplier provided Medium Voltage Transformer (MVT)
- Installed Inverters ranged from 2,000 KVA to ~ 5,000 KVA/ integrated skid
- Inverters were either Owner or RES procured
- Since then, 2 out of 5 Suppliers have left the central inverter business

Choice of inverter has major impact on project availability and opex.

RES encounters many Owners of existing PV assets encountering reliability issues due to initial inverter selection.

However, RES finds Inverter downtime is not as major an issue as compared to some balance of system (BOS) issues (i.e. transformers, switchgear, and corrosion), when the measures below are in place:

- Good maintenance capability (preventative & corrective)
- Good relationship with OEM
- Rapid Response Times
- Ample Spares
- Pro-active versus reactive firmware updates

Failure Types

Inverter Failures fall into two categories, both types have implications for projects in the Construction and Operations & Maintenance Phase

Inverter Failures

Obvious Fault or Equipment Failure

- Inverter generated fault codes or alarms
- Visibly damaged equipment

Underperformance with no Clear Failure Mode

- Obvious underperformance
- No fault codes/alarms or visible equipment failure
- Requires data analytics and deductive evaluation to rule out other PV system component failures as root cause which results in Increased Project Delay Risk

Observed Types of Failures during Construction Phase

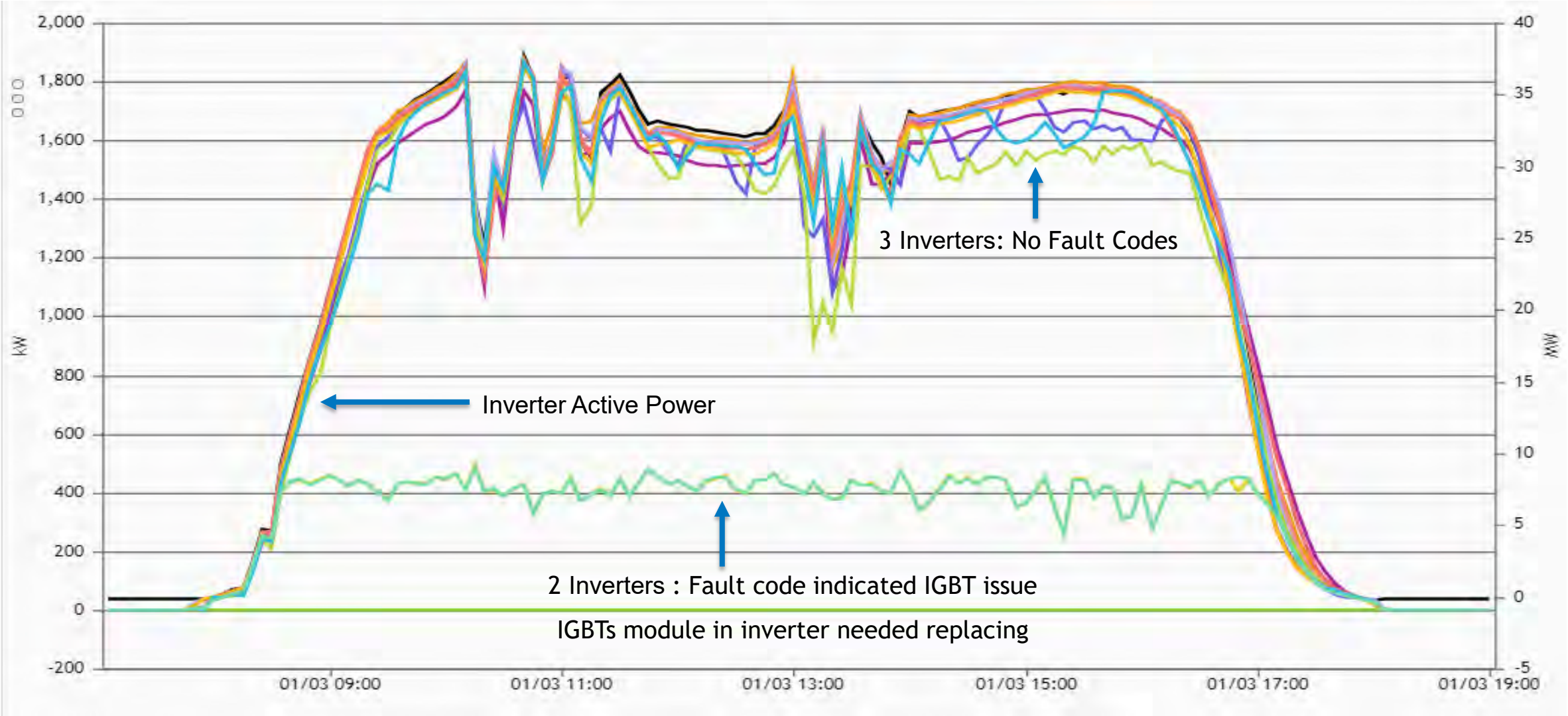
Project	Integrated Skid/ Transformer	IGBT Stack replacements	Other
Project #1	(1) Skid with Inverter + transformer replaced Major Shipping Damage	(6) IGBT Stack replacements	(8) Controller Boards Replaced
Project #2		(1) IGBT Stack replacement	(3) Inverters required Insulation Resistance Reprogramming and (1) Insulation Resistance Monitor Replaced
Project #3			
Project #4			Identified Plant wide Inverter Underperformance due to PPC algorithm issues.
Project #5		(5) IGBT Stack replacements	(1) Inverter major internal faults. Entire inverter replaced.

Only includes items that caused significant downtime or project production losses. Other minor issues that caused downtime or required repair / resolution (door alarms, communications failures, CT failure, etc.) not included.

Construction Phase: Underperformance & Obvious Failure Examples

Identified prior to contractual performance testing, post inverter commissioning and utility testing.

Clear Sky window with Stable, Plane of Array Irradiance (POA)



Construction Phase: Underperformance Example

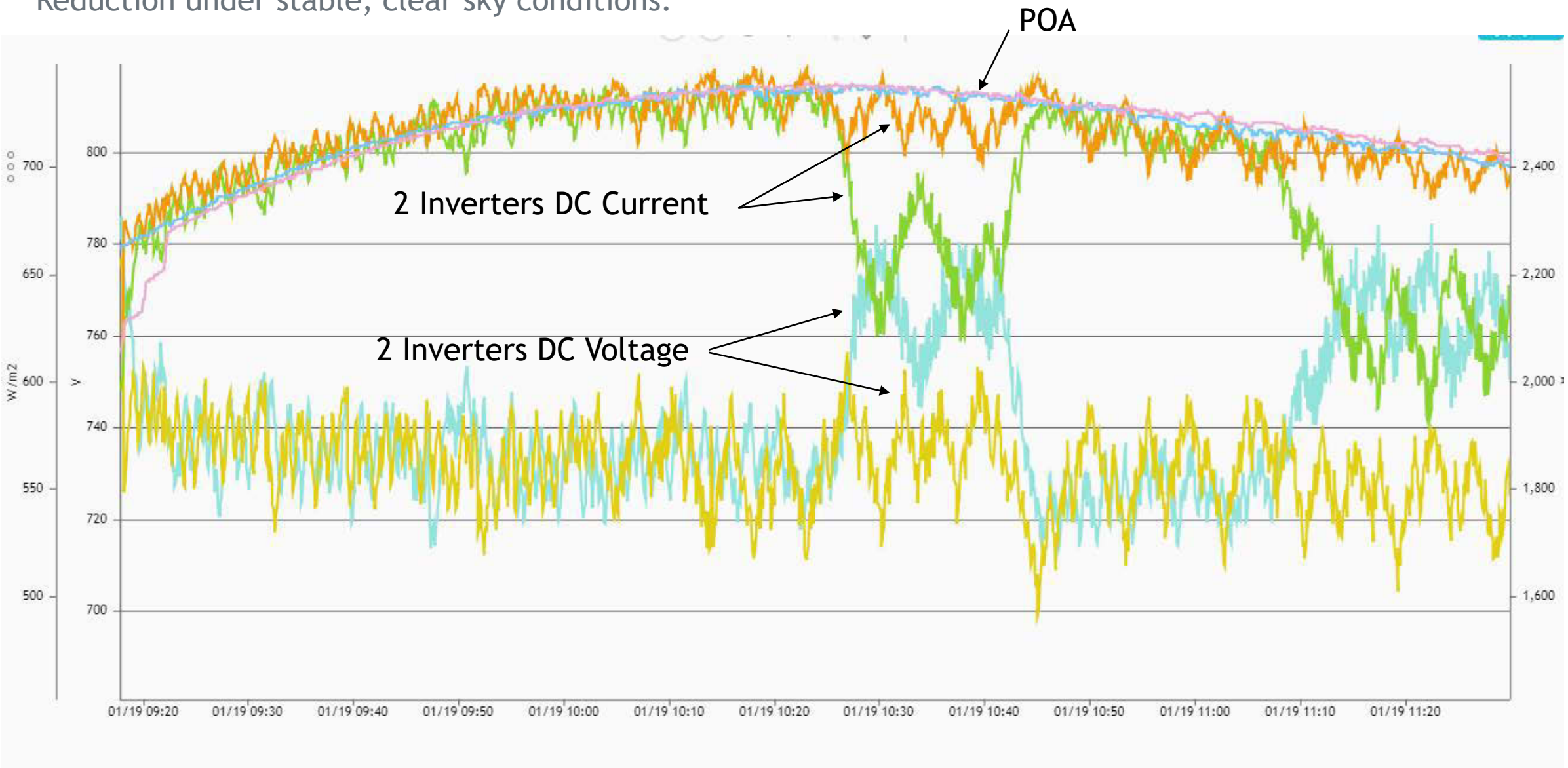
Inverter Supplier Requested Additional Data and Run - time to confirm that the issue wasn't related to:

- Overall system design
- Installation quality: including taking combiners feeding inverter DC bus off-line to ensure no field fault issue
- Defective PV modules
- Power Plant Controller (PPC) settings and point mapping

RES, Owner, Inverter supplier and other BOS suppliers spent time evaluating.

Construction Phase: Underperformance Example

Once removed from the PPC, underperforming inverters still showed DC Voltage Rise and DC Current Reduction under stable, clear sky conditions.



Construction Phase: Underperformance Example

Once Inverter Supplier satisfied other balance of system (BOS) components not the root cause, a process of elimination was initiated to identify if internal inverter component was causing the issue:

- Inverter internal DC Bus Voltage reading versus actual DC voltage in terms of voltage gain issue
- CT replacement
- IGBT module swap out
- Controller Board Replacement

After 3 Months, confirmed that 8 out of 25 Inverters needed to have a Controller Board replaced. The Controller board was defective and causing issues with the Maximum Power Point Tracking, (MPPT).

- Resulted in major schedule delays
- Extra Project costs incurred

RES UK O&M Case study - Inverter Re-build

- During the peak generating period a defect resulted in a fire and damage to the inverter
- Inverters had no DC disconnector and no way to shut off current in case of internal short circuit.
- Although the failure was covered by the warranty, the manufacturer could not attend site for several weeks
- RES re-built the inverter using available spares as approved by OEM. Estimated OPEX savings - £10,000/$13,000 USD

RES O&M Case Study - Inverter Repowering

- RES took over O&M of a UK plant built in 2011 which had chronic inverter and transformer issues.
- Following a critical inverter failure, the client asked RES to propose a repowering option.
- RES procured a replacement inverter
- The project was challenging due to the need to retrofit a solution to an existing site. The retrofit was completed and RES to repower a further 4 inverter stations.

RES O&M Case Study - Inverter upgrades and re-powering

Substantial rebuild of inverters following fire incidents and lack of OEM support. Retrofit of fire suppression system to **minimise plant downtime. Estimate £20k or $26k year USD opex and revenue saving.**

Retrofit of upgraded inverters to existing scheme at 8 year old site due to original equipment reaching end of life. **Reliability and efficiency improvement of £50k or $65k/year USD**.

Next Steps

- Continue to work with suppliers, and Owners to strategize methods for minimizing equipment failure risk during the project close phase.
  - For example, evaluate buying 1 spare integrated inverter/transformer skid per project to mitigate construction schedule risk since Central inverter and medium voltage transformer supply can mean months to secure replacement.

- Continuing to Collaborate with industry partners (Suppliers, IEs, labs, standard committees, etc.) to better understand inverter and inverter supplied medium voltage transformer reliability.

- Continue to partner with inverter suppliers to increase RES technical training.

- Incorporate O&M team lessons learned into new Project designs, procurement and construction lessons learned phases.

Questions?
Thank you!

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NEXTracker
A Flex Company

Wind Standards, Plant Lifetime, and Aeroelasticity of PV Trackers

Alex Roedel, Sr. Director Design & Engineering

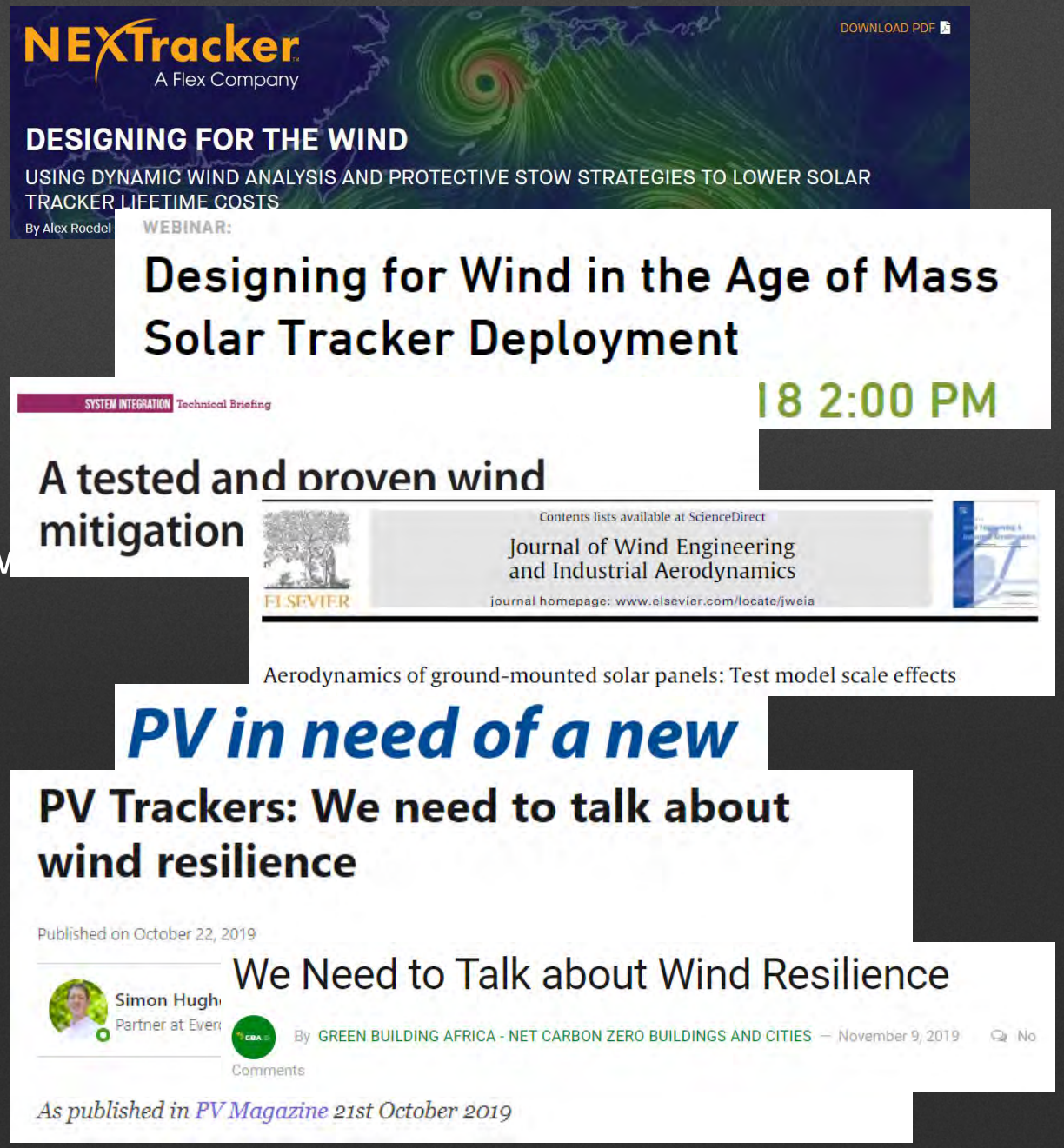
Presented at NREL PV Reliability Workshop

November 2020

Maturing Industry

Global Attention on Dynamic Wind Analysis

- NEXTracker released a ground breaking white paper on dynamic wind analysis in September 2018
- Growing industry attention on understanding and enforcing dynamic issues
- “Torsional galloping” and “aeroelastic instability” now commonly known by engineers and non-engineers alike
- Dynamic analysis now done by all leading racking manufacturers



PV Tracker Failure – Spain

Failures Happen at Low Wind Speeds

Industry Only Understands Basic Dynamic Effects

- Misunderstanding of dynamic loads and effects results in failures at operational wind speeds
- Greater focus needed on proven stability for multiple major aeroelastic effects
- Areas with *frequent*, not high winds, need the greatest analysis and focus across the industry

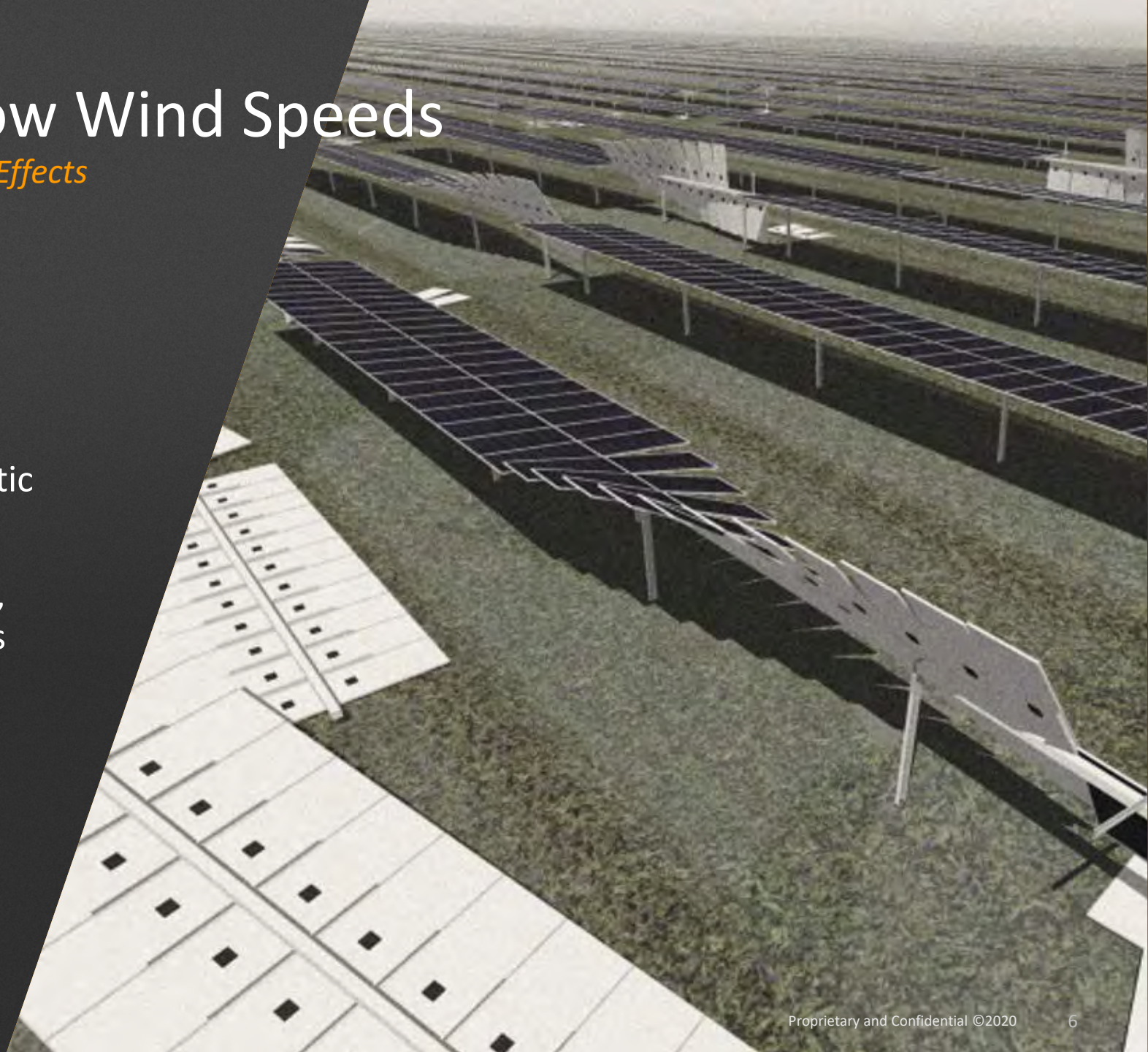


Photo Courtesy: Everoze

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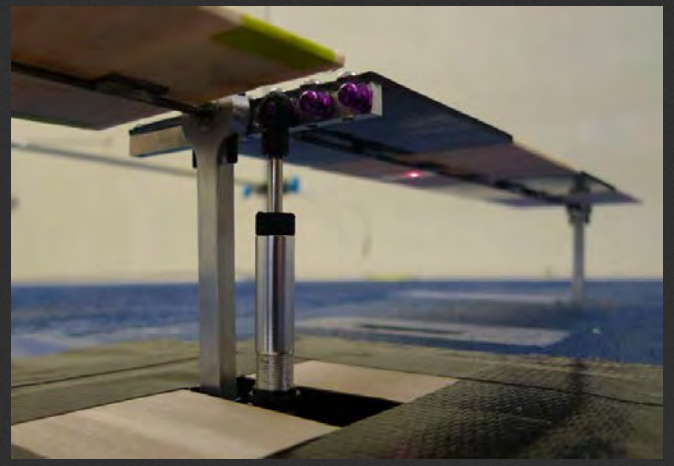
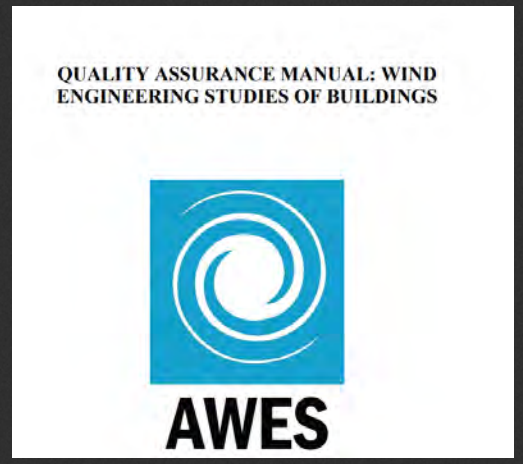
Understanding Accuracy

There may be several ways to approach this, but they should give the same answer."

-David Banks, CPP

- ASCE 49-12, AWES QAM (and others) list the wind tunnel testing standards that need to be followed
  - *Not intended to limit innovation*
- Confusion amongst professionals as to which method provides the correct results
- If wind loads are lower, there should be a good reason why.
  - *Low-load lab shopping*





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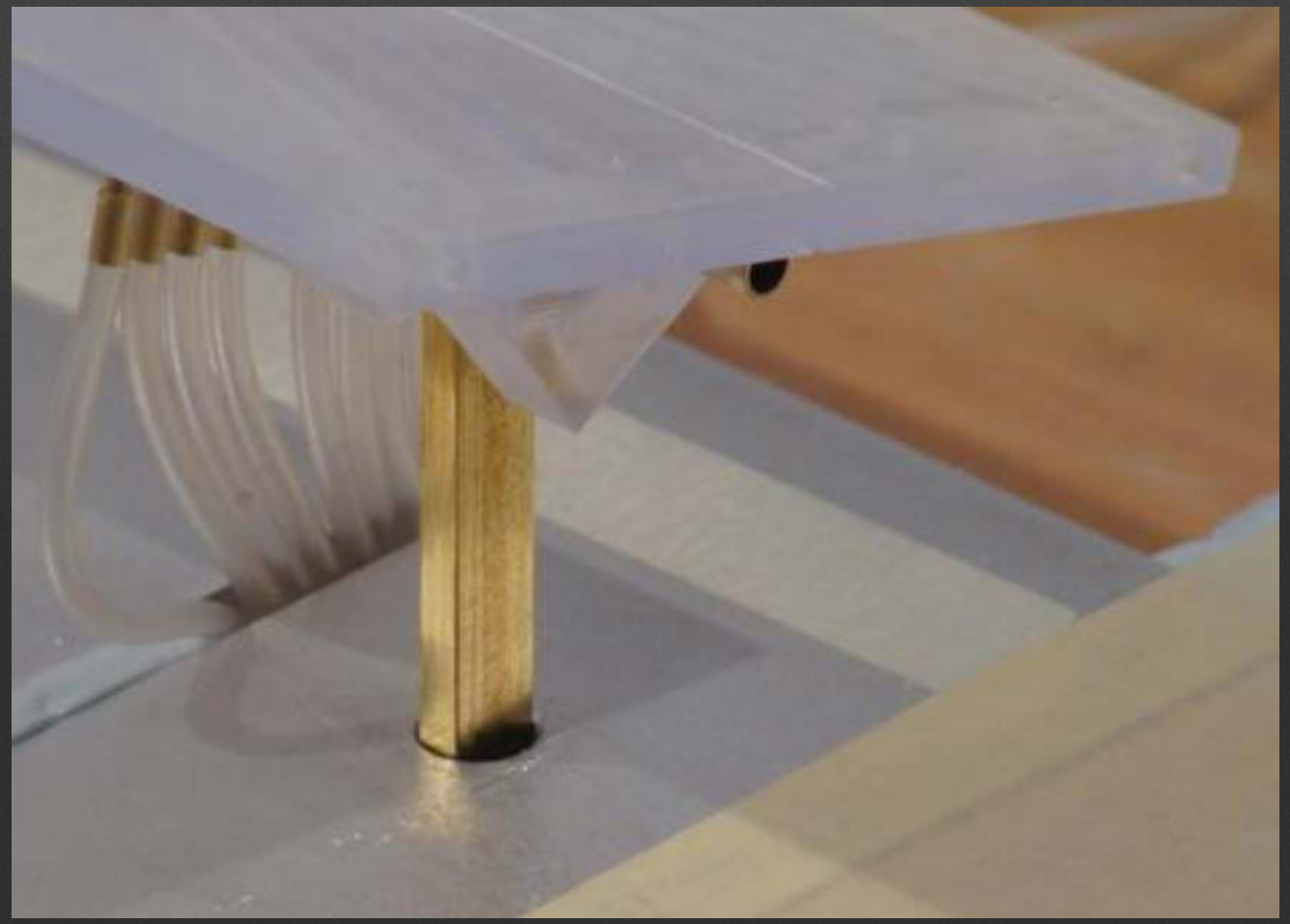
Reporting Module Pressure Values

Reported Pressures Can Vary up to 20%

- IEC 61215 defines methods for approving modules on structures
- Design only includes static analysis for approval
- Rewards trackers that stow at the vulnerable position of 0 degrees due to static torsional divergence
- Only stable trackers allow modules to perform for their intended design life



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Peer Review Process

Only Experts have the Credentials to Verify Results

- Examine the wind profile characteristics simulated in the tunnel
- Validate the calibration and suitability of wind tunnel instrumentation
- Thoroughly check the efficacy of the data and if possible, conduct an independent analysis of the data set
- Offer theoretical consistency of observed results and conclusions
- Best way to verify right from wrong

Figure 1: Wind tunnel model of the NEXTracker array section.

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On Resiliency and Solar's Competition

As Solar increases in prevalence, so will its critics

The Confidant
EC

Florentino solar panels fly away. Should I have put mills?

In the process of selling its renewable energy division, the strong winds of Lower Aragon have undone a giant puzzle of photovoltaic solar panels that it builds in Zaragoza

Panels shattered by the wind. (LaComarca.net)

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Demanding Higher Standards

The Solar Industry needs to continue its push to be the most reliable energy source

- Module Manufacturer's, Owners, Insurers, Banks, and Independent Engineers need to revisit their design requirements
- All manufacturers should be required to complete aeroelastic wind tunnel tests
- All wind tunnel tests must be peer reviewed to ensure accuracy
- Only when this is completed can solar plants last for the intended lifetime

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Thank You

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Aeroelastic Modeling and Full-Scale Loads Measurements for Investigation of Single-Axis PV Tracker Wind-Driven Dynamic Instabilities

Scott Dana & Ethan Young

NREL PV Reliability Workshop

February 27, 2020

Acknowledgments

Key contributors:

Chris Ivanov, Xin He, Jerry Hur, Ryan King

Jeroen van Dam and Dave Corbus

Brian Wares of Sunpower

A special thank you to Teresa Barnes and DuraMAT!

TOPICS

1 Project Background

2 Study Trajectories

3 Field Campaign

4 Field Results

5 Modeling Approach

6 Modeling Results

7 Comparison and Future Work

Motivation

Wind-related failures are widespread

- Range of wind speeds and geographic locations
- Unclear sources (galloping vs. divergence)
- Unclear stow guidance
- Industry response: Damper or mass add-ons, redesign

Shortcomings to address

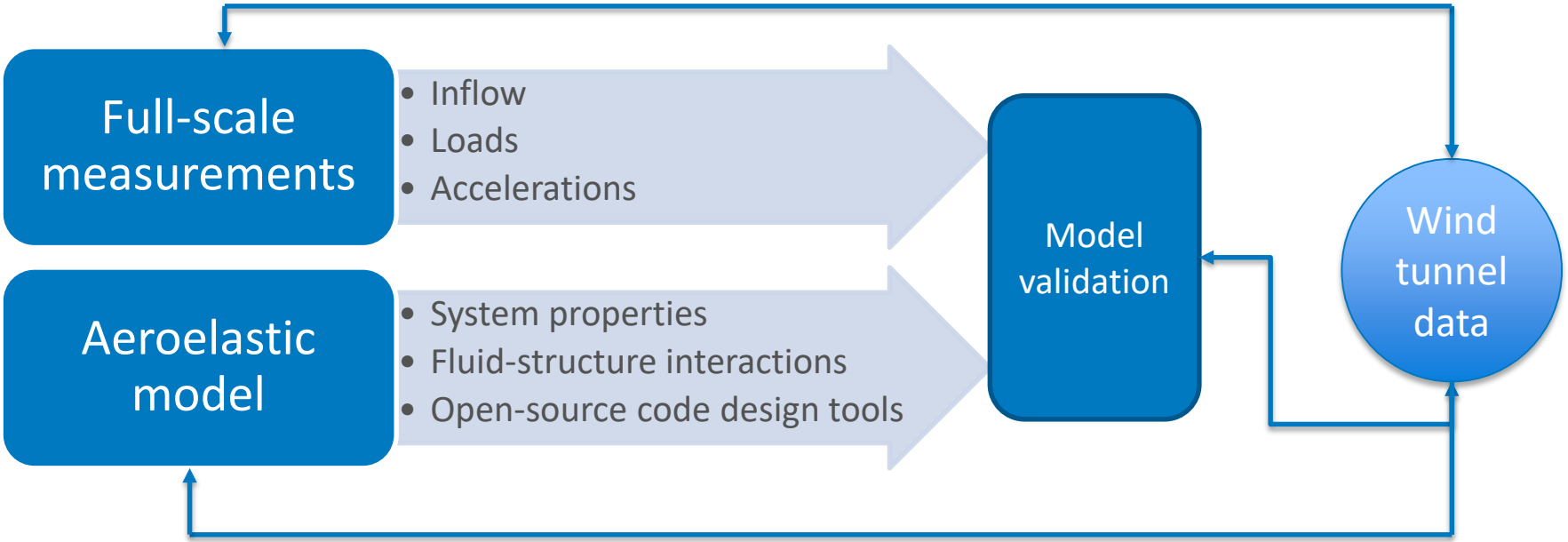
- Wind-tunnel-testing-driven design
- Proprietary models/design codes
- Full-scale loads measurements
- Model validation.

[1] GTM and NEXTracker Webinar, *Driving the Standard: Wind Testing, Solar Trackers, and Peer Review*, December 10, 2019
[2] PV Magazine Webinar, *Can a tracker be as stable as a fixed tilt?* December 10, 2019
[3] PV Magazine Webinar, *High or low tilt angles for single-axis trackers in extreme winds – different approach*, December 16, 2019

Parallel Paths Forward

DuraMAT funding source

- Address PV resilience
- Investigate dynamic instabilities
- Conduct first-of-kind study



NREL–Flatirons Campus Field Campaign

NREL Flatirons Campus (National Wind Technology Center)

- Extreme winds > 110 mph (50 m/s)
- Wind season October through May
- Decades of engineering, research, and field validation of high-wind physics and modeling

Photo by Dennis Schroeder, NREL 25861

Home to DuraMAT Field Campaign

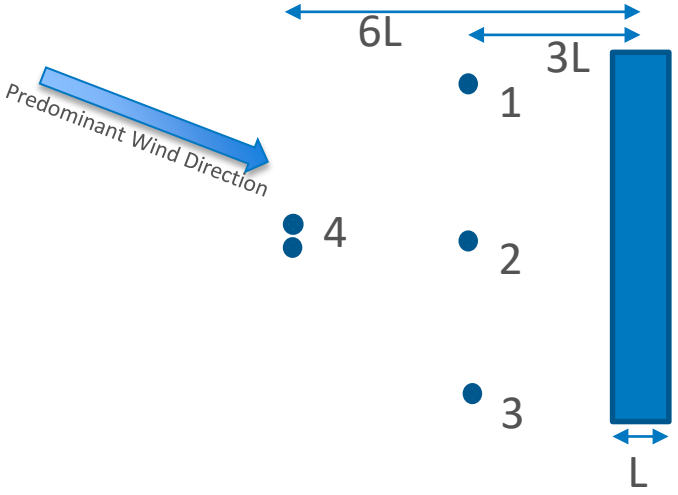
- Single-axis tracker
- Single-slew drive at center
- 24.25-m length
- 4-m width
- 2-m axis height.

Photo by Scott Dana, NREL

Photo by Scott Dana, NREL

Instrumentation Setup

- Inflow and atmospheric
- Torque loads = TQ
- Pier bending = PB
- Rotary encoders = RE
- Panel deflections = PD
- Accelerations = A



Sonics = 1,2,3
Cup & vane = 4
Temp, humid, press = 2

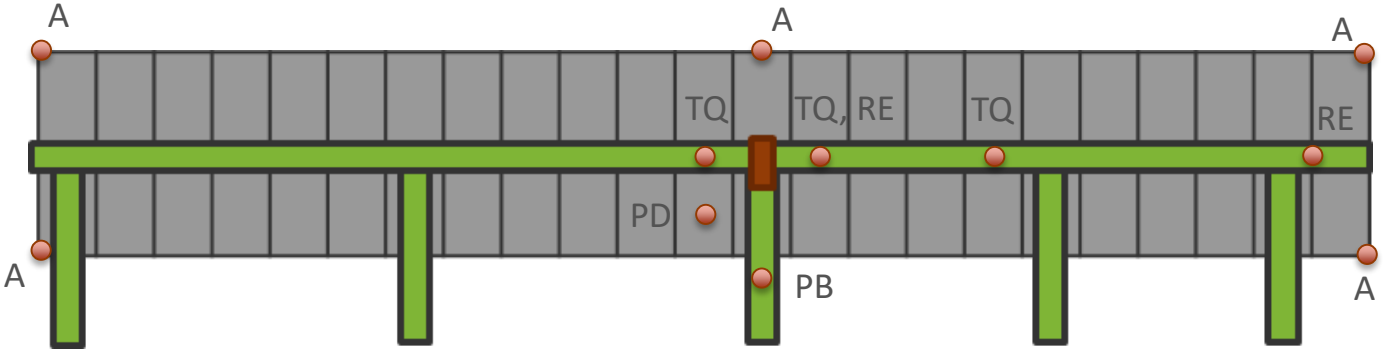
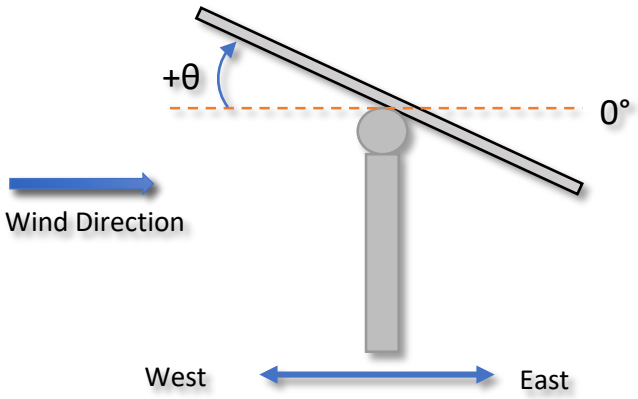


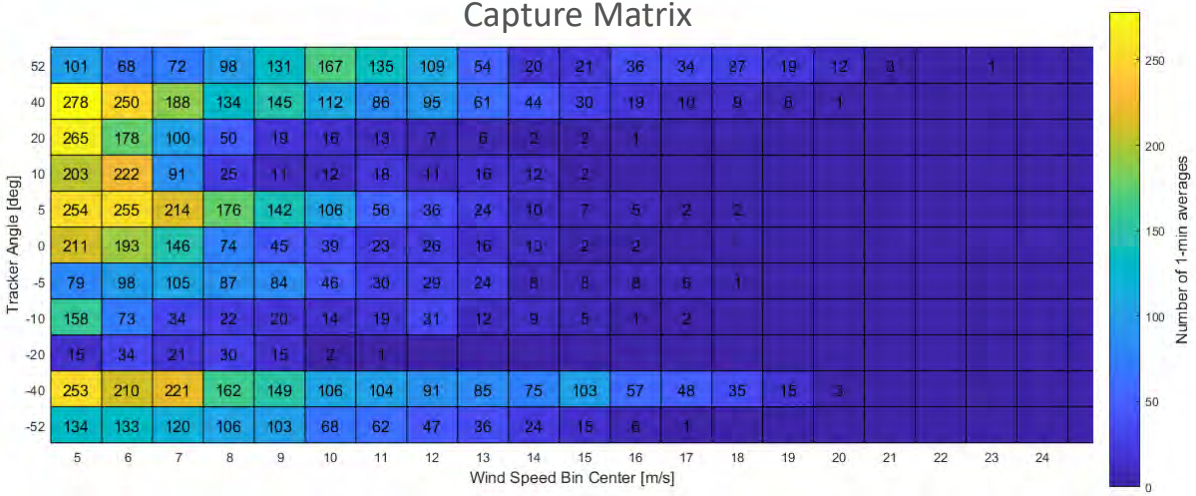
Photo by H. Ivanov, NREL

Data Collection and Analysis Approach

- Cycle through discrete tracker stow angles
  - -52, -40, -20, -10, -5, 0, 5, 10, 20, 40, 52
  - Start with “safe” stow angles
  - Move to “riskier” stow angles
- Time-series data collected
- 50-Hz and 1-Hz storage rates
- Inflow sector filter: 255° to 285°
- Postprocess for loads
- Calculate 1-minute statistics
- Bin stats
  - By wind speed
  - By tracker angle.



Capture Matrix



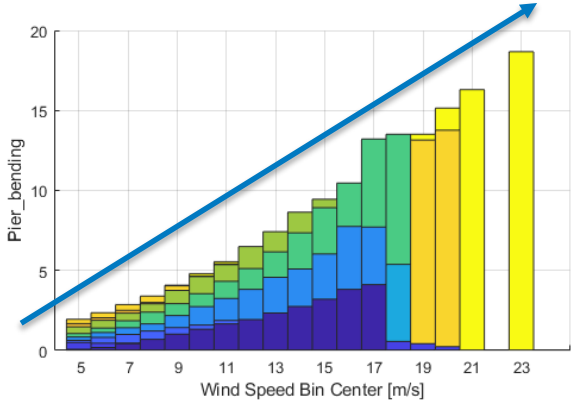
Pier Bending Moment

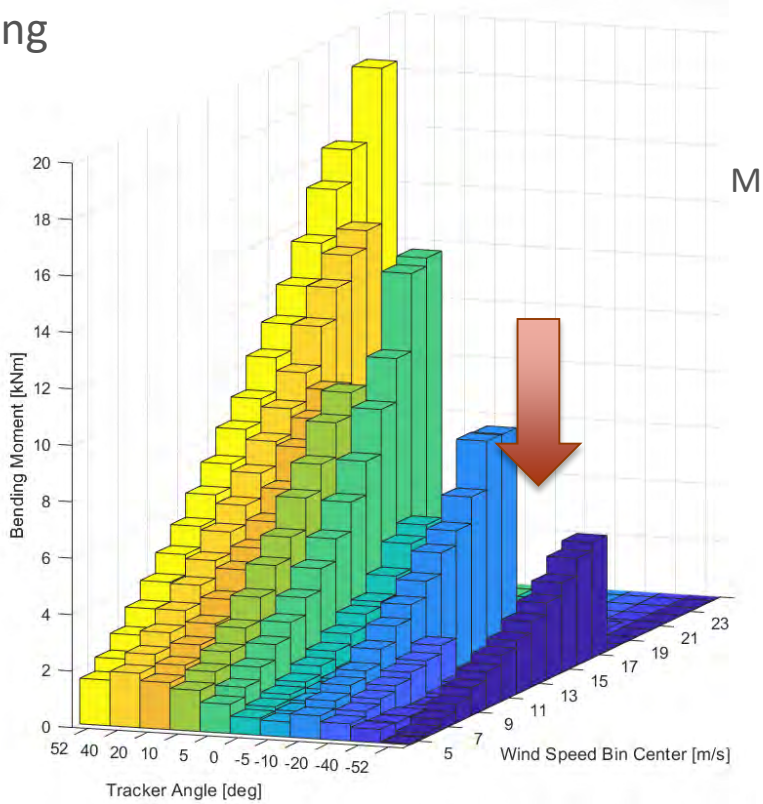
Absolute values of mean bending moment

Wind speed range limitations

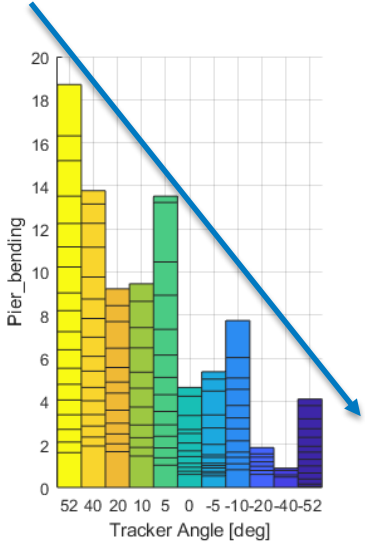
- -20 degrees
- Most bins beyond 17 m/s.

Mean Load Wind Speed Envelope

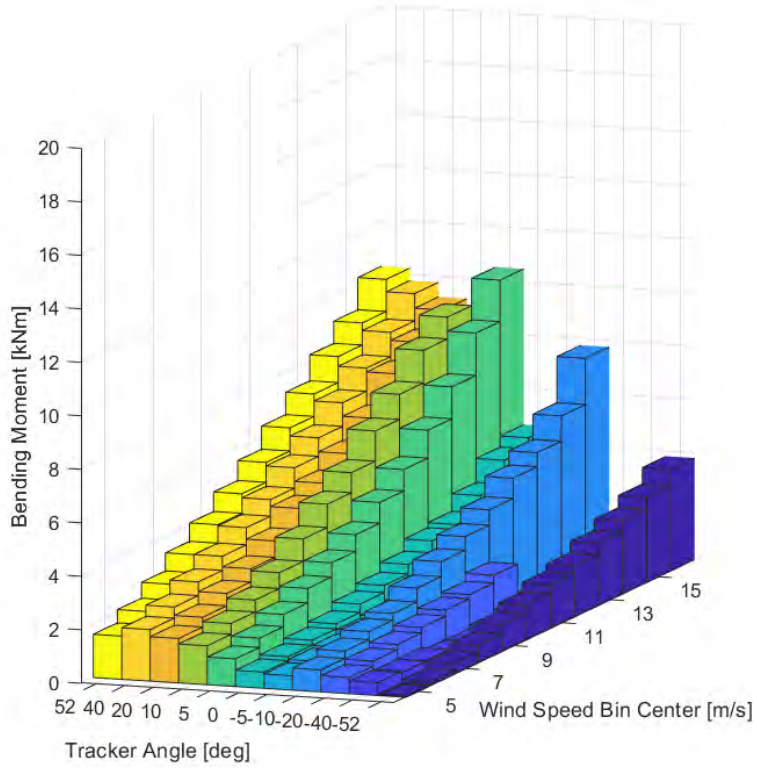




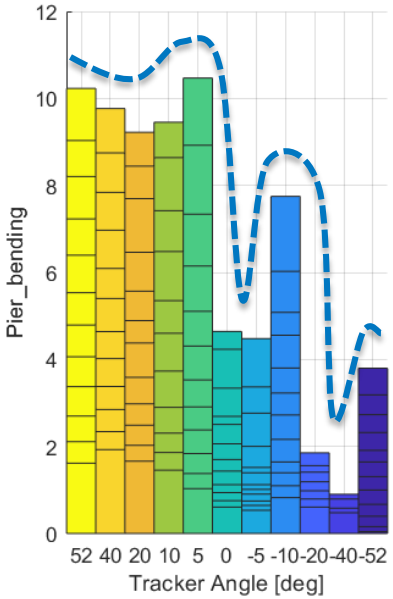
Mean Load Stow Angle Envelope

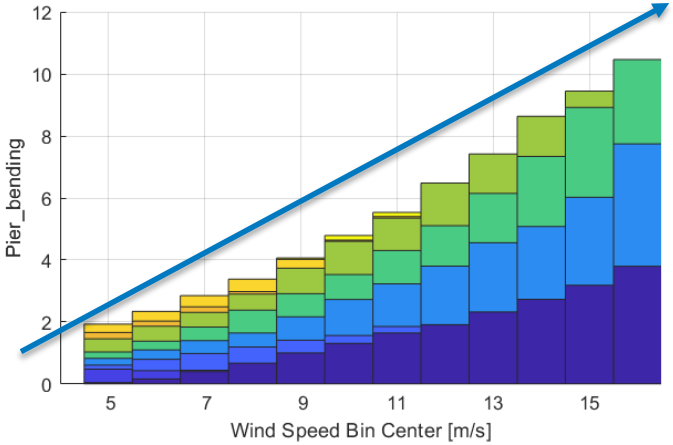


Pier Bending Moment—Closer Look



- Slice data to evaluate bin parity
- Statistical confidence up to 16 m/s
- -20° limited beyond 9 m/s—ignore, although trend present
- Tracker angle trend generally favors negative stow angle > 10°.

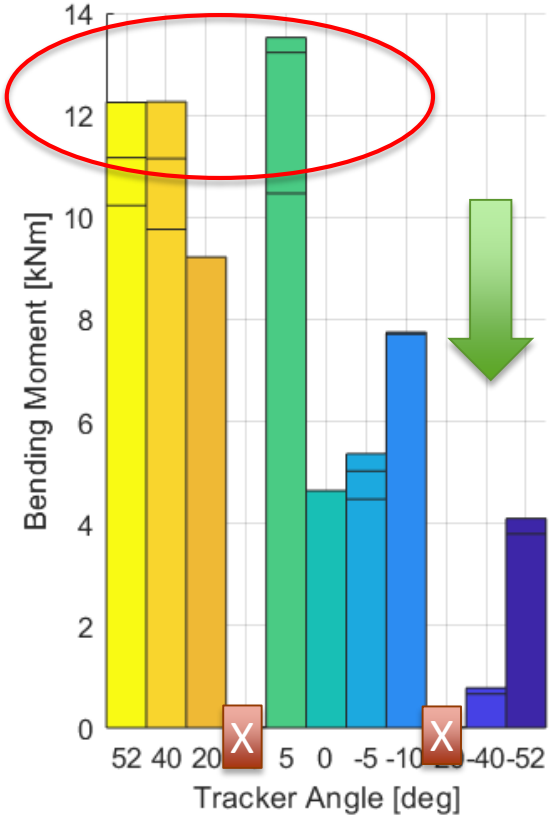




Pier Bending Moment—Closer Look

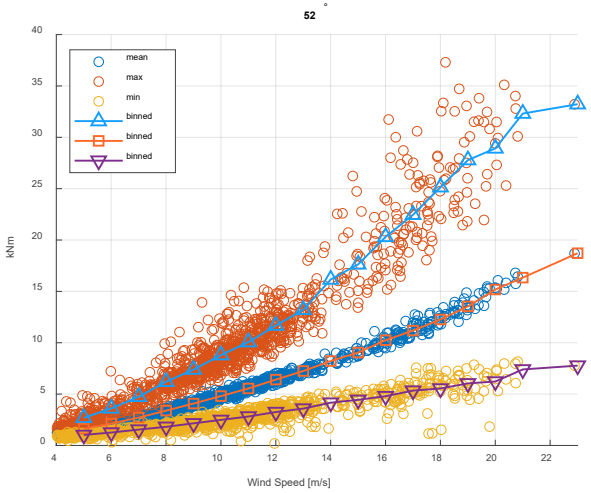
- Higher wind speeds
- 17 m/s and 18 m/s are statistically complete
  - Exception of +10° and -20° stow angles

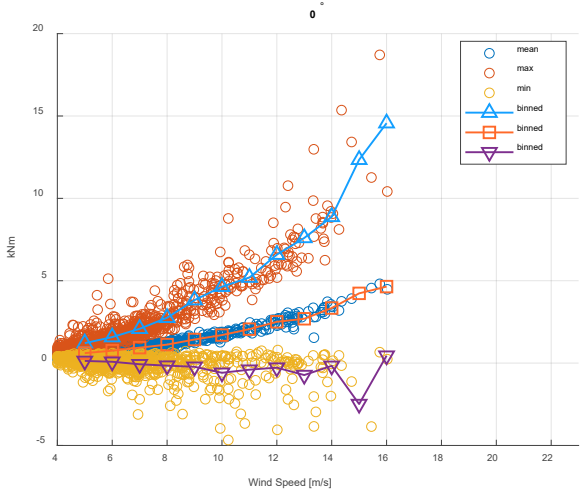
- -40° remains most favorable
- Positive angles, consistently higher loads.

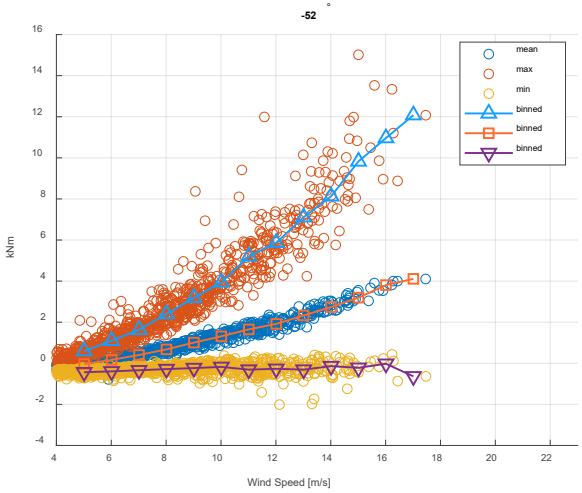


Pier Bending Moments—Scatter and Binned

- Examples of statistical scatter and binning







- Generally, other tracker angles follow these trends
- Torque scatter displays similar trends.

Torque Tube Loads

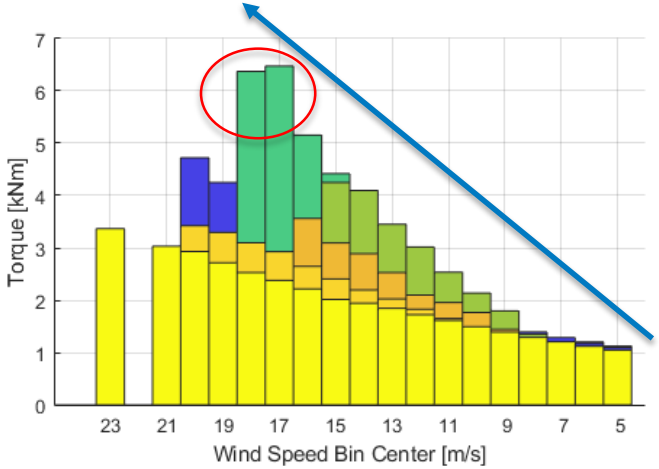
Absolute value of mean torsional loads at drive only

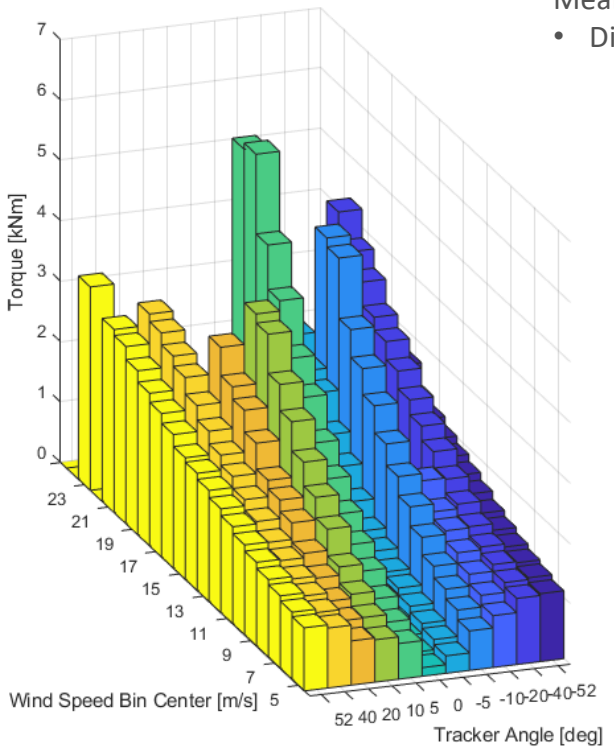
As with all data, some limitations:

- -20 degrees
- beyond 17m/s

Mean Torque Wind Speed Envelope

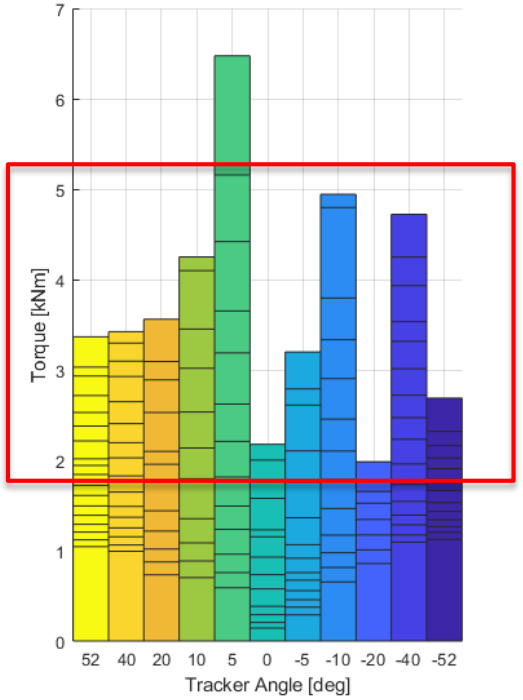
- Trends with wind speed
- +5° possible outliers—no statistical relevance





Mean Torque Stow Angle Envelope

- Difficult to ID trend or "favorable" angle



Panel Deflections

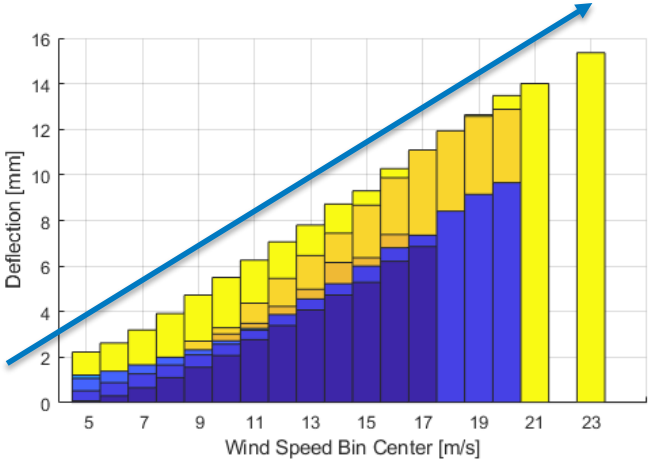
Absolute value of mean deflections at midpanel only

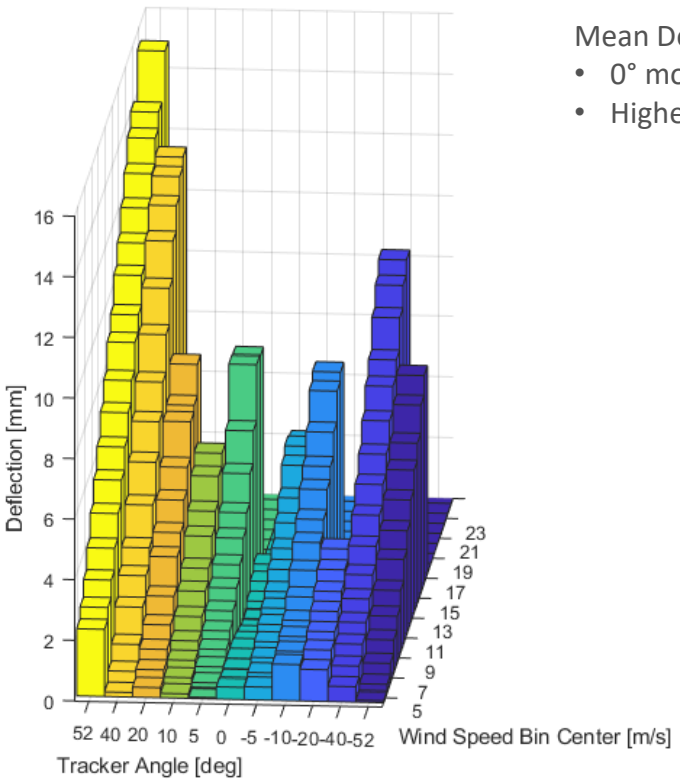
As with all data, some limitations:

- -20 degrees
- beyond 17 m/s

Mean Deflection Wind Speed Envelope

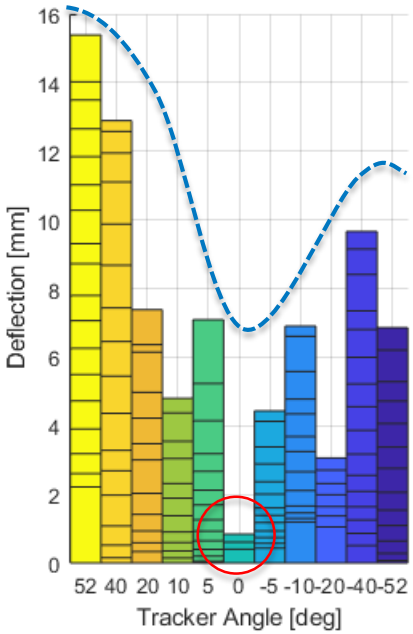
- Trends with wind speed
- Common artifact among all components



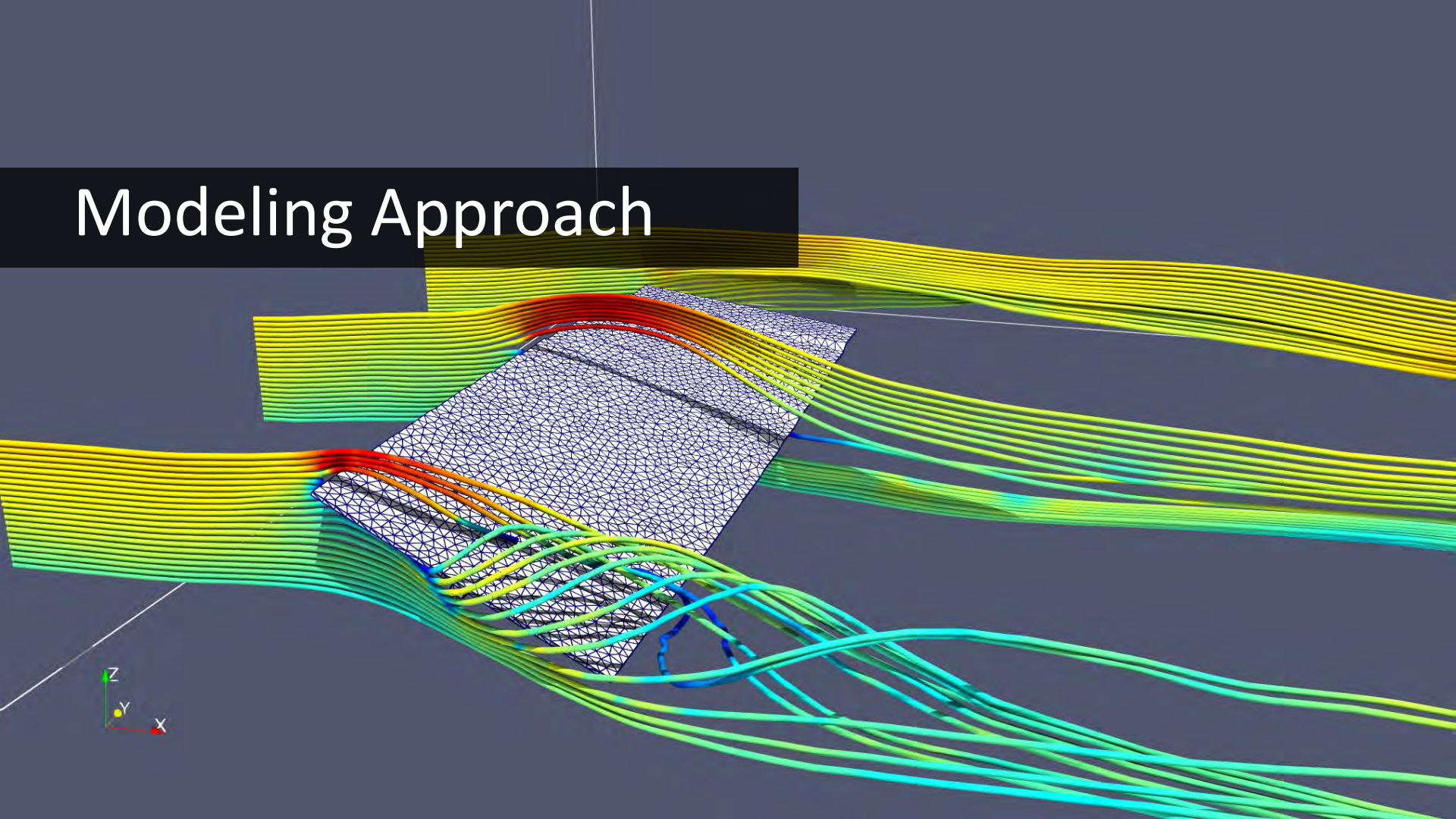


Mean Deflection Stow Angle Envelope

- 0° most favorable, as expected
- Higher angles result in largest deflections



Modeling Approach

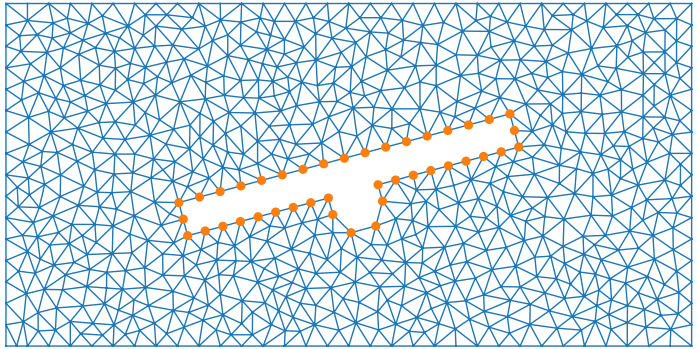


Methodology

- A pressure correction scheme is used to solve the Navier-Stokes equations while enforcing incompressibility.

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{c}\cdot\nabla\mathbf{u}\right) = -\nabla P + \mu\nabla^2\mathbf{u}$$

$$\mathbf{c} = \mathbf{u} - \hat{\mathbf{u}}$$

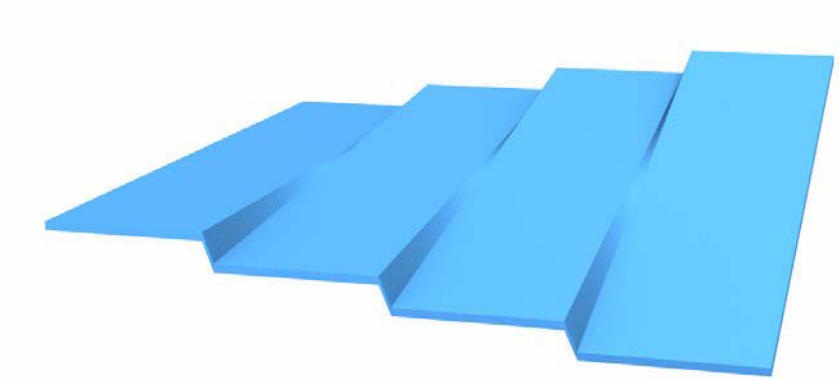


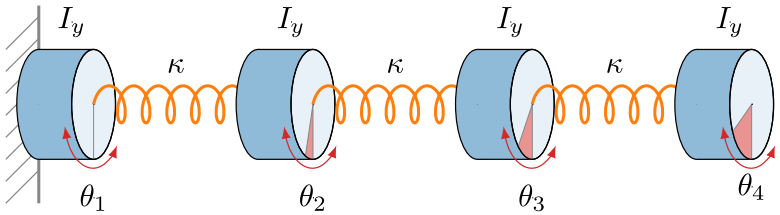
- The fluid stress around the immersed surface creates a torque, τ, on each panel.

Methodology

- Panels are treated as **rigid masses** linked with **rotational springs**.
- This mass-spring approximation is used to model the fluid-structure dynamics.

$$I_y \alpha + \kappa \theta = \tau$$

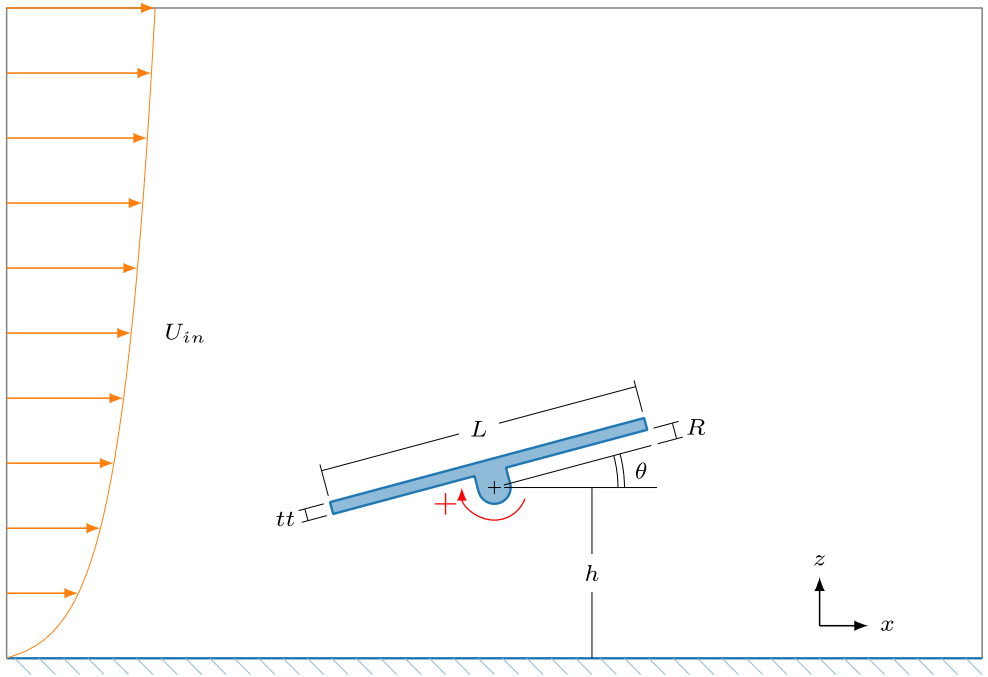




Simulation Setup

Fluid Property	Value
ρ	$1.0\,\mathrm{kg}\cdot\mathrm{m}^{-3}$
μ	$1.8\times10^{-5}\,\mathrm{Pa}\cdot\mathrm{s}$

Structure Property	Value
$L\times W\times tt$	$4\,\mathrm{m}\times12\,\mathrm{m}\times0.05\,\mathrm{m}$
h	$2.1\,\mathrm{m}$
R	$0.085\,\mathrm{m}$
E	$148\,\mathrm{GPa}$
m	$50.8\,\mathrm{kg}$



Pressure Interpretation

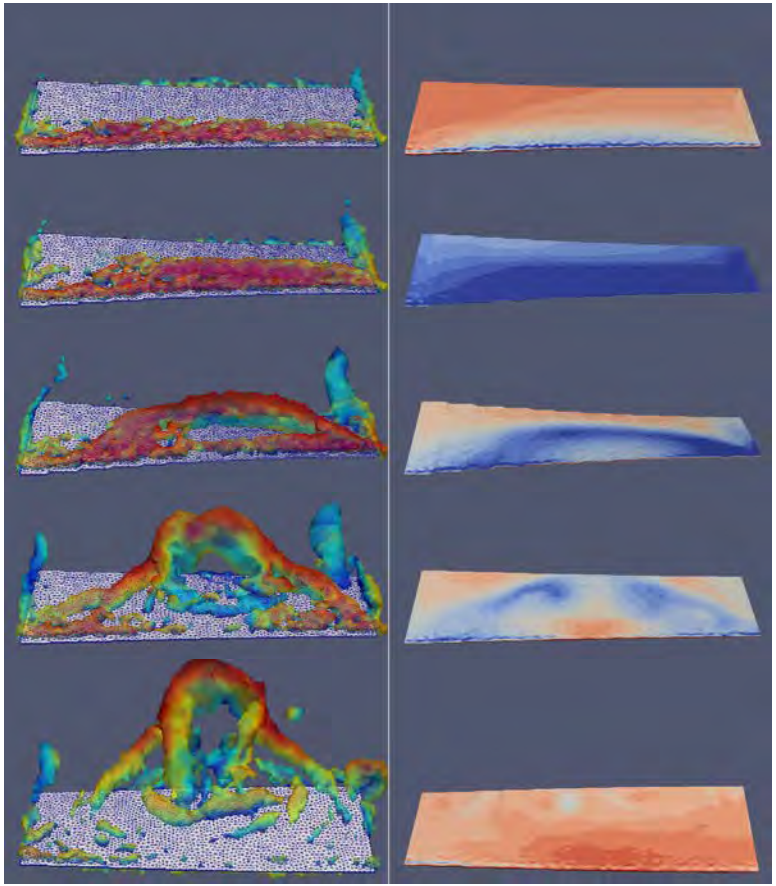
$t^* = 0\,\mathrm{s}$

$t^* = 0.049\,\mathrm{s}$

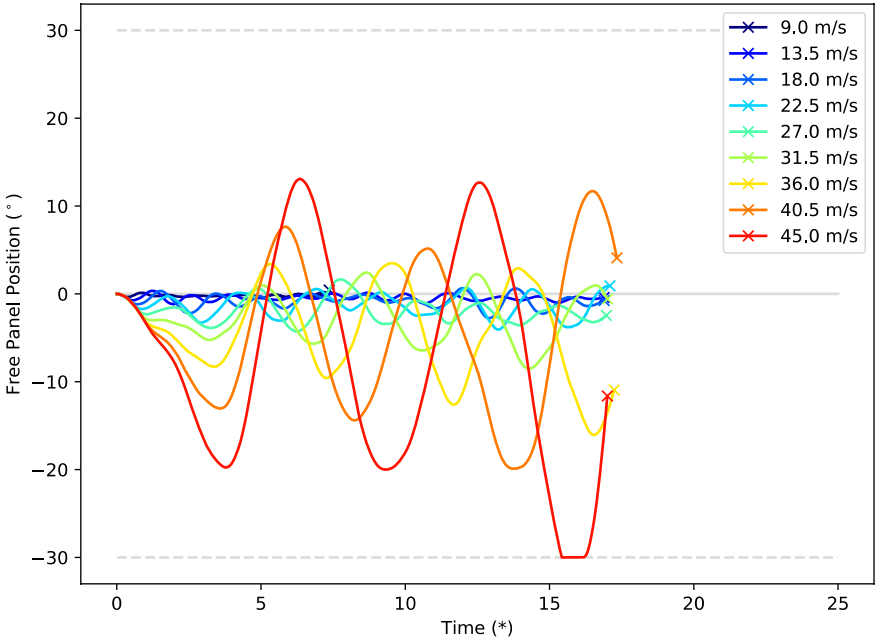
$t^* = 0.148\,\mathrm{s}$

$t^* = 0.247\,\mathrm{s}$

$t^* = 0.346\,\mathrm{s}$

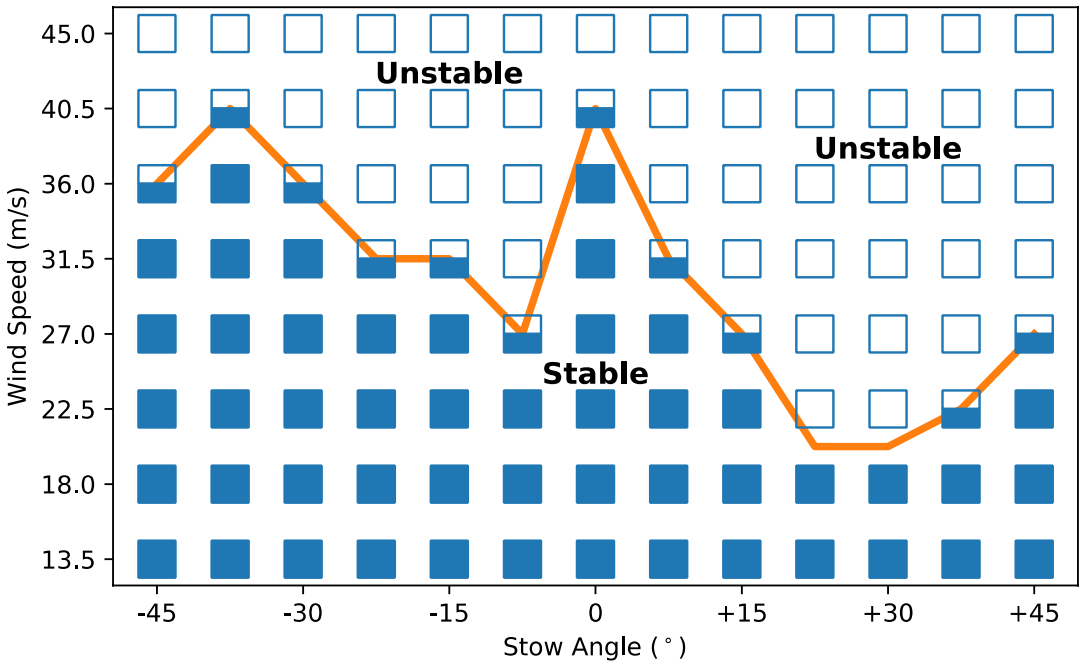


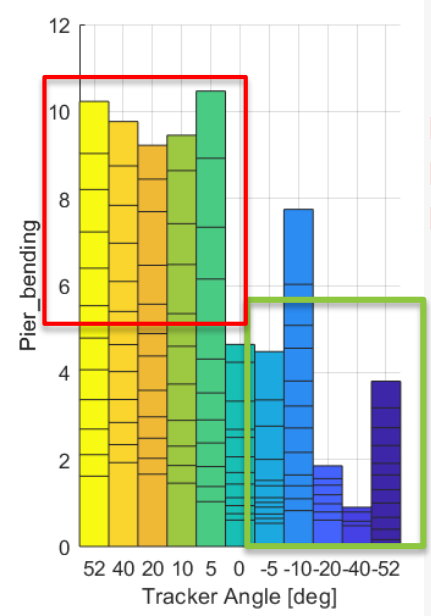
Effect of Wind Speed



Panel stability at $\theta = +8.5^\circ$

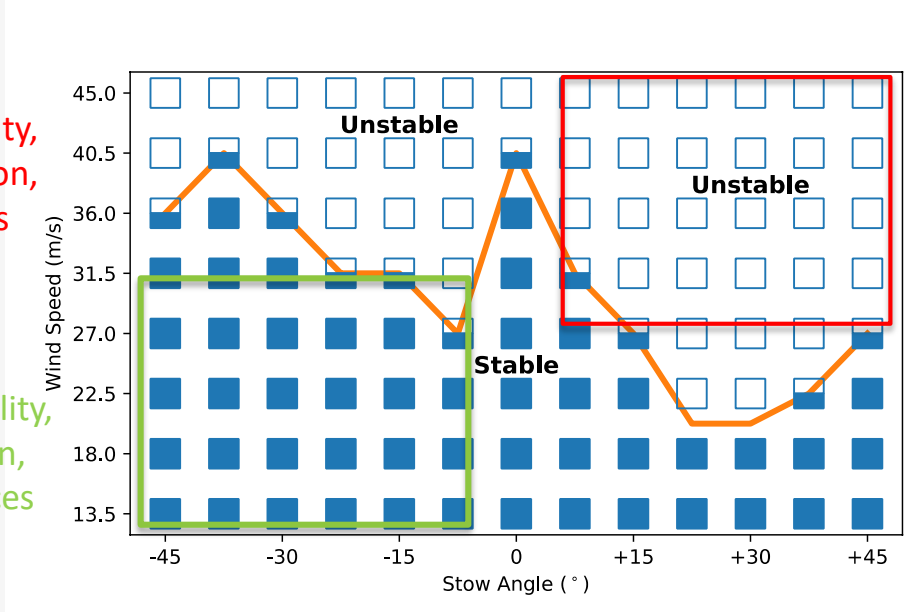
Panel Stability





Lower Stability,
More Rotation,
Larger Forces

Higher Stability,
Less Rotation,
Smaller Forces

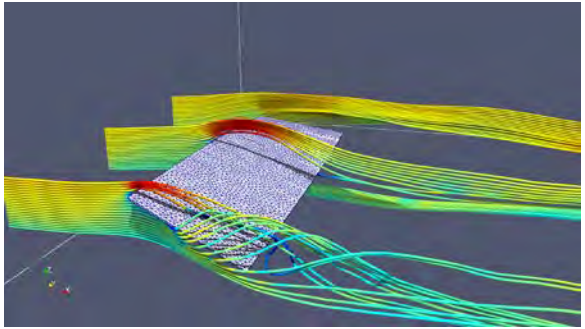


Field & Model Convergence

Both the field campaign and the computational model indicate a significant **sensitivity to panel stow angle**.

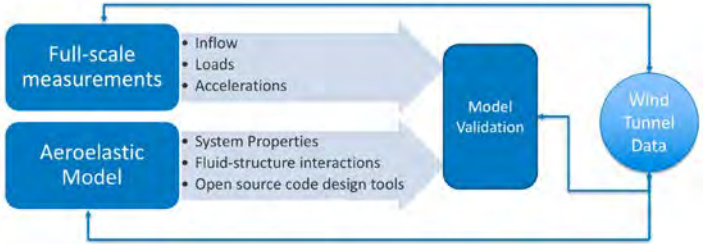
Next Steps

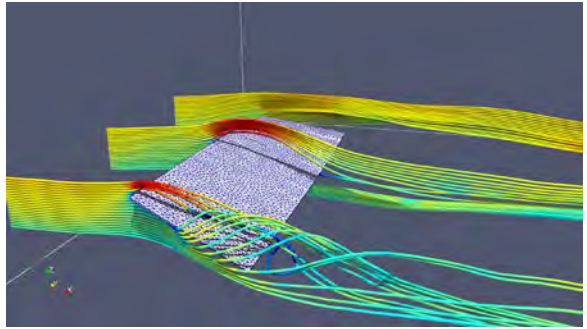
- **Field Campaign**
  - Rich database for ongoing analysis
  - Rigorous study of acceleration trends
    - Operational Deflection Shapes
    - Torsional galloping/divergence ID
  - Component fatigue life studies
  - Round-out database
    - -20° stow angle
    - Higher wind speed bins
    - More stow angles
- **Modeling Approach**
  - Implement improved stability criterion
  - Compounding effect of multiple panel rows
  - High-fidelity model to capture deformation effects.



Next Steps

- **Field-Model Validation**
  - Current efforts have shown good qualitative agreement between field measurements and simulation results regarding stow angle.
  - We currently have a wealth of data to interrogate for the further refinement of both approaches.





Thank You

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Measured DC Arc-Flash Incident Energy in PV Plants

Bijaya Paudyal, PhD and Michael Bolen, PhD

Photovoltaic Reliability Workshop
(02-27-2020)

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About This Work

Goals

- Increase understanding of dc arc-flashes, their hazards, and codify results
- Ensure appropriate personal protective equipment (PPE) for field workers in large-scale PV plants

Objectives

- Increase understanding of hazards through **lab and field tests**
- Develop detailed **physics-based arc-flash models** that can be used to design and mitigate incident energy in new equipment
- Codify more accurate **incident energy prediction method**, such as analytical formula or easy-to-use calculator

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

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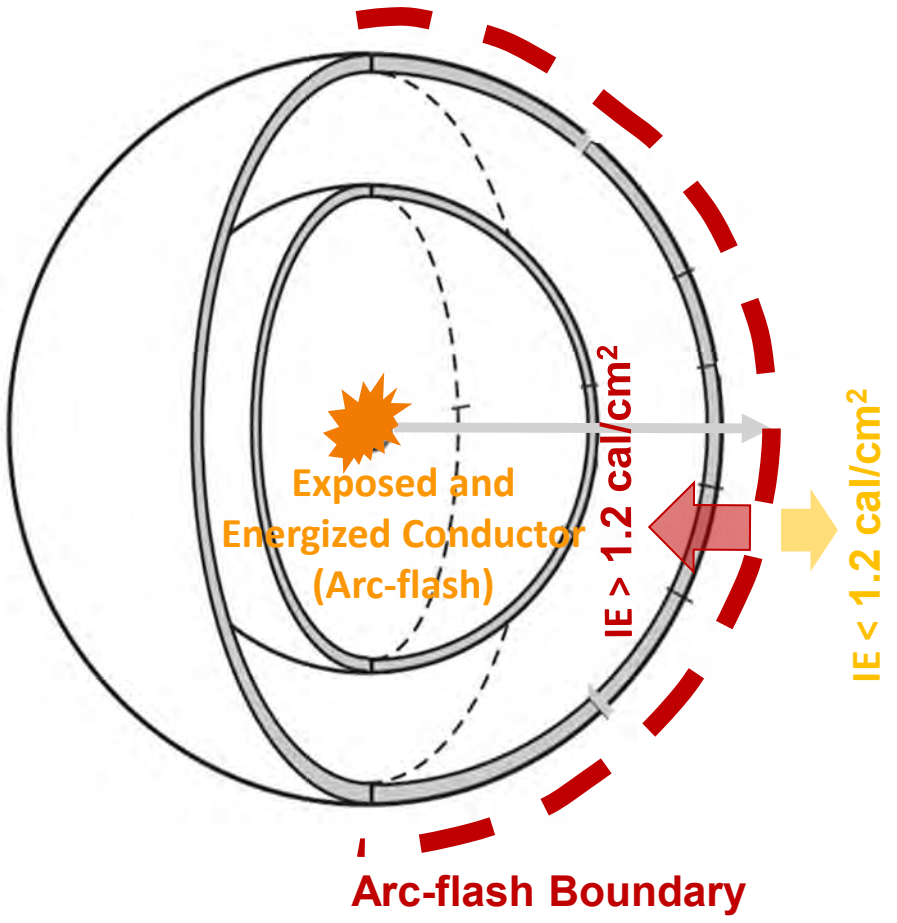
Incident Energy and Arc-flash Boundary

Incident Energy (IE): The amount of thermal energy ***impressed on a surface***, a certain distance from the source, generated during an electrical arc event.

- Typically expressed in calories per square centimeter (cal/cm^2).

Arc Flash Boundary (AFB): The distance at which a person is likely to receive a curable second degree burn.

- The skin receives **1.2 cal/cm^2** of ***IE*** *(for 1 second)*
- Less than 80°C (176°F) on skin (without PPE).



Limits of Approach: NFPA 70E(C.1.2.3)

Incident Energy (Thermal) < Total Arc Energy

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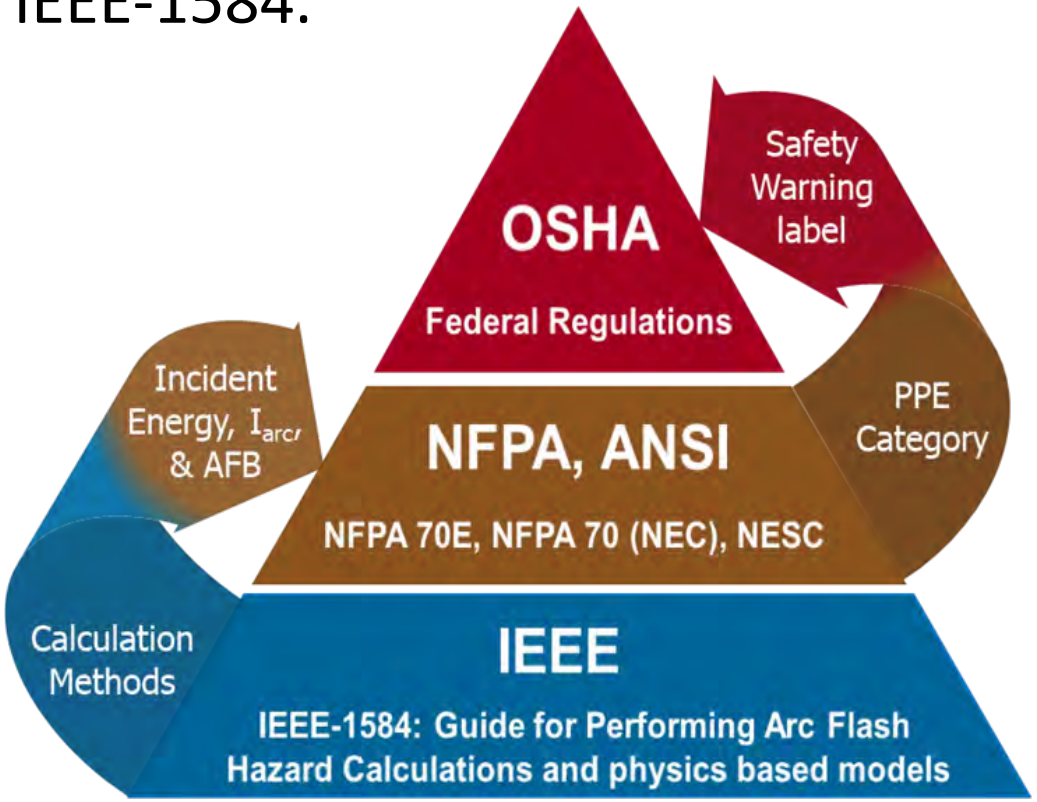
Standards and codes for Arc-flash safety

The General Duty Clause of **OSHA** in the case of arc-flash safety would be satisfied by implementing NFPA 70E using IEEE-1584.

NFPA 70E: *Standard for Electrical Safety in the Workplace*-2018

IEEE-1584: *IEEE Guide for Performing Arc-Flash Hazard Calculations*-2018

- Covers ac system only
- dc inclusion in discussion
- Relevance to PV system (?)



Standards and Codes Pyramid of Arc-flash safety

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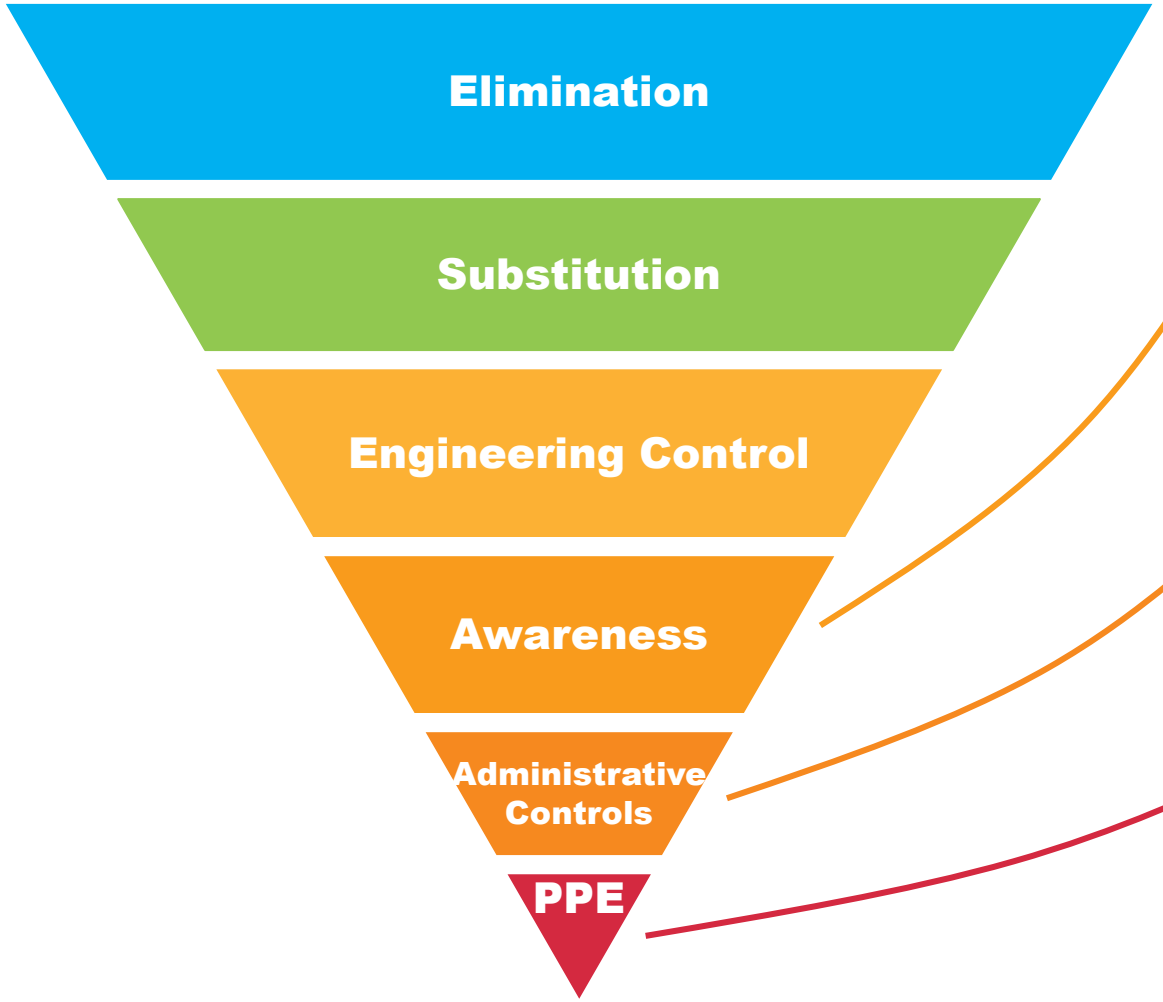
The Hierarchy of Risk Control and NFPA-70E for Arc-Flash



Notifying workers of risks

- Warning Stickers, Lights
- Each Equipment (>50 Vdc)

Standardize the way to perform task

- Develop Policies and Provide Trainings

Reduces the effects in attempt to make injury survivable

- Arc Rated Clothing, Safety Glasses, Head and Footwear, Gloves, and so on.

The Hierarchy of Risk Control Methods. NFPA 70E-2018, Article 110.1(3)

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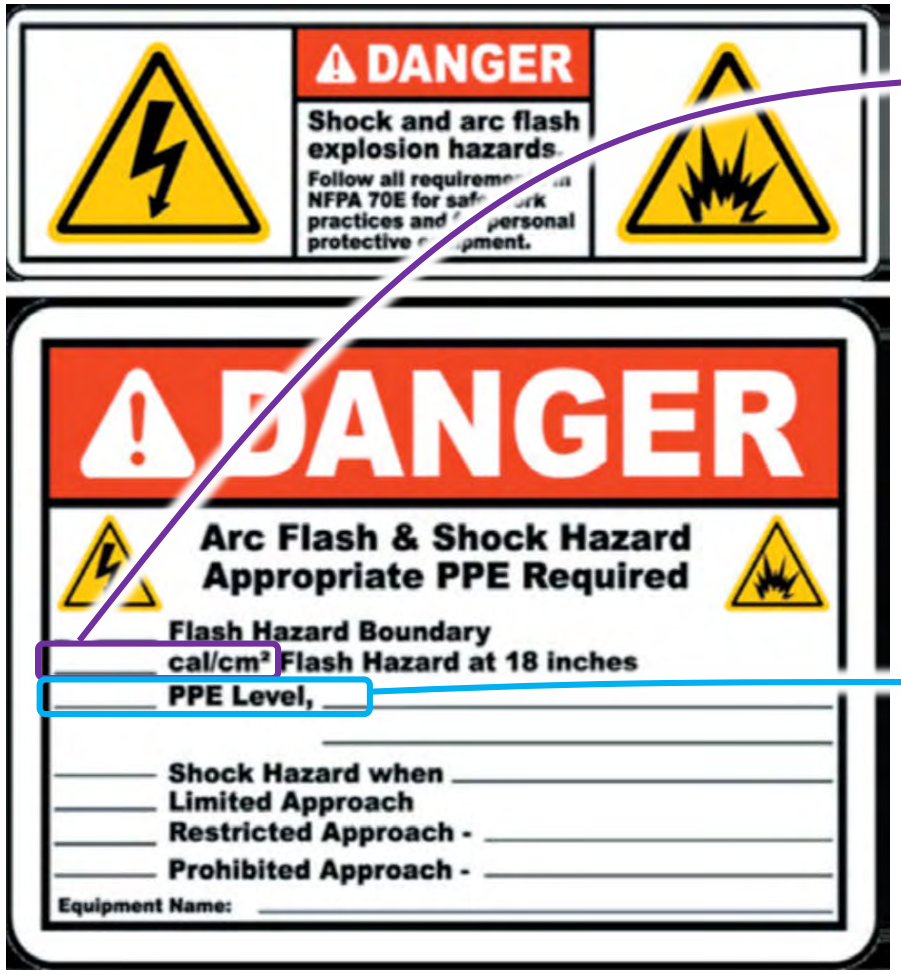
Incident Energy required for Warning Stickers and PPEs



Example Arc-flash and shock risk Warning Sticker

Source (Warning Label): NEC Section 110.16

Calculate or measure ***Incident Energy***

Arc-flash PPE Categories	PPE # 1	PPE # 2	PPE # 3	PPE # 4
	IE ≤ 4	4 ≤ IE ≤ 8	8 ≤ IE ≤ 25	25 ≤ IE≤ 40

Lower PPE is a safety compromise;
Higher PPE can reduce worker dexterity

Source (PPE Table): NFPA 70E-Article 130, Table 130.7(C)(15)(c)

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Calculation methods for *Incident Energy (IE)*

Identify equipment requiring arc-flash IE assessment

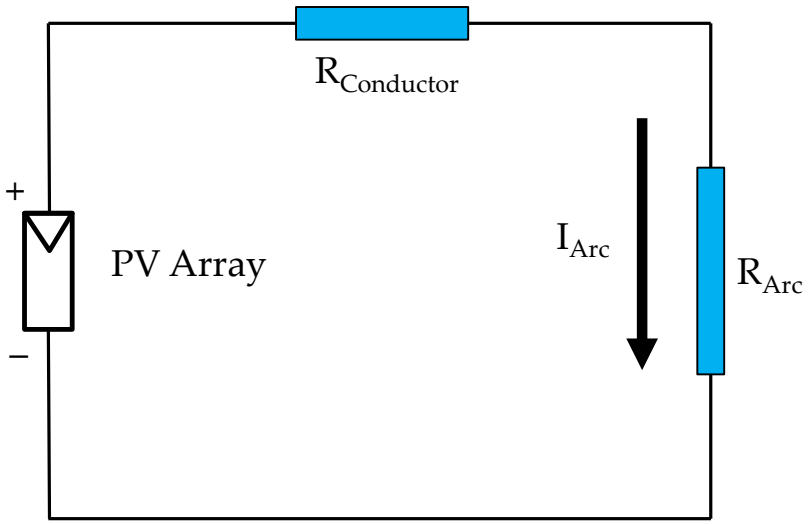
Collect equipment data and plant/circuit specifications

Draw circuit one-line diagram

Perform fault current study and estimate I_{Arc} (and V_{arc})

Calculate *Incident Energy*

Process flow of IE calculation for a dc system



$$IE_{Max} = \frac{0.01 \times V_{Sys} \times I_{Arc} \times t_{Arc}}{d^2}$$

Simplified Equations	Input Variables
Doan (NFPA- 70E) and ***Enrique et. al.***	*V_{System} (Voc), I_{Arc} (I_{SC}), t_{Arc}, and working distance*
Paukert and ***Stokes & Oppenlander***	*V_{System} (Voc) , I_{Bf} (I_{SC}), t_{Arc}, working distance, and **arc-gap***

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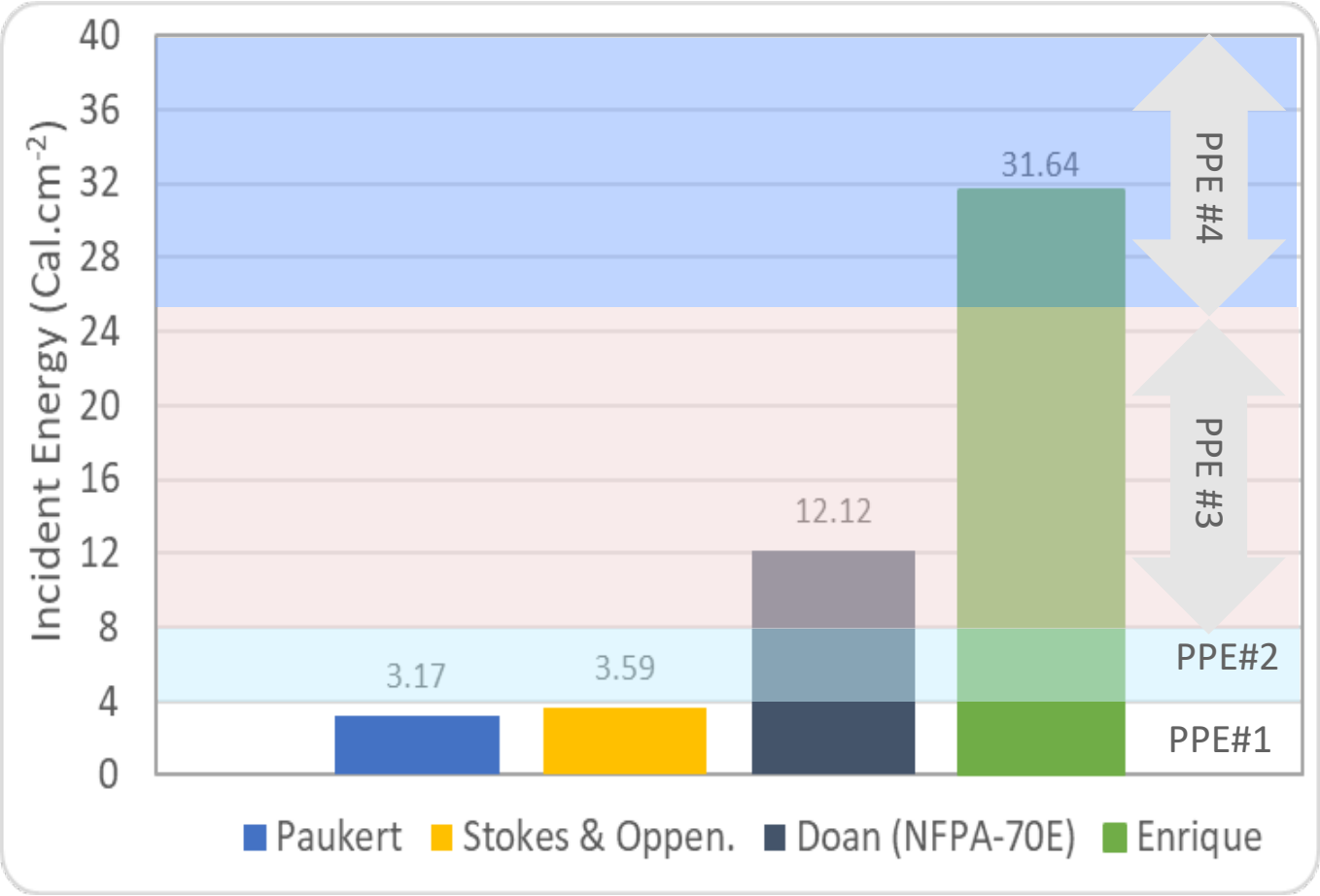
Current IE calculation models are contradictory

- Each model has a varying degree of ***conservatism***
- Each arc-flash model predicts a different incident energy - and appropriate PPE-for the same system
- Most of the models are designed for a ***conventional dc power sources*** (linear)



Calculated *IE* using simplified models 1-MW, 1 kV dc (nameplate) PV plant

"All models are wrong, but some are useful" – George Box (mathematician)

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Arc-flash Tests at PV Plants and Results

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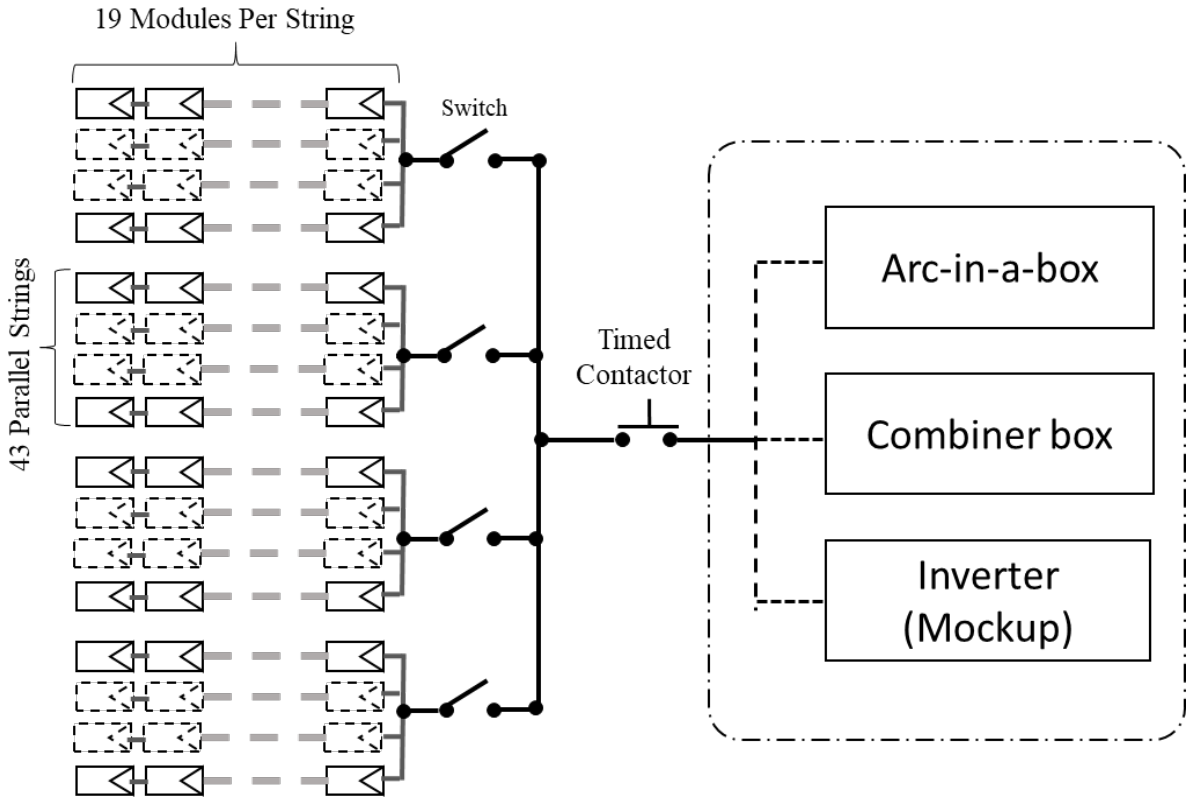
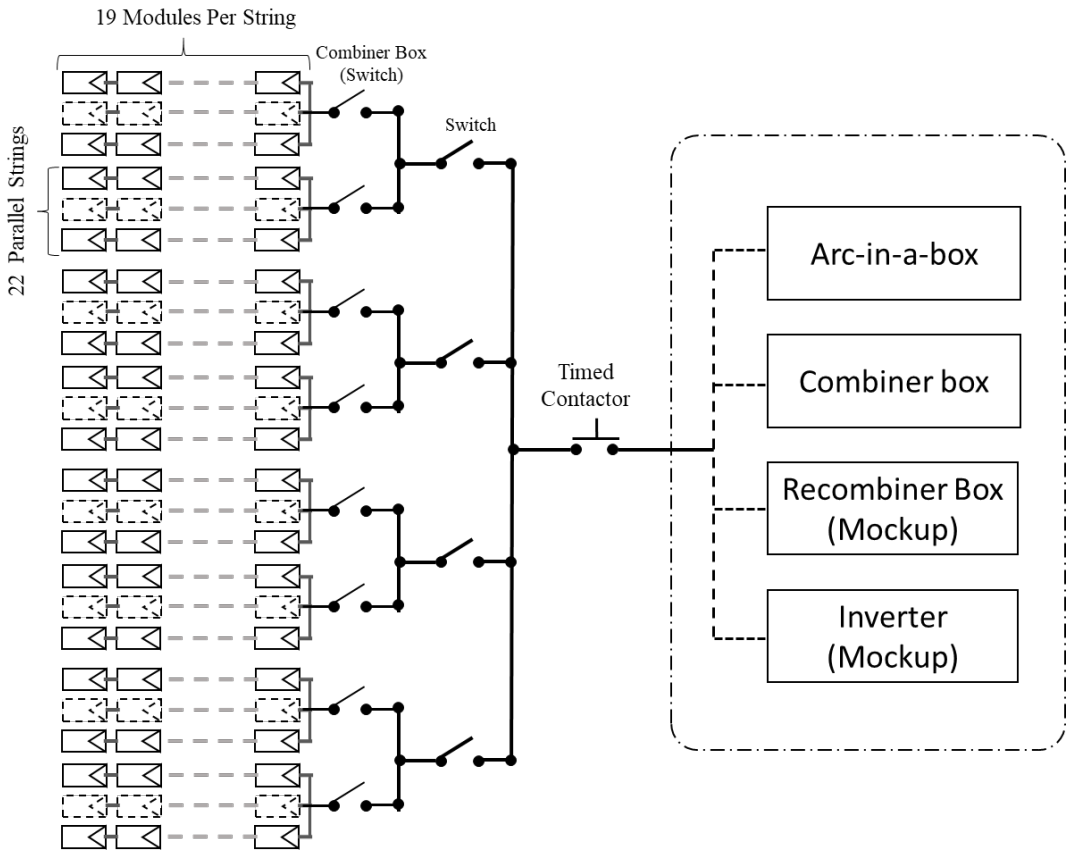
Arc-flash experiments in a PV plant

A series of arc-flash experiments were performed in ground-mounted large-scale, ~1 MWdc PV plants.



Plant A: 1,000 kWdc, 1000V



Plant B: 1,054 kWdc, 1000V

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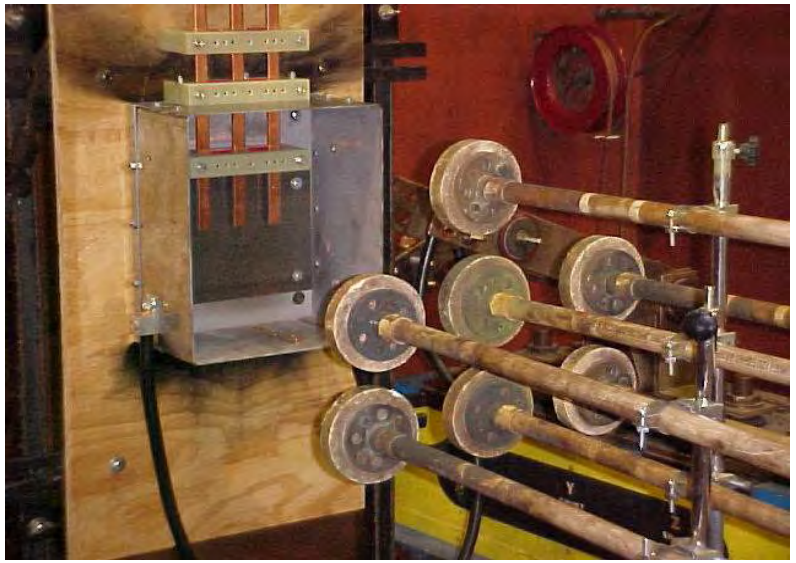
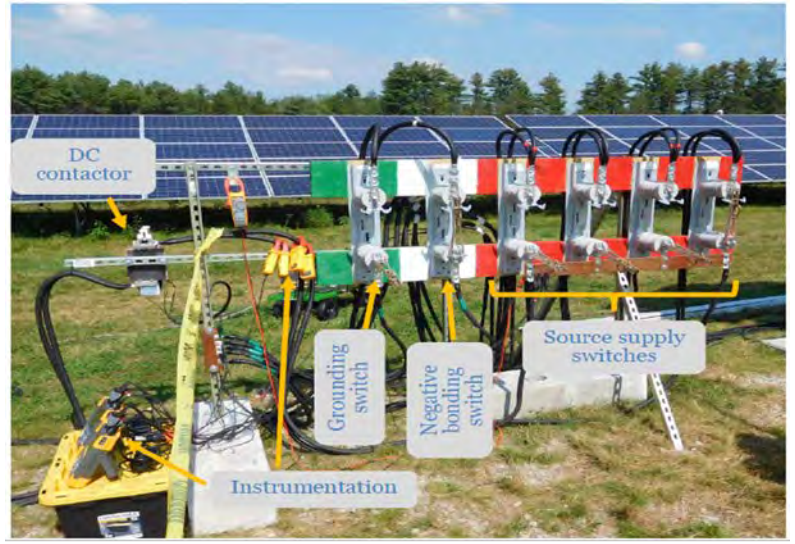
Staged arc-flash experiments: Measure *IE*, I_{Arc} and V_{Arc}

- ***Incident Energy Measurement***
  - Array of slug calorimeters based on ASTM 1959
  - Positioned at 18-inches from the arc-initiation point.
- ***Electrical measurements***
  - *DC current clamps (Fluke i1010)*
  - *Power quality and energy analyzer (Fluke 435 series II)*
  - *Custom DAQ system (I, V, and Temp)*
  - *Video cameras*
  - *Pyranometers*



IE measurement setup for a arc-flash



Setup showing the dc contactor and switches for controlling PV source

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Arc-flash field test: Instrumentation

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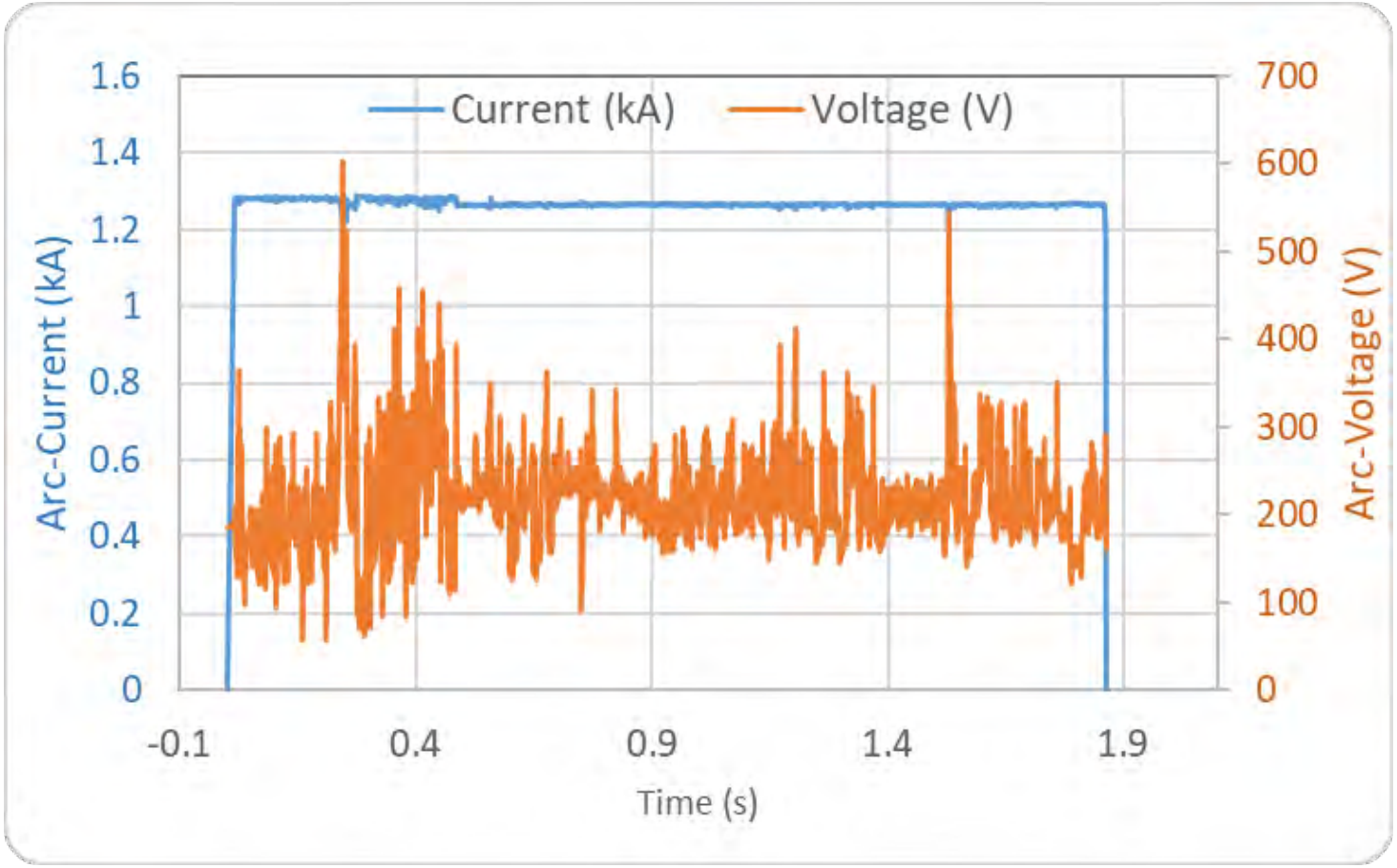
Arc-flash current (I_{Arc}) and voltage (V_{Arc})

- PV array act as a relatively constant current dc source
- V_{Arc} fluctuates (as the plasma moves)
- A sustainable arc-flash has been demonstrated



Time response of a I_{Arc} and V_{Arc} during an arc-flash

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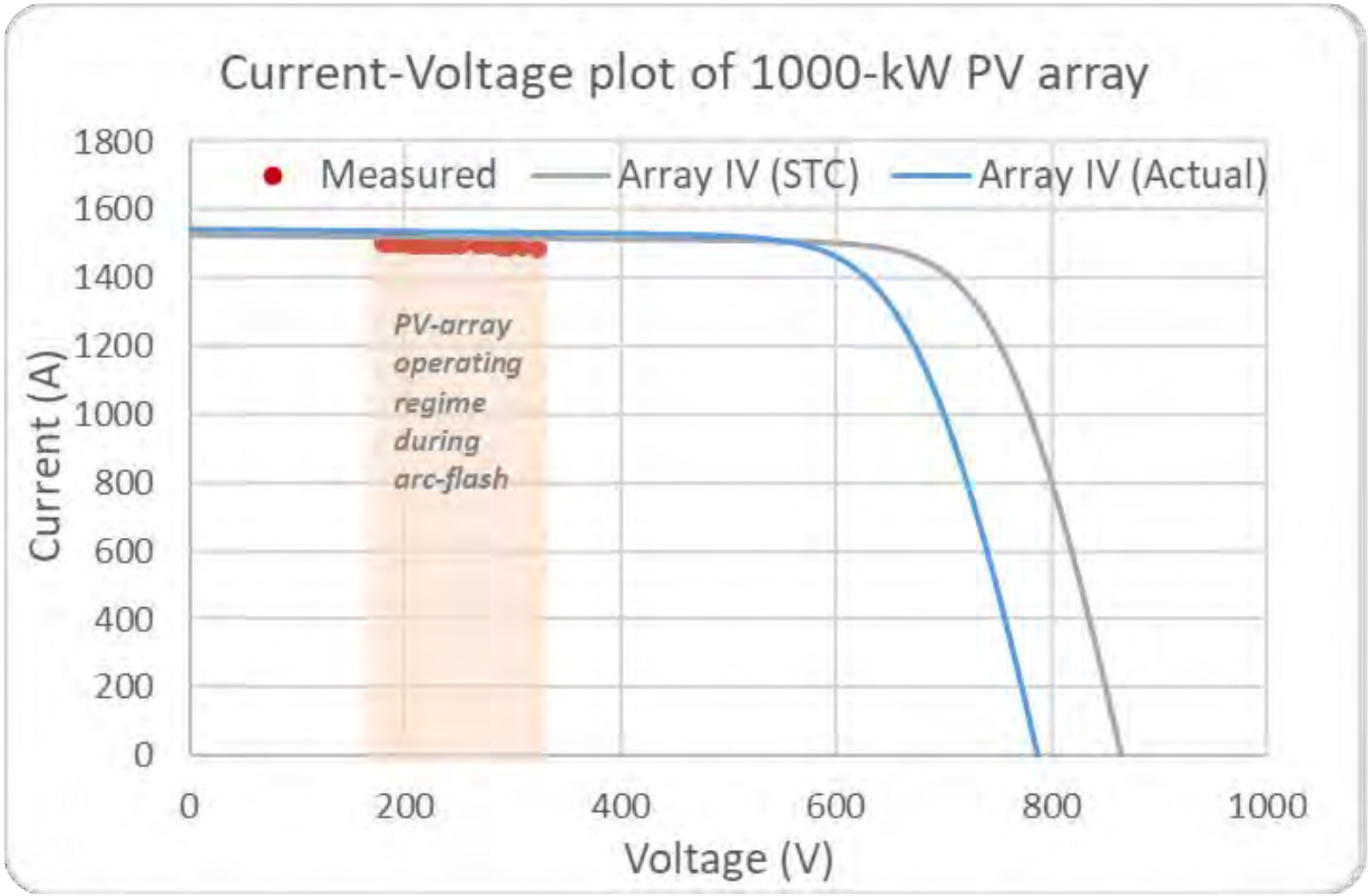
Operating regime on IV curve

- PV array behaves as a current-limited power source: ($I_{SC} > I_{Arc} > I_{MP}$)
- Upstream switchgear (Overcurrent protection) is not likely to be activated



I-V curve of a PV array under arc flash

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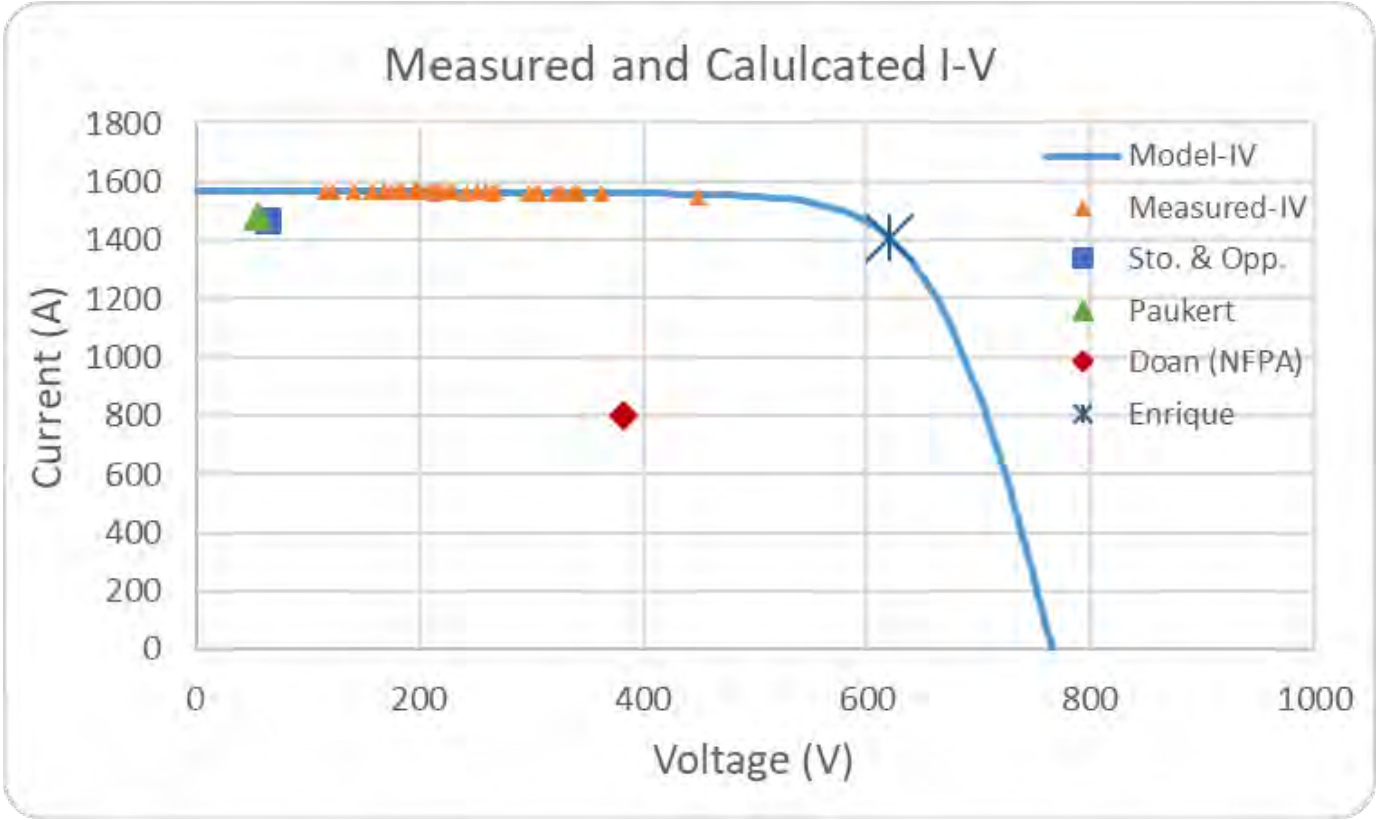
Arc current and Voltage Energy: Measured Vs Calculated

- Paukert et al.
  - Assumes the arc has a nonlinear resistance.
  - The resistance of the arc is based on a table of nonlinear functions for several electrode gaps.
- Stokes and Oppenlander:
  - Assumes that the arc has a nonlinear resistance based on electrode gap and arc-current.
- Doan (NFPA-70E):
  - Assumes maximum power transfer
  - $V_{Arc} = V_{Oc}/2$ and $I_{Arc} = I_{Sc}/2$.
- *Enrique et al.*
  - Tailored to PV systems
  - Assumes that the maximum PV array power transfers to the arc.
  - The voltage and current are both at the maximum-power point.
  - $V_{Arc} = V_{Mp}$ and $I_{Arc} = I_{Mp}$



Calculated and measured I_{Arc} and V_{Arc} during an arc-flash

Paukert et al. and Stokes & Oppenlander models both predict much small V_{Arc} than measured.
Doan (NFPA) and Enrique et al. model predict V_{Arc} higher than measured.

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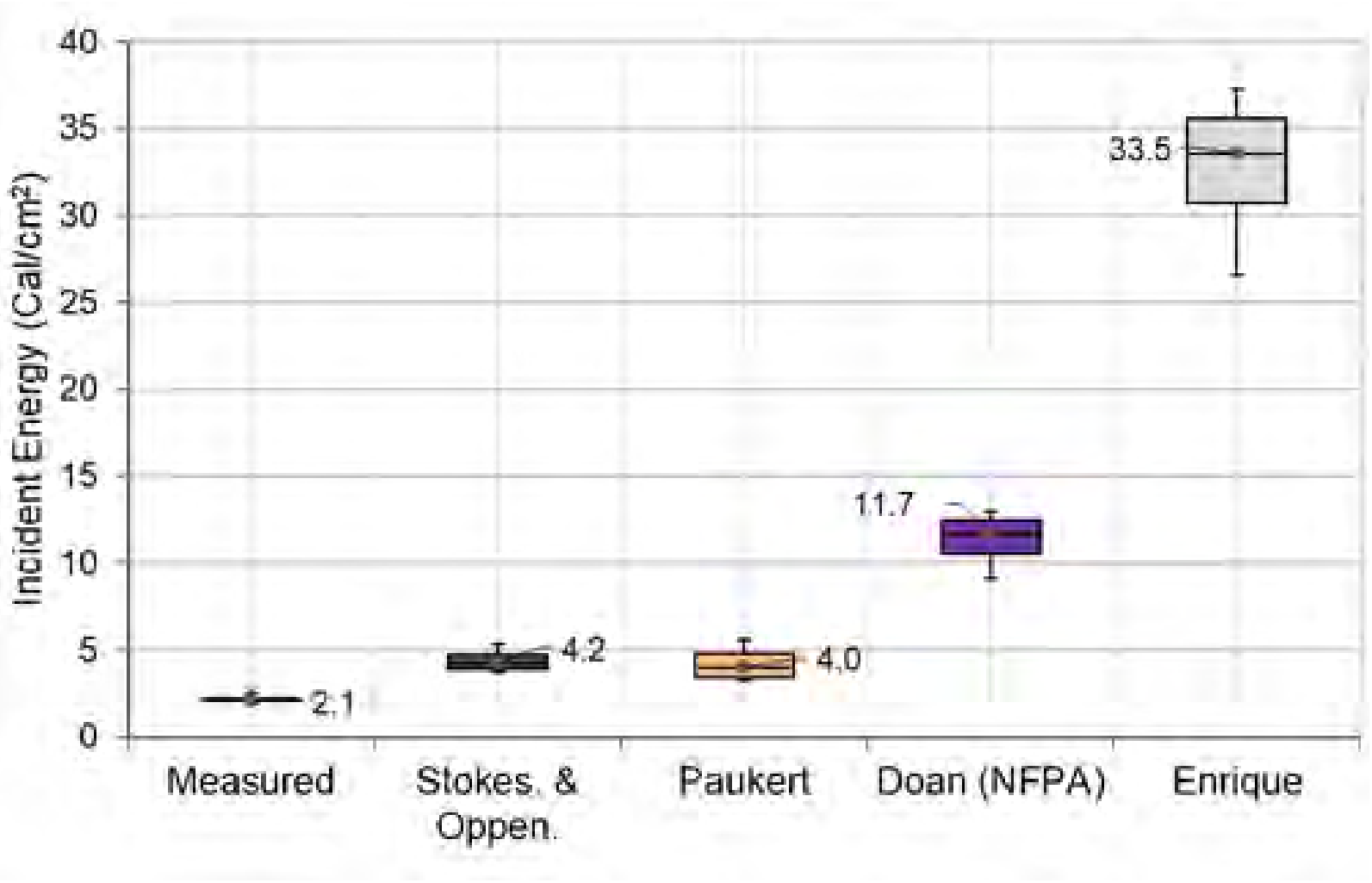
Measured Vs Calculated Incident energy



Available dc arc-flash model are overly conservative

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Proposed Model:
Guideline to Estimate Incident Energy in a PV Plant

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PV focused empirical equation for IE estimation

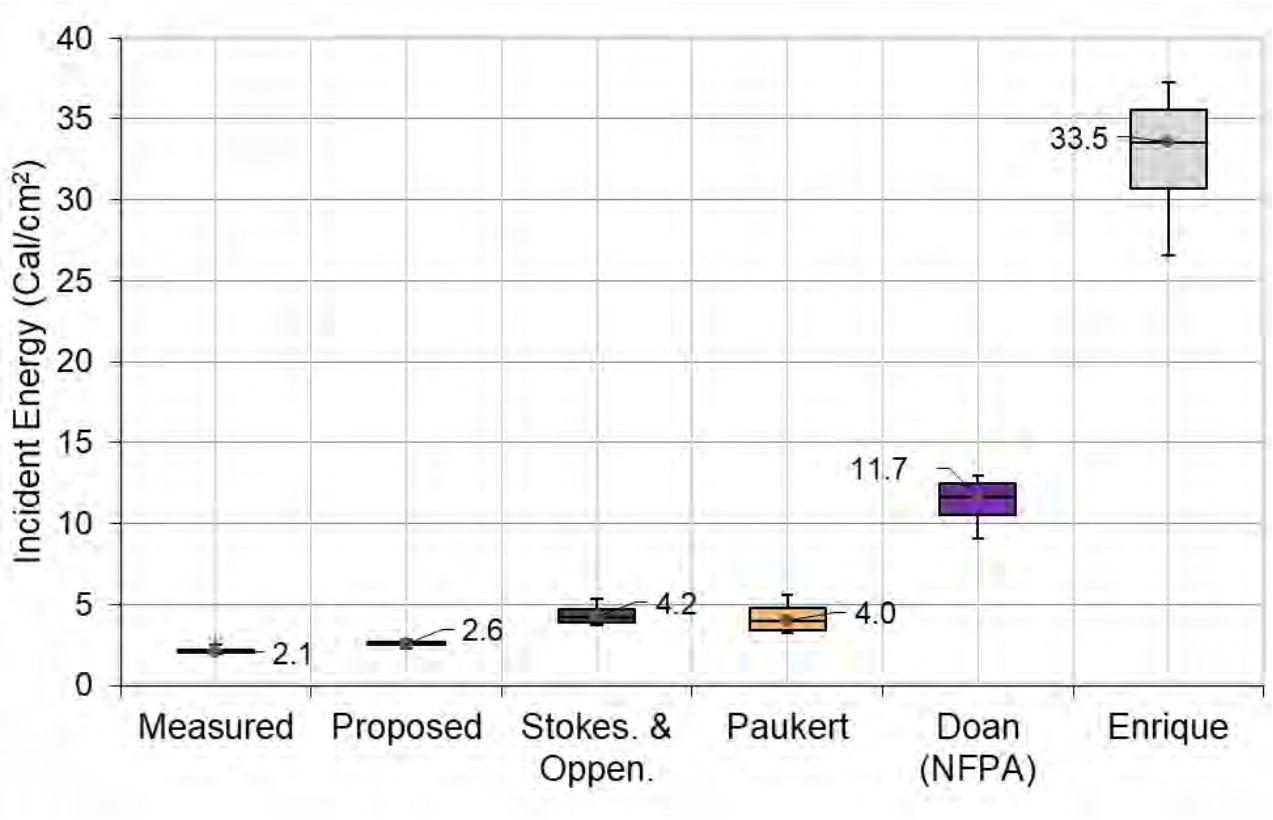
- Based on measured arc-flash data and IEEE-1584 guideline.

$$IE = I_{Arc} \times V_{Arc} \times t_{Arc} \times k_x$$

- Further simplifies to:

$$IE = 0.00087 \times I_{Sc} \times t_{Arc} \times \left(\frac{D}{45.7}\right)^{-1.6}$$

D is the working distance in cm and power -1.6 is the distance coefficient.



Proposed model predicts the incident energy in PV plants (1,000 Vdc)

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Summary and Future Work

- Existing dc arc-flash calculation models for PV power systems are ***not accurate.***
  - Can be overly conservative
- ***In-field arc-flash experiments*** provide accurate assessment of arc-flash risks.
  - A ***sustainable dc arc-fault*** is possible in PV plants due to overcurrent protection devices having similar rating as short-circuit current.
- ***Controlled lab-based*** experiments and ***physics-based models*** to develop better calculation models
- More arc-flash experiments in **1,500 Vdc PV plants** and equipments

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Other publications

- *Measured and Calculated DC Arc-Flash Incident Energy in a Large-Scale Photovoltaic Plant,* in IEEE JPV, vol. 9, no. 5, pp. 1343-1349, Sept. 2019.
- *Measured dc Arc-flash Risk in a Photovoltaic System*, *IEEE-PVSC,* Chicago, IL, USA, 2019, pp. 3140-3143.
- *Direct current arc-flash hazards of solar photovoltaic systems*, EPRI, Palo Alto, CA, 2018, 3002014641 https://www.epri.com/#/pages/product/000000003002014641/?lang=en-US
- *DC Arc Flash on Photovoltaic Equipment.* EPRI, Palo Alto, C, 2018, 3002014124 https://www.epri.com/#/pages/product/000000003002014124/?lang=en-US

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PV FIRES | Italian experiences

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Vincenzo Puccia — **National Fire Brigade - Italy**

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VIGILI DEL FUOCO CORPO NAZIONALE
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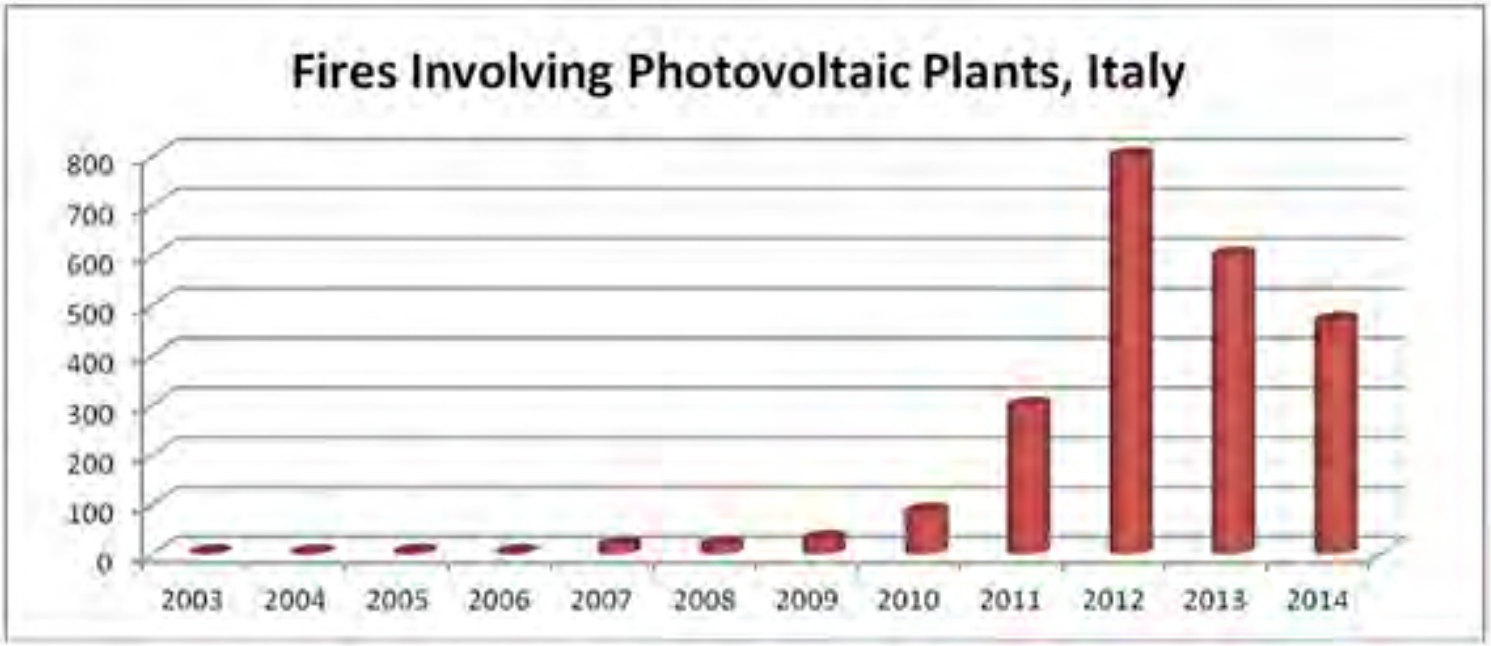
COMMERCIAL FACILITIES

BUILDINGS

STATISTICS OF CARRIED OUT INTERVENTIONS THAT INVOLVED PHOTOVOLTAIC SYSTEMS



In 2012, statistics provides the data of about 800 interventions, which slightly reduced to 600 in 2013 and about 450 in 2014 (approximately 500,000 are the systems installed).

The statistical data refers to the totality of interventions that involved PV systems, regardless of the complexity and magnitude of the event.

No data are yet available on the effect of component aging.

6th April 2012: fire at the Eripressa Cicerale plant (Salerno). Thermoplastic molding company, developed large black cloud…. [2]

Causes and dynamics still under investigation. Some hypotheses speak of a construction site for the repair of the bituminous coat roof. Vertical propagation of the fire from the PV roofing panels through the skylights to the underlying machinery and deposits.

[2] source: http://www.salerno.coldiretti.it; http://www.stiletv.it

On April 21, 2012, the Fire Brigade intervened in San Tammaro (Caserta) to extinguish a fire on a roof with photovoltaic panels on it for a total area of about 5000 m^2.[3]

The roof covered a stable of a well-known farm; animals rescued. The local press [4] reports as a possible cause an electrical failure of the photovoltaic system and the subsequent spread of the fire on the roof and from the roof to the rooms below. The flames were also fueled by a strong south-north wind.

[3] source: www.vigilfuoco.it

[4] source: www.caiazzorinasce.net

July 8, 2012: fire on the roof at Elmas, the smoke detector gives the alarm on time [5]

Thanks to the technicians of the company from Carraia (Empoli) and to the arrival of the Fire Brigade, the flames, which started from the photovoltaic system on the roof, were extinguished.

[5] source: http://www.gonews.it/articolo_143624_incendio-tetto-alla-Elmas-limpianto-rileva-fumi-lallarme-tempo.html

Case study references:

http://www.sfpe.org/?page=FPE_ET_Issue_99

https://www.researchgate.net/publication/266622061_Fire_risk_analysis_of_photovoltaic_plants_A_case_study_moving_from_two_large_fires_from_accident_investigation_and_forensic_engineering_to_fire_risk_assessment_for_reconstruction_and_permitting_purpos

METHOD

- The fire risk assessment is the tool that organisations have to adopt to analyse the fire-related risks typically concerning health and safety, environment, business continuity, and reputation. During the last years, an increasing need has emerged to incorporate the company's safety management system into that phase, in a bidirectional approach, under the push of some technical standards, including ISO 31000 and ISO 45001. Bowties are the methodology that better reaches this goal, and they unveiled extremely powerful when organisation are called to managed multiple assets under fire risk.

- BowTie method has been selected.

- Towards a relative risk ranking. Organisations managing a portfolio of multiple similar assets (e.g. PV plants, waste treatment sites, railway stations, process plants) need to have a uniform and consistent approach in fire risk analysis, in order to have a proper overview about how the risk is distributed within the company and to prioritize corrective actions, that means making risk-based informed decisions and budget allocations.

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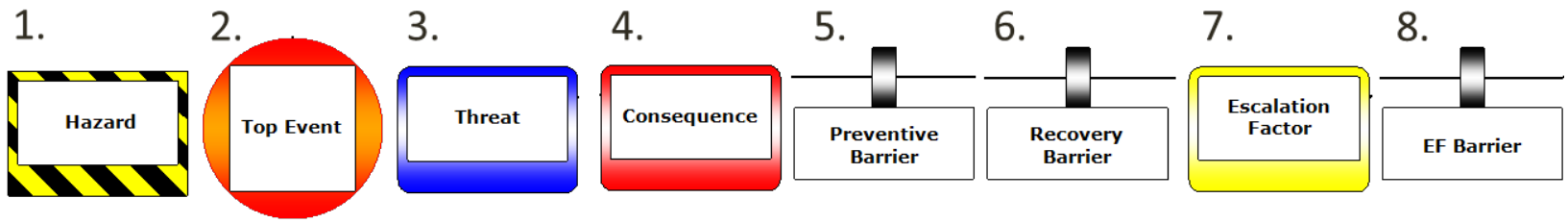
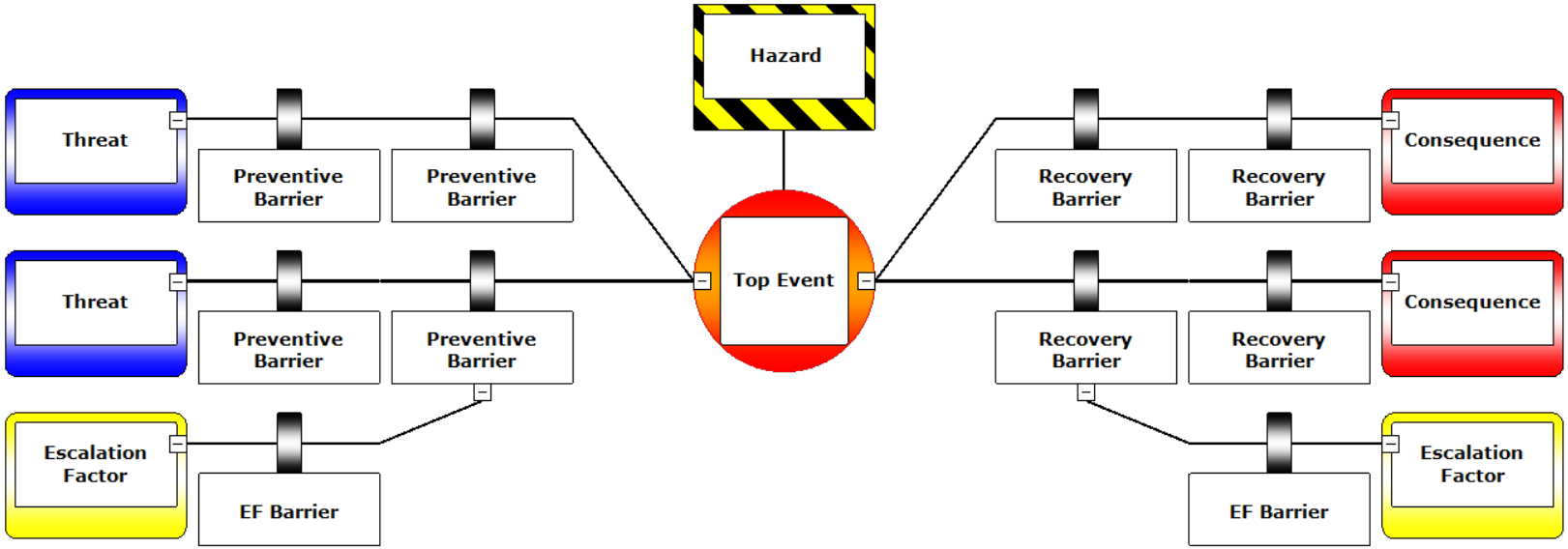
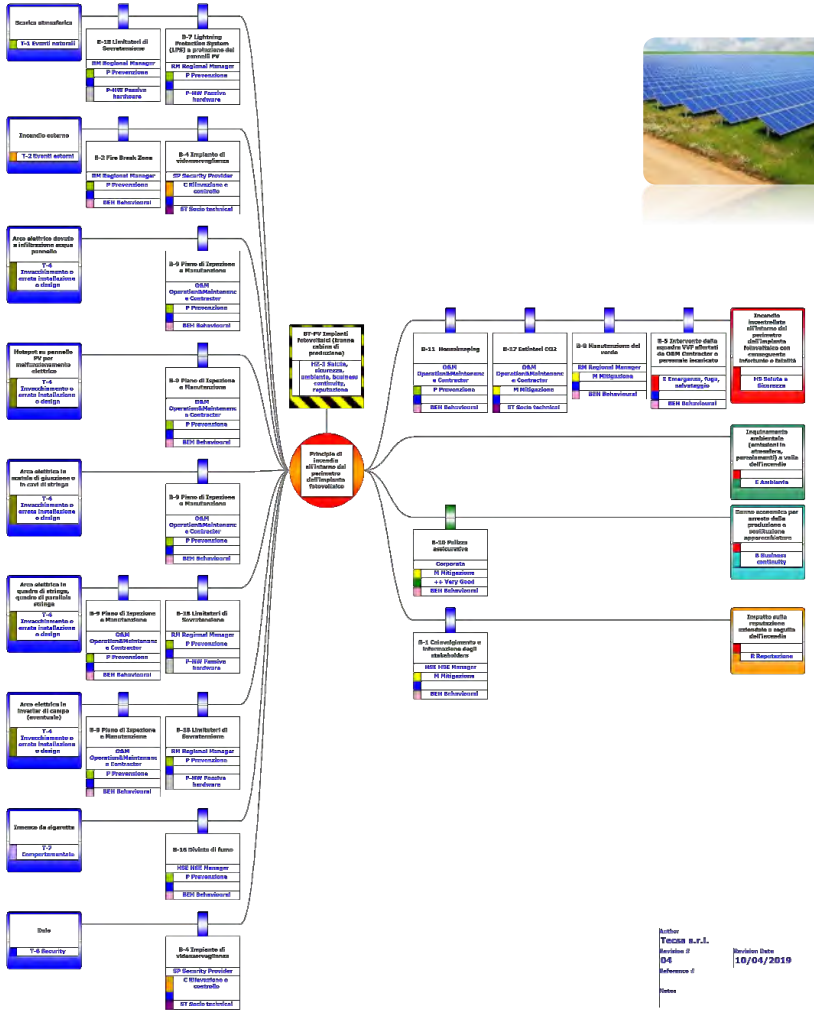
BOW-TIE


1.
Hazard
2.
Top Event
3.
Threat
4.
Consequence
5.
Preventive Barrier
6.
Recovery Barrier
7.
Escalation Factor
8.
EF Barrier


Hazard
Threat
Preventive Barrier
Preventive Barrier
Threat
Preventive Barrier
Preventive Barrier
Escalation Factor
EF Barrier
Top Event
Recovery Barrier
Recovery Barrier
Consequence
Recovery Barrier
Recovery Barrier
Consequence
EF Barrier
Escalation Factor

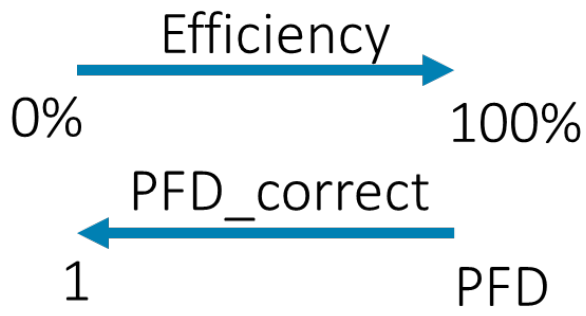
BowTie

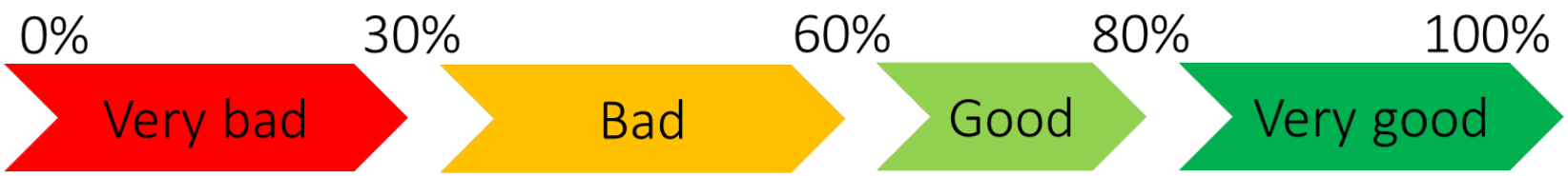
- Barriere
  - Coinvolgimento e informazione stakeholders
  - Fire Break Zone
  - Formazione del personale
  - Impianto di videosorveglianza
  - Intervento squadra VVF allertati da O&M Contractor o televigilanza
  - Lightning Protection System a protezione pannelli PV
  - Manutenzione del verde
  - Piano di ispezione e manutenzione
  - Polizza assicurativa
  - Housekeeping
  - Sistema di rivelazione automativa incendi con sezionamento inverter e intervento tempestivo O&M Contractor
  - Sistema di sezionamento inverter contro malfunzionamenti elettrici
  - Sistema di riduzione automatica della produzione, su rilevatore di temperatura (derating)
  - Ventilazione forzata / impianto condizionamento
  - Divieto di fumo
  - Estintori CO2
  - Limitatori di sovratensione
  - Derattizzazione
  - Recovery Plan



Performance Standards

PS	Score	Description
++	1	In place and fully effective
+	0,66	In place and partially effective
-	0,33	In place and but poorly effective
--	0	Not in place
IM	0,33	Info not available





Barrier efficiency scale

Performance standards against barriers in several plants

Tabella 5.3/D – Efficacia delle barriere

Barriera		Efficacia barriere	
Codice	Descrizione	NOME IMPIANTI	
B-1	Coinvolgimento e informazione degli stakeholders	100%	0%
B-2	Fire Break Zone	NA	0%
B-3	Formazione e addestramento del personale	33%	33%
B-4	Impianto di videosorveglianza	0%	0%
B-5	Intervento della squadra VVF allertati da O&M Contractor o personale incaricato	83%	0%
B-7	Lightning Protection System (LPS) a protezione dei pannelli PV	NA	66%
B-8	Manutenzione del verde	NA	100%
B-9	Piano di Ispezione e Manutenzione	50%	50%
B-10	Polizza assicurativa	100%	100%
B-11	Housekeeping	50%	50%
B-12	Sistema di rilevazione automatica incendi con sezionamento inverter e intervento tempestivo O&M Contractor	100%	NA
B-13	Sistema di protezione dell'inverter mediante sezionamento in caso di malfunzionamenti elettrici	50%	50%
B-14	Sistema di sicurezza dell'inverter (riduzione automatica della produzione, su rilevatore di temperatura, per diminuire il surriscaldamento)	50%	50%
B-15	Ventilazione forzata o impianto di condizionamento	50%	50%
B-16	Divieto di fumo	66%	66%
B-17	Estintori CO_2	83%	83%
B-18	Limitatori di sovratensione	0%	0%
B-19	Derattizzazione	50%	50%
B-20	Recovery Plan	0%	0%

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REFERENCES

Technical standards

[1] IEC 31010:2009. Risk management – Risk assessment techniques; 2009.

[2] ISO 31000:2018. Risk management – Guidelines; 2018.

Other references

[3] CNVVF - Nucleo Investigativo Antincendi, "Relazione tecnica sugli incendi coinvolgenti impianti fotovoltaici";

[4] CCPS. Guidelines for enabling conditions and conditional modifiers in layers of protection analysis. Wiley; 2013.

[5] CCPS. Guidelines for initiating events and independent protection layers in layer of protection analysis. Wiley; 2015.

[6] CCPS. Layer of Protection Analysis: Simplified Process Risk Assessment. New York: Wiley; 2011.

[7] CCPS. Process Safety Glossary: Bow Tie Diagram. Available online at www.aiche.org/ccps/resources/glossary/process-safety-glossary/bow-tie-diagram; last access on April, 30th 2018.

[8] CCPS. Project 237: Guidelines for Barrier Risk Management (Bow Tie Analysis), 2017 (in progress).

[9] CCPS-EI. BowTies in Risk Management. AIChE-Wiley, 2018.

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PV FIRES | Italian experiences

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VIGILI DEL FUOCO CORPO NAZIONALE

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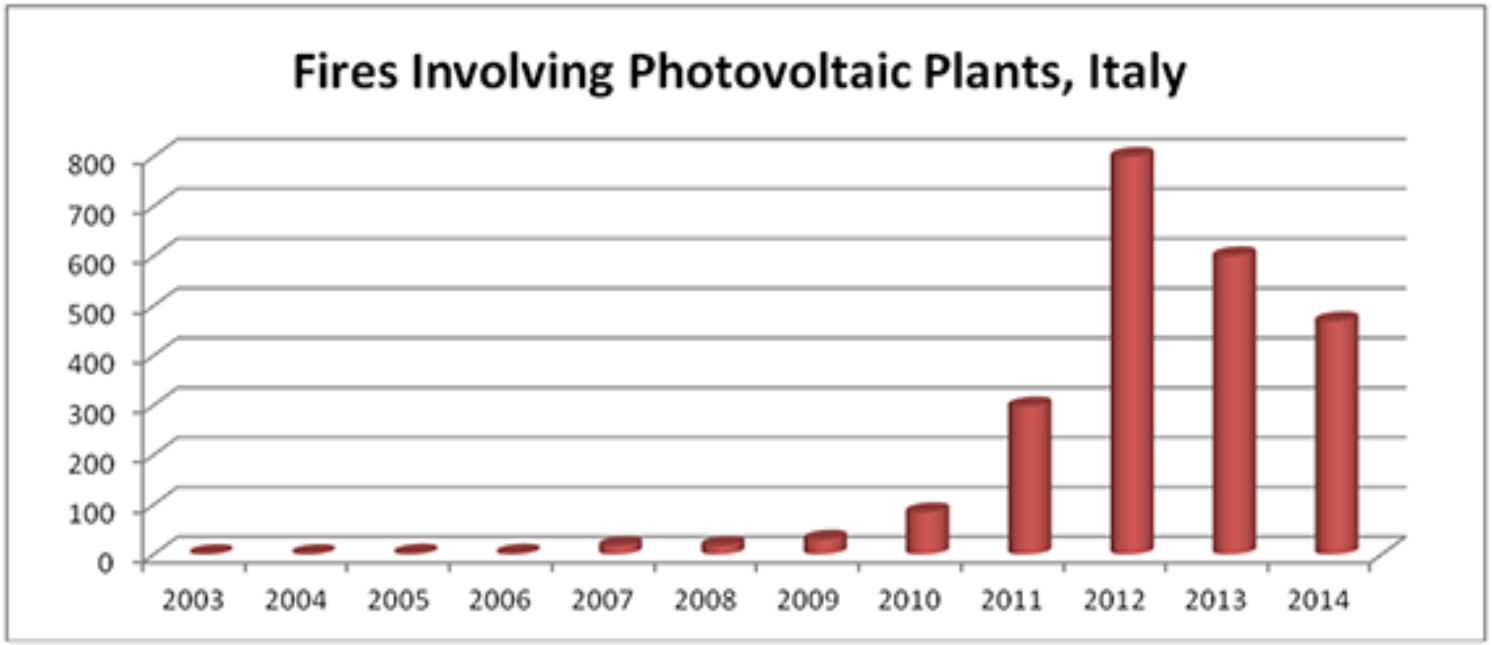
COMMERCIAL FACILITIES

BUILDINGS

STATISTICS OF CARRIED OUT INTERVENTIONS THAT INVOLVED PHOTOVOLTAIC SYSTEMS



In 2012, statistics provides the data of about 800 interventions, which slightly reduced to 600 in 2013 and about 450 in 2014 (approximately 500,000 are the systems installed).

The statistical data refers to the totality of interventions that involved PV systems, regardless of the complexity and magnitude of the event.

No data are yet available on the effect of component aging.

6th April 2012: fire at the Eripressa Cicerale plant (Salerno). Thermoplastic molding company, developed large black cloud…. [2]

Causes and dynamics still under investigation. Some hypotheses speak of a construction site for the repair of the bituminous coat roof. Vertical propagation of the fire from the PV roofing panels through the skylights to the underlying machinery and deposits.

[2] source: http://www.salerno.coldiretti.it; http://www.stiletv.it

On April 21, 2012, the Fire Brigade intervened in San Tammaro (Caserta) to extinguish a fire on a roof with photovoltaic panels on it for a total area of about 5000 m^2.[3]

The roof covered a stable of a well-known farm; animals rescued. The local press [4] reports as a possible cause an electrical failure of the photovoltaic system and the subsequent spread of the fire on the roof and from the roof to the rooms below. The flames were also fueled by a strong south-north wind.

[3] source: www.vigilfuoco.it

[4] source: www.caiazzorinasce.net

July 8, 2012: fire on the roof at Elmas, the smoke detector gives the alarm on time [5]

Thanks to the technicians of the company from Carraia (Empoli) and to the arrival of the Fire Brigade, the flames, which started from the photovoltaic system on the roof, were extinguished.

[5] source: http://www.gonews.it/articolo_143624_incendio-tetto-alla-Elmas-limpianto-rileva-fumi-lallarme-tempo.html

Case study references:

http://www.sfpe.org/?page=FPE_ET_Issue_99

https://www.researchgate.net/publication/266622061_Fire_risk_analysis_of_photovoltaic_plants_A_case_study_moving_from_two_large_fires_from_accident_investigation_and_forensic_engineering_to_fire_risk_assessment_for_reconstruction_and_permitting_purpos

METHOD

- The fire risk assessment is the tool that organisations have to adopt to analyse the fire-related risks typically concerning health and safety, environment, business continuity, and reputation. During the last years, an increasing need has emerged to incorporate the company's safety management system into that phase, in a bidirectional approach, under the push of some technical standards, including ISO 31000 and ISO 45001. Bowties are the methodology that better reaches this goal, and they unveiled extremely powerful when organisation are called to managed multiple assets under fire risk.

- BowTie method has been selected.

- Towards a relative risk ranking. Organisations managing a portfolio of multiple similar assets (e.g. PV plants, waste treatment sites, railway stations, process plants) need to have a uniform and consistent approach in fire risk analysis, in order to have a proper overview about how the risk is distributed within the company and to prioritize corrective actions, that means making risk-based informed decisions and budget allocations.

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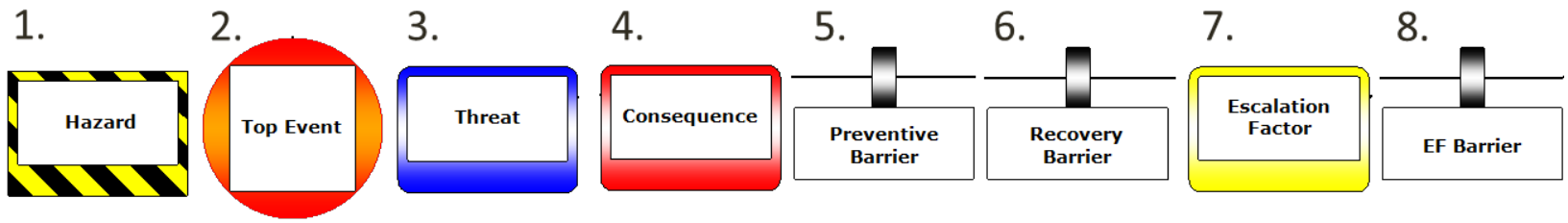
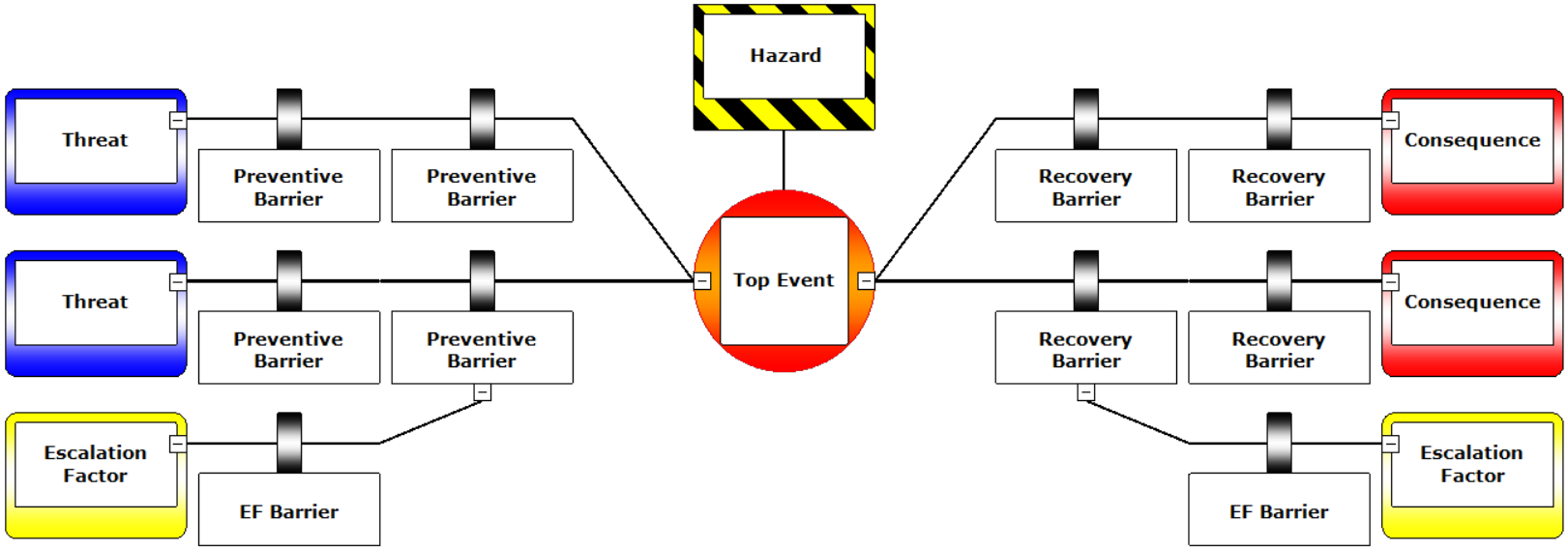
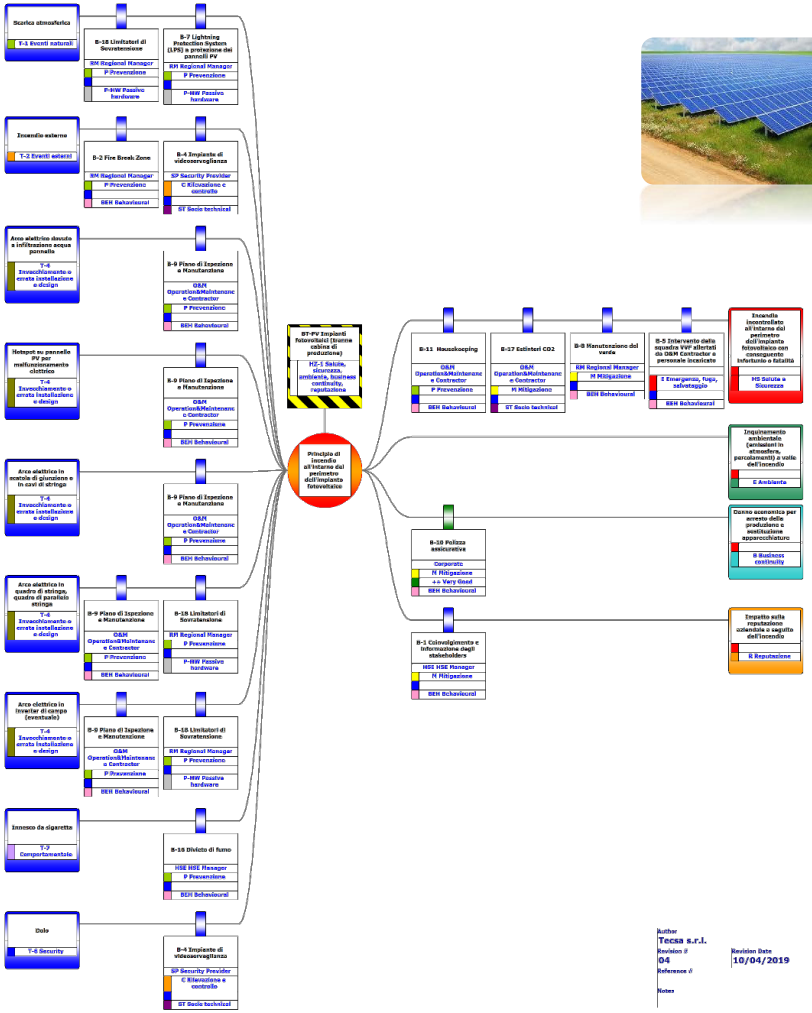
BOW-TIE


1.
Hazard
2.
Top Event
3.
Threat
4.
Consequence
5.
Preventive Barrier
6.
Recovery Barrier
7.
Escalation Factor
8.
EF Barrier


Hazard
Threat
Preventive Barrier
Preventive Barrier
Threat
Preventive Barrier
Preventive Barrier
Escalation Factor
EF Barrier
Top Event
Recovery Barrier
Recovery Barrier
Consequence
Recovery Barrier
Recovery Barrier
Consequence
EF Barrier
Escalation Factor

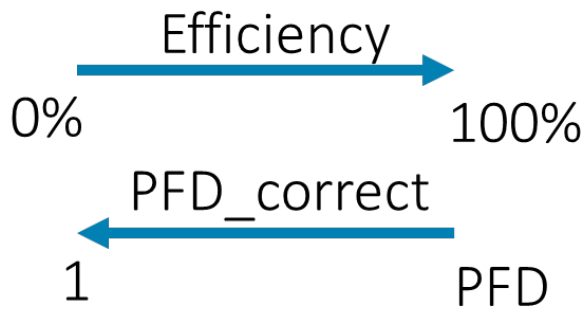
BowTie

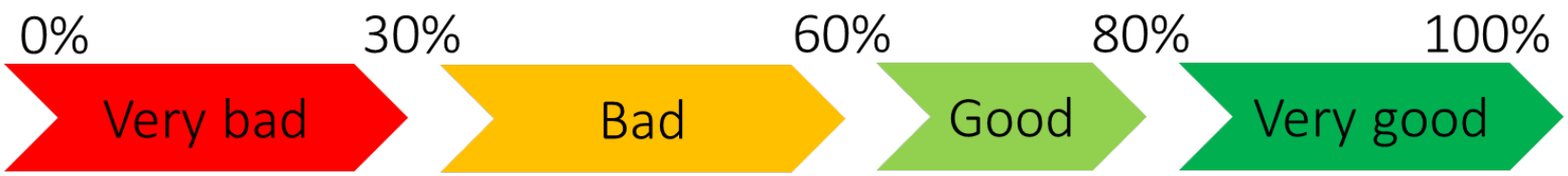
- Barriere
  - Coinvolgimento e informazione stakeholders
  - Fire Break Zone
  - Formazione del personale
  - Impianto di videosorveglianza
  - Intervento squadra VVF allertati da O&M Contractor o televigilanza
  - Lightning Protection System a protezione pannelli PV
  - Manutenzione del verde
  - Piano di ispezione e manutenzione
  - Polizza assicurativa
  - Housekeeping
  - Sistema di rivelazione automativa incendi con sezionamento inverter e intervento tempestivo O&M Contractor
  - Sistema di sezionamento inverter contro malfunzionamenti elettrici
  - Sistema di riduzione automatica della produzione, su rilevatore di temperatura (derating)
  - Ventilazione forzata / impianto condizionamento
  - Divieto di fumo
  - Estintori CO2
  - Limitatori di sovratensione
  - Derattizzazione
  - Recovery Plan



Performance Standards

PS	Score	Description
++	1	In place and fully effective
+	0,66	In place and partially effective
-	0,33	In place and but poorly effective
--	0	Not in place
IM	0,33	Info not available





Barrier efficiency scale

Performance standards against barriers in several plants

Tabella 5.3/D – Efficacia delle barriere

Barriera		Efficacia barriere	
Codice	Descrizione	NOME IMPIANTI	
B-1	Coinvolgimento e informazione degli stakeholders	100%	0%
B-2	Fire Break Zone	NA	0%
B-3	Formazione e addestramento del personale	33%	33%
B-4	Impianto di videosorveglianza	0%	0%
B-5	Intervento della squadra VVF allertati da O&M Contractor o personale incaricato	83%	0%
B-7	Lightning Protection System (LPS) a protezione dei pannelli PV	NA	66%
B-8	Manutenzione del verde	NA	100%
B-9	Piano di Ispezione e Manutenzione	50%	50%
B-10	Polizza assicurativa	100%	100%
B-11	Housekeeping	50%	50%
B-12	Sistema di rilevazione automatica incendi con sezionamento inverter e intervento tempestivo O&M Contractor	100%	NA
B-13	Sistema di protezione dell'inverter mediante sezionamento in caso di malfunzionamenti elettrici	50%	50%
B-14	Sistema di sicurezza dell'inverter (riduzione automatica della produzione, su rilevatore di temperatura, per diminuire il surriscaldamento)	50%	50%
B-15	Ventilazione forzata o impianto di condizionamento	50%	50%
B-16	Divieto di fumo	66%	66%
B-17	Estintori CO_2	83%	83%
B-18	Limitatori di sovratensione	0%	0%
B-19	Derattizzazione	50%	50%
B-20	Recovery Plan	0%	0%

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REFERENCES

Technical standards

[1] IEC 31010:2009. Risk management – Risk assessment techniques; 2009.

[2] ISO 31000:2018. Risk management – Guidelines; 2018.

Other references

[3] CNVVF - Nucleo Investigativo Antincendi, "Relazione tecnica sugli incendi coinvolgenti impianti fotovoltaici";

[4] CCPS. Guidelines for enabling conditions and conditional modifiers in layers of protection analysis. Wiley; 2013.

[5] CCPS. Guidelines for initiating events and independent protection layers in layer of protection analysis. Wiley; 2015.

[6] CCPS. Layer of Protection Analysis: Simplified Process Risk Assessment. New York: Wiley; 2011.

[7] CCPS. Process Safety Glossary: Bow Tie Diagram. Available online at www.aiche.org/ccps/resources/glossary/process-safety-glossary/bow-tie-diagram; last access on April, 30th 2018.

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Pre-installation EL & I-V Solar Panel Testing in a Mobile Test Lab

Andrew M. Gabor[1], Ankil Sanghvi[2], Andrew Anselmo[1], Rob Janoch[1], Robert Lockhart[2], and Abdu Elrefaiy[3]
[1]BrightSpot Automation LLC, Westford, MA, USA; [2]Acuity Power Group, Waltham, MA, USA; [3]NRGTree, Lowell, MA, USA

1. Opportunity

- EL (Electroluminescence) & I-V testing of modules prior to installation has the benefits of
  - Ensuring that system investors are not receiving panels with cracked cells or low power, thus potentially reducing the degradation rate, improving energy delivery, and reducing O&M costs
  - Avoiding finger pointing later on if problems are seen after installation
  - Helping to optimize shipping and handling
  - Establishing a baseline of performance to reference against later
  - Reducing degradation and performance risk to investors
- A mobile testing lab can perform such tests under repeatable conditions, day or night

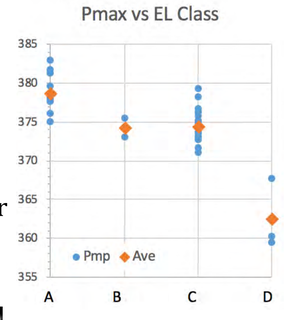
2. *MobileTestSpot* Background

- A+ spatial uniformity and temporal stability for I-V testing
- Continuous warm-white spectrum LED boards for simplicity and low-cost
  - Calibrate with reference modules
  - Slow I-V scans for high efficiency modules
- EL imaging with 24 MegaPixel camera
- Heat by EL power supply and/or LED boards to generate energy delivery matrix of efficiency vs irradiance & temperature
- 90 second cycle timing including loading

3. Field Observation and Lessons Learned

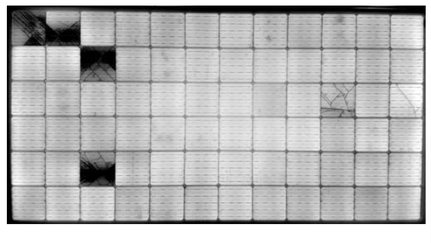
Lesson 1: **Module power is frequently correlated to EL class**

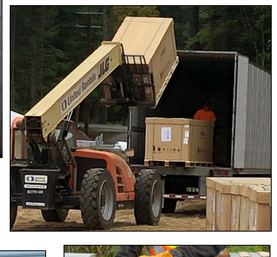
- Using MBJ Solar Module Judgment Criteria v3.4
  - **Class A** – No abnormalities that can lead to premature drop in power
  - **Class B** – A few abnormalities that do not lead to a premature drop in power
  - **Class C** – Increased abnormalities that may lead to a premature drop in power
  - **Class D** – Negative properties that can directly lead to a drop in power



Lesson 2: **If the cardboard on the pallet looks damaged, there's a good chance there are cracked cells inside. Prioritize sampling from these pallets.**

- Forklift/lull damage from unloading pallets and moving pallets around





Lesson 3: **Place pallets on even ground. Prioritize sampling from damaged pallets and badly tilted pallets.**

- Uneven ground, tree roots, rocks and other debris underneath pallets can bow and break deckboards or cause pallets to touch each other, thus shocking and stressing panels

Lesson 4: **Minimize restaging of pallets**

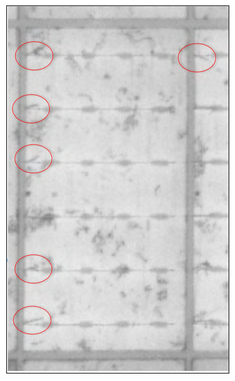
- Every restaging event adds additional risk from handling and replacement on uneven ground

Lesson 5: **Pallets should be wrapped if left in field for extended periods in rainy weather**

- Exterior cardboard may deteriorate and fail causing stress and damage to modules and allowing water into cable connectors.

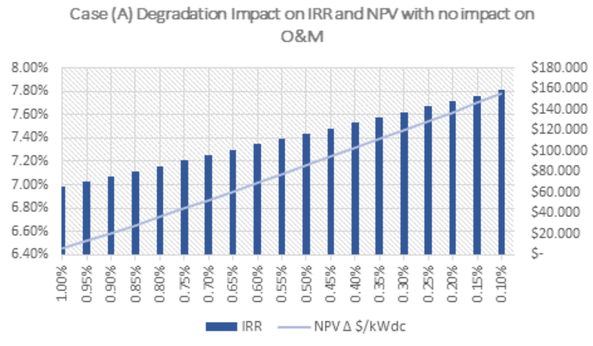
Lesson 6: **Half-cut cells can be sensitive to cracks at the laser cut edges**

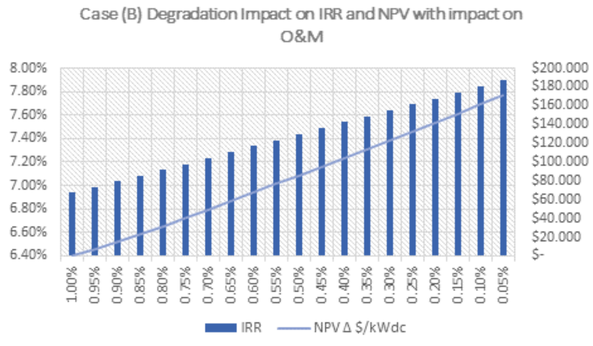
- Close examination of EL images is necessary to see these short cracks



4. Financial Benefits of Pre-install Testing

- Pre-install testing has potential to reduce system degradation rates and O&M costs
- For reducing annual degradation rates by 0.5%/year, IRR can increase by 0.45%, and NPV can increase by $83/kWdc
- Reduced O&M costs may add a further benefit of 0.06% in IRR and $8/kWdc in NPV
- Reduction of risk may enable lower insurance rates and a lower cost of capital





Assumptions for the above calculations

- System Size 1MWdc, fixed tilt
- Developed Value of $2.25 MM
- kWh/KWp 1,227
- ITC 26%
- PPA Rate of $0.18465/kWh (Massachusetts NSTAR SMART Block 4 + Roof Adder)
- PPA Post-Smart Value year 20-30 $0.10/kWh
- Operating Expense Margin 25%
- O&M is assumed in Case (B) to be reduced and its overall impact on Operation Expenditures will be 1% reduction per 0.5% improvement in annual degradation rate

This material is based upon work supported in part by the Massachusetts Clean Energy Center under the InnovateMass program

Module Imaging for Hail Damage Assessment and Two-Year Follow Up

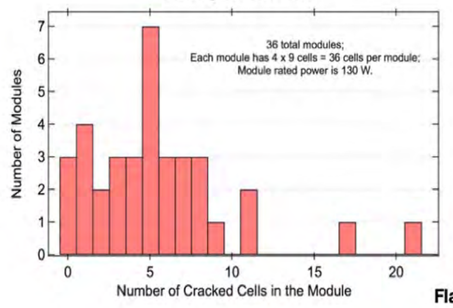
Steve Johnston, Dana B. Sulas-Kern, and Dirk Jordan
National Renewable Energy Laboratory, Golden, CO, 80401, U.S.A.

An array of 36 multicrystalline silicon modules installed in 2007 is oriented facing south at a tilt angle of 30 degrees above horizontal. It is located approximately 2 km southwest of NREL in Golden, CO.

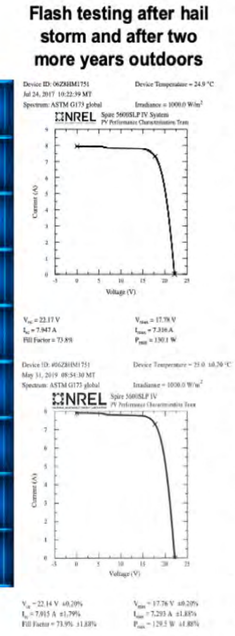
Hail storm

May 8, 2017

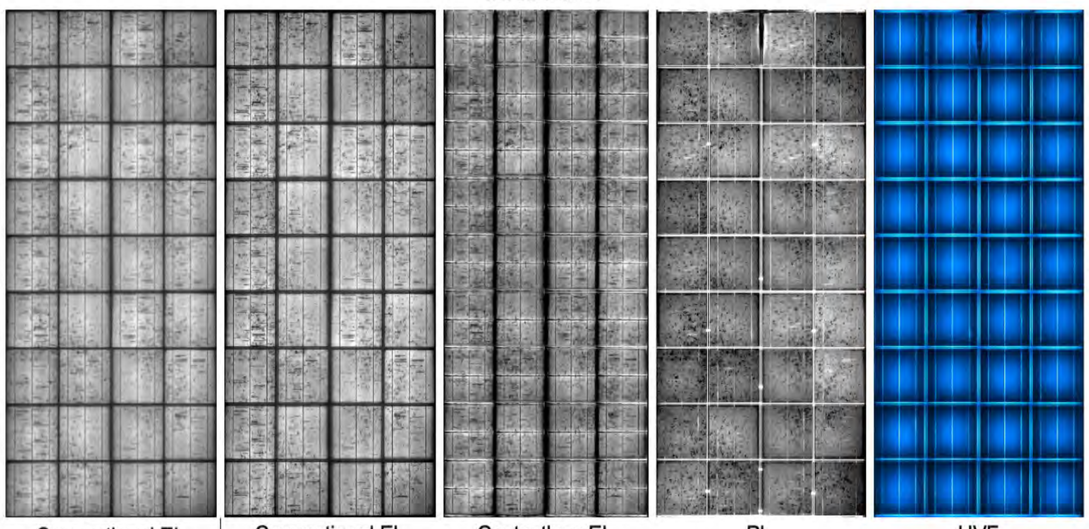
Histogram of hail-induced cracked cells per module



Flash testing after hail storm and after two more years outdoors



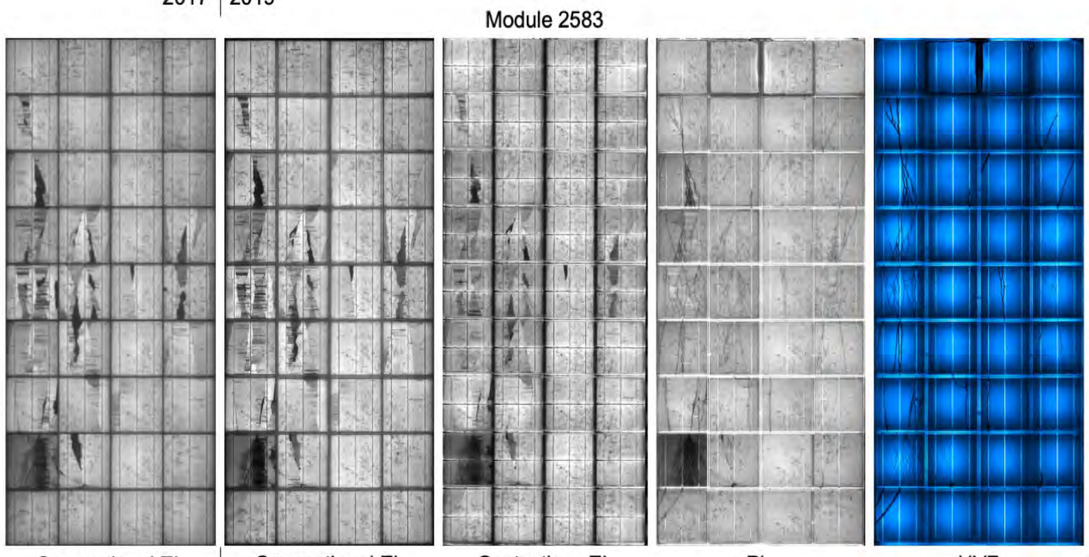
Module 1751



Conventional EL | Conventional EL | Contactless EL | PL | UVF

2017 | 2019

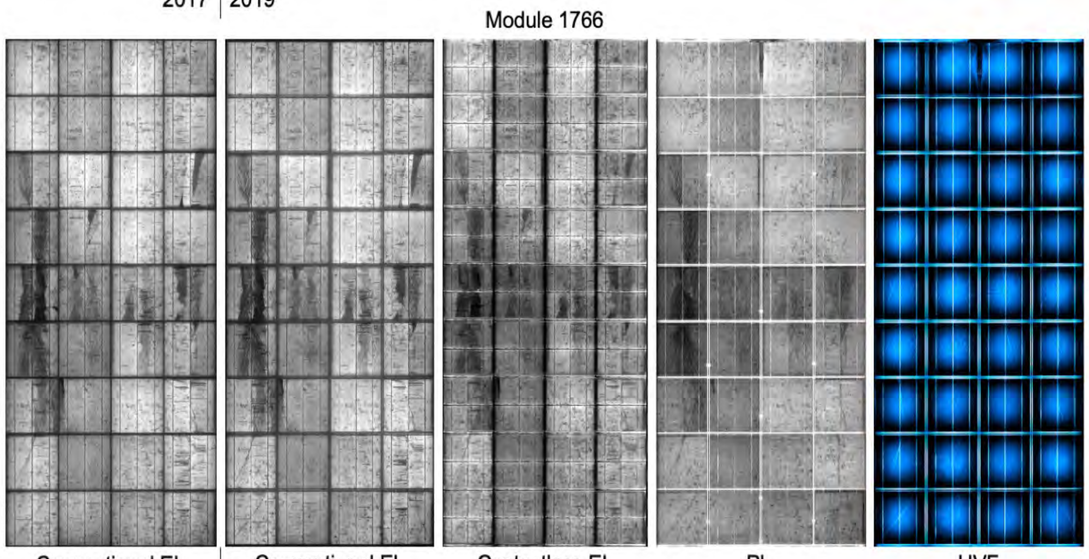
Module 2583



Conventional EL | Conventional EL | Contactless EL | PL | UVF

2017 | 2019

Module 1766



Conventional EL | Conventional EL | Contactless EL | PL | UVF

2017 | 2019

Module imaging techniques:

An example of extreme hail damage on a PV array in Colorado.

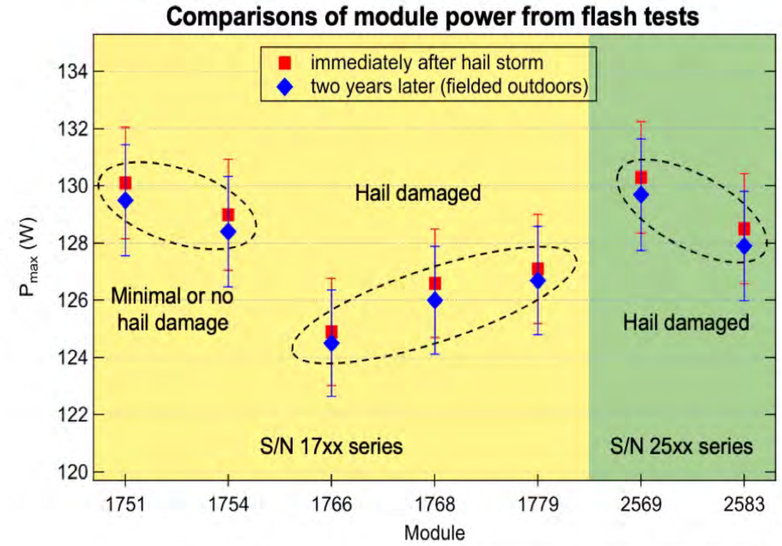
Electroluminescence (EL) images are collected cell-by-cell using a Princeton Instruments PIXIS 1024BR Si CCD camera with 1024 x 1024 pixels. The images are stitched together into a montage to show the full module EL image of all cells. The EL imaging was collected using parameters of 5A of forward bias current and a 10 second exposure time per cell.

Contactless EL has the potential for easier outdoor imaging in the field since cables do not need to be disconnected. Here, contactless EL is collected using an InGaAs camera with 640 x 512 pixels. The camera is positioned above the module such that the field of view is approximately half of a cell. There is an enclosure to reduce stray light from the camera's view of the half-cell of interest, as shown below. Light emitting diodes (LEDs) illuminate the non-imaged half of the cell and are placed in rows just outside of the imaging area, also shown here. LEDs are positioned on both sides of the imaging area so that either top halves or bottom halves of the cells can be imaged while the opposing half is being illuminated. The camera and LEDs are mounted on an x-y stage motion system, and they are stepped around the module using an automated computer program. The program steps the camera to the cell of interest, collects an image, turns on the LEDs, collects a second image, turns off the LEDs, subtracts the light-off image from the light-on image, and then crops and stores this half-cell image to the corresponding position of an accumulating image data file.

Photoluminescence (PL) images are collected cell-by-cell using the PIXIS camera. Excitation light from two 808-nm laser diodes is spread out uniformly over an area slightly larger than a cell. The module is stepped around using x-y stages to collect PL images using approximately 0.25 Suns intensity and 20 second exposure times per cell.

Ultraviolet fluorescence (UVF) imaging collects the fluorescence of ethylene vinyl acetate (EVA) after fluorophores form during module weathering. Between cells and within cracks of a cell, oxygen diffuses through the polymer backsheet and back EVA to reach the front EVA and degrade/photobleach the fluorophores. For UVF imaging, two 365-nm, 3-Watt flashlights are used to illuminate the area of a cell. Similar to EL and PL, the module is stepped around, and UVF images are collected cell-by-cell and then stitched together for the full-module image

Comparisons of module power from flash tests



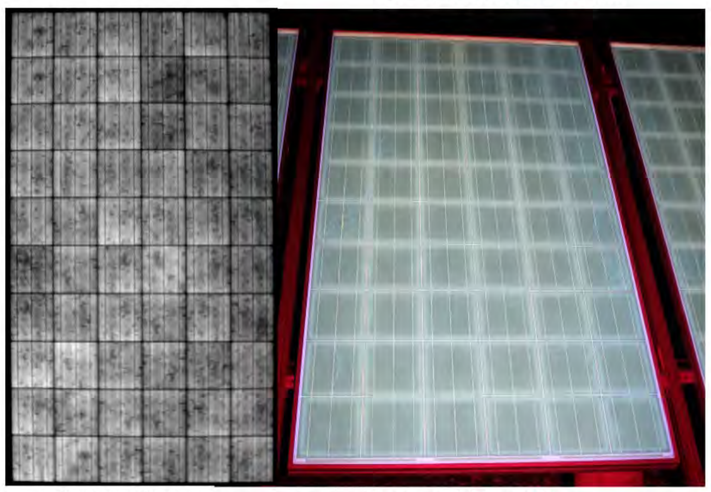
Camera crane setup for conventional nighttime outdoor EL module imaging

Summary

- For series S/N 17xx, hail-damaged modules exhibit power loss due to cell cracking.
- After two years, modules with hail-induced cell cracks do not yet appear to have a higher degradation rate than same-series modules with little to no hail-induced cracks.
- Series S/N 25xx may have started with higher initial power since hail-damaged modules have higher power compared to similarly-damaged 17xx modules.
- Cell cracks appear dark in UVF for series S/N 25xx modules. However, cell cracks for 17xx modules are bright in UVF due to strong UVF of the backsheet.

Acknowledgements: The authors thank Tim Silverman and Will Hobbs (Southern Co.) for NREL UVF imaging, Steve Rummel for flash-test I-V measurements, and Byron McDanold and Bill Sekulic for outdoor imaging assistance.

Example outdoor images from the NREL Outdoor Test Field



Outdoor EL at night | Outdoor UVF at night

NREL arrays have not shown examples of extensive hail damage, and this image sampling has correlated well with power tracking in that no statistically significant drop in array performance has been attributed to the hailstorm that occurred two years ago.

The information contained in this poster is subject to a government license. *Photovoltaic Reliability Workshop • Lakewood, CO • Feb. 25-27, 2020*

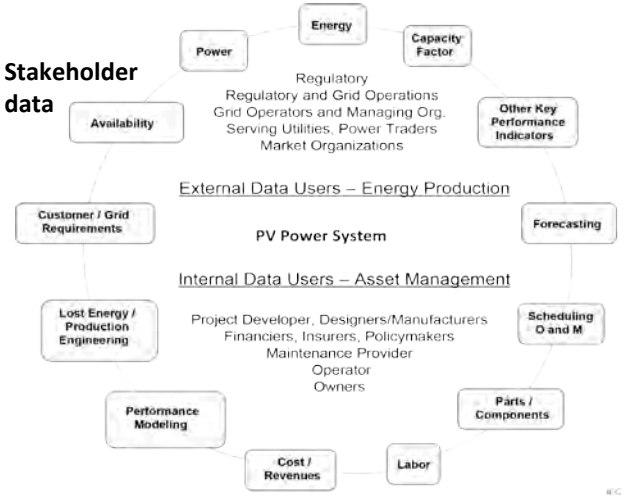
Progress in IEC PV Availability and Reliability Standards

Roger R Hill, LLC Consultant to NREL for DOE SETO Agreement # 34172 PV O&M

IEC, the International Electrotechnical Commission develops and publishes standards concerning electrical technologies in today's modern world.

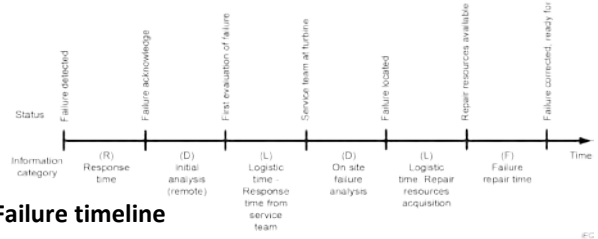
1. IEC 63019 'Photovoltaic Power Systems (PVPS) – Information Model for Availability" published 2019

Stakeholder data



Outage questions:

How often? How long? How Much?



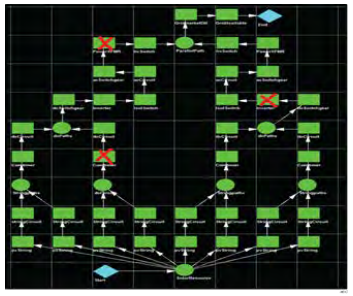
Failure timeline

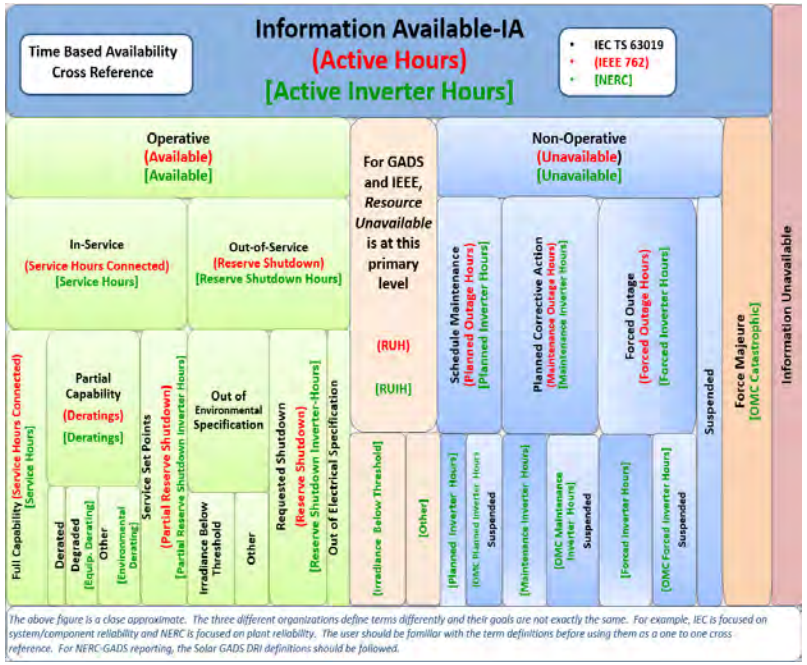
Reliability issues primarily reside in Forced Outages, Scheduled Maintenance, Planned Corrective Actions, Partial Capabilities, and Out of Environmental Specification

Availability: The available state is where the PVPS, a subsystem, or a component can provide service, regardless of whether it is in service and regardless of the capacity level that can be provided

Reliability: Probability that an item (component, assembly, or system) can perform its intended function for a specified interval under stated conditions.

Reliability Block Diagram



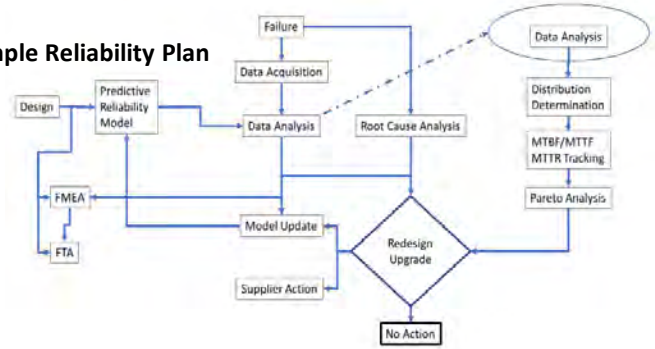


The above figure is a close approximate. The three different organizations define terms differently and their goals are not exactly the same. For example, IEC is focused on system/component reliability and NERC is focused on plant reliability. The user should be familiar with the term definitions before using them as a one to one cross reference. For NERC GADS reporting, the Solar GADS DRI definitions should be followed.

Time Based Availability Cross Reference
Source: NERC

2. "Roadmap for Robust Reliability of a PVPS" now in review - Multiple tools and techniques shown in illustrations

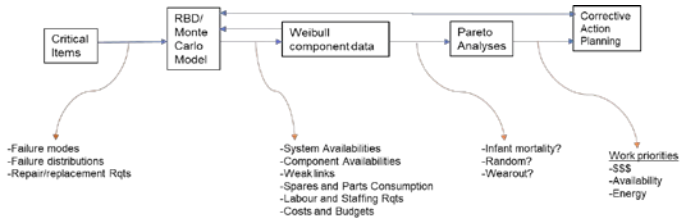
Example Reliability Plan



Asset Management questions:

Whose clock is it on?
What did we get?
What did we expect?
Why or why not?

Reliability Tools Information Flow



3. "Reliability practices for the operation of photovoltaic power systems" approved as a project for Technical Specification development

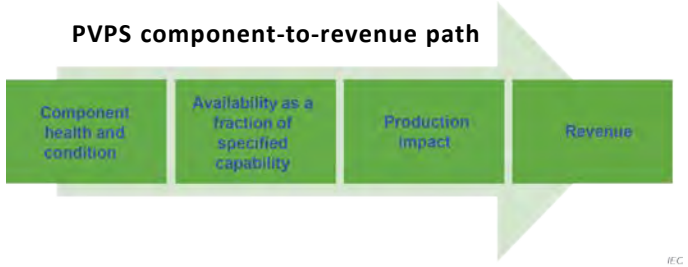
A Reliability Plan for the PVPS is recommended in order to ensure adherence to best practices and optimum economics

Further definition of the practices employed in the cost-effective asset management of the PVPS needed, i.e. standardized input and output reporting

In order to implement a reliability plan, requirements, needs, expectations and technical capabilities will need assignments.

It is imperative that records be kept from the initiation of a project throughout its lifetime. Component population failures must be maintained for ownership during the warrantee period and for use after, or for new ownership during a change of ownership.

PVPS component-to-revenue path



Reduced Operating Temperature to Improve Durability and Efficiency of Solar Modules

Martin A. Green, Jessica Yajie Jiang, Zibo Zhou, Supriya Pillai, Mark Keevers, Jose Bilbao Bernales, Jinyi Guo, Ned Ekins-Daukes
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UNSW SYDNEY Australia's Global University

Motivation

A Si PV module typically operate 20-30°C above ambient

- Reduces Eff & power output ΔEff/ΔT = -0.5%(rel.)/°C
- Increases degradation (2×/10°C), reduces durability & life
- Less lifetime energy production [1]

→ We investigate passive cooling approaches (without major changes in module design) [2]

- Potential 10°C cooler module

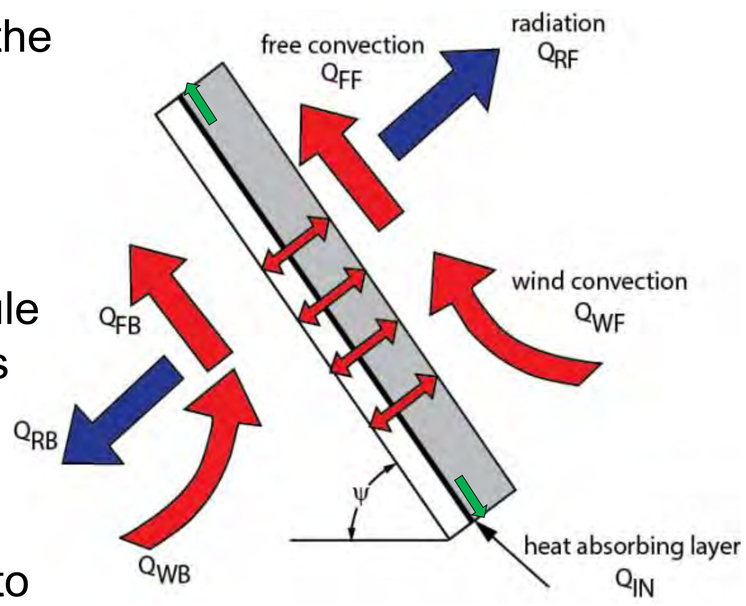
5% more power + ½ degradation rates > 2× lifetime energy production

- Less ambitious 5°C cooler

> 50% higher lifetime energy production

Four passive cooling approaches: Preliminary results

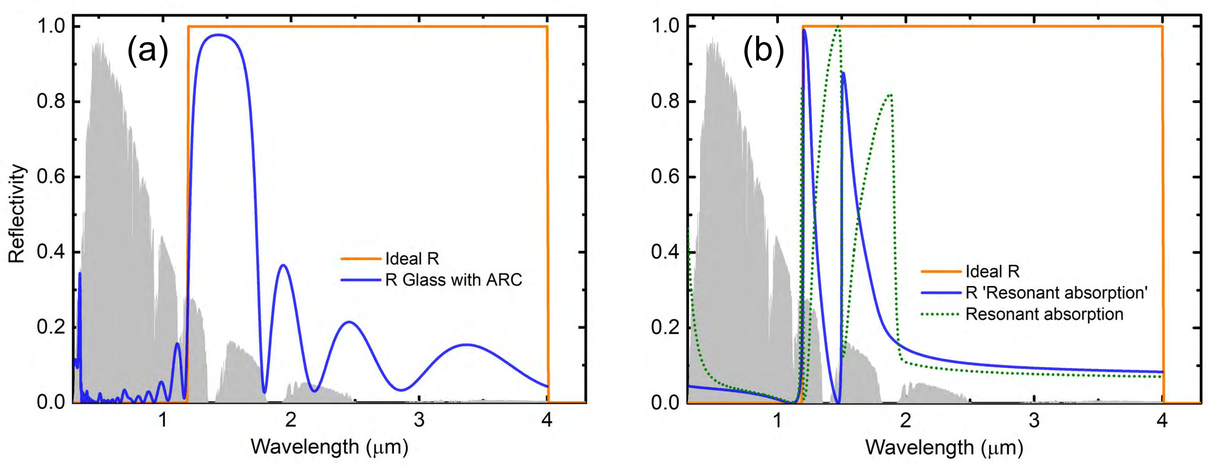
Sunlight is absorbed in the module, largely in the cells. Some power is extracted as electricity. The waste heat is conducted to both module surfaces from where it is dissipated radiatively and by free and forced convection. Some conduction also occurs to the module frame.



Module energy balance

1. Reject unwanted near IR (reduce Q_{IN})

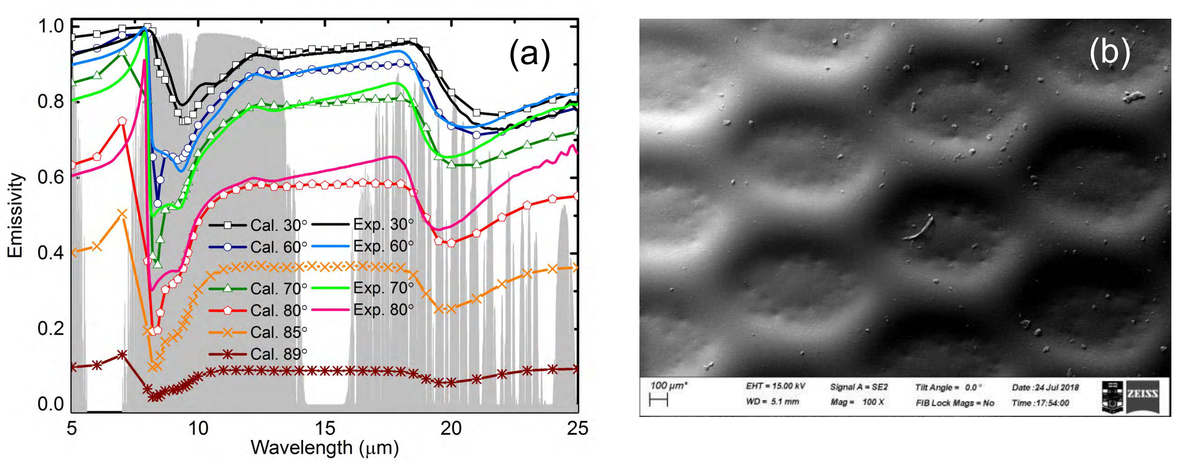
- Glass SLAR coating → Multilayer designs
- Introduce resonant absorbers λ @ atm absorption band



Calculated reflectance of glass for (a) preliminary ARC designs and (b) 'resonant absorption', compared with ideal near IR rejection.

2. Increase radiative loss in the mid IR (Q_{RF} and Q_{RB})

- Module radiates to 3K through atmosphere's transparency window @ 8-13 μm
- Increase glass emissivity, esp. at oblique angles
- e.g. Macroscopic (mm-scale) glass front surface texture
  → Reduces rays at oblique angles
  Simulation shows 10% increase in radiative emission



(a) Calculated vs measured glass emissivity, (b) glass texture

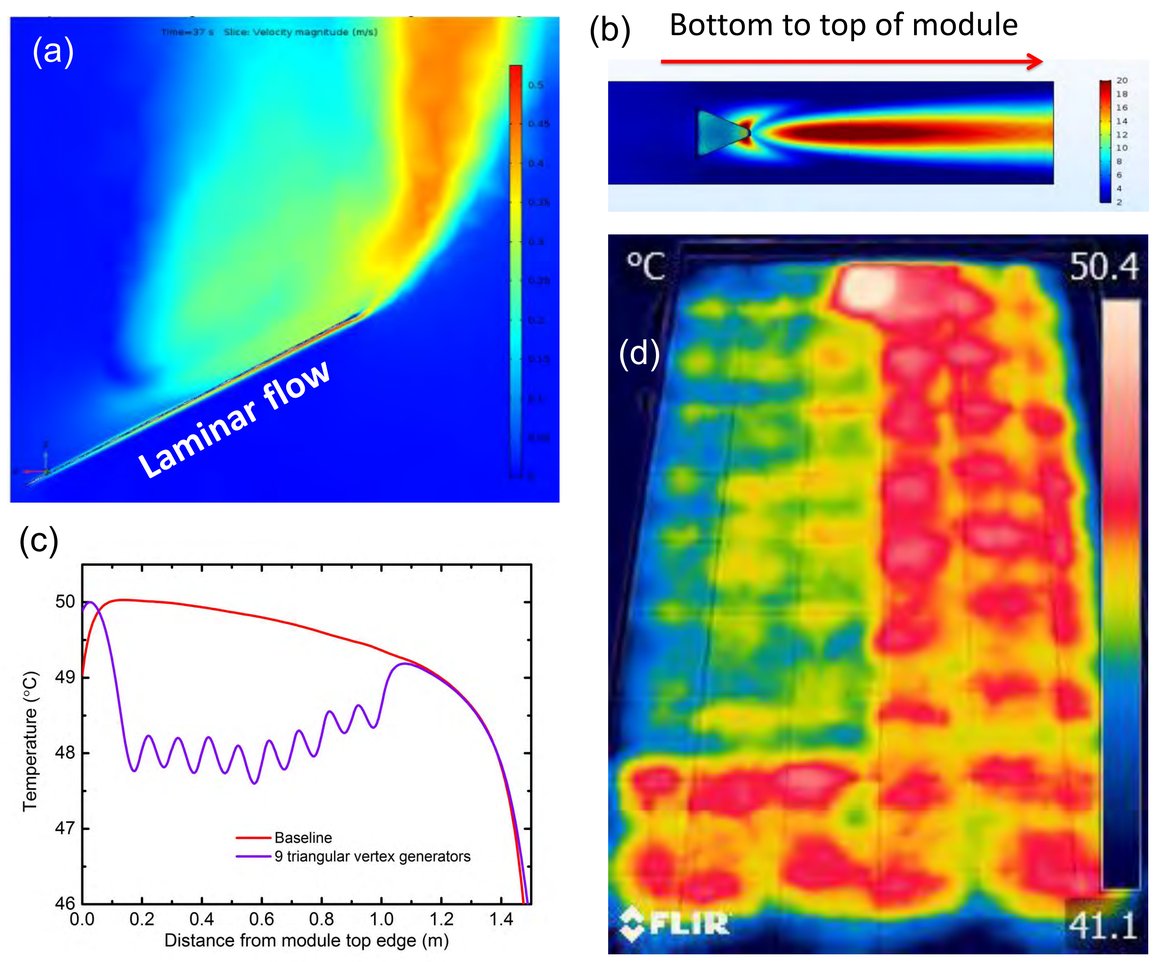
3. Increase convective loss (Q_{FF} and Q_{FB})

- In free convection, rising hot air is confined to the module underside but it breaks free of the top surface
- Vortex generators (VGs) on the rear disrupt laminar flow

→ e.g. COMSOL simulations show 5× local heat transfer coefficient for triangular 'flap', reducing T by ~2°C

- First VG prototypes fabricated by 3D printing
- Outdoor measurement capability established
- Preliminary tests of module with VGs on half of back

→ Initial results suggest the module half with VGs is cooler, consistent with modeling

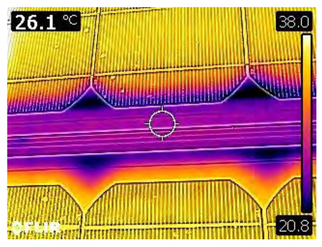


(a)-(c) COMSOL simulations, (d) experimental testing of prototype VGs

- Enormous potential to retrofit existing PV fields and to apply to new PV modules

4. Increase conductive loss to frame (Q_{Cf})

- Thermally conductive insulated metal backsheet e.g. AiT's SOLAR-IMB
- Thermally conductive, electrically insulating EVA composites



IR image showing cool frame

Summary

Novel approaches are introduced to reduce module operating temperature for improved efficiency and durability: (1) reject unwanted near IR, (2) increase radiative loss in the mid IR, (3) increase convective loss (with vortex generators), and (4) increase conductive loss to the frame. A combination of these approaches has the potential to reduce module operating temperature by 5-10°C, increase efficiency by 2-5% relative and extend module life by 50-100%. Preliminary modeling and experimental results are promising.

References

[1] O. Dupré, R. Vaillon, M. A. Green, *Thermal Behavior of Photovoltaic Devices: Physics and Engineering*. 2016: Springer International Publishing.
[2] M.A. Green, M. Keevers, Z. Zhou, Y. Jiang, N. Ekins-Daukes, Australian Provisional Patent 2018900639, 2018900640, 2018900641. 2018.

ARENA
Australian Government
Australian Renewable Energy Agency
ACAP

A NEW MANUFACTURING QUALITY CONTROL PROGRAM BASED ON IEC TS 63209

Q CELLS
Engineered in Germany

NREL Workshop 2020

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→ MOTIVATION

Module qualification standards such as IEC 61730 and IEC 61215 are insufficient to assess module durability and quality. They focus on avoiding known infant mortality issues and are usually applied to prototypes only.
There is increasing demand for extended stress protocols to assess durability of modules from production to increase customer confidence and reduce risks.
The multitude of different test protocols proposed and currently in use by test labs and independent engineers leads to unnecessary duplicate testing effort and high testing costs.
The upcoming IEC TS 63209 extended stress protocol is an opportunity to align such test protocols and to design a comprehensive quality control protocol building on this standard. This should not only address initial qualification of a product but also continuous verification of mass production including third party oversight thereby making additional testing by customers unnecessary and at the same time increase customer confidence.

CURRENT EXTENDED STRESS PROTOCOLS

Many major labs and institutions have developed their own extended testing protocols

- VDE Quality Tested
- Qualification Plus
- PVEL PQP program
- ANSI/CSA C450
- MAST, FAST-MAST, C-AST,
- and many more

Programs contain different combinations and durations of climate chamber tests and have varying requirements on sample selection.

They focus (with exception of VDE Q.Tested) on a one-time snapshot of the product

This leads to unnecessary duplicate testing as each customer has his own preferred program.

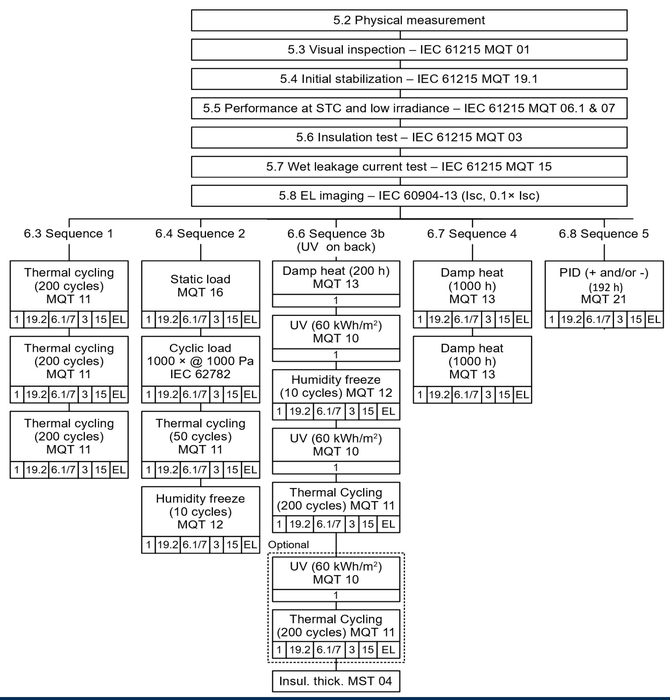
Some of the programs also require samples to be pulled under specific conditions making it impossible to re-use results for other customers.

→ unnecessarily high cost and effort without benefit

→ binds resources that could otherwise be used for more thorough and targeted testing

CURRENT STATUS OF IEC TS 63209

- IEC TS 63209 is intended to unify and align the many different extended testing programs
- The draft is currently in the final stages of alignment before being circulated as DTS
- Current version of the test flow:



QUALITY CONTROL PROGRAM - OVERVIEW

Permanent third party verification and surveillance

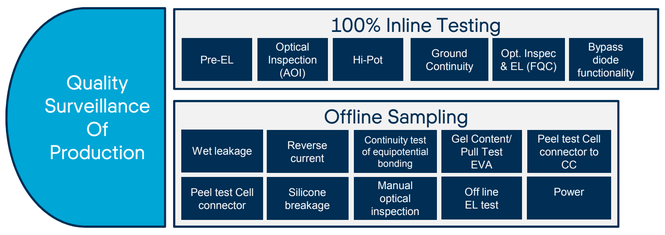
Extended initial product qualification based on IEC TS 63209	Continuos product quality monitoring	Continuos supplier & material surveillance
▪ Initial design assessment with respect to known failure modes and intended service life ▪ Extended durability tests based on IEC TS 63209 ▪ Additional durability tests based on internal experience ▪ Inclusion of tests for current failure modes such as e.g. LETID ▪ In case of BOM change requalification required	▪ 100% inline testing for key parameters and safety ▪ Random selection of samples from running production by third party ▪ Wide array of regular sampling tests that can be done quickly ▪ Regular durability testing based on IEC TS 63209 ▪ Continuous on-site presence of a third party representative	▪ Thorough incoming inspection including random sample picking ▪ Selection of critical materials for testing and implementation of material verification tests to ensure constant quality ▪ Regular review of supplier evaluation and audits ▪ Detailed material analysis and material durability tests

INITIAL QUALIFICATION

- Initial design assessment & qualification
  → thoroughly test against known failure modes
  → assess risk of potentially new failure modes via FMEA
  → verify intended service life via extended tests
- Qualification of key components before consideration for use
  → material durability testing based on IEC TS 62788 series or internal protocols
- Full qualification of product
  → following IEC TS 63209
  → add internal tests for new failure modes, e.g. LETID, extended UV testing
- Retesting of BOM changes
  → according to retest guideline IEC 62915
  → additional tests via material qualification checklist developed from past experience
  → additional tests for BOM transfer between production lines to avoid risks from differences in production line setup

REGULAR PRODUCTION SAMPLING

- Continuous verification of product qualitiy in production
  → focus on safety and performance
  → 100% tests in-line combined with random sampling on a daily basis
- Third party oversight of the sampling process and testing
- Alignment of criteria and production quality accross all global production sites



CONTINUOS DURABILITY MONITORING

- Monthly selection of random samples through a third party for durability testing
  → at each production site
  → subset of reliability tests from IEC TS 63209
  → additional internal tests
  → root cause analysis & reaction plan for deviations
- Regular repetition of full IEC TS 63209 on random samples pulled from production by a third party
- Quarterly verification of alignment of test results via central testing at German module test center

SUPPLIER AND MATERIAL SURVEILLANCE

- Regular audits of key suppliers, scorecard for suppliers and improvement measures
- Comprehensive incoming inspection of BOM components including random sample picking and thorough tests
- Analyses to better understand influence of material fluctuations on durability
- Characterization tests to identify material footprints
  → regularly check during incoming inspection that materials haven't changed since initial qualification

THIRD PARTY OVERSIGHT

- Results of testing are only valuable for customers when it is ensured that sample taking was random and the manufacturer cannot influence the results
- Permanent presence of a third party employee (from a certification / testing institute) at each site
  →oversees sampling activities
  →oversees qualification testing in module test lab
  → randomly selects samples
- With this, such an internal program can potentially replace witnessing and durability testing programs that are currently required by many large customers

→ CONCLUSION

- IEC TS 63209 is able to replace many different extended stress testing protocols thereby removing duplicate testing effort
- We have developed a comprehensive quality control program based on IEC TS 63209 together with a third party testing institution that
  - Assesses module designs with respect to durability and service life beyond what IEC 61215 and IEC 61730 do
  - Continuously monitors production quality via sampling tests
  - Includes regular durability tests on random samples from production
  - Includes third party oversight at all steps, i.e. during initial qualification, sampling and monitoring
- Such a program can reduce the need for additional testing with programs such as e.g. PQP
- The program is planned to be implemented within this year

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Spread Spectrum Time Domain Reflectometry to Detect and Locate Disconnects in Large-Scale PV Arrays

Ayobami S. Edun[1], Cody LaFlamme[1], Mashad U. Saleh[2], Samuel Kingston[2], Evan Beniot[2], Hunter Ellis[2], Jack Mismash[2], Michael A. Scarpulla[2], Cynthia M. Furse[2], Joel B. Harley[1]

[1] Department Electrical and Computer Engineering, University of Florida, FL 32611

[2] Department of Electrical and Computer Engineering, University of Utah, UT 84112

Motivation

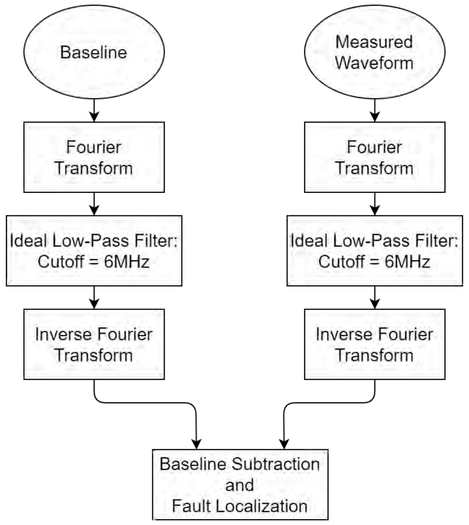
- **Detecting and Locating Faults in Photovoltaics**
  - Research has shown success using Spread Spectrum Time Domain Reflectometry (SSTDR) to detect
    - Open faults (i.e., broken wires)
    - Shorts (i.e., connections between wires)
    - Broken cells
    - Shading of panels
  - Yet, there has not been successful research in identifying faults in large strings of panels up to 1000V
  - The long-term goal of this project is to use SSTDR to detect and locate faults in photovoltaic (PV) panels
- **What is an SSTDR signal?**
  - When a signal propagates through a transmission line, it will reflect energy at any impedance mismatch
  - Data is characterized by reflection coefficients

$$(\ ) = \frac{\text{reflect ed}(\ )}{\text{incid ent}(\ )} = \frac{(\ ) - {}_0(\ )}{(\ ) + {}_0(\ )}$$

  - The location of a fault is determined from the maximum of the cross-correlated data

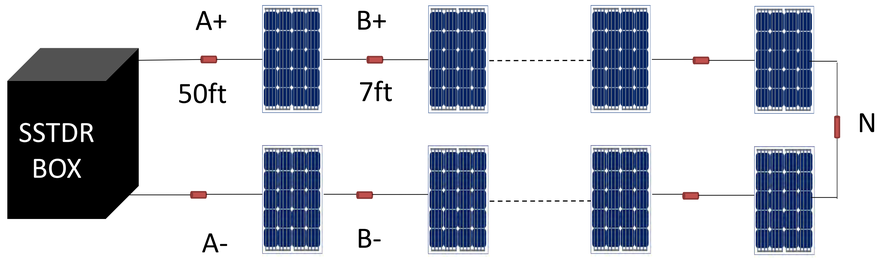
Methodology

- **Real-Time Remote Monitoring**
  - We designed a system can monitor faults in real-time. Distributed sensors can monitor a large solar farm and report to a single remote location.
  - At the remote location, an algorithm is applied to detect and localize faults

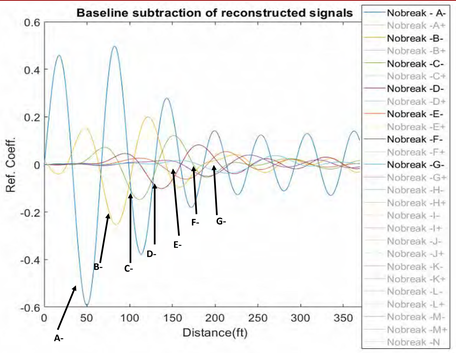


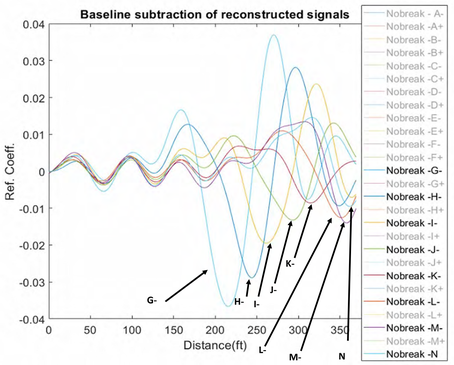
Experimental Setup

- **Large-scale solar array testing**
  - Measured 26 panels with 13 modules in a row connected in series
  - 7 ft cable between each panels
  - Rated Voc of 1024V
  - Measured 941 V while testing



Results





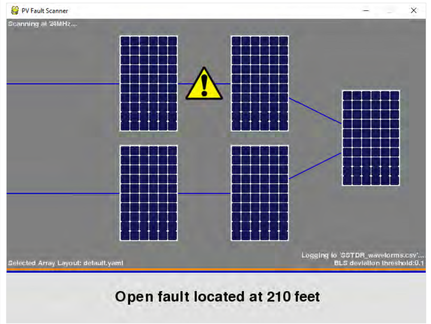
Breaks (x)	Peak locations (feet)	Actual Disconnection Location (feet)	Correcting the actual disconnection location (feet)	Difference in Localization accuracy (feet)
A-	50	50	50	0
B-	84.7	57	77	7.7
C-	111.5	64	104	7.5
D-	137.3	71	131	6.3
E-	165.8	78	158	7.8
F-	190.7	85	185	5.7
G-	215	92	212	3
H-	244	99	239	5
I-	262.1	106	266	3.9
J-	293	113	293	0
K-	315	120	320	5
L-	351	127	347	4
M-	358.4	134	374	15.6
N	361.5	141	401	39.5

Acknowledgements

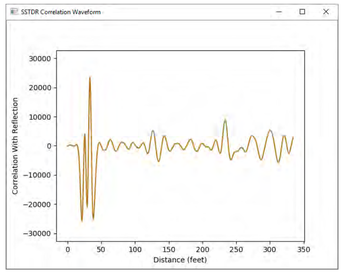
This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0008169 in collaboration with Livewire Innovation and the National Renewable Energy Laboratory.

Real Time Monitoring

- **Our goals are:**
  - Monitor solar panels in real time
  - Inspect reflection behavior of Panels
  - Identify faults in Panels
  - Extend to large number of industry-sized panels



Real-time User Interface



Conclusions

- **We created a monitoring system that can:**
  - Collect real time data
  - Inspect the data for faults
  - Localize the faults with an accuracy that is within one module

Other works by our group

- **SSTDR for PV Monitoring**
  - Quantifying variabilities in SSTDR
  - Quantifying the effect of environment on reflection signatures
  - Full system simulation
  - Spread Spectrum Time Domain Reflectometry (SSTDR) and Dictionary Matching to Measure Capacitance for PV cells

Link to our papers: **Bit.ly/PVSSTDR**

Dr. C.M. Furse is a co-founder of LiveWire Innovation, Inc. which is commercializing SSTDR technology, and therefore has a financial conflict of interest with this company.

References

[1] S, P., Furse, C. and Gunther, J. (2005). Analysis of spread spectrum time domain reflectometry for wire fault location. *IEEE Sens. J.*, 5(6), pp.1469-1478.

[2] Saleh, M., Deline C., Kingston S, et. al. (2019). Detection and Localization of Disconnections in PV Strings Using Spread Spectrum Time Domain Reflectometry.

[3]. A. S. Edun, N. K. T. Jayakumar, S. Kingston, C. Furse, M. Scarpulla and J. B. Harley, "Spread Spectrum Time Domain Reflectometry with Lumped Elements on Asymmetric Transmission Lines," in IEEE Sensors Journal.

Quantifying Impact of Environment on Spread Spectrum Time Domain Reflectometry Signatures of PV Arrays and Implications for Fault Detection

Cody LaFlamme [2], Ayobami S. Edun [2], Evan Benoit [1], Michael A. Scarpulla [1], Cynthia M. Furse [1], Joel B. Harley [2]

[1] Department of Electrical and Computer Engineering, University of Utah
[2] Department Electrical and Computer Engineering, University of Florida

Background

Faults in PV Strings:

- **Ground faults**: A panel is grounded erroneously
- **Open Fault**: There exists an open circuit between panels
- **Arc Faults**: An arc has occurred between panels

- Faults can **damage panels, start fires, and reduce power production.**

- Traditional fault detection methods monitor current and voltage, but cannot locate faults, which must be done by technicians. Some faults, such as double ground faults, may not be detected.

Spread Spectrum Time Domain Reflectometry:

- Uses a unique pseudo-noise binary code to modulate an electronic signal, which is sent down a wire.

- **At points of sudden impedance change, such as at open circuits, short circuits, or arcs, the probe signal is partially reflected, much like sound hitting a wall.**

- Since the sent signal is unique, it can be identified when it returns.
- Travel time and reflection strength reveal information about the source of reflection.

- **However, to identify which reflections are normal, a baseline measurement must be collected. This baseline may not accurately represent the PV string in all conditions.**

Related Work

Our group studies other facets of SSTDR, focusing on its application to fault detection in PV arrays. This includes:

- Modelling/analysis of SSTDR signals in solar panels
- Machine learning for advanced fault detection

For a list of all our related work, please visit: bit.ly/PVSSTDR

Scan this QR code to see SSTDR fault detection in action! We locate disconnects in ~1000V strings at NREL.

Summary & Conclusion

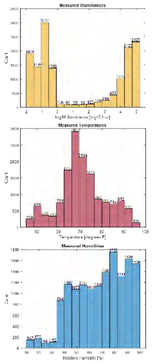
We model the effect of temperature, humidity and illuminance on SSTDR measurements of PV strings.

We find that illuminance and humidity cause large changes in measurements.

SSTDR-based fault detection can use this model, or similar, to become robust to the environment.

Methodology

- We measure temperature, humidity and illuminance once a minute for ten days. We also take baseline measurements of a small PV string at these times.
- We use linear regression to predict a collected baseline from only temperature, humidity and illuminance.



Above: Our experimental setup. We have five small panels in series. The pink shape in the bottom left corner is our weather-protected environment sensor.

Left: Histograms of the environment data collected in this work. It represents a wide range of values.

Measured SSTDR data matrix: X — N x 1000
Environment data matrix: E — N x 4
Coefficient Matrix: M — 4 x 1000
Predicted SSTDR data matrix: Y — N x 1000

$$E_n = [1 \quad log10(illuminance) \quad temperature \quad humidity]$$

$$\text{Ideally: } X = EM$$
$$M = E^{-1}X$$

Acknowledgement & Disclosure

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number DE-EE0008169 in collaboration with Livewire Innovation and the National Renewable Energy Laboratory.

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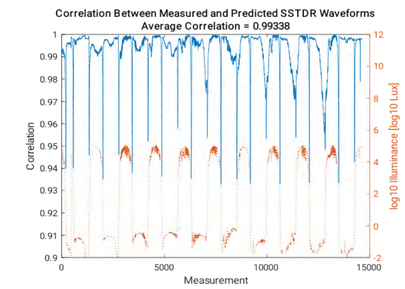
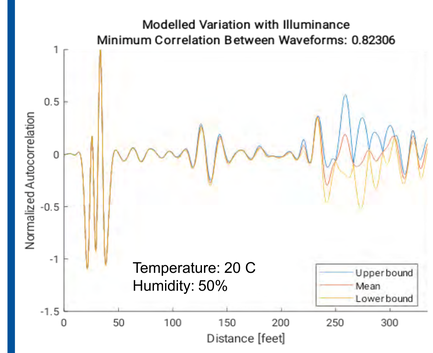
Results

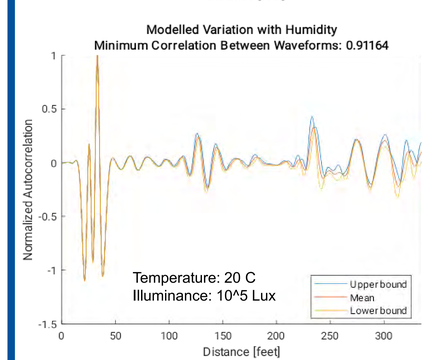


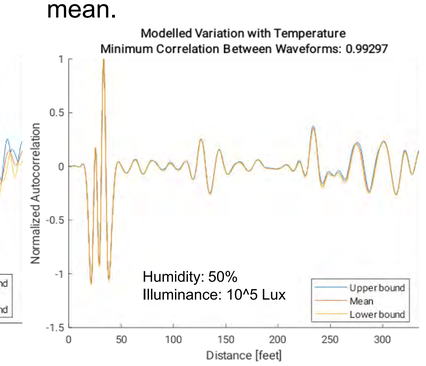
Left:
The accuracy of our model. Average correlation coefficient between predicted baselines and actual baselines is 0.99. Dips in accuracy occur at sunrise and sunset, since we have less data for these times.



Surrounding figures illustrate the effect of isolated factors on baseline measurements. We fix two of humidity, temperature and illuminance, and vary the third across all measured values.

Illuminance has the greatest effect, followed by humidity and temperature. Bounds are +/- 2 standard deviations from the mean.





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[4] Saleh, M., Deline C., Kingston S, et. al. (2019). Detection and Localization of Disconnections in PV Strings Using Spread Spectrum Time Domain Reflectometry.

Quantitative Electroluminescence Imaging Of PV Modules: Quality Enhancement Through Multi-Frame Super Resolution

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SERIS Solar Energy Research Institute of Singapore

Abstract

This work presents methods to improve image quality of EL images taken by an unmanned aerial vehicle (UAV) of mono- and polycrystalline silicon modules, installed in a PV plant in Southeast Asia (Fig. 1). In contrast to indoor EL imaging, the chosen low resolution InGaAs camera allows exposure times from 5 to 10 ms. Resolution and quality of single frames taken by InGaAs cameras are inferior to DSLR or CCD cameras but allow for fast and continuous measurement.

In the tested setup, single captured frames are not suitable for qualitative or quantitative analysis. An average of multiple frames however, after precise alignment (Fig. 2c) is able to largely remove random noise and improve the image resolution 60%. This procedure (patent pending) allows a scanning speed around 5 m/s. The data was provided through an industry partner and includes a 100% EL measurement of a ~10 MW plant (background figure).

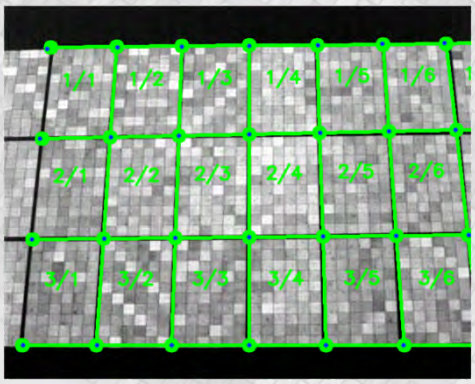

Fig. 1: EL frame taken by UAV with detected modules.

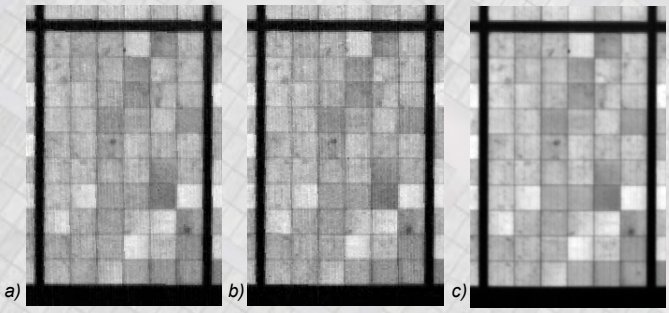

Fig. 2: a,b) Single frames of module 3/5 (Fig. 1); c) 30 frame average, f_{res}=1.6

Multi-frame Super Resolution (MFSR)

MFSR methods presented in literature are either based on neural networks [1] or traditional image processing [2]. While AI-based methods need training data and suitable hardware, traditional methods can be computational expensive and usually need multiple parameters, such as image sharpness and noise to be known in prior.

Due to the requirements of this projects (process 1MW per hour on an office laptop) a faster alternative was chosen. It is based on the precise detection of the frame to frame deflection and successive frame average. The resolution of multiple low resolution images of an captured object can be increased if the object position differs between the frames (Fig. 3).

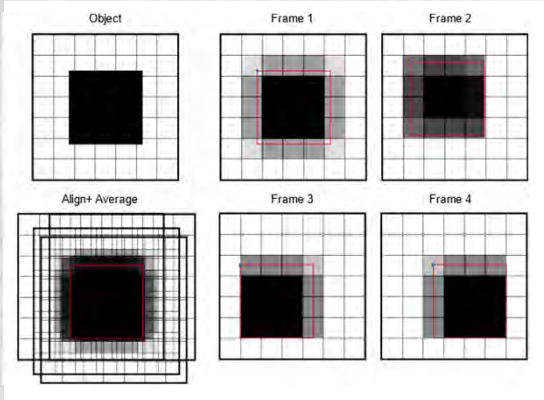

Fig. 3: Schematic an object discretized with different deflection vectors. Alignment and averaging improves resolution.

Results

MFSR methods based on frame stack averages cannot increase resolution beyond factor 2. This is due to interpolation/antialiasing errors during the alignment step. Another method in development (X) avoids this step and was able to improve resolution up to 7 times (Fig. 4). Further details cannot be disclosed at this time.

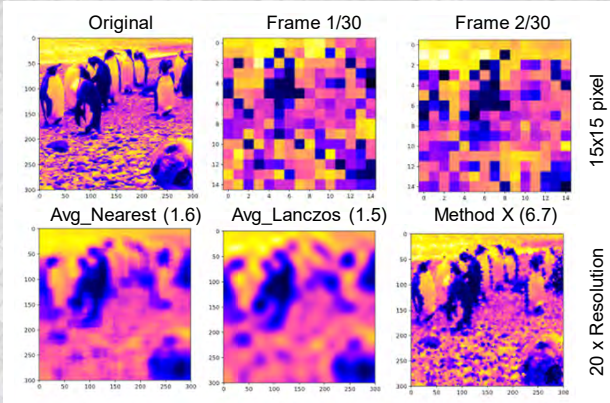

Fig. 4: Result of different MFSR methods executed on a photo downscaled and translated with known deflection. Resolution improvement in brackets.

Resolution improvement (f_{res}) between low resolution image (I_L) and super resolution result (I_S) was calculated from the standard deviation of a Gaussian blur kernel (σ_G) applied on the original image (I_0) that causes minimum absolute deviation to I_S [3].

$$\cdot_G = \text{argmin}(|I_S - \text{Gaussian}(I_0, \sigma_{Gi})|) \quad (1)$$

$$f_{res} = \frac{s_S}{2s_L \cdot \sigma_G} \quad (2)$$

Conclusion

The current method (Avg_Nearest) used to enhance image quality cannot beat existing MFSF methods with $f_{res} = 3 \ldots 4$. It however is robust and with computation times around 1 s per module faster. A method in development (X) can, for sharp low-resolution frames, increase resolution 7 times. Implementation is ongoing.

References

[1] M. Deudon *et al.*, "HighRes-net: Multi-Frame Super-Resolution by Recursive Fusion." 2020.
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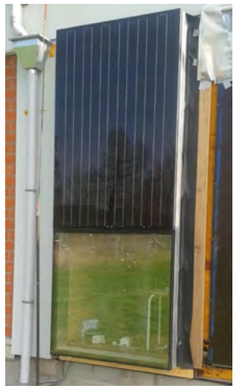
Module-level Inverters and Converters for BIPV

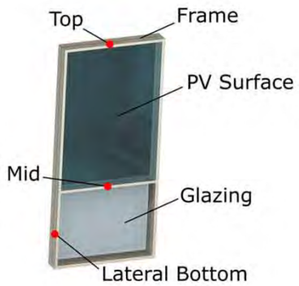
Performance Limitations and Reliability Aspects

J.D. Moschner[1], S.Ravyts[1], W. Van De Sande[2], M. Daenen[2], J. Driesen[1] [1] KU Leuven [2] UHasselt [1&2] EnergyVille

Goal: Integrate module-level power converters into building façade elements

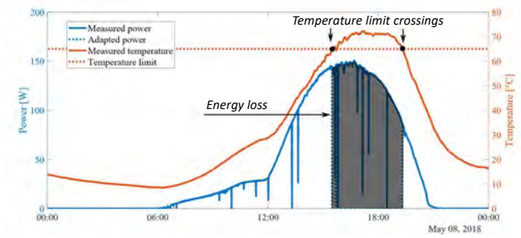
Why?
- Ease of integration
- Prefabrication of entire element including converters
- Adaptation to local irradiation, variable sizing
- Direct connection to building DC (nano)grids



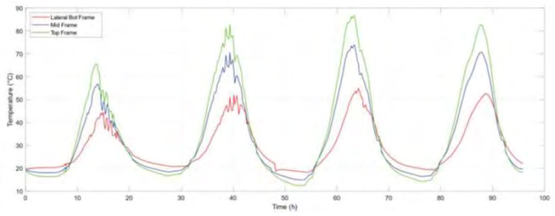


Curtain wall element under test at KU Leuven and converter placement options

Where to place it?
- on the module → large temperature swings
- inside the building → stable ambient temperature
- in/on the frame → large heat sink

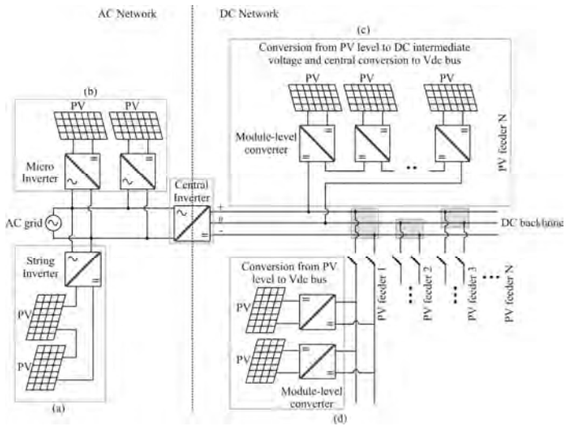


Large temperature swings can lead to shutdown due to high operating temperature, and consequential energy losses. The 65°C temperature limit is imposed by the linear power optimizer under test.



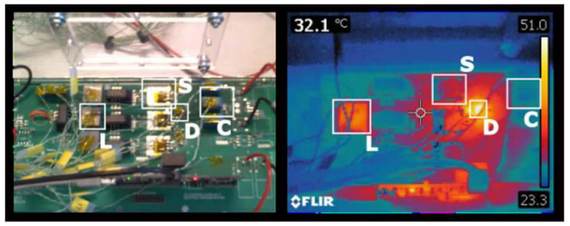
Dependent on placement, peak ambient / frame temperature varies by up to 35°C.

Which type of converter?
- Micro-inverters - *tested*
- DC converters – *own development*
  a) one-stage (IIBC)
  b) two-stage system (boost)
- (Power optimizer & central inverter – not addressed here)

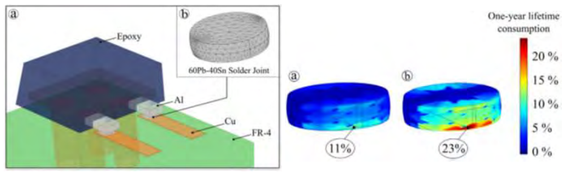


Integration options of PV into a building (nano)grid. The bipolar DC grid assumes voltages of ±350…±400 V.

Reliability analysis
- Temperature profiling
- Determination of operating temperature
- FEM simulation
- Lifetime prediction



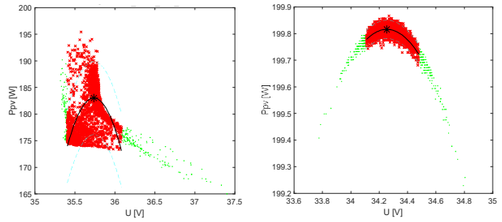
*Visual and thermal image of a DC/DC boost converter prototype featuring diode (**D**), switch (**S**), inductor (**L**) and capacitor (**C**).*



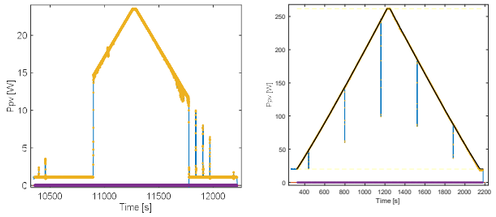
FE Model of a solder joint and predicted lifetime consumption after one year of thermal cycling (extreme case)

Performance analysis

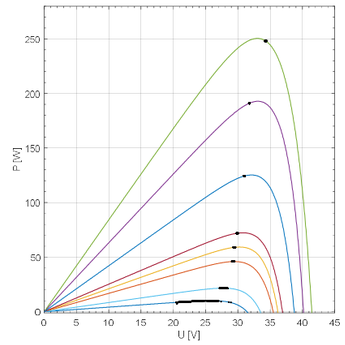
Micro-inverter test analog EN50530
- not possible to test with digital I-V simulation due to fast perturbation
- using PV modules and constant-current supply instead
- deficiencies at low power and late start leading to energy yield losses
- hard (input) power limit not always according to specs
- frequent off-MPP operation



Microinverter efficiency test with digital I-V simulator (left) showing interference of the MPPT algorithm and simulator, and PV module (right). Curves are a second-order fit to the data with 95% confidence intervals; the star denotes the calculated MPP. Note the different power scales!

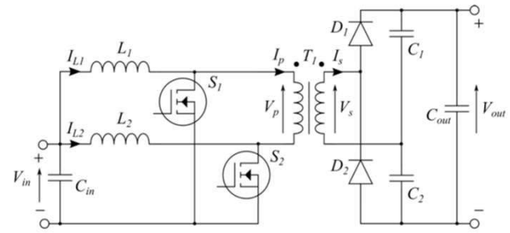


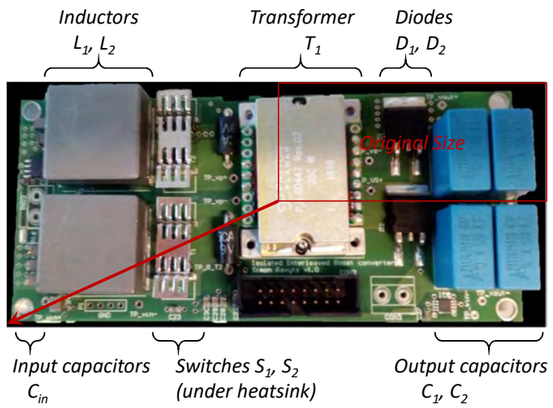
Input power in micro-inverter start-up test of 1…10% of P_{nom} over 15 min (left); no power is delivered for < 6%. String inverter for comparison (right).



Input power in micro-inverter tests at 5, 10, 20, 25, 30, 50, 75, and 100% of P_{nom}, showing frequent off-MPP operation. Black point clusters = data of 10 min of operation at the respective setting, RMS averages of 200 ms.

Development of own converters
- DC/DC, DC-nanogrid-ready
- Buck or boost for small V ratios
- Interleaved boost for larger ratios and/or isolation
- Compact form factor for façade integration
- Design for Reliability, target lifetimes > 30…40 years
- Novel materials (GaN) for higher resilience and smaller footprint





Compact 300 W Isolated Interleaved Boost Converter for 10…30 V to 400 V, 100 kHz, sized 125 x 55 mm²

Conclusions

Integration of converters into the façade is feasible, but needs specific attention to:
- thermal interactions
- performance
- mechanical integration
- design for reliability

Future work
- Establishing mission profiles for appropriate reliability testing for BIPV applications
- Co-design/modeling with building elements to account for mutual interactions of PV system and building
- Demonstrator including converter in frame
- Advanced integrated bussing solutions

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Benchmarking PV Module Quality in the Factory: Quality Risk Statistics Over GWs of Projects in a Very Dynamic Sector

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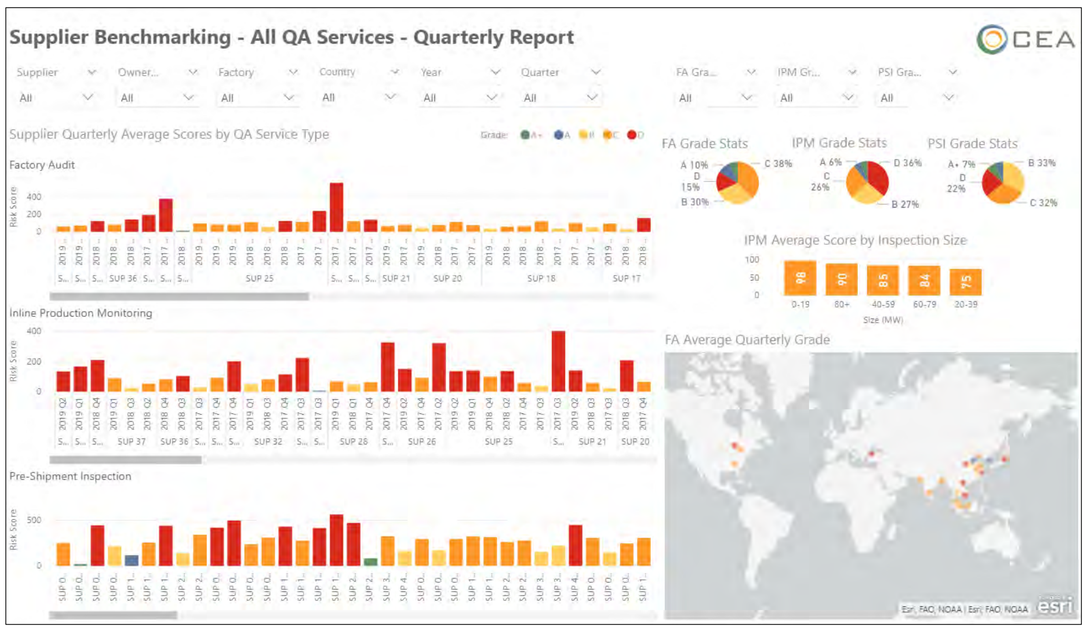
CEA Clean Energy Associates | Investment Confidence

The Supplier Benchmarking Program (SBP) Platform

To measure and benchmark PV module production quality, CEA has developed the Supplier Benchmarking Program, which is based on production quality data from quality assurance engagements from over 15 GW of projects and hundreds of Factory Audits. The Supplier Benchmarking Program data are accessible via an interactive online platform, with powerful data visualization capabilities. The data can be filtered in many different ways, and the map gives insights into the logistics of supply.



Collecting Production Quality Data

CEA performs Quality Assurance work before, during, and after the production of PV modules, performing three (3) main auditing activities:

Factory Audit (FA)
- A team of engineers audits a factory location using a 1,000+ points checklist
- Processes and Systems are audited
- Every finding is recorded and classified according to its risk potential

Inline Production Monitoring (IPM)
- A team of engineers continuously monitors all stations of a factory location during the production of an order, using a 260+ points checklist
- Production processes and inline quality control are monitored
- Every finding is recorded and classified according to its risk potential

Pre-shipment Inspection (PSI)
- A team of engineers performs visual, EL and IV inspections to a randomly sampled lot of finished modules, according to a list of vetted quality criteria
- Only finished product is audited
- Every defect is recorded and classified according to its risk potential

Finding: a process or system non-compliance event identified during FA or IPM

Defect: a finished product non-compliance event identified during PSI

These terms are not interchangeable, and their use is distinguished between FA/IPM and PSI, which are fundamentally different auditing activities

The Scoring and Grading System

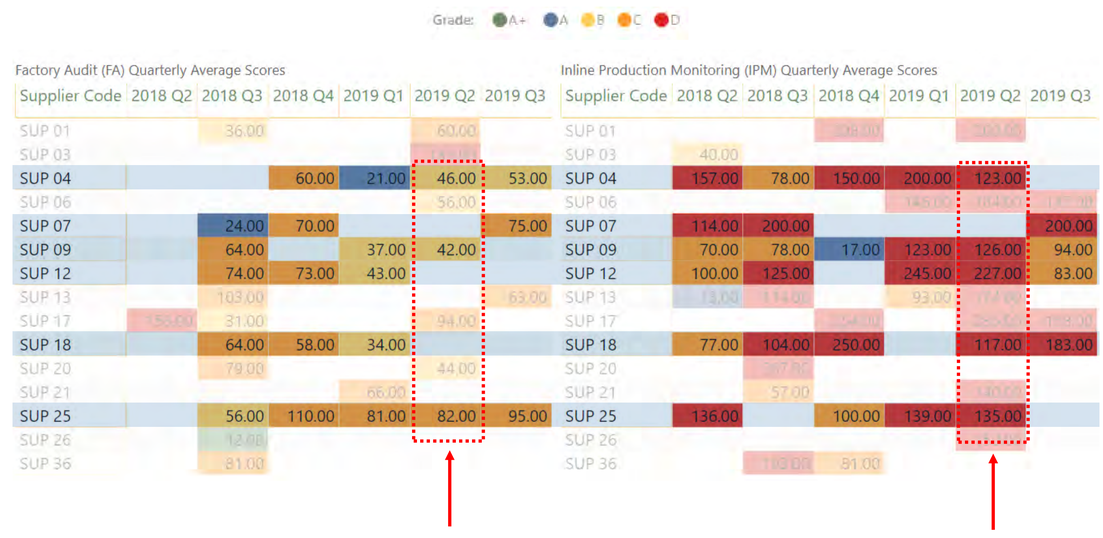
All audit and inspection findings as well as defects are assigned risk scores, according to their severity, which are then added and normalized for each location and project. The scores do not have an absolute significance and are only used to benchmark suppliers against each other. Therefore, a grading system was developed that grades suppliers according to their relative ranking in each of CEA's main Quality Assurance activities. The grade ranges for each QA activity were defined by plotting scores of a large number of projects, excluding outliers and dividing the core range in sub-ranges based on percentile distribution.

This method is not based on forced ranking and a perfect score would be zero.

Grade	Quality Risk Analysis (Supplier / Factory)	Factory Audit (FA) Score Range	Inline Production Monitoring (IPM) Score Range	Pre-shipment Inspection (IPM) Score Range
A+	Very low risk	0 - 16	0 - 3	0 - 92
A	Low risk	17 - 27	4 - 18	93 - 122
B	Average risk	28 - 57	19 - 50	123 - 227
C	Increased risk	57 - 120	51 - 100	228 - 360
D	Very high risk	Over 121	Over 100	Over 360

Insights: a one-off Factory Audit is not enough

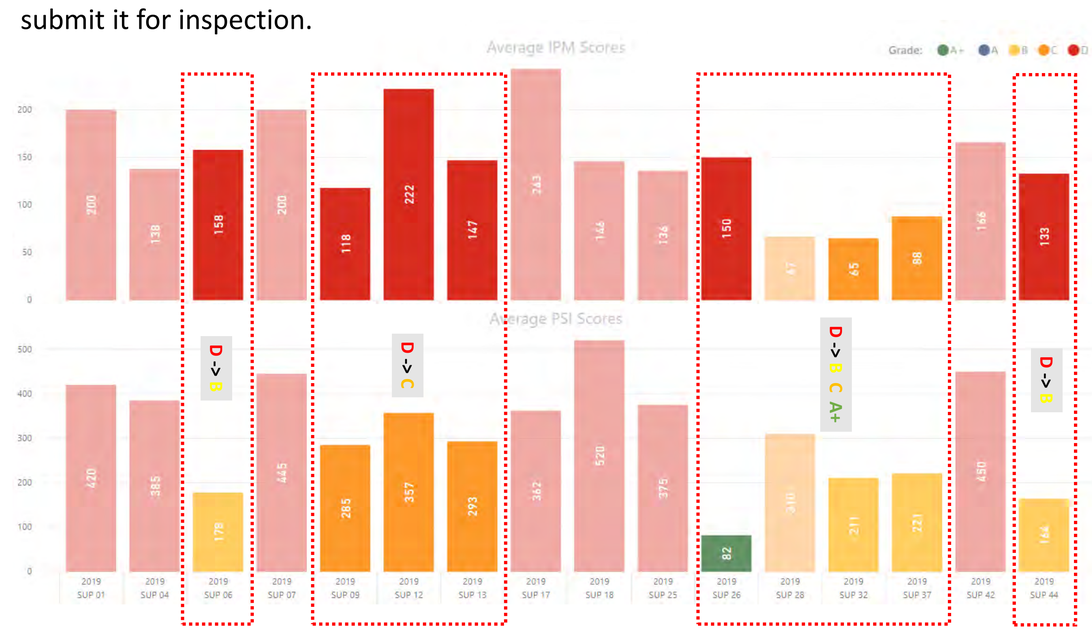
Factory Audits can identify acceptable suppliers, but Inline Production Monitoring (IPM) is absolutely necessary to check a supplier's quality performance. Suppliers can perform well during an FA, but can have lots of issues during production, which can last several weeks or even months for big projects, until fully resolved.



In Q2 2019, the highlighted suppliers had fairly good FA scores, but very bad IPM scores. Similar observations apply for other highlighted periods too.

Insights: IPM and PSI are complementary

For H1 2019, in 50% of QA cases, quality improved significantly from inline process monitoring (IPM) to pre-shipment inspections (PSI). In 100% of QA cases the deviation from grade cut-off thresholds improved from IPM to PSI. In simple terms, the suppliers diverted problematic product identified during IPM to other projects and did not submit it for inspection.



Insights: Quality Declined in 2019 in Almost All Regions

New Products, New Problems: New products (bifacial, half-cut, glass/glass, shingled, multi busbar, and others) are introducing novel production line problems at new and established facilities.

Tightened Criteria, Rising Scores: New types of defects and quality issues have been identified and additional criteria were inserted to all checklists (FA, IPM, and PSI) to account for new findings and defects.

Need for Constant Adaptation in the QA Space: For example, modules and materials were found to be re-stickered with different product codes. CEA caught such errors and doubled down on material verification and now has an extra "record falsification" category in every QA checklist.

Closing the Loops on Solar Photovoltaics Modules

An agent-based modeling approach for the study of circular economy strategies

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Background

- ***Problem:*** *Between 2015 and 2060, demand for raw materials are expected to increase (87000% for electric vehicles, 3000% for PV) [1]*
- ***Solution:*** *The circular economy (CE) encourages material efficiency, e.g., through reusing or recycling products*
- ***Example:*** *2050 projected PV waste: 7.5-10 million t → CE could capture value from waste, lowering demand for raw materials [2]*
- ***How?*** *Industrial symbiosis (IS) and end of life (EoL) behaviors are key enablers for closing the loops of solar photovoltaics [3-4]*

Approach

- ***Research question:*** *What factors behind relationships and decisions of PV actors will help lead to increased circularity of PV systems?*
- *Agent-based modeling (ABM): bottom-up method simulating a system's behavior from its entities (agents) which interact with each other and their surroundings*
- *EoL behaviors based on Theory of Planned Behavior (TPB) [5] → depend on people's attitude, subjective norms (peer pressure), and cost (Fig. 1)*
- *Manufacturers-recyclers relationship based on industrial symbiosis [3]*
- *Baseline scenario based on literature: 30% initial recycling rate [2], 55% potential repair rate [6], TPB parameters from [5] (Table 1)*

Model's parameters	Values
Initial recycling rate	30%
Repair rate	55%
Recycling costs	25-30 ($/Module)
Landfilling costs	0.6-2.1 ($/Module)
Second/first-hand module price ratio	40-100%
Repair cost	3.5-49 ($/Module)

Table 1: Model's parameters and values (We welcome your feedback!)

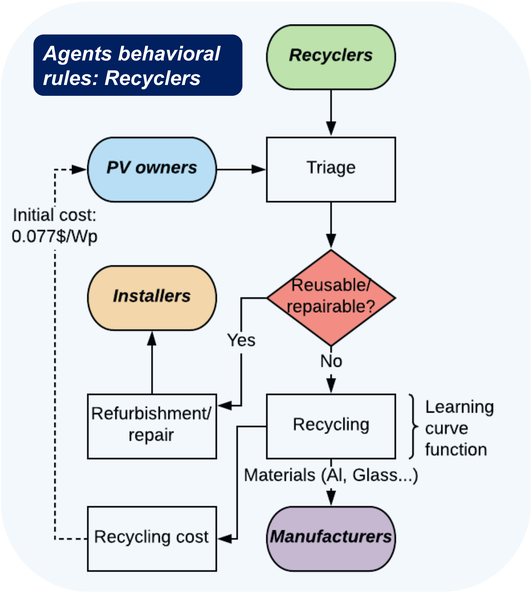
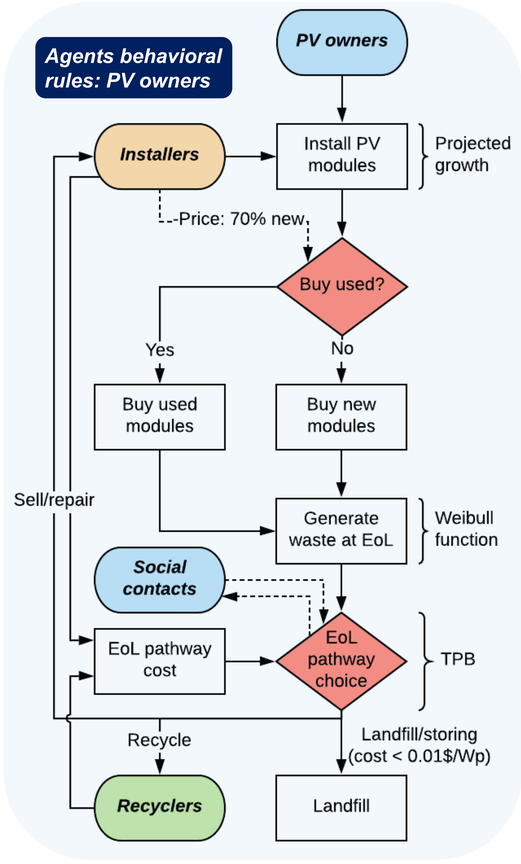
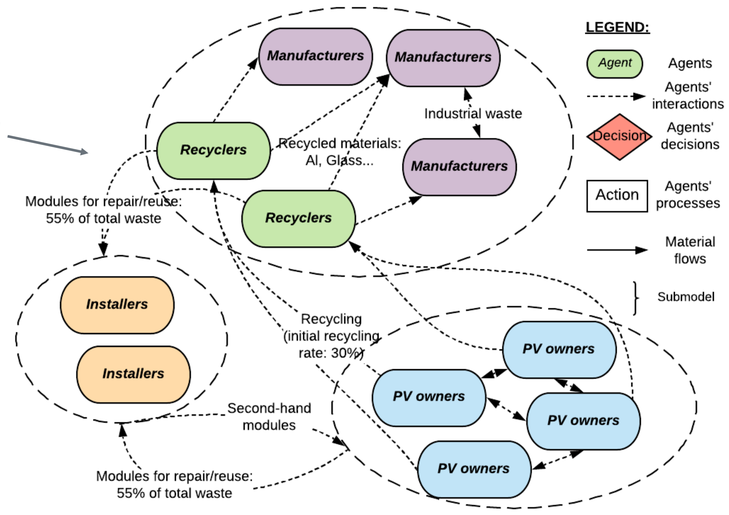


Figure1: Architecture of the ABM and agents' behavioral rules





Results

- *The secondary market quickly becomes the EoL pathway of choice because it is financially beneficial but is limited by the repair potential of modules (Fig. 2)*
- *The recycling and reuse EoL pathways compete with one another: selling is beneficial for PV owners, and subjective norms drive recycling behaviors*
- *As recycled PV waste increases, recycling costs decrease, which further drive recycling behaviors (Fig. 3, Table 2)*

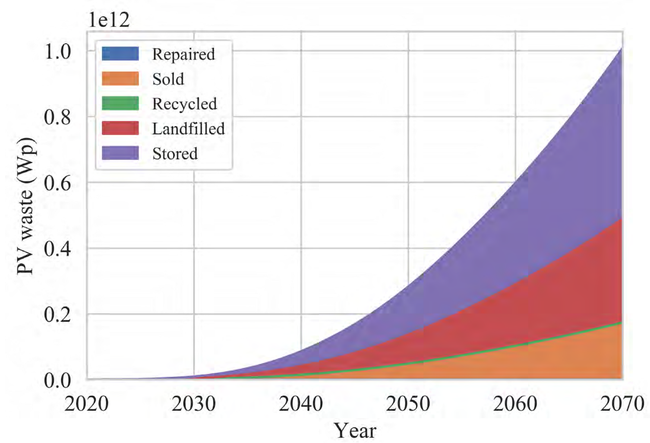


Figure 2: Distribution of PV waste according to each EoL pathway for the baseline scenario

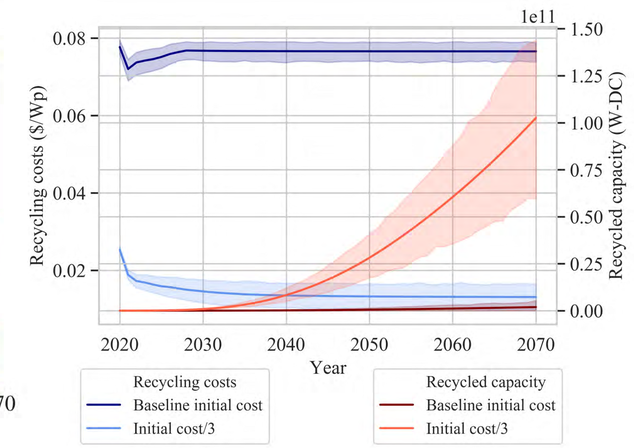


Figure 3: As recycled PV volumes increase, recycling costs plummet

Table 2: A lower initial recycling cost leads to a greater amount of PV waste diverted from landfill

Shares of waste in each EoL pathway	Initial recycling cost	Recycling cost / 3
Recycled	1%	10%
Repaired /sold	17%	16%
Landfilled /stored	82%	74%

Conclusion

- *ABM enables identifying factors favoring certain EoL pathway e.g., the subjective norms, the cost related to each behavior and the initial recycling cost (Table 2)*
- *Based on available data, one factor leading to increased circularity of PV systems is a low initial recycling cost which could be achieved through R&D in recycling processes*

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[5] Tong, X., et al. (2018). "Behaviour change in post-consumer recycling: Applying agent-based modelling in social experiment." Journal of Cleaner Production.
[6] Tsanakas, J. A., et al. (2019) "Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification." Progress in Photovoltaics

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PV Reliability Workshop
Sheraton Denver West Hotel - Lakewood, Colorado
February 25th – 27th
NREL/PO-6A20-76139

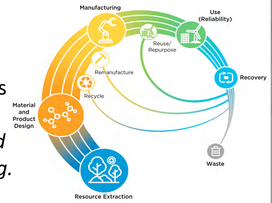
De-fluffing Circular Economy Metrics with Open-Source Calculator for PV

Silvana Ayala Pelaez, Heather Mirletz, Timothy Silverman, Alberta Carpenter, Teresa Barnes

This project presents an open-source tool under development to help quantify and assign a value framework to efforts on re-design, reduction, replacement, reusage, recycling, and lifetime and reliability increases on PV.

Circular Economy

Definition: economic system in which no materials are wasted at any part of the life of a product. *i.e. Feedstock extraction, manufacturing, lifetime, and decommissioning including (but not only) recycling.*



Assigning a value framework to a PV technology, to gauge were are efforts best served to improve economics and reduce the solar pv industry's environmental impact is key to identify pathways for future research.

Did you know: Circular Economy for Energy Materials (CEEM) is one of the three critical objectives in NREL's long term strategy.

Talk to me Metrics

Not much agreement on the definition of "circular" or how to implement it for energy technologies.
Ellen MacArthur Foundation proposes for **Circularity Index (CI)**:

$$= - \frac{\text{Virgin Material} + \text{Waste}}{\text{Mass of the product} + \sigma \frac{(\ )^{-} (\ )}{\text{Each material in the PV panel}}}$$

Waste from Feedstock & Manufacturing

Waste from recycling process

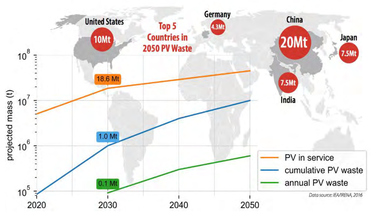
Circularity Index Calculator

Open-source python calculator in Github, leveraging published data from different sources on PV manufacturing and predicted technological changes.

Be able to answer questions like:

How will a 50 year module change our CI and feedstock material needs vs a 15 year one?
I mean, is reliability really important?

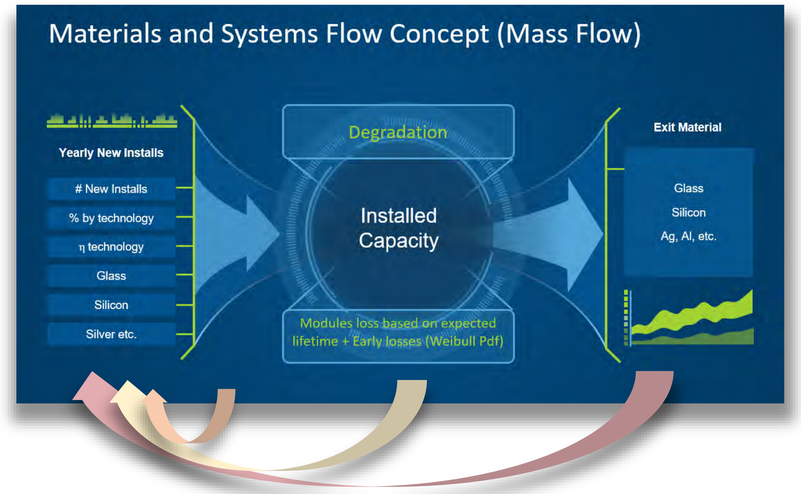
How much glass will be needed in 20 years if bifacial PV becomes the norm in the next 5 years.
And what about natural disasters?



What environmental impacts will that needed mass of glass have each year? (tie-in to LCA analysis)

How much material will be saved if I invent a process to reduce X material feedstock losses? that's money, yo!

Calculator Requirements



Capture/calculate the yearly:

- Increase in solar installations/capacity for different technologies (i.e. mono, silicon, multi)
- Yearly energy yield, based on the year's new and already installed modules with a specific efficiency and degradation from date of install.
- MASS input for each year (and MASS input losses ($W_{F(x)}$))
- Modules at EOL, and resulting MASS output and waste (W and $W_{R(x)}$)
- MASS output -- modules at EOL

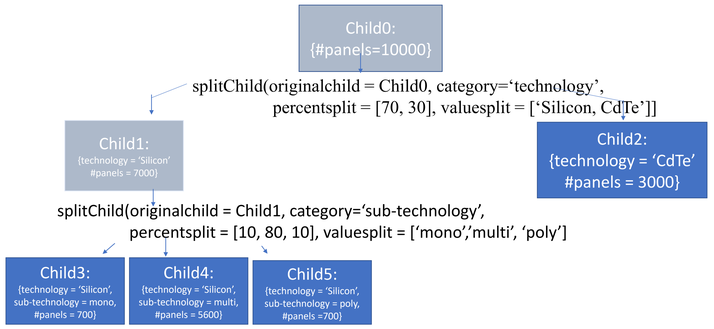
Based on all of this, calculate a Circularity Index

Allow for sensitivity analysis and comparison with a **baseline**

Challenges and Looking Forward

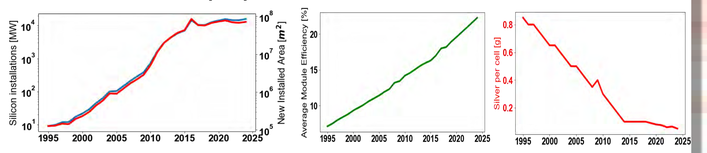
- Too many unknowns and assumptions. Track boundaries for confidence/uncertainty in results.
- Unavailable or Conflicting information, depending on the source
- Quickly evolving field. It's tough to make predictions, especially about the future.
- Capture the level of detail needed and flexibility.

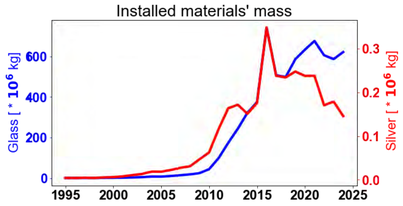
Next iterations of the calculator will move towards OOP.

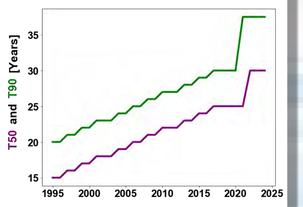


Preliminary Results

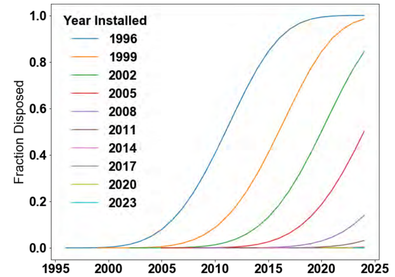
Baseline Scenario (US)



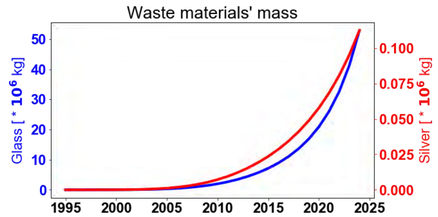


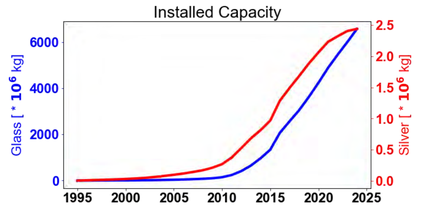


The T50 (Median Time to Fail), where 50 percent of units fail, and T90 are used to shape a Weibull lifetime distribution.



By predicting the lifetime with the Weibull distribution we get a sense of how many modules are disposed each year from each generation cohort.





Assumptions:
US installed capacity based on [2] (prior to 2010) and [3] after 2010. Assumes US market share is the same as global market share from [4]. Assumes that everything installed before 2008 was p-type mono-Si. Efficiency estimates obtained from global numbers from [4]. Prior to 2008, linear extrapolation used. Assumes modest improvements in lifetime of the modules (t50 and t90). Silver contents based on [5] predictions, prior to 2009 extrapolated with linear fit. Glass contents calculated assume all modules have 1 sheet of 3.5 mm thickness.

REFERENCES

[1] Ellen MacArthur Foundation (2015). Circularity indicators: An approach to measuring circularity. *Methodology*.
[2] IEA-PVPS T1-19:2010 report
[3] Q4 2019 Wood Mackenzie Power & Renewables/SEIA U.S. Solar Market Insight
[4] 2018-2019 Photovoltaic Manufacturer Capacity, Shipments, Price & Revenues (SPV Market Research)]
[5] ITRPV 2019

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