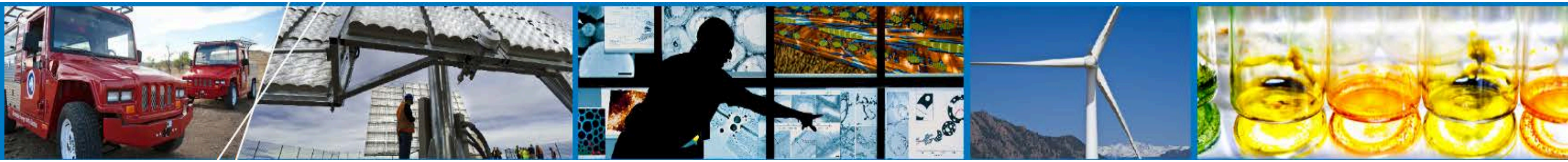
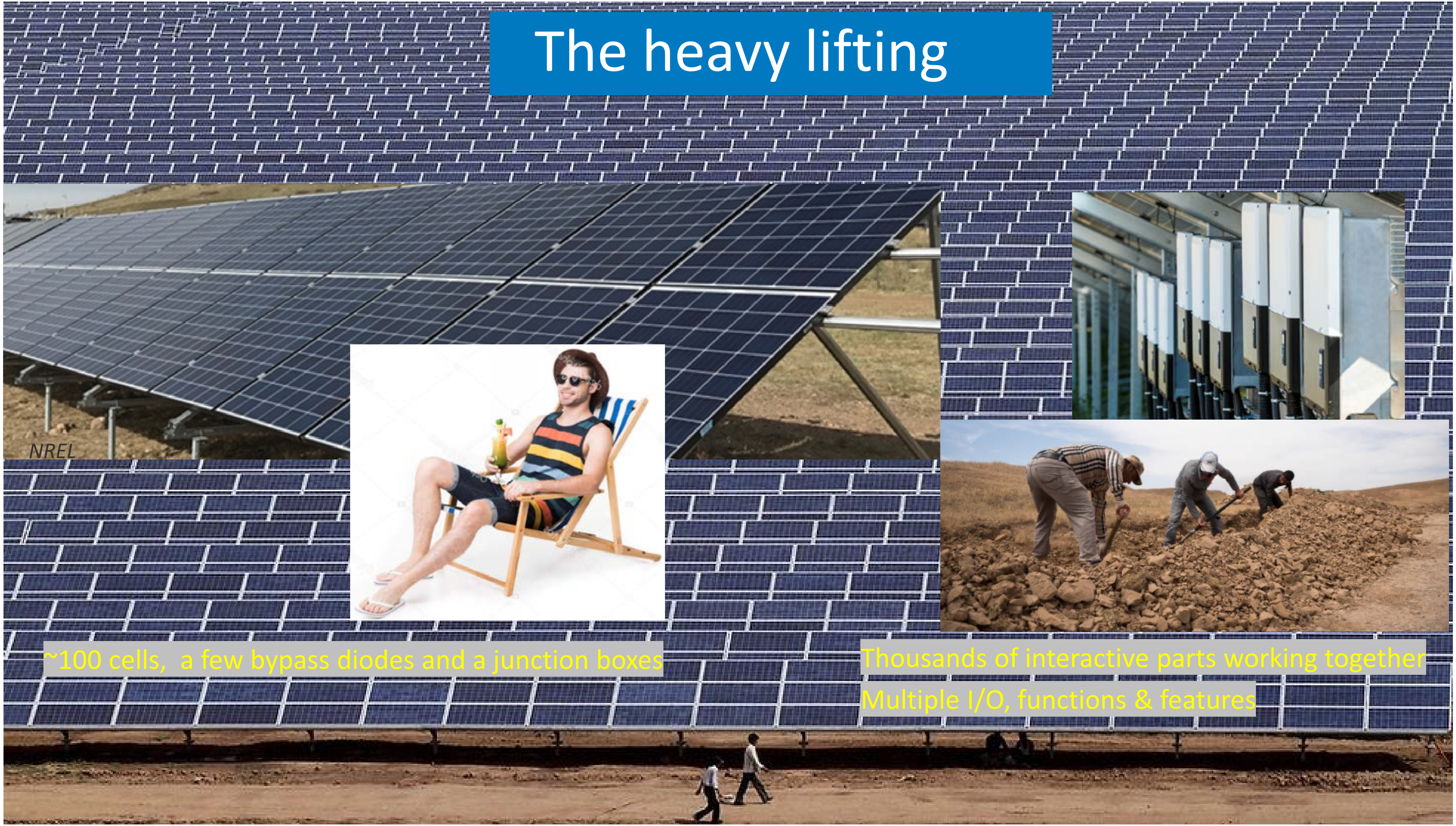
Inverters: A Pivotal Role in PV Generated Electricity



EU PVSEC 2021 online

Peter Hacke[1], Jack Flicker[2], Ramanathan Thiagarajan[1], Daniel Clemens[3] and Sergiu Spataru[4]
[1]National Renewable Energy Laboratory
[2]Sandia National Laboratory
[3]SMA Solar Technology AG
[4]DTU Fotonik

The heavy lifting



Evolving features in the inverter market

Microinverter/
module level power electronics

Enphase

String inverter

SMA

- PV (DC, maximum power tracking)
- AC
- Battery (hybrid inverters)
- Digital communications
- Performance monitoring (DC & AC)
- PID mitigation
- Grid support function
- Grid forming
- Ground fault protection
- Rapid shutdown
- Arc fault protection

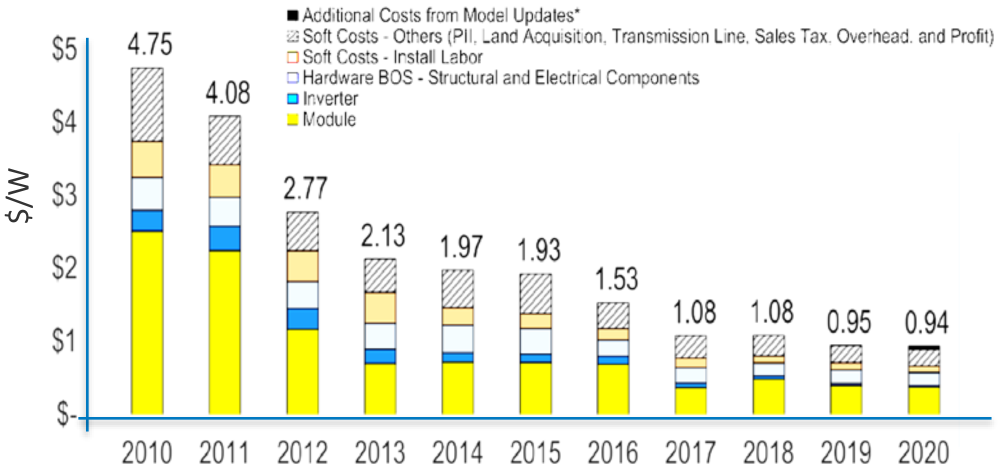
Central inverter

Power Electronics

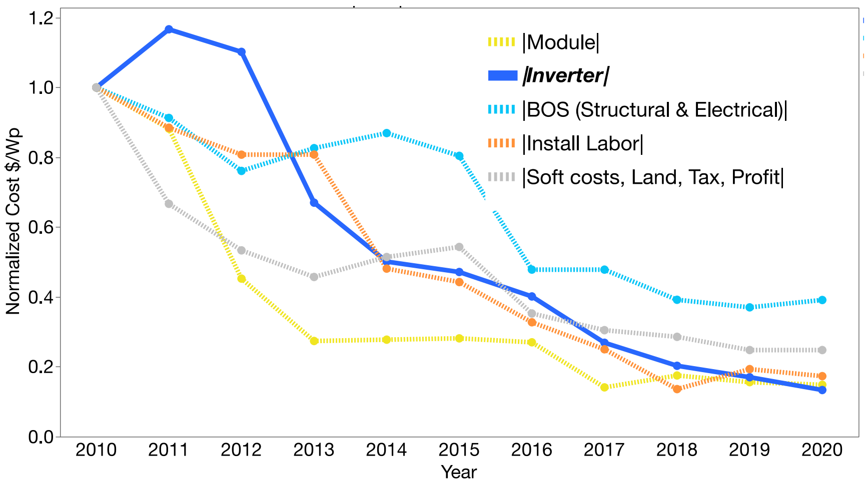
- Most features of the string inverter
- Integrated "solution"
  - DC combiner
  - Modular, swappable components
  - Parallel
    - Multiple MPP trackers/inverters
  - Transformer
  - Switchgear
- Climatic control

Cost Down in the system

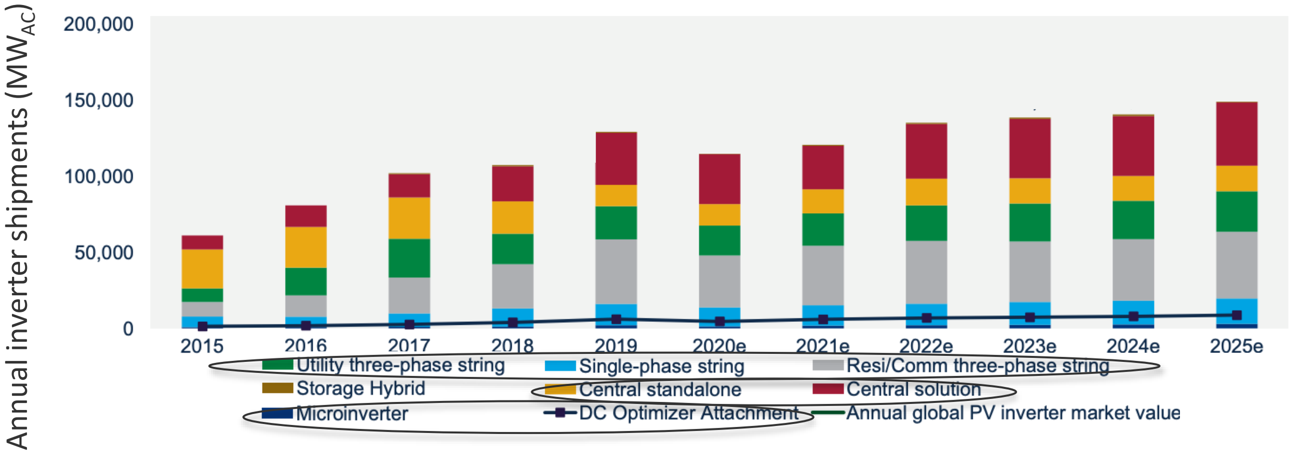
(Utility Scale)



Feldman et. al. NREL/TP-6A20-77324 (2021)



- Inverters are carrying their share of cost reduction



Annual market value $8B - $10B US

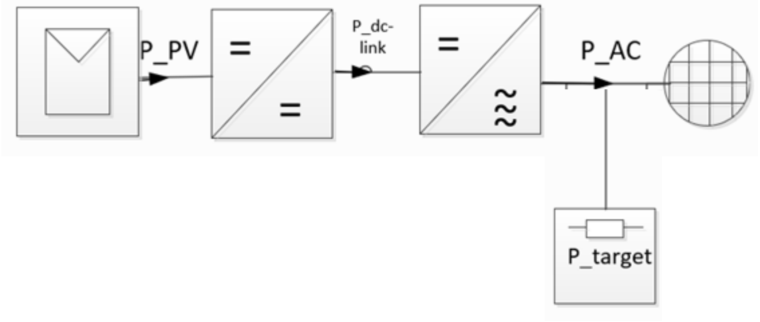
Wood Mackenzie
Global solar PV inverter and MLPE landscape 2020

Inverter segments

- **String inverters are the largest segment if you include utility, residential 3-phase and single phase string inverters**
- Central Inverters gaining capability with medium-voltage transformers and switchgear built-in, for the category **Central Solution Inverter**

2019 YoY growth

- Microinverter market grew by 74%
- Single phase string inverter, 18%



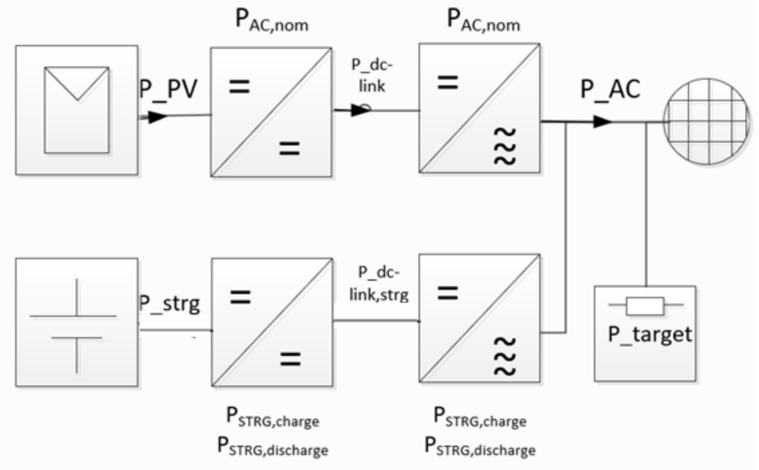
Stand alone PV system

- How is this evolving?

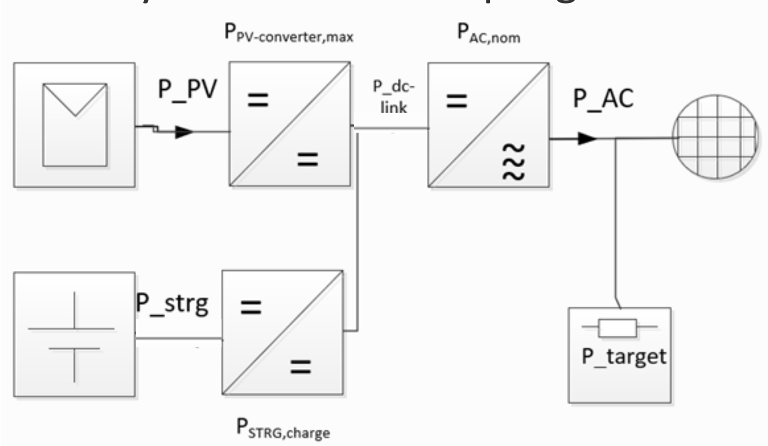
Features – Hybrid inverters

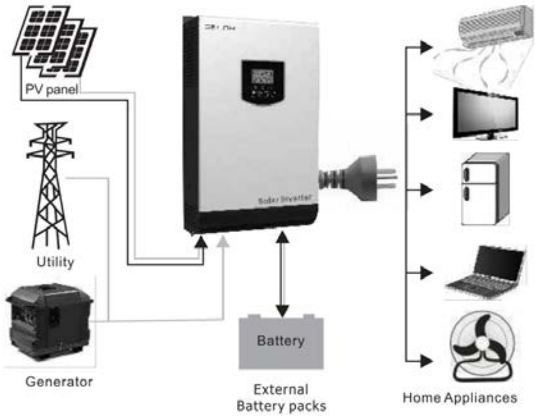
Including storage – critical for PV growth

Hybrid with AC coupling



Hybrid with DC coupling





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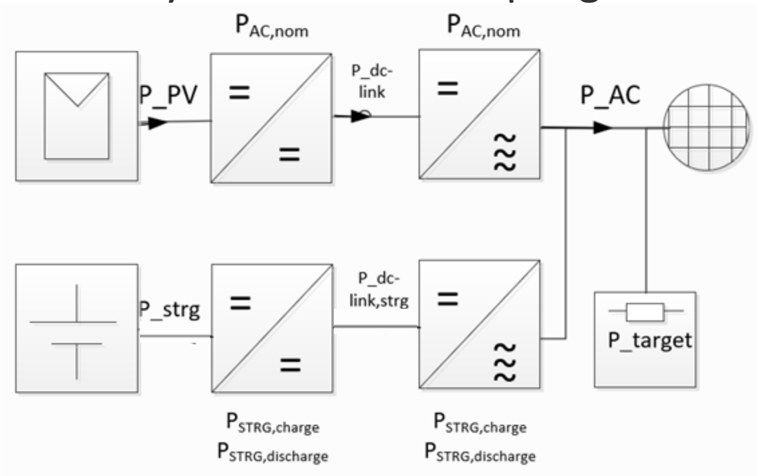
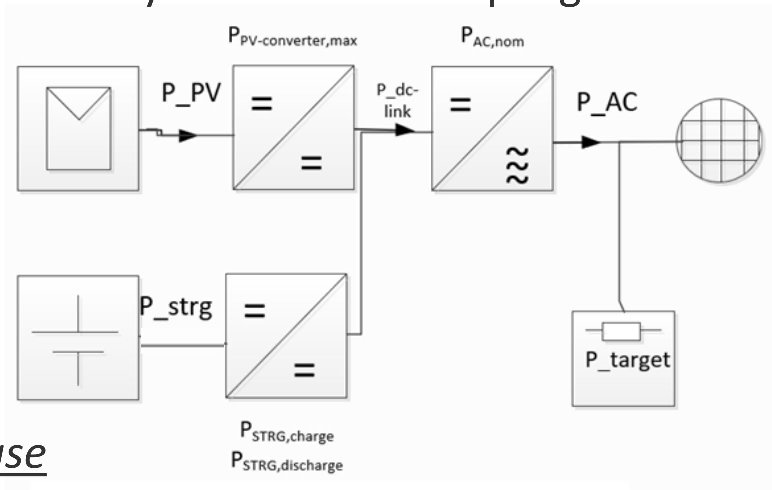
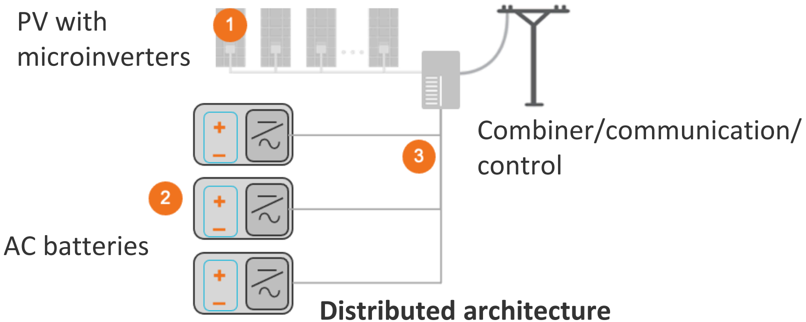


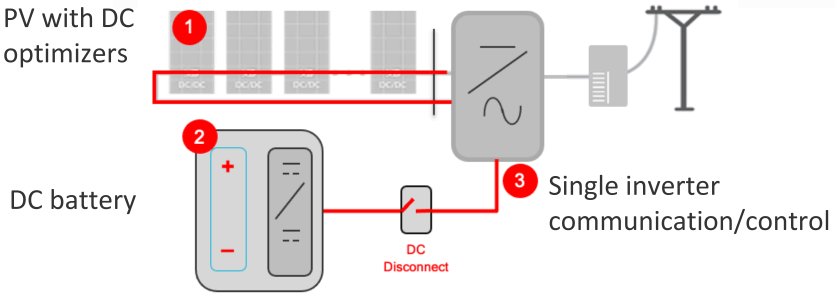
Hybrid with DC coupling



MLPE case



Distributed architecture



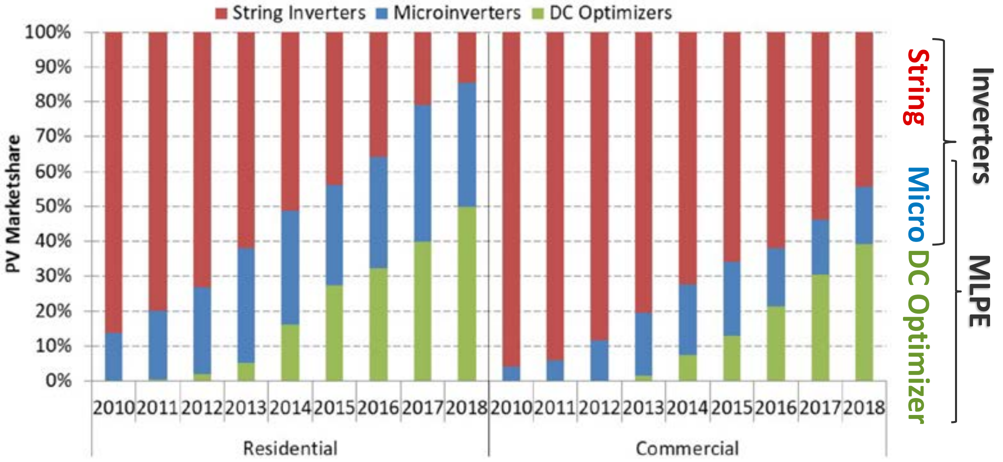
Centralized architecture

Intentional island (per IEEE 1547.4 definition) for operation in backup when grid goes down

MLPE vs string inverters

Trend toward MLPE: Residential & Commercial

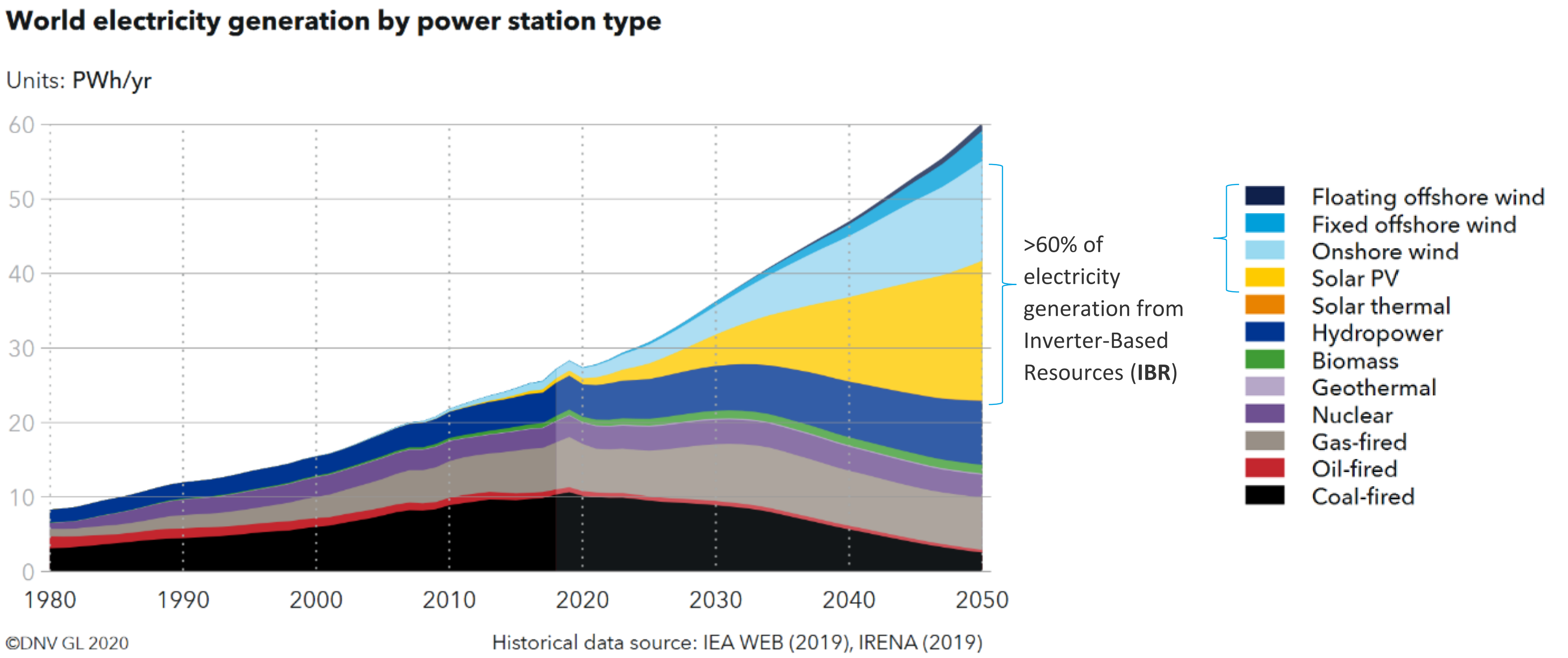
- Rapid shutdown capability (e.g., 2014, 2017 NEC)
    - Cut energy at distances of 1.5 m inside a building or 3 m from a PV module array
- Application Guide VDE-AR-E 2100-712:2018-12
    - Reduction to below 120 V in DC lines
- Eliminates mismatch problems
- Shade tolerance
- Module level diagnostics
- Expandability
- Can have lower efficiency



U.S. residential and commercial inverter market from the Tracking the Sun data set,[a] 2010–2018

[a] Barbose and Darghouth (2019)

Increasing PV penetration requires new consideration for grid connection



Grid Following, supporting, & Forming

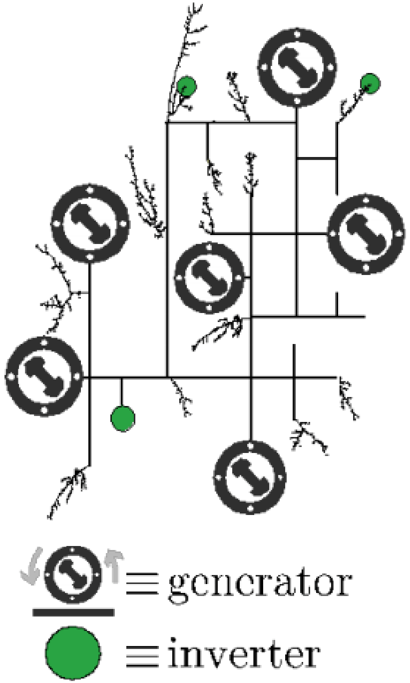
0% | 20%...30% | INVERTER PENETRATION | 60%...70% | 100%

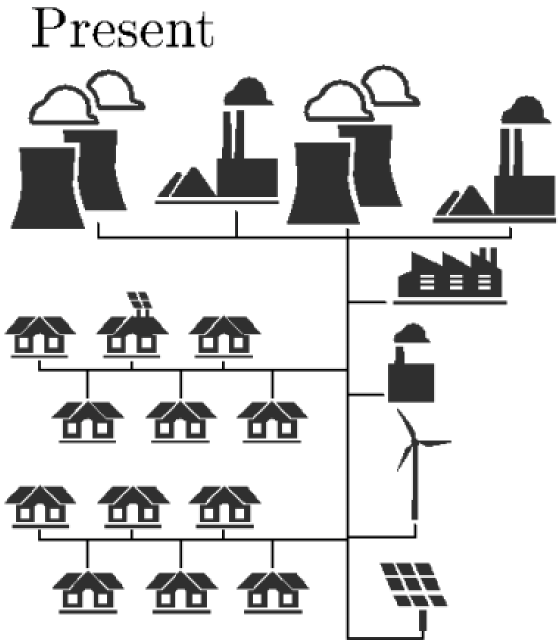
Grid Following
PAST

Aim
- → **Maximum energy yield** due to highest possible active power feed-in

Control Tasks
- → **Current source** behavior
- → Synchronization to voltage, MPP operation
- → Priority on delivering power

Disadvantages
- → **Challenges in weak grids**
- → Depends on an available grid voltage





Knobloch, A. et al: "Grid stabilizing control systems for battery storage in inverter-dominated island and public electricity grids", 13th ETG/GMA-Symposium on Energy Transition in Power Supply – System Stability and System Security , Berlin, 2019

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- **Increase of connected RES capacity** by grid-friendly active & reactive power contribution

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- **Current source** behavior
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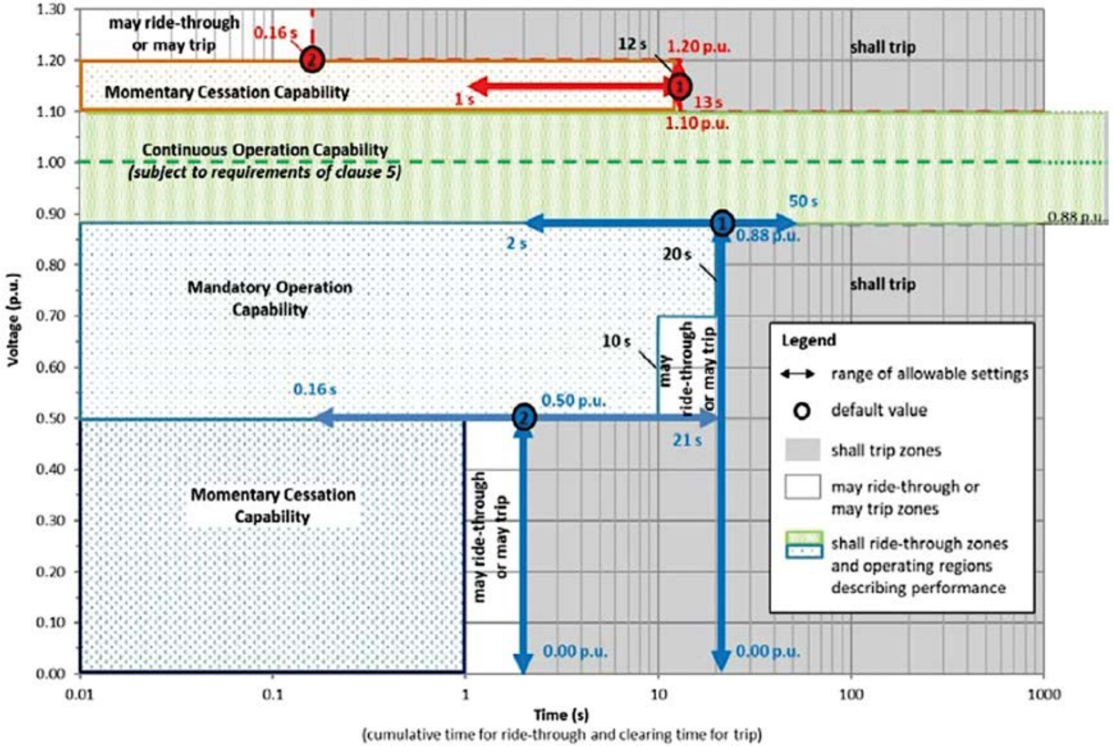
- Stabilizing reactive power and/or power factor control to transient grid conditions

Disadvantages
- **Challenges in very weak grids**
- Depends on available voltage source (or grid)
- Grid stabilization functionality can lead to **Loss of earnings**

Knobloch, A. et al: "Grid stabilizing control systems for battery storage in inverter-dominated island and public electricity grids", 13th ETG/GMA-Symposium on Energy Transition in Power Supply – System Stability and System Security , Berlin, 2019

Grid support example: Voltage ride-through



USA Example: IEEE 1547:2018/AMD1:2020
Voltage – time ride-through and trip definitions

These also exist for:

- Frequency
- Reactive power (AC phase angle)

Different countries have their own standards (partial list below)

- Yasutoshi Yoshioka/Fuji Electric Europe GmbH
- Prof. Christof Bucher/Bern U. of Applied Sciences

working on harmonization in:

IEC 63409-series “Photovoltaic power generating systems connection with grid - Conformity assessment for power conversion equipment”

Other country-specific Grid Support Standards (examples)

DK TR 3.2.2	“For power plants above 11 kW”
AT TOR D4	Technische und organisatorische regeln fur betreiber und benutzer von netzen
VDE 4105	Power generation systems connected to the low-voltage distribution network
IT CEI0-21	Regola tecnica di riferimento per la connessione di Utenti attivi e passivi alle reti AT e MT delle imprese distributrici di energia elettrica
EN 50549-1	Requirements for generating plants to be connected in parallel with distribution networks
SA v2.9 `	Grid connection code for RPPs in South Africa
AS/NZ S 4777.2	Grid connection of energy systems via inverters Inverter requirements

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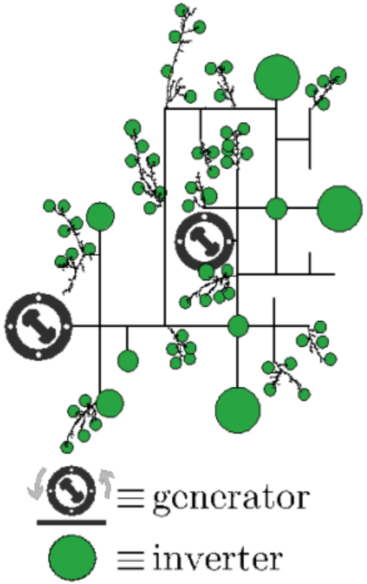

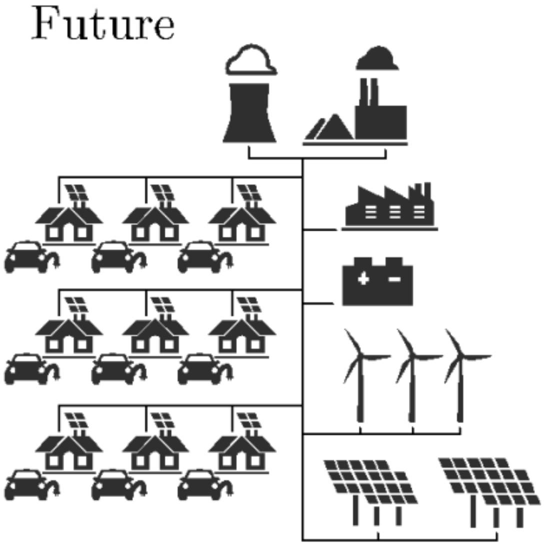

Grid Forming

FUTURE: Today / Tomorrow

Aim
- **Enables 100% renewable penetration** by voltage and frequency provision & stabilization

Control Tasks
- **Voltage source** behavior
- Voltage & frequency provision (in harmony with other Voltage & Current sources)
- Power and power factor control results automatically & with same priority

Disadvantages
- **Challenges in very strong grids** (decoupling)
- Appropriate overload protection necessary
- **Priority: Stability** (appropriate storage & control solutions for synchronization must be used)

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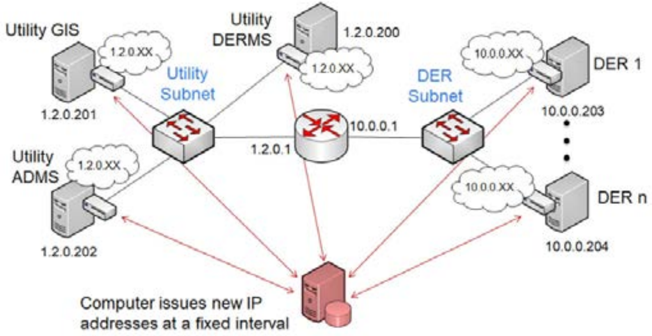
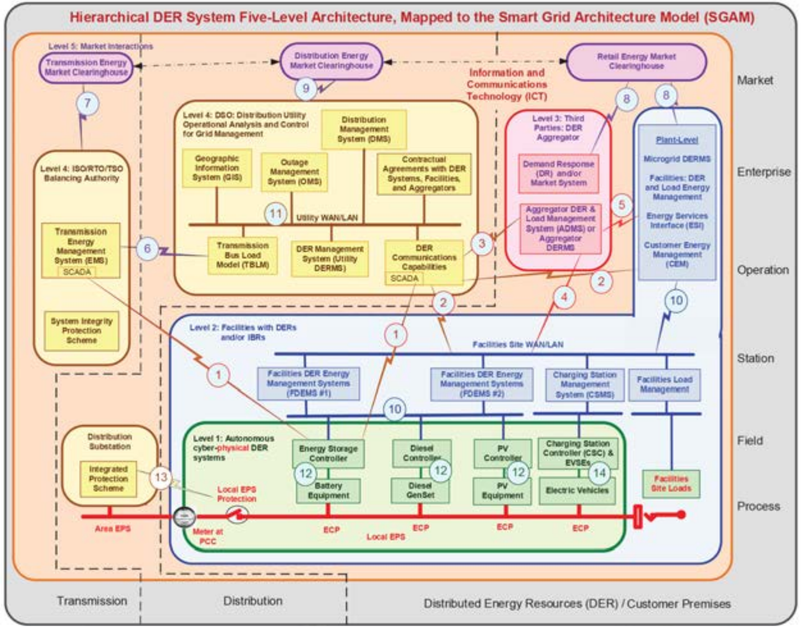
Communications for distributed energy resources (DER)

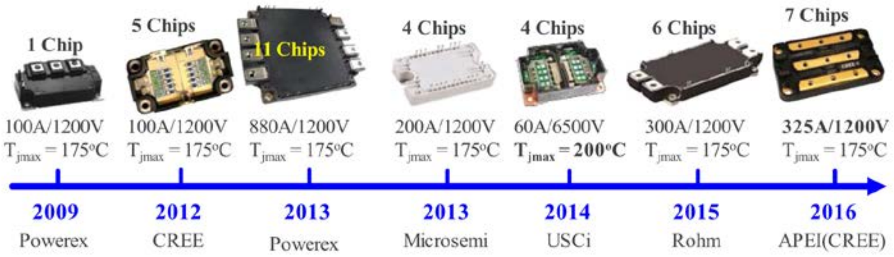
IEC 61850-7-420
"Communication networks and systems for power utility automation: Basic communication structure – Distributed energy resources and distribution automation logical nodes"
Security layer

- SCEPTRE / SunSpec protocol-compliant photovoltaic inverters
    - Network segmentation
    - Encryption
    - Moving target defense (MTD) security

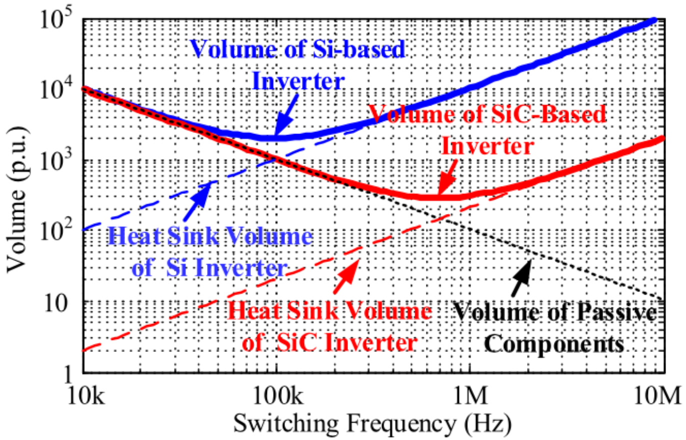




J. Johnson et al. IET Cyber-Phys. Syst., Theory Appl. (2020)



Silicon Carbide Power Modules



Zeng et. al. *Renewable and Sustainable Energy Reviews* 78 (2017) 624–639

Refusol 020K-SCI,
20.2 kW (from 2012)

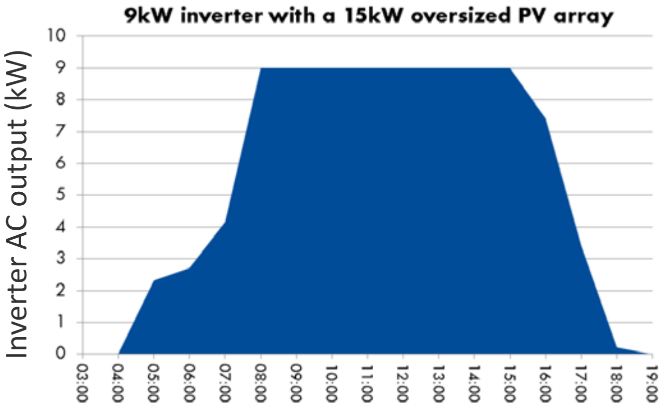
Silicon Carbide power devices

10 x higher breakdown voltage

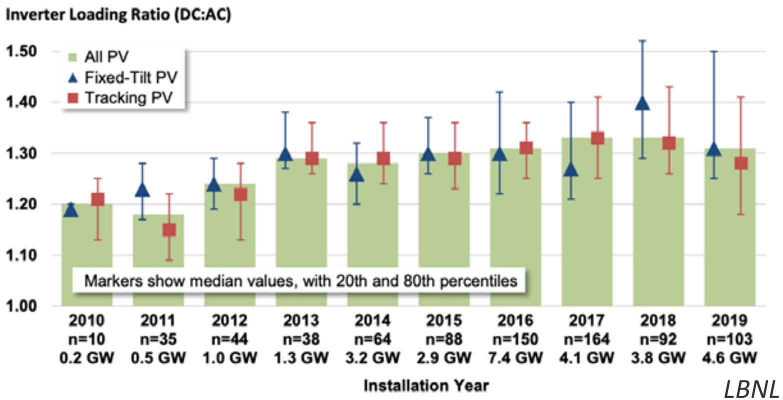
- 2x – 10x higher switching frequency
- Reduced passive component size (inductors & caps)
- Parts reduction
- 2x Higher power density devices
- Higher operating temperature capability
- Losses reduced, higher efficiency
- A path to medium voltage grid connection

Kaco's blueplanet 150 TL3: high power density 3-phase string inverter (205 kVA)

SMA Solar Technology (SMA)/
Infineon Technologies
PEAK3 125 kW—1,500 VDC, 480 VAC



SMA



LBNL

Inverter undersizing

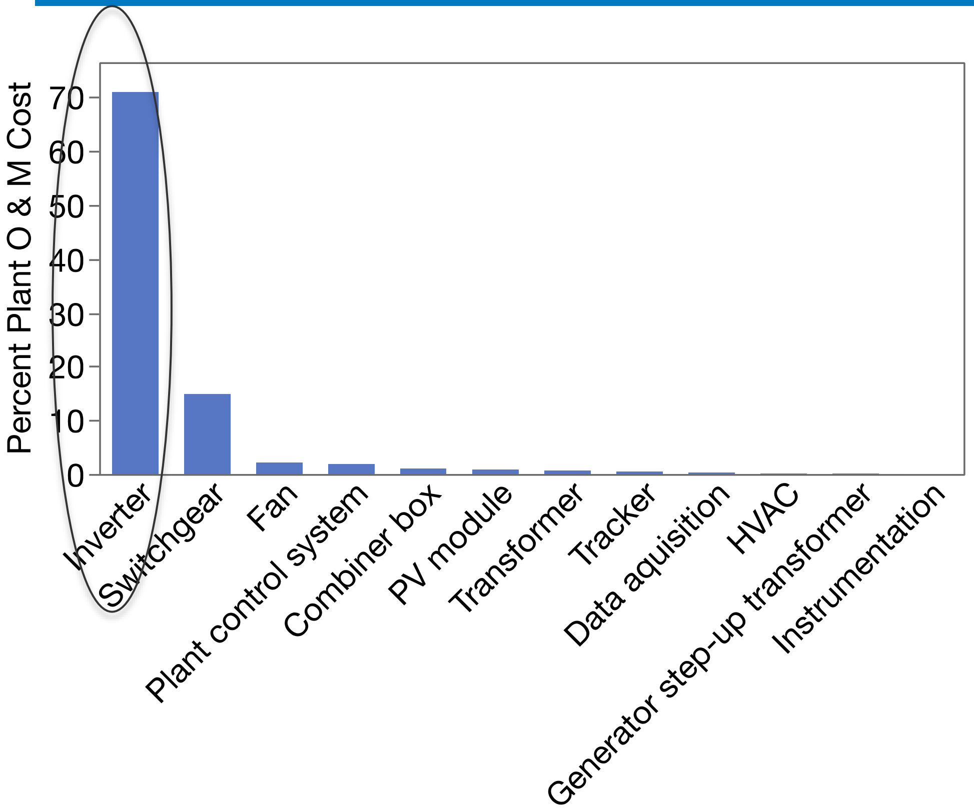
Inverters with lower than nominal DC inputs of the PV array

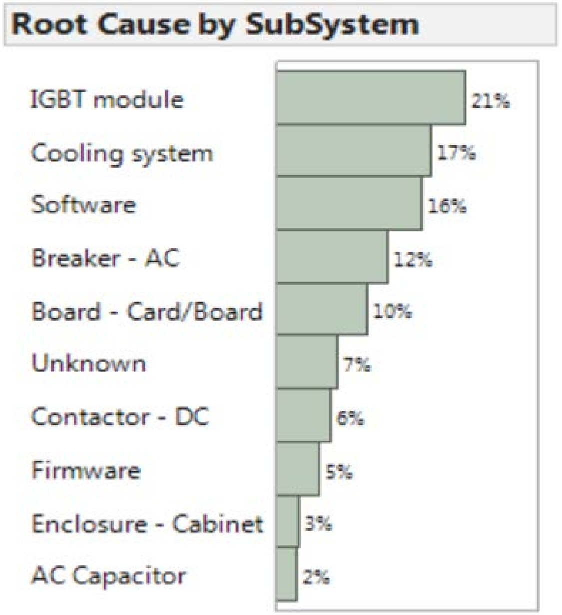
- Cost reduction
  - mid-day curtailing
  - avoid peak-capacity grid charges
- Improved power output at beginning & end of day closer to sweet spot of inverter efficiency
- Reduce intermittency from effects of variable irradiance conditions
- PV modules are cheap

But…

- Time of maximum stress on inverter is increased—but inverters are increasingly built to handle it.
- It is a little harder to detect degradation of PV panels

Pareto of O&M costs versus asset category





Adapted from: S. Lokanath and P. Williams, *IEC TC82 WG 3 & 6 Meeting, Tempe, AZ, May 14, 2016*
Sumanth Lokanath, *Proceedings 2017 PV Reliability Workshop, March 2017. Lakewood, CO.*

Reliability

Reliability (larger conversion per unit vs. redundancy)

- **Central Inverter** impact of a single outage is much greater
    - Environmentally controlled enclosures
    - O&M & P/M protocols (swappable components & subsystems)
- **String inverter** Easiest to switch out in case of failure
- **Microinverter** has more parts, but smaller, allowing for more statistical testing to reduce future failures
    - can be a nuisance to switch out
    - marketed with longest warranty lengths.

– for 1 MW of conversion –

Inverter Type	Central – 1MW	String – 50kW	MLPE - 500W
Number of Inverters for 1MW	1	20	2000
TargetAnnual Failure Rate	1%	1%	1%
Number of Critical Components per Inverter	20	15	10
Total Number ofCritical Components	20	300	20,000
Minimum Reliabilityper Critical Component (after 20 years)	99.0%	99.93%	99.999%
Required sample size for testing to 60 % confidence level	91	1,374	91,629

D. Clemens (SMA) , *Proceedings 2019 NREL PV reliability workshop (PVRW)*

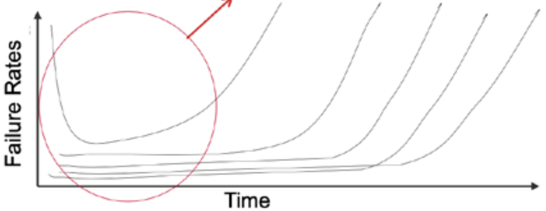
IEC 62093 ed 2:Final Draft stage

"Power conversion equipment for photovoltaic systems – Design qualification testing"

Encourages basic standard of quality

	Qualification	Comparative	Lifetime
Purpose	Minimum Design Requirement	Comparison of Products	Substantiation of Warranty
Quantification	Pass / Fail	Relative	Absolute
Failure Modes	Early-stage	Wear out	Wear out
Climate / Application	No differentiation	Differentiated	Differentiated

Focus on qualification testing

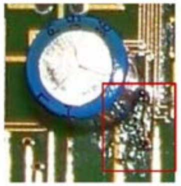


Bathtub curves of different products

PV inverter boost stage gate driver damaged

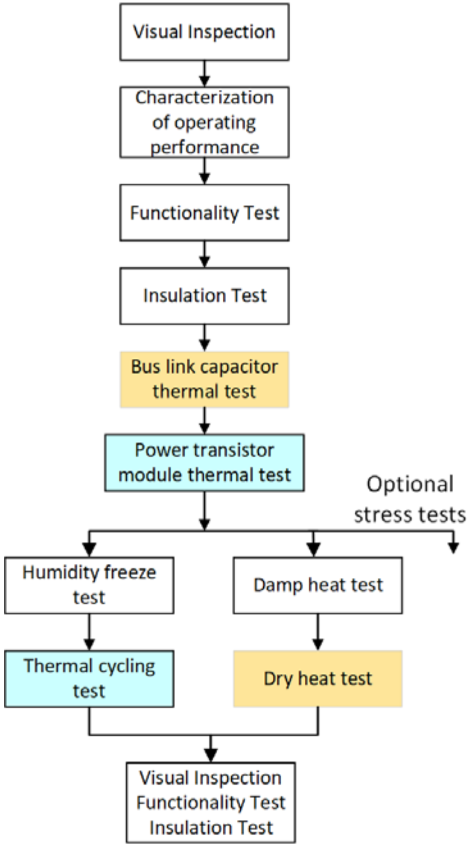
IGBT burnout failure

capacitor flashover



Electrolyte leakage

Test flow



Ground faults

Source of fault

1) Cable insulation damage;
2) Module insulation degradation
3) Capacitance effects in PV arrays (bleed off time)
   Time delay inserted as a result to reduce nuisance trips
4) Conduit, junction box, and combiner box shorts with powered conductor

Ground fault detection fuse requirements (UL)

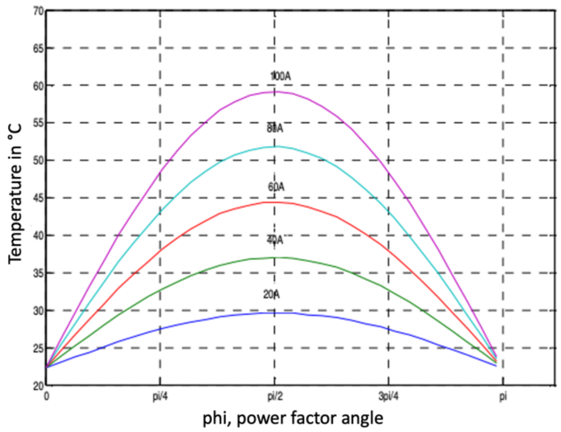
Inverter DC Rating (kW)	Maximum Ground Fault OCPD Rating (Amps)
0–25	1
25–50	2
50–100	3
100–250	4
> 250	5

IEC 62109-2: Fault if resistance is less than $R = (V_{MAX}$ PV/30 mA) ohms

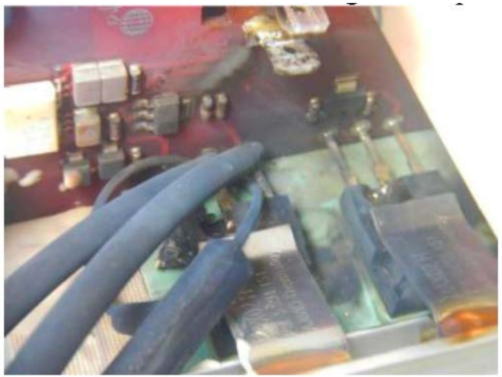
Type	Grounding	Where used
Ground fault detection and interruption (GFDI) Fuse	Grounded PV systems	Primarily USA
Residual current device	Largely ungrounded systems	Primarily EU, some USA
Isolation resistance (Riso)	Largely ungrounded systems	Common in Europe

Emerging questions in inverter reliability

Stress incurred with grid support



Junction temperature variation of the IGBT vs. power factor angle (V-I phase shift), for different current levels
(power factor = cos Φ =kW/kVA)



Power transistors in string inverter fail after 8 h of non-unity operation (pf= 0.85), where a 13 % increase in bus voltage and 60% increase in voltage ripple was seen.

Other areas:

- Solar heat gain
  -Stress & predictability in derating
- Condensation on critical electrical components
- Extra stress on integrated charge controllers for solar-plus-storage systems
- Severe climates and conditions
- Subsystem testing for central inverters to reduce cost and facilitate their testing.

These issues may be addressed by appropriate design – evaluation is necessary

-Reddy, Lakshmi et. al. In *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 783-788. IEEE, 2012.
-Armijo, Kenneth et. al. *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, pp. 1-6. IEEE, 2015.

In summary

- Inverter: center of the system—increasingly becoming the brain, more features and capabilities (hybrid systems, safety, islanding, monitoring…)
- Increasing inverter-based generated electricity associated with many renewable energy sources
- Increased dependence for grid support and forming capability
- Communication within the grid and security increasingly required
- Increasing complexity leads to more chances to fail
- As in most PV segments, there is cost reduction pressure, which makes it more challenging to keep the reliability high

Thank you

www.nrel.gov

NREL/PR-5K00-80991

Thanks to Firoz Khan (Enphase), Adrian Haering (Solar Edge) for sharing some material to understand their market segments

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