NREL
NATIONAL RENEWABLE ENERGY LABORATORY

National Center for Photovoltaics

# Opportunities and Challenges for Power Electronics in PV Modules

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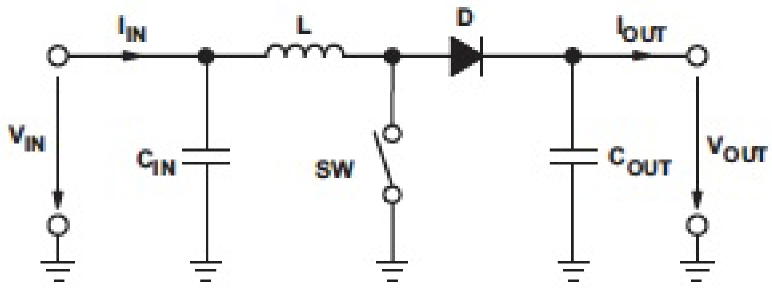
# Outline

- What are we talking about?
  - Power electronics: DC-DC converters, smart bypass diodes, microinverters
  - Imperfect solar cells
  - Ways to implement power electronics in module
- Opportunities: Enables new technologies/approaches
  - Non-uniform thin film and thin silicon wafers that sometimes crack
  - High-shading configurations
  - Potential to mitigate safety issues
  - System-level savings
- Challenges: Daunting for some implementations; easier for others
  - Efficiency – parasitic losses can be greater than benefits
  - Cost – goal is to reduce cost of power electronics by factor of two, while increasing performance
  - Reliability – could be a nightmare
- Conclusions

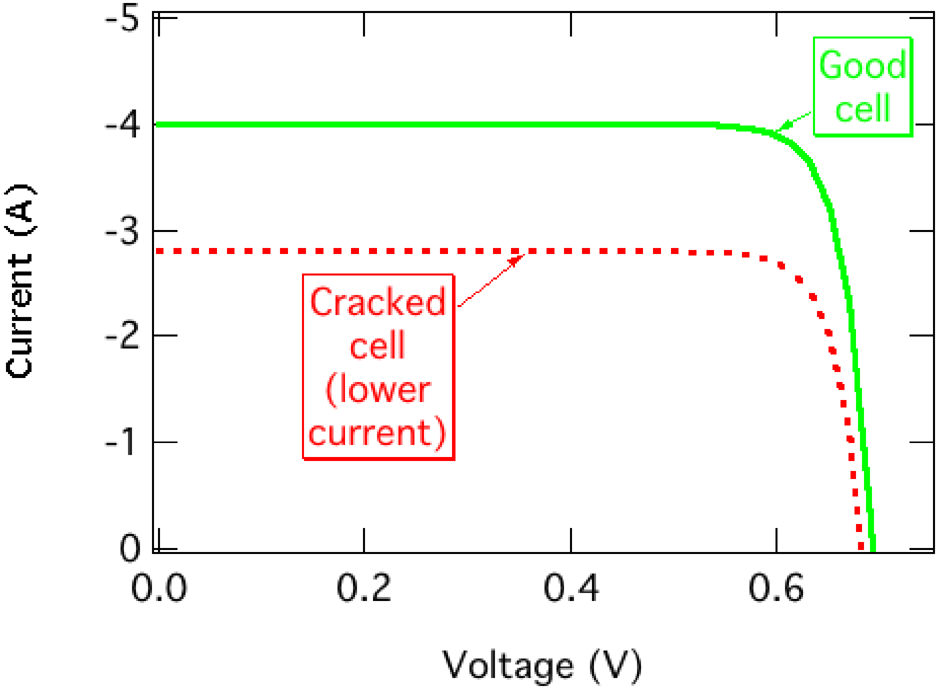
# Power electronics: Example: DC-DC converter

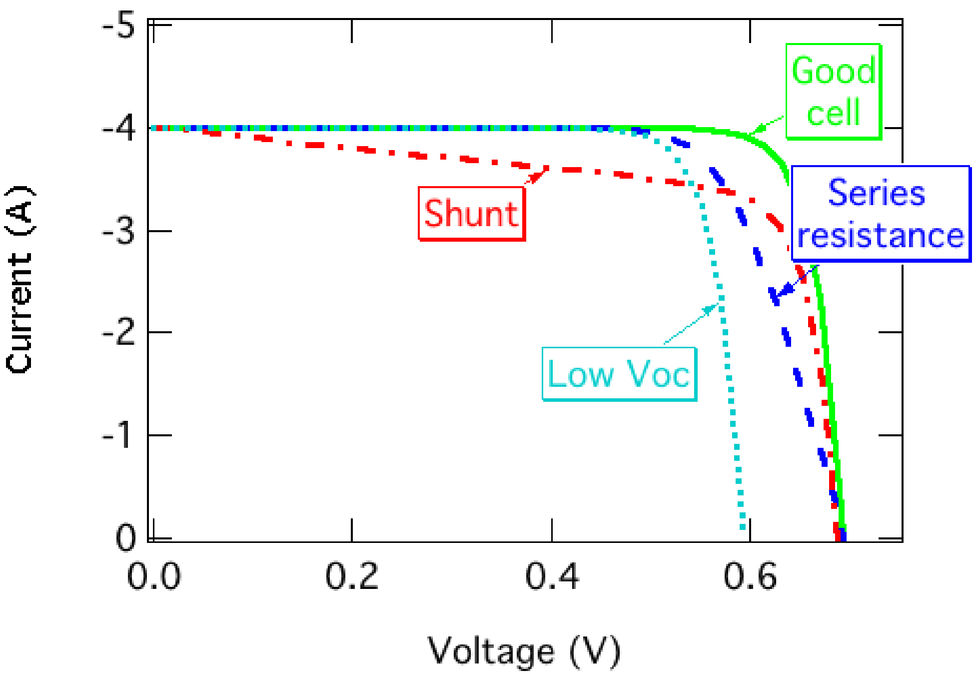



- What is a DC-DC converter? Just as a transformer can step up or step down the voltage for AC power, a DC-DC converter can efficiently adjust the DC voltage in a circuit.
- Have been used for decades
- What's new??: lower cost and increased efficiency
- DC-DC converter is probably used in your laptop or cell phone to stabilize output voltage of the battery.
- Efficiencies of 96%-99% are available.

# Imperfect Solar Cells

- A solar cell may produce less electricity because of reduced photocurrent.
- Today's thinner Si cells sometimes crack.
- Could power electronics help?



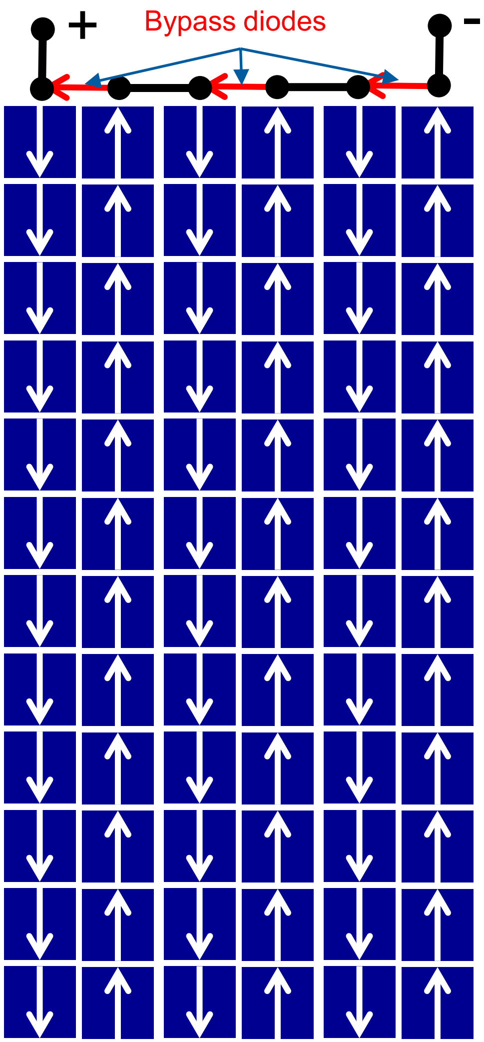

- Solar cells may fail in lots of ways.
- Usually the fill factor (squareness of the curve) is reduced
- Increased series resistance may be most common, but not always
- Usually, all parameters are affected
- Could power electronics help?

# Examples of imperfections

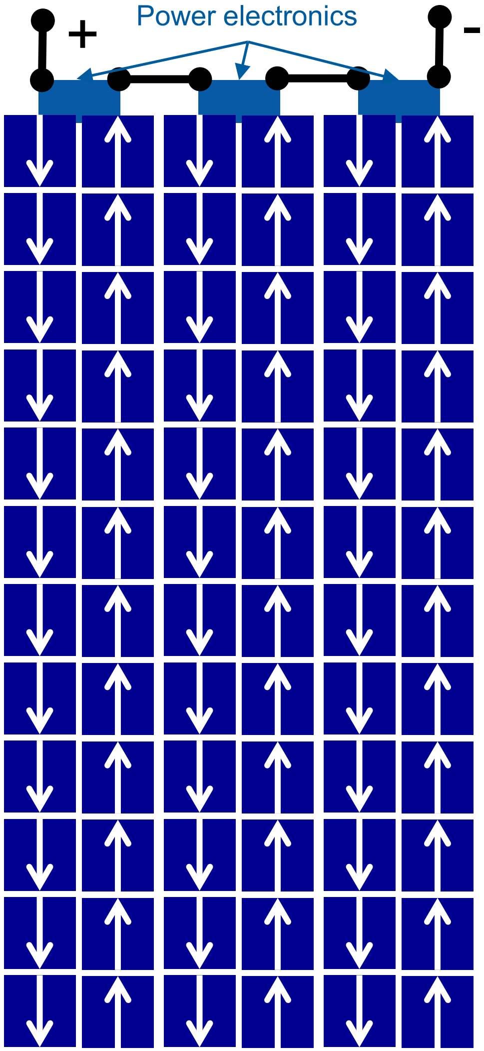
- Silicon – low photocurrent because of cracked cell
- CdTe – high series resistance because of back contact
- CIGS – high series resistance because of hydrolysis of ZnO transparent conductor
- Amorphous silicon – reduced photocurrent from light-induced degradation

- All technologies see some degradation of photocurrent, photovoltage, and fill factor
- A full list would cover many pages

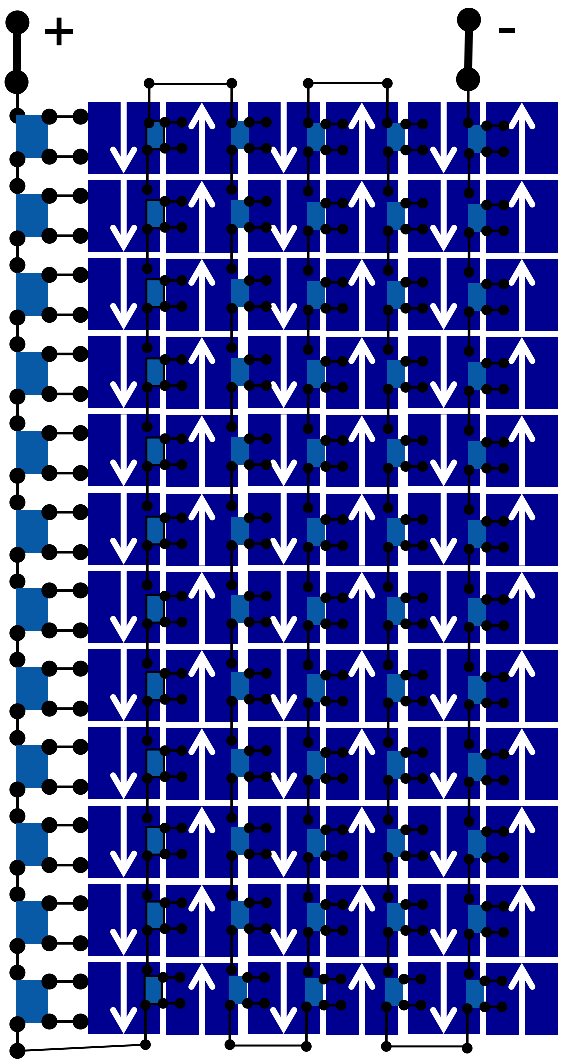
# Wiring in modules – examples incorporating power electronics




Conventional wiring

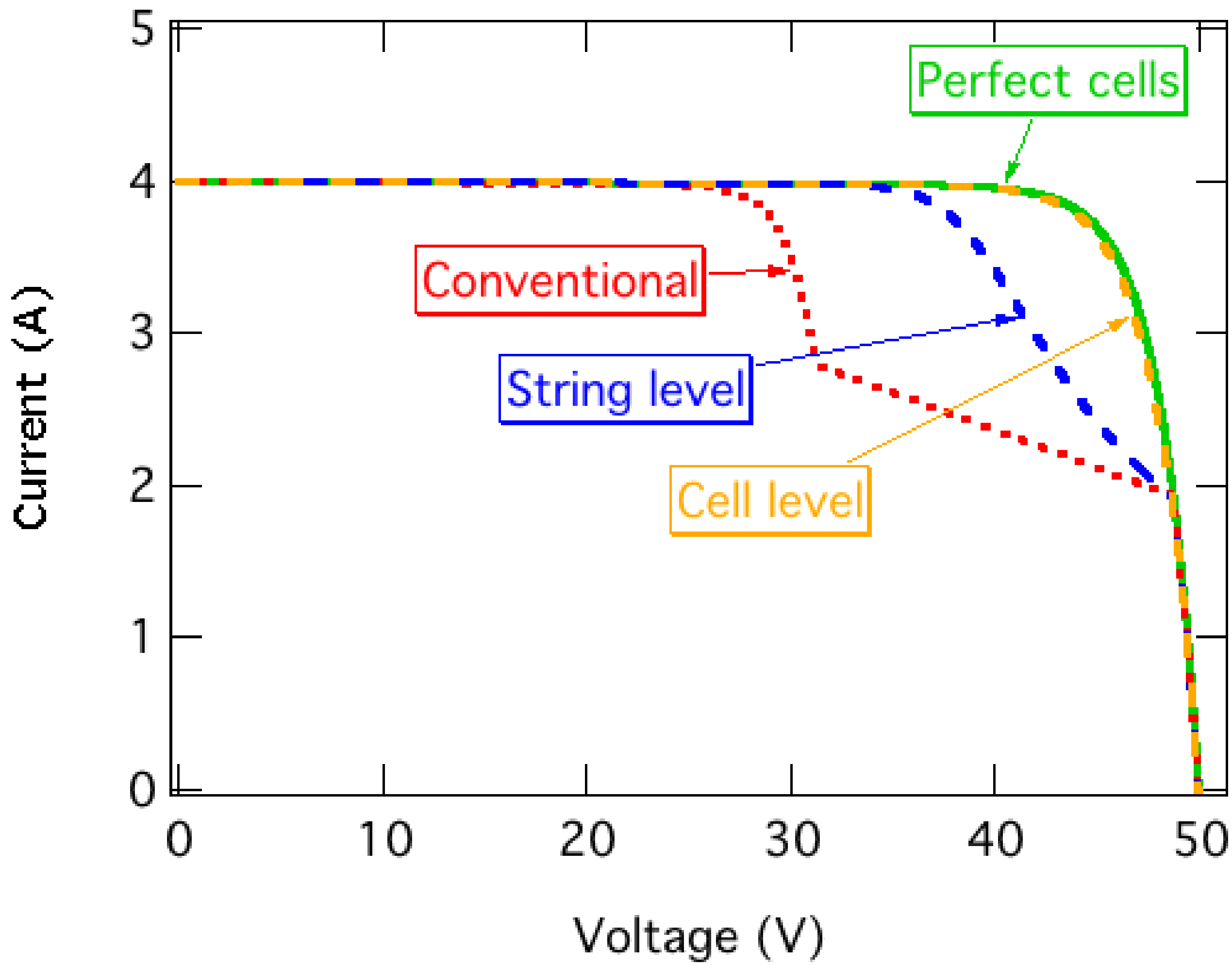



String-level electronics




Cell-level electronics

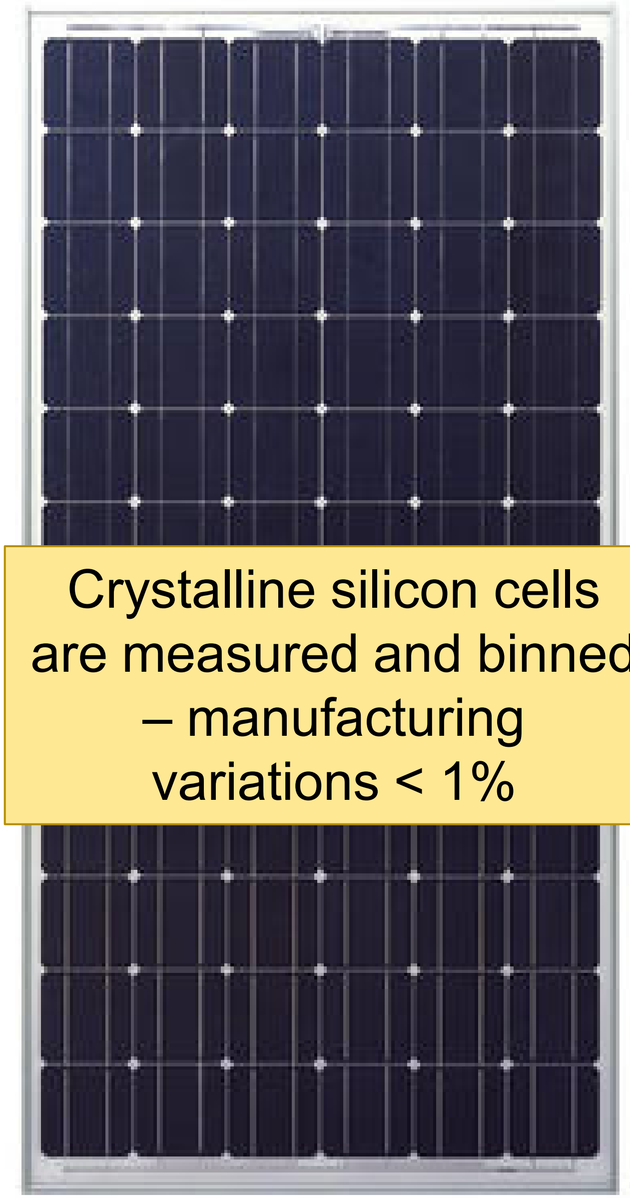
# Value of power electronics




Simulation of 50% loss of current from 1 cell; power electronics 100% efficient; Three strings of 24 cells each, only one string has bad cell.

Cell-level electronics recover more of lost power, but add complexity

# Opportunities – manufacturing variability



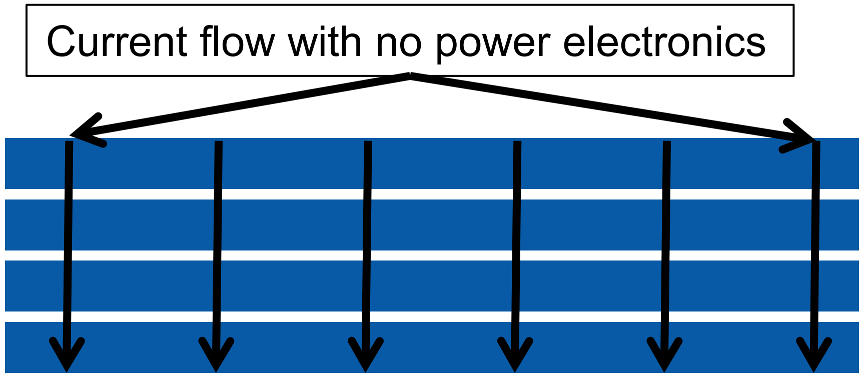
Crystalline silicon cells are measured and binned – manufacturing variations < 1%

- For crystalline silicon, the binning process is highly automated, so adds minimal cost
- Binning is useful to test for highly defective cells so manufacturers want to keep it
- The binned cells may vary in current by only ~1%
- Adding power electronics is unlikely to be cost effective for this application

# Opportunities – manufacturing variability

- Strips in thin-film modules cannot be binned
- Variability across thin-film module can be high
- Opportunity for power electronics, but challenging to implement
- Adding power electronics to each cell will require redesign of module

Most thin-film cells cannot be binned; variability can be large, especially for new products, providing possible opportunity for power electronics



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*Lateral current flow encounters resistance of transparent conductor*

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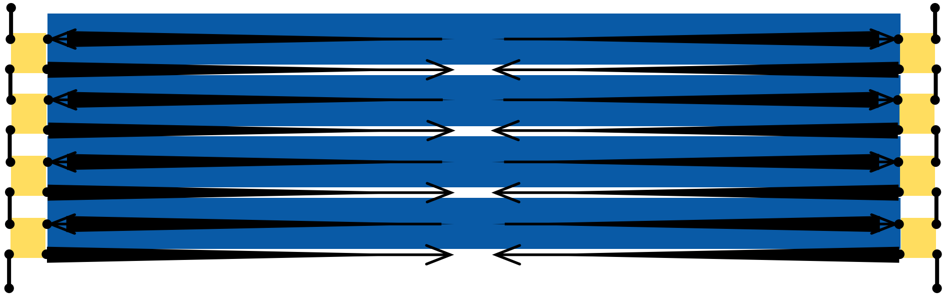
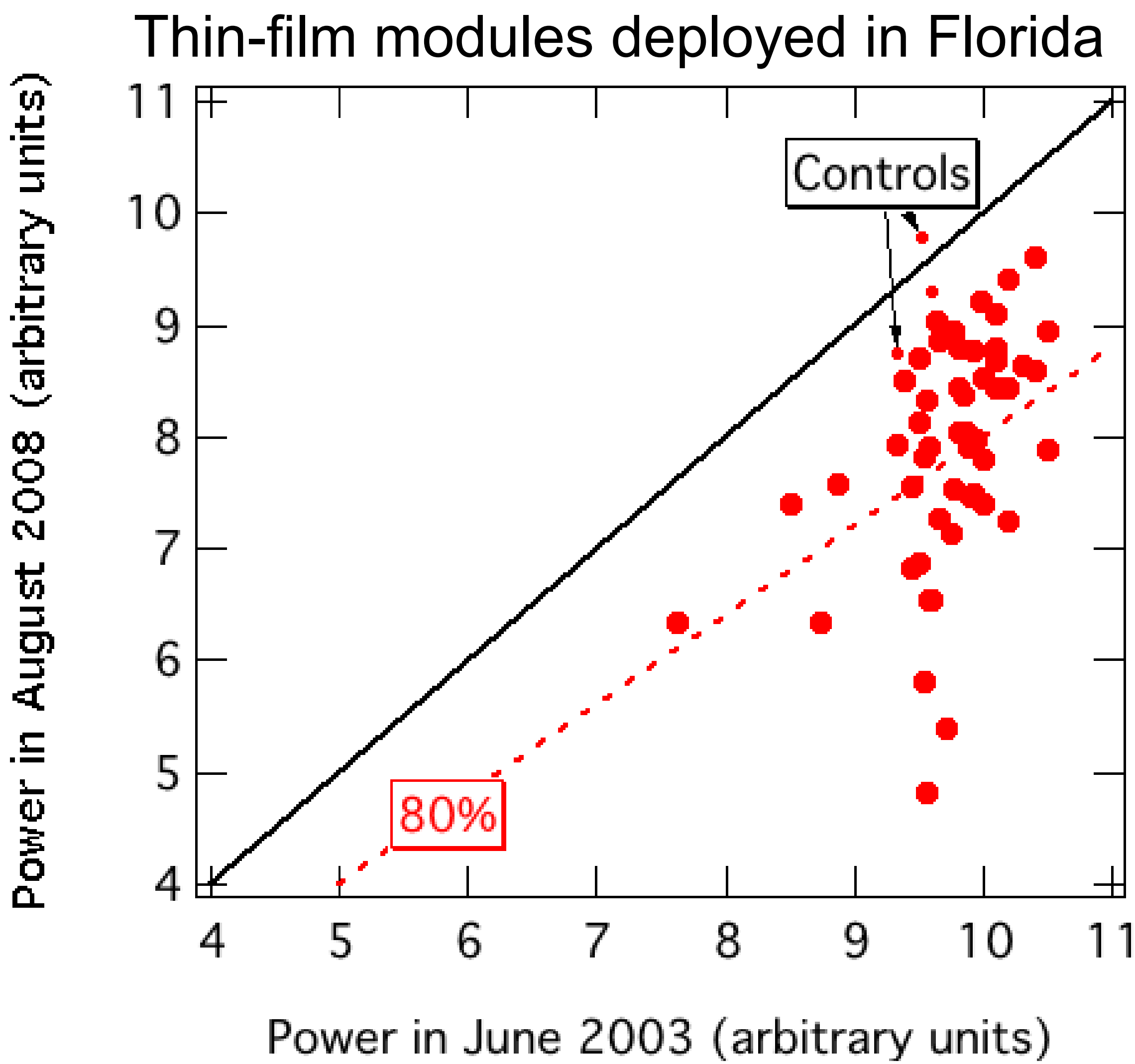
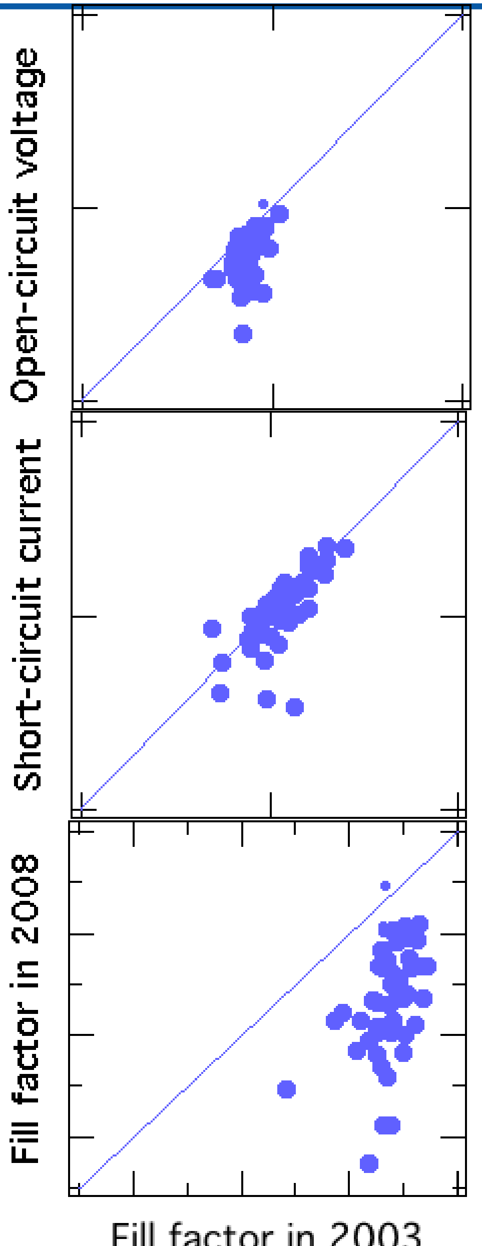
Current flow with power electronics at ends



# Opportunities – degradation variability



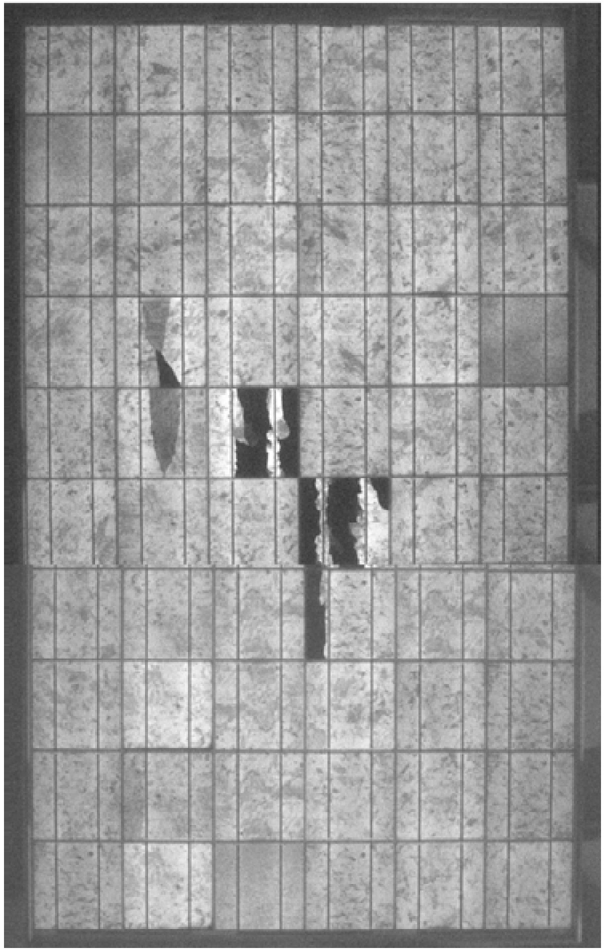

Immature thin-film PV designs show variable degradation – opportunity for power electronics?

# Opportunities – enables new technologies

*Thinner silicon cells have lower cost but are observed to crack sometimes*

+ DC-DC converters can mitigate issues if thin cells break

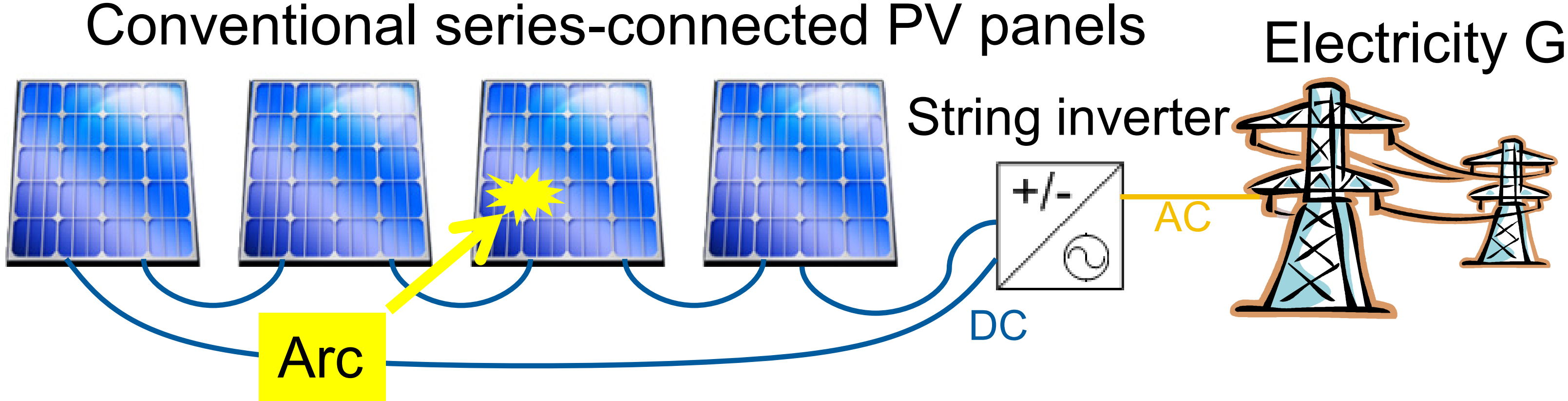
- May be a temporary problem: broken cells are undesirable – need to avoid breakage



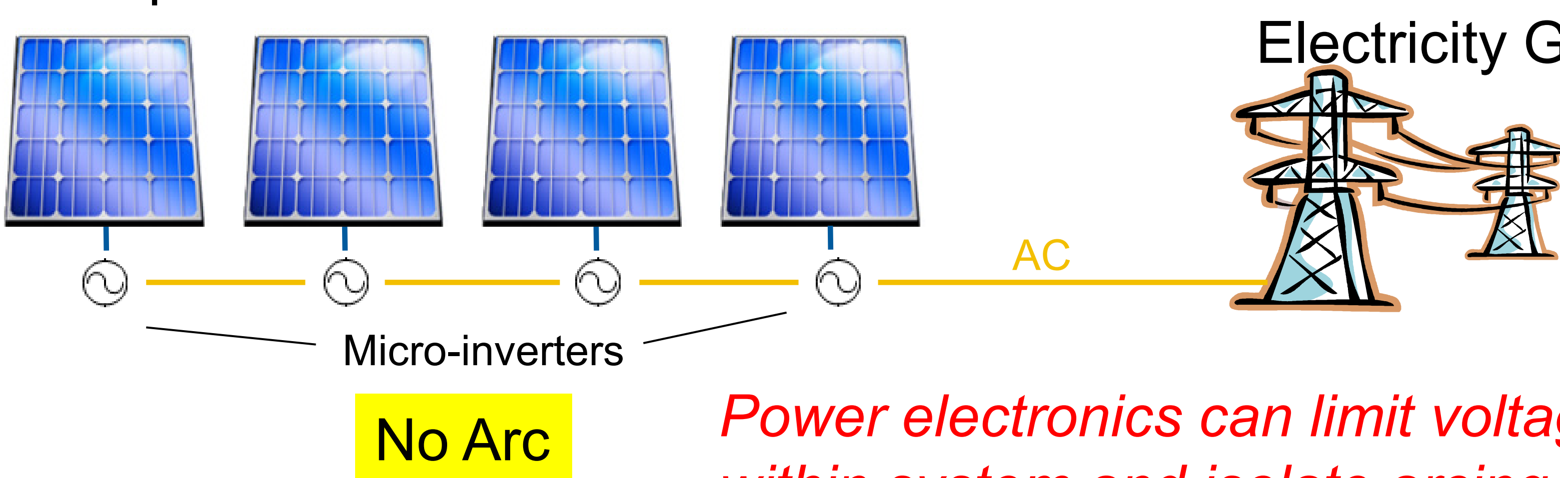
# Opportunities – improve safety - arcing

Arcs may appear if high voltage (~100 V) can appear across a gap

Conventional series-connected PV panels

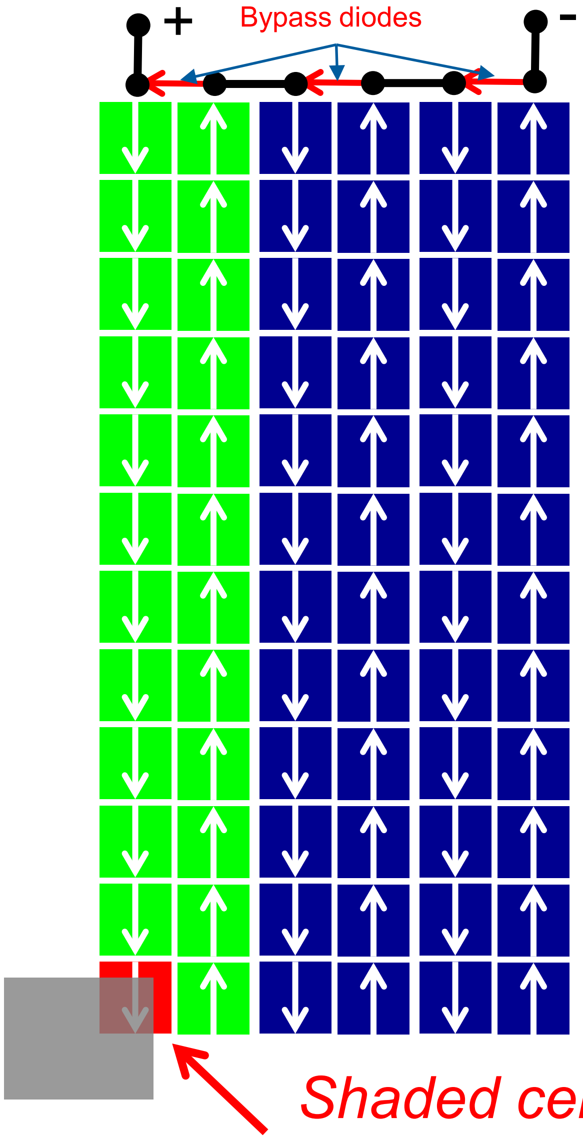



PV panels connected to AC micro-inverters




*Power electronics can limit voltages within system and isolate arcing areas*

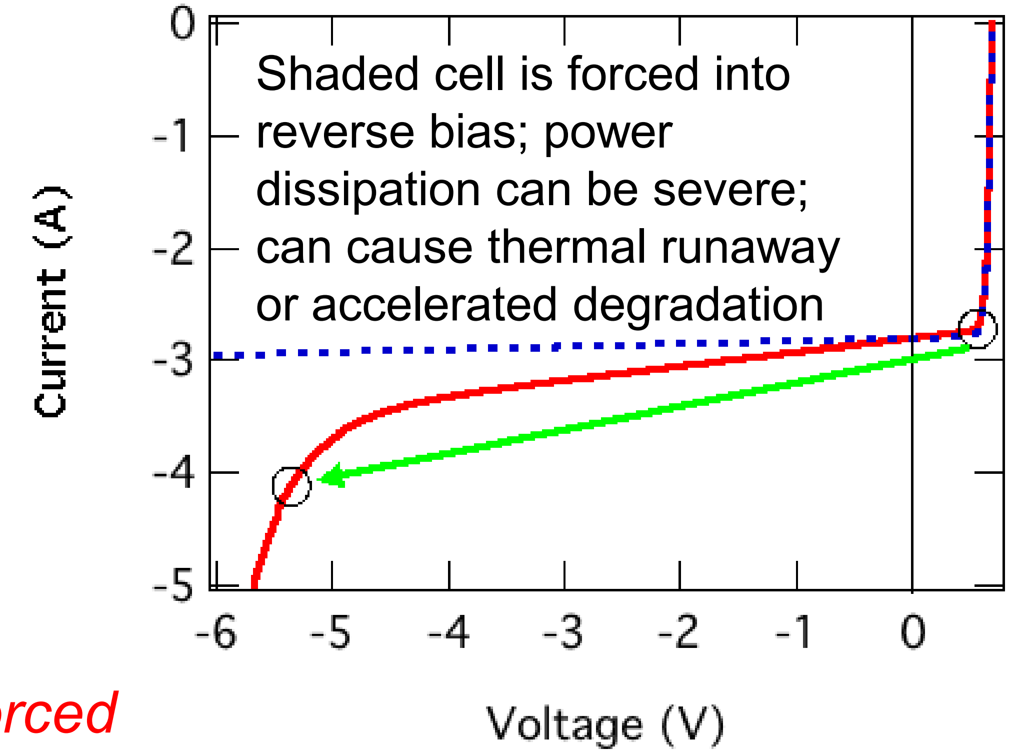
# Opportunities – improve safety – hot spots




*Shaded cell is forced into reverse bias*

Hot spots can be caused by shading

1. Shading blocks flow of current
2. Shaded cell goes into reverse bias
3. Bypass diode protects cell
4. If bypass diode fails, heating may be severe
5. Smart electronics may be more effective




"Hot-spot test" is part of qual test

# Opportunities – enables new technologies

*Creative designs may be enabled (e.g. shade tolerant)*

+ tenKsolar uses DC-DC converters to enable higher packing density on roof, boosting power with mirrors

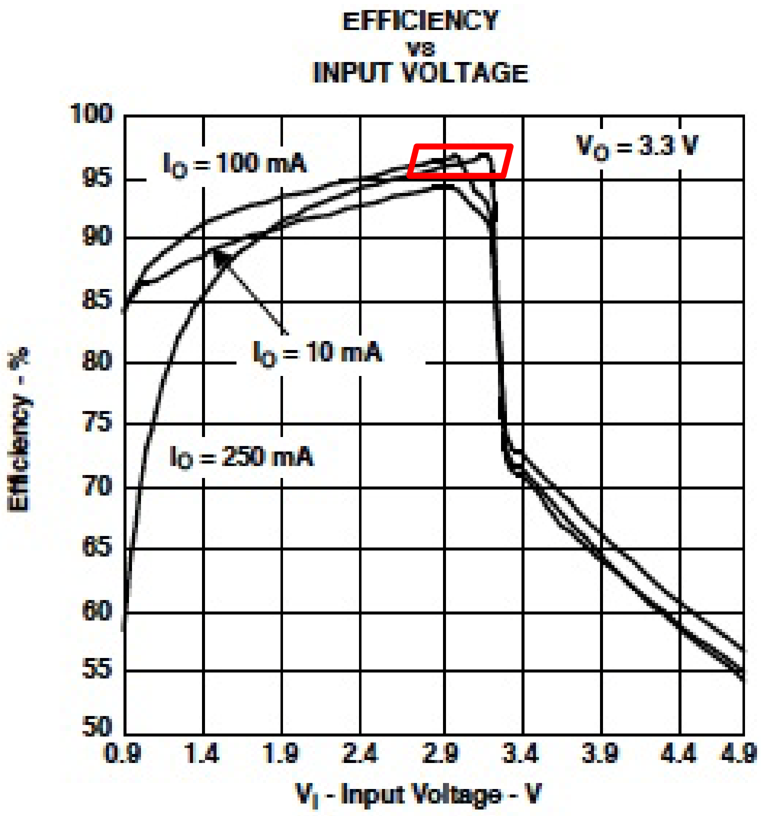
Shade tolerant designs can be attractive when space is constrained or, when output can be enhanced, as in this case using mirrors; *System-level advantage*

*DC-DC converters may enable designs that would otherwise be dismissed*

# Challenges – Parasitic losses

*Parasitic losses may affect every kWh*

*Stated efficiency may not represent average efficiency*

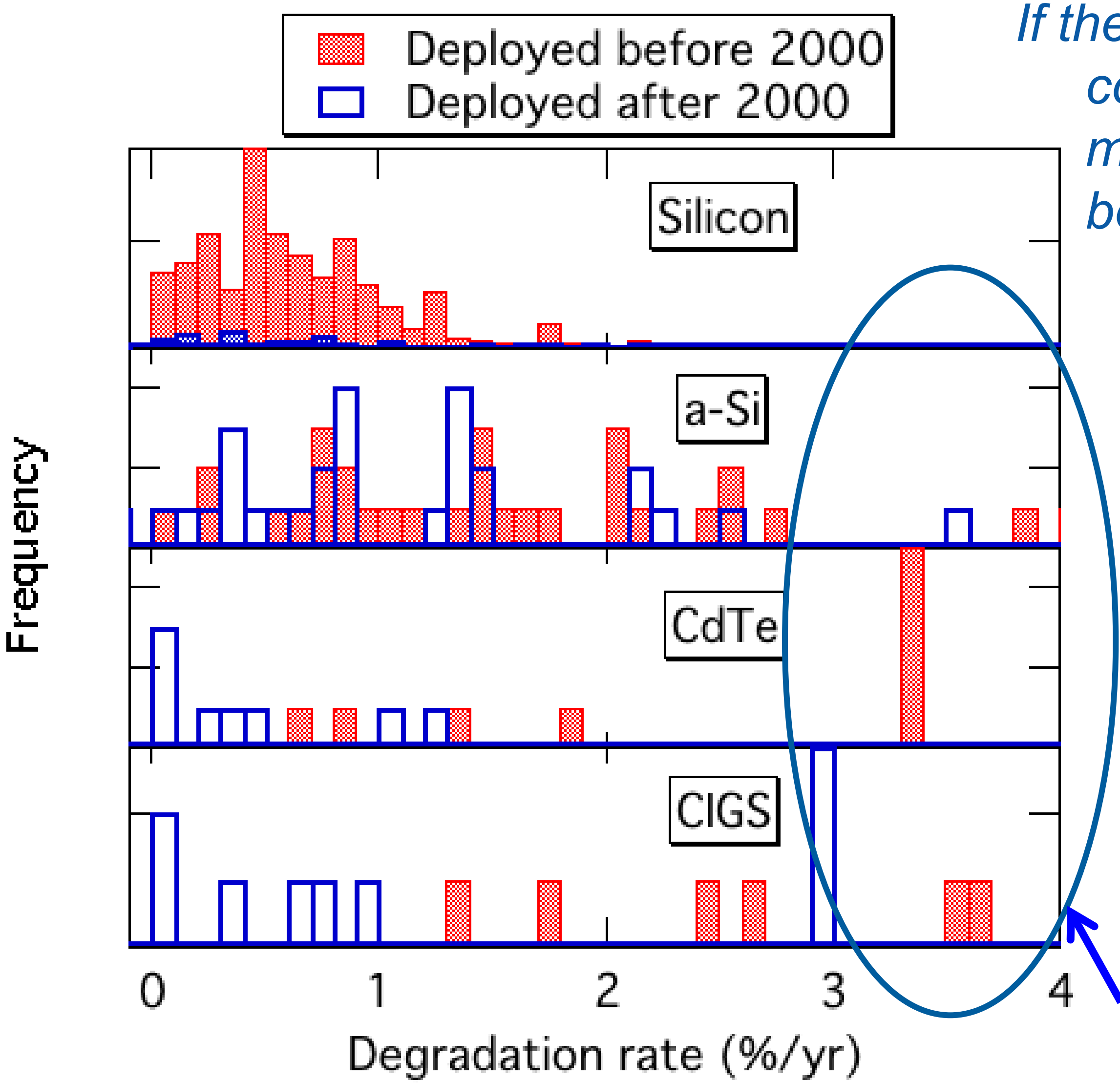



"96% efficient converter" (as long as conditions don't vary too much)

Higher voltage converters tend to have higher efficiencies and wider windows

Low efficiency could limit cell-level implementation

# Challenges – Benefits may be transient




Thanks to Dirk Jordan for this graph, published in SolarPro, Dec 2010

*If there are losses from inconsistent construction or degradation, these must be reduced, reducing the benefit of power electronics*

- ***CdTe & CIGS modules installed before 2000 showed higher degradation rates; after 2000 show improved stability.***
- ***New designs may benefit from power electronics, then the benefit may decrease***

Most benefit, but degradation is unacceptable – community expects < 1%/yr degradation

# Challenges – Cost

*At cell level, any increase in cost needs to be offset by increased performance*

*If used to replace bypass diodes, then cost target is equal or less than diode cost (~0.1 cent/W)*

*If power electronics can replace the inverter, then cost goal is half of current cost.*

*Two strategies:*

- *Look for ways to avoid cost (materials or processing)*
- *Look for ways to increase power so that higher cost can be tolerated*

# Challenges – Reliability

- *At cell level, power electronics that fail will be a nightmare*
  - *Today's inverters are weakest part of the system, but are tolerated because replacement can be simple.*
  - *Elecctronics embedded in the module must match the reliability of the module*
- *At string level, power electronics could be in junction box, making them replaceable, but replacement for a field would still be a nightmare*
- *At module level, reliability is still important, but replacement becomes more feasible, especially if devices are self diagnostic*

# Targets

- Performance:
  - Benefit (reduce losses from shading and other differences)
  - Parasitic losses (may affect total output)
  - Net benefit = Loss from imperfection X Fraction recovered - Parasitic losses
  - Example: If shading losses are 20% with 80% of that recovered and parasitic losses are 6 %, then Net benefit = 0.2 X 0.8 – 0.06 = 10%
- Cost
  - Would like to reduce total cost of power electronics by factor of two
  - When considering energy yield, acceptable cost increase depends on level of shading or other losses (application dependent)
- Reliability
  - 25 yr life is expected for modules
  - If replacement is inexpensive and convenient, life needs to comparable to inverter life

# Conclusions

- Opportunities – innovation opens doors

  Enable new technologies, until they achieve consistent performance

  Compensate for shading (see advantage at system level)

  Improve safety

- Challenges – daunting?

  Implement while decreasing cost

  Implement with excellent reliability

- Easiest place in a module to use smart electronics may be to replace the current bypass diodes – other opportunities at system level

# Resources

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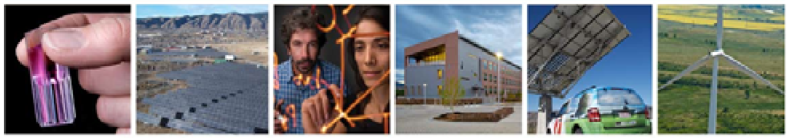

**A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems**

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http://www.nrel.gov/docs/fy11osti/50003.pdf

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