Productive. Reliable. Smart. Safe.

enphase ENERGY

Brandon J. Pierquet

The Impact of Microinverters in Photovoltaic Systems

Overview

Energy and PV Introduction

PV Module Characteristics

Understanding Installations

Inverter Hardware Design

Advanced Grid Controls

Enphase installations

Total Energy Generated By All Enphase Systems

47.4 GWh

>20,000 North American installations in 30 months

Energy and PV

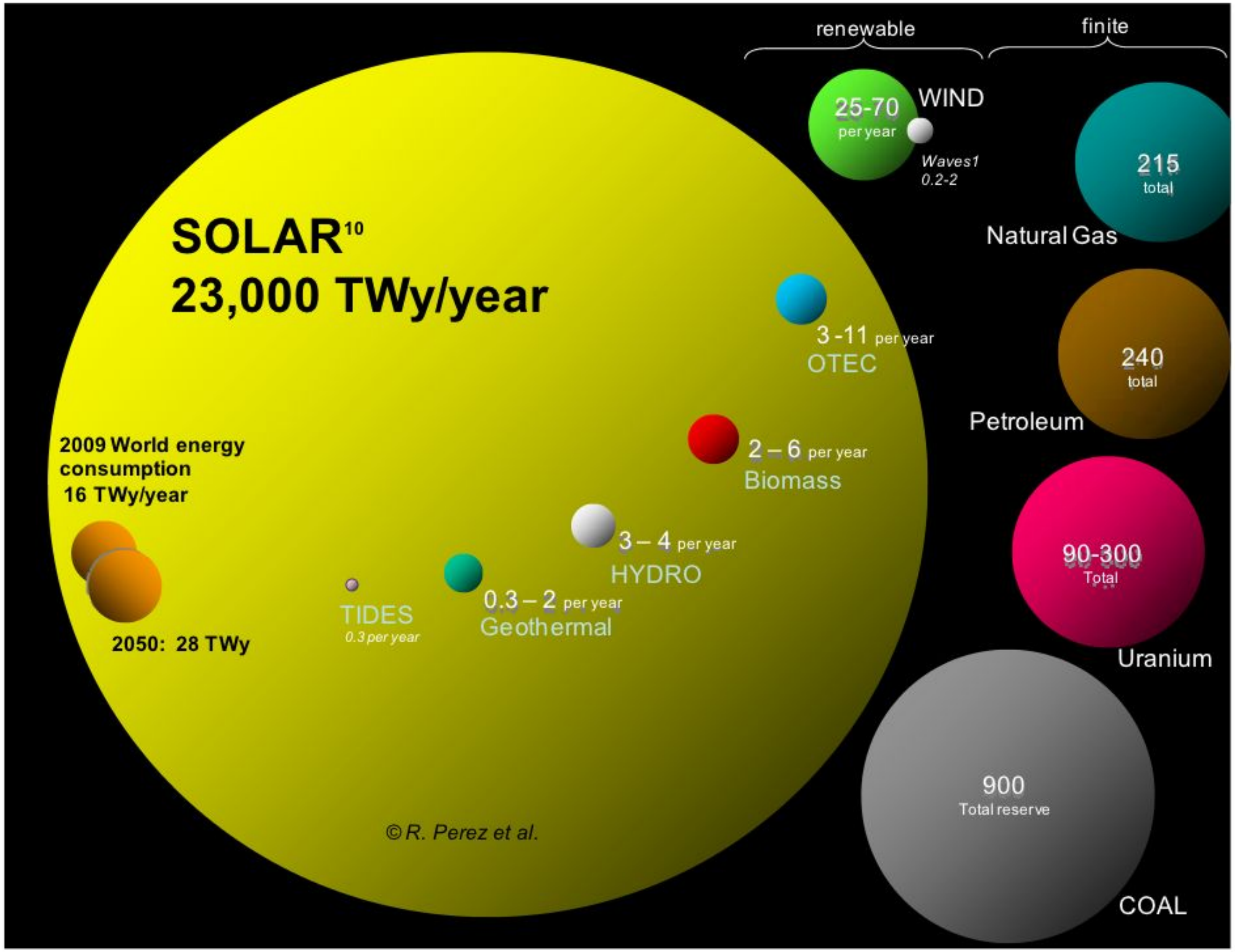
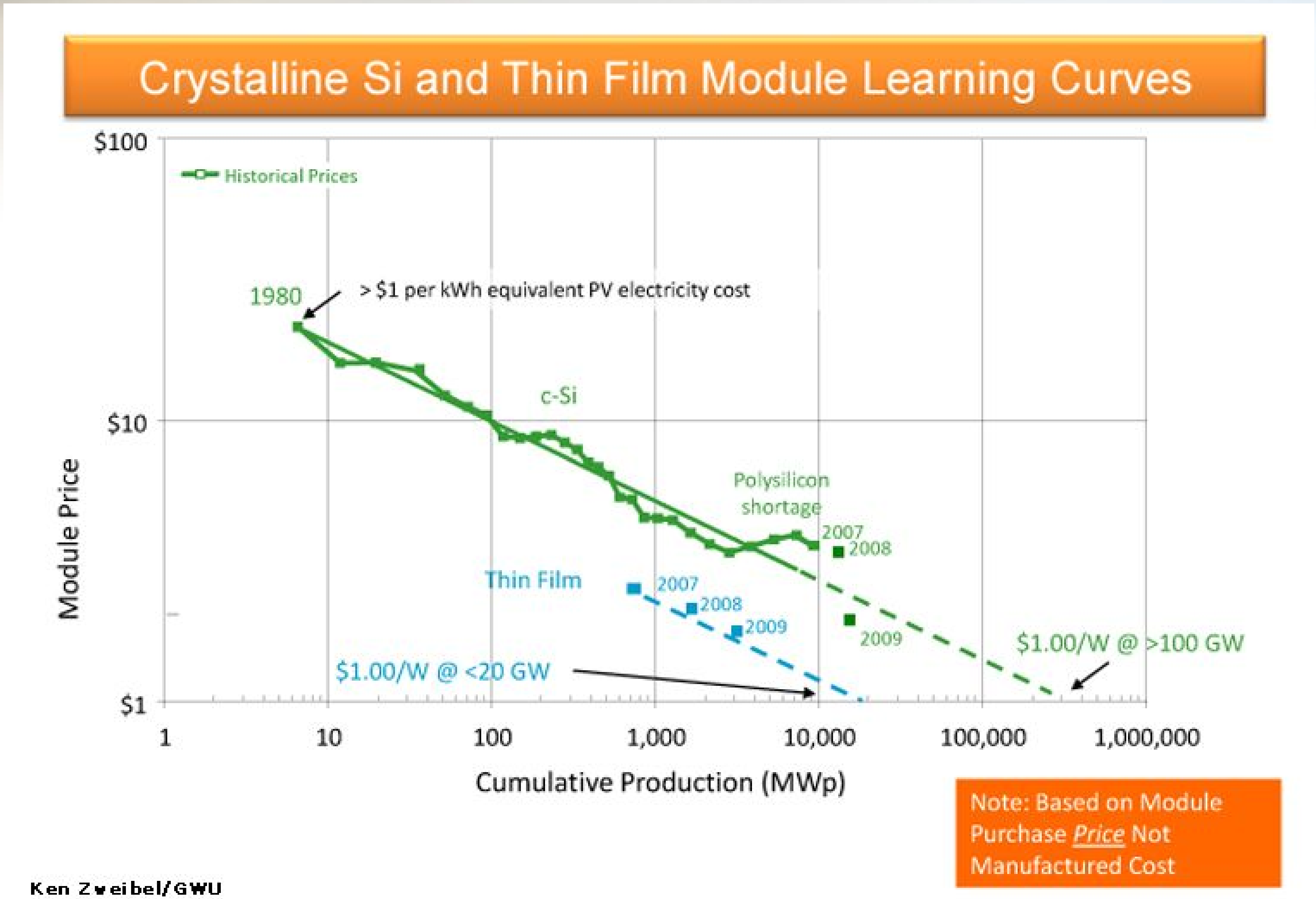


Figure 1: Comparing finite and renewable planetary energy reserves (Terawatt-years). Total recoverable reserves are shown for the finite resources. Yearly potential is shown for the renewables (source: Perez & Perez, 2009a)

Photovoltaic Module Costs



Ken Zweibel/GWU

- http://solar.gwu.edu/

Photovoltaic Source

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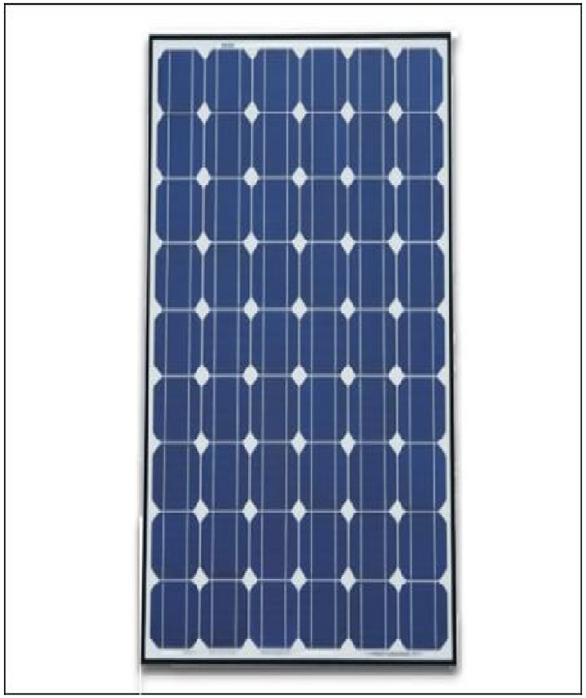
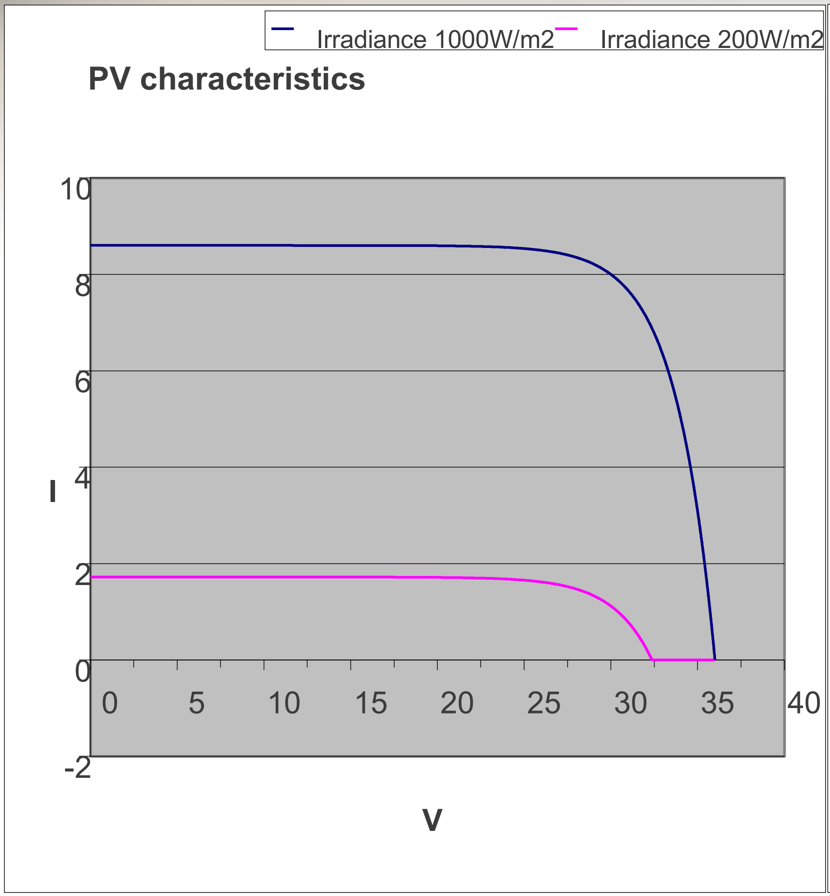
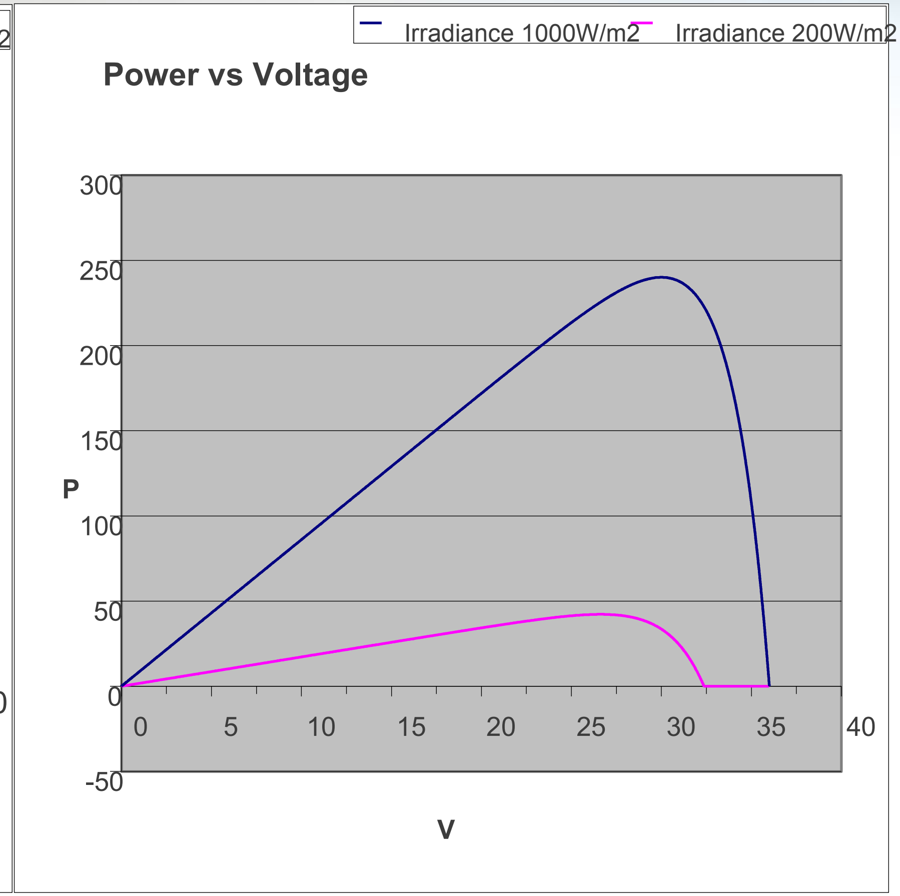
- PV *module* (not panel)
  - Translates light into electricity
  - Series connected *cells*
- Multiple types of cells
  - Crystalline Silicon (poly, mono)
  - Multi-juntion
  - CdTe, CdInGaS, GaAs
- Environmental Dependency
  - Temperature
  - Soiling
  - Age/Optical degradation
- Efficiency from 12-20%



PV module I/V curve





- Changes in irradiance modify the IV characteristic
- Superposition of a string can lead to suboptimal curves, local maxima

Inverters and Installations

"Typical" Considerations

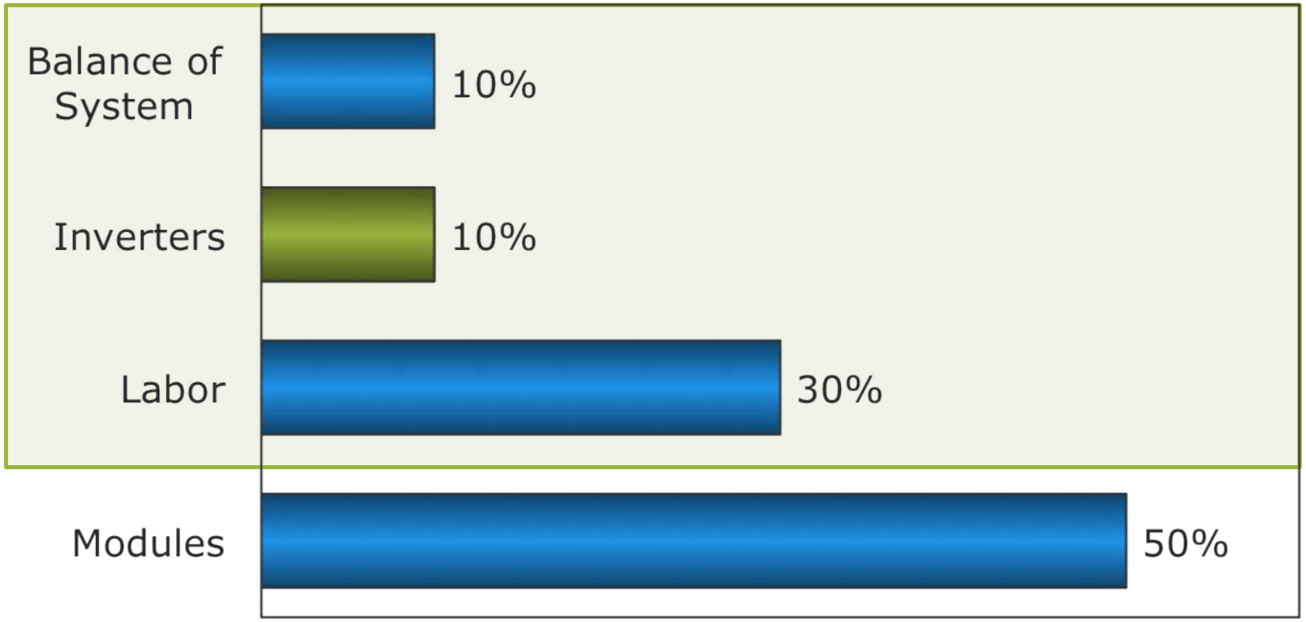
- System Cost

- Single centralized inverter
- Decentralized module-level inverters
- Hybrid approach – dc-dc optimizers

- Residential – Primarily Rooftop
- Commercial – Rooftop and carpark
- Ground-mount Utility

The Other 50% of Solar Costs

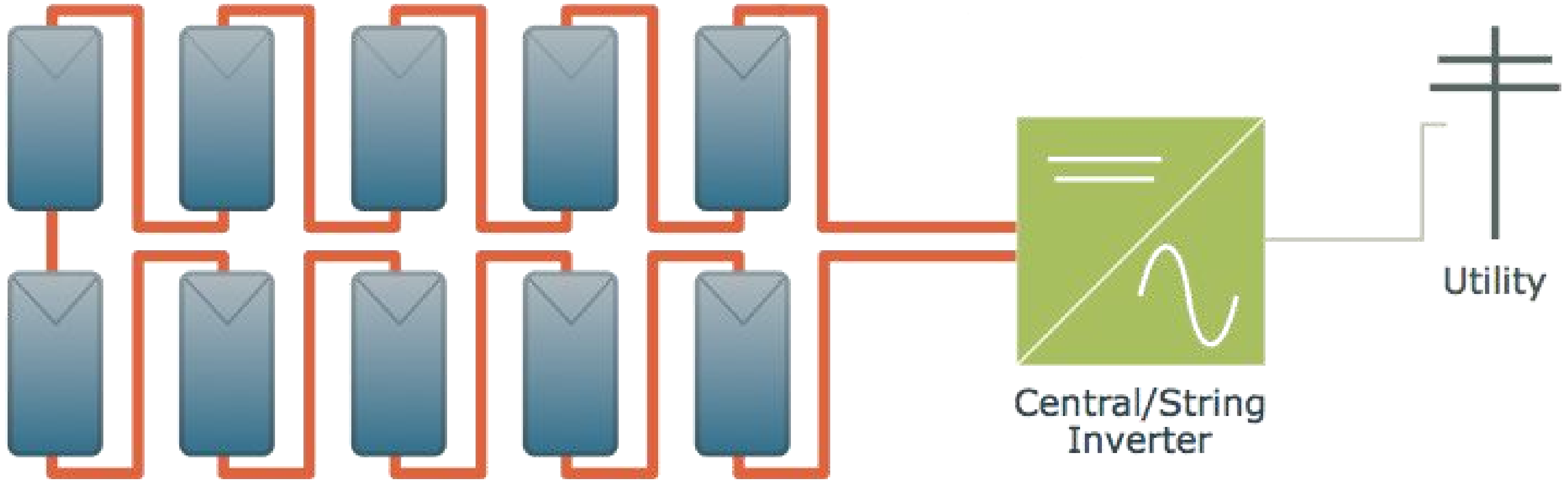
Total Solar Installation Cost (%)



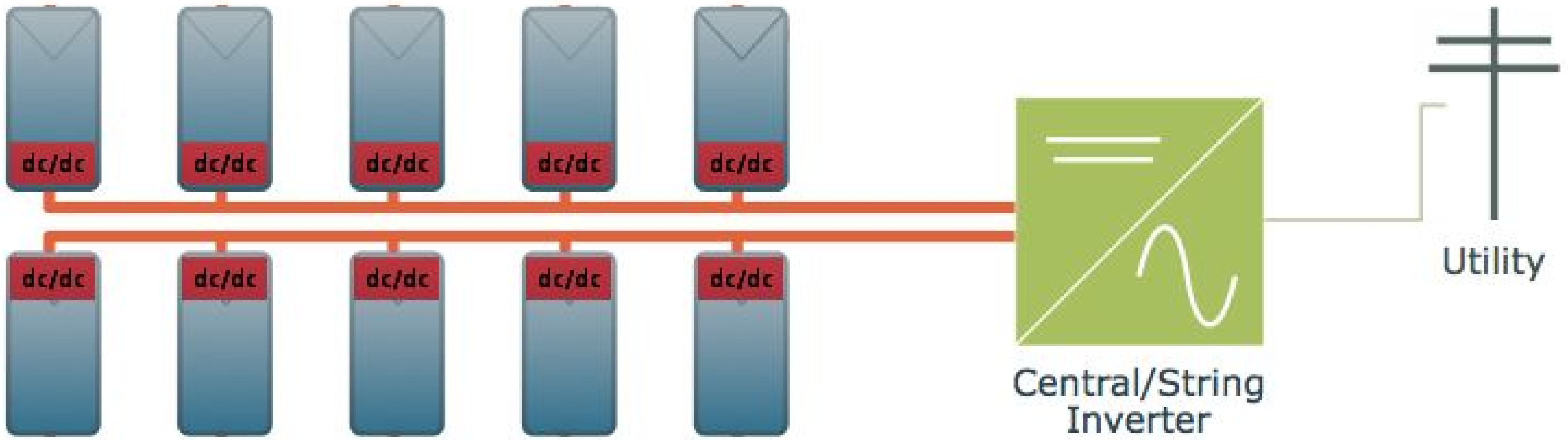
Source: Enphase Energy estimates

Microinverters are only 10% of the total system cost, yet affect BoS and labor costs more than any other component.

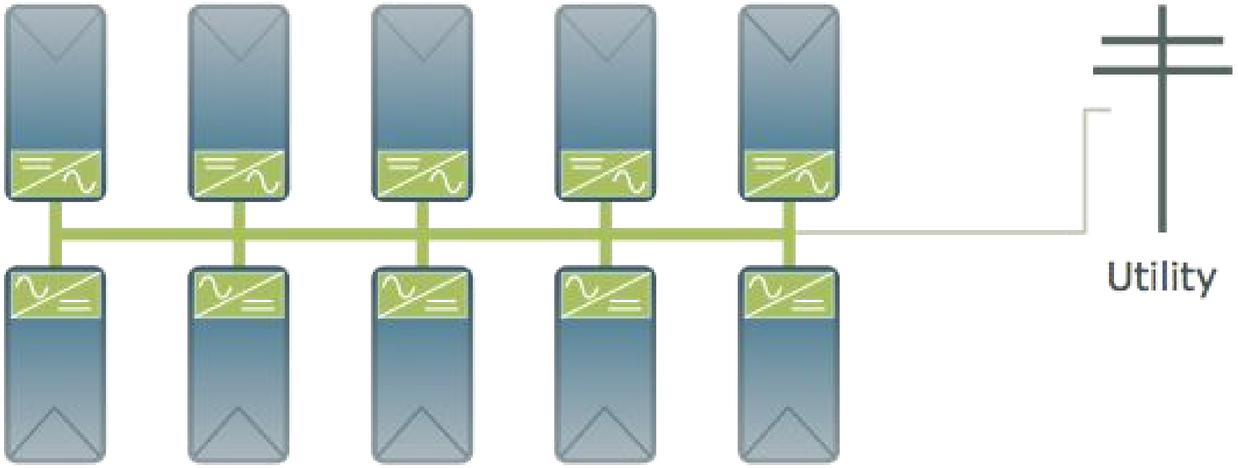
Central String Inverter



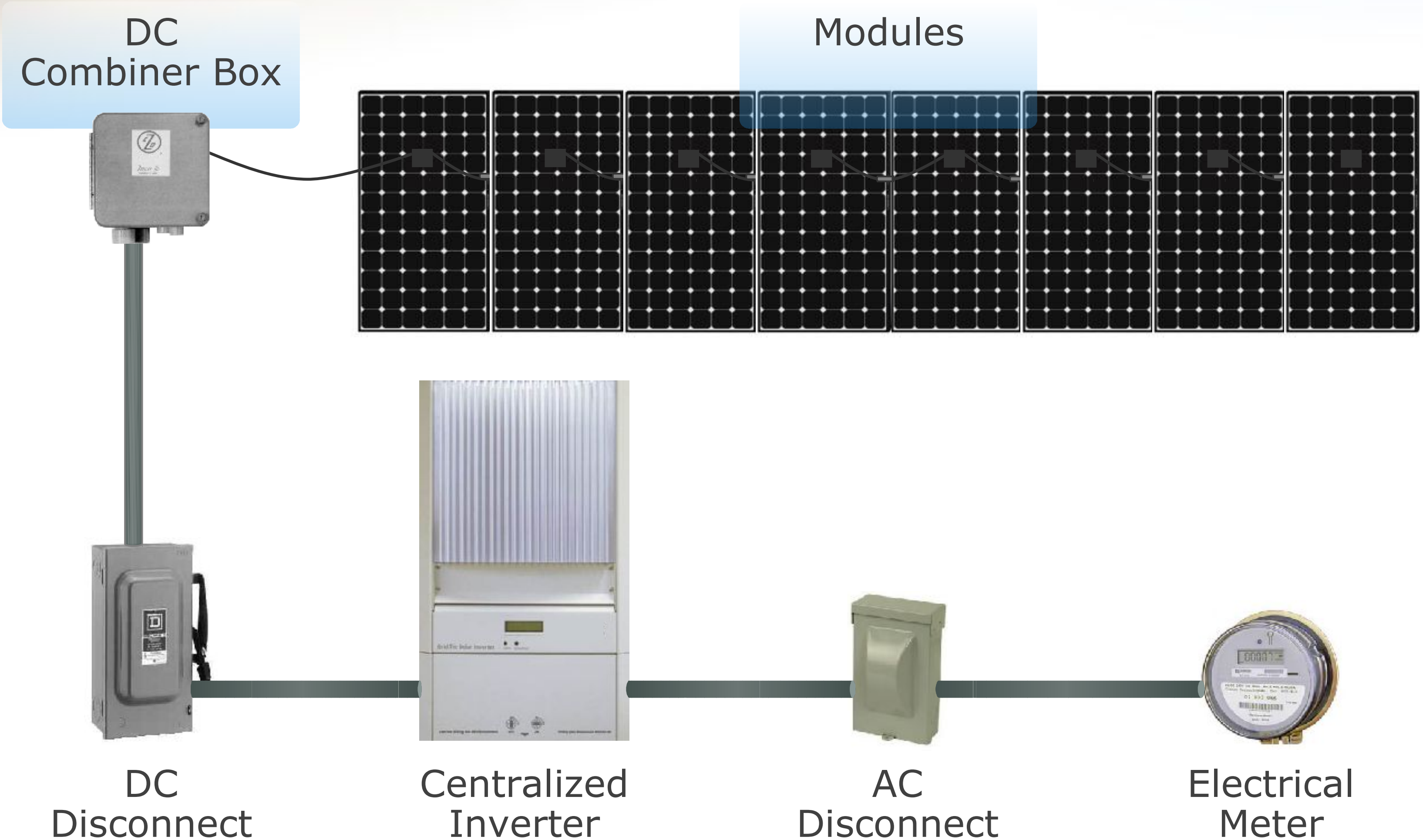
Central dc-dc Optimizer System



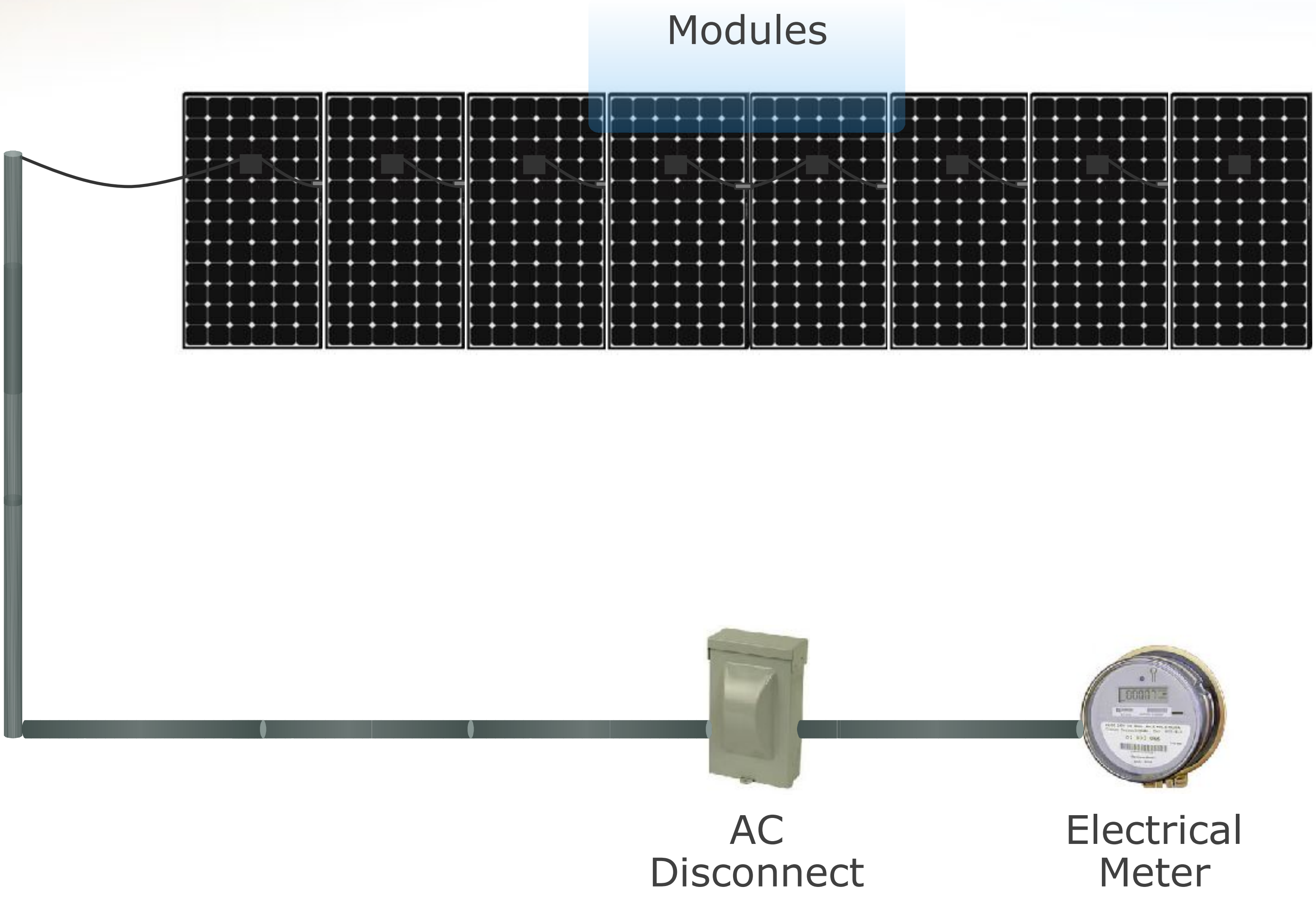
Microinverter System



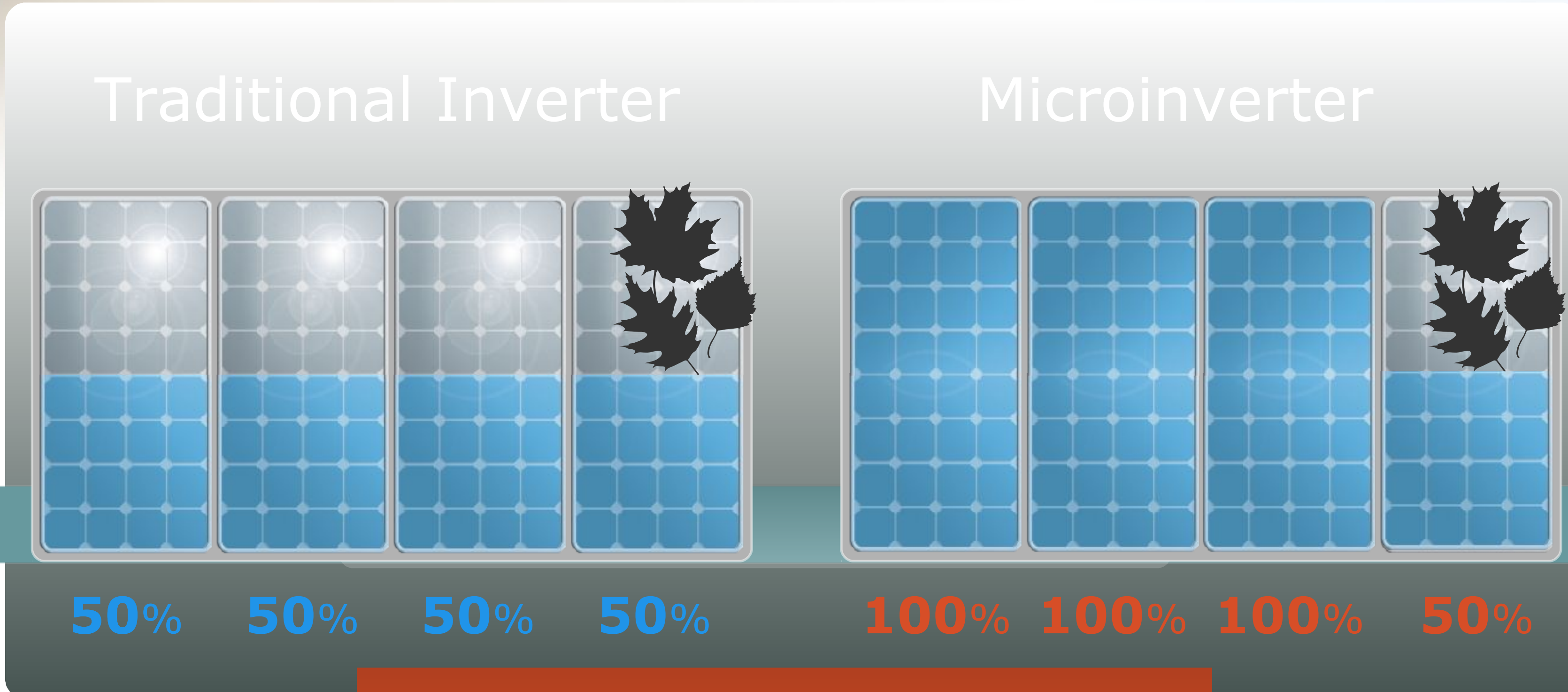
Traditional Centralized/Hybrid Inverter



Traditional Microinverter



Advancing Performance

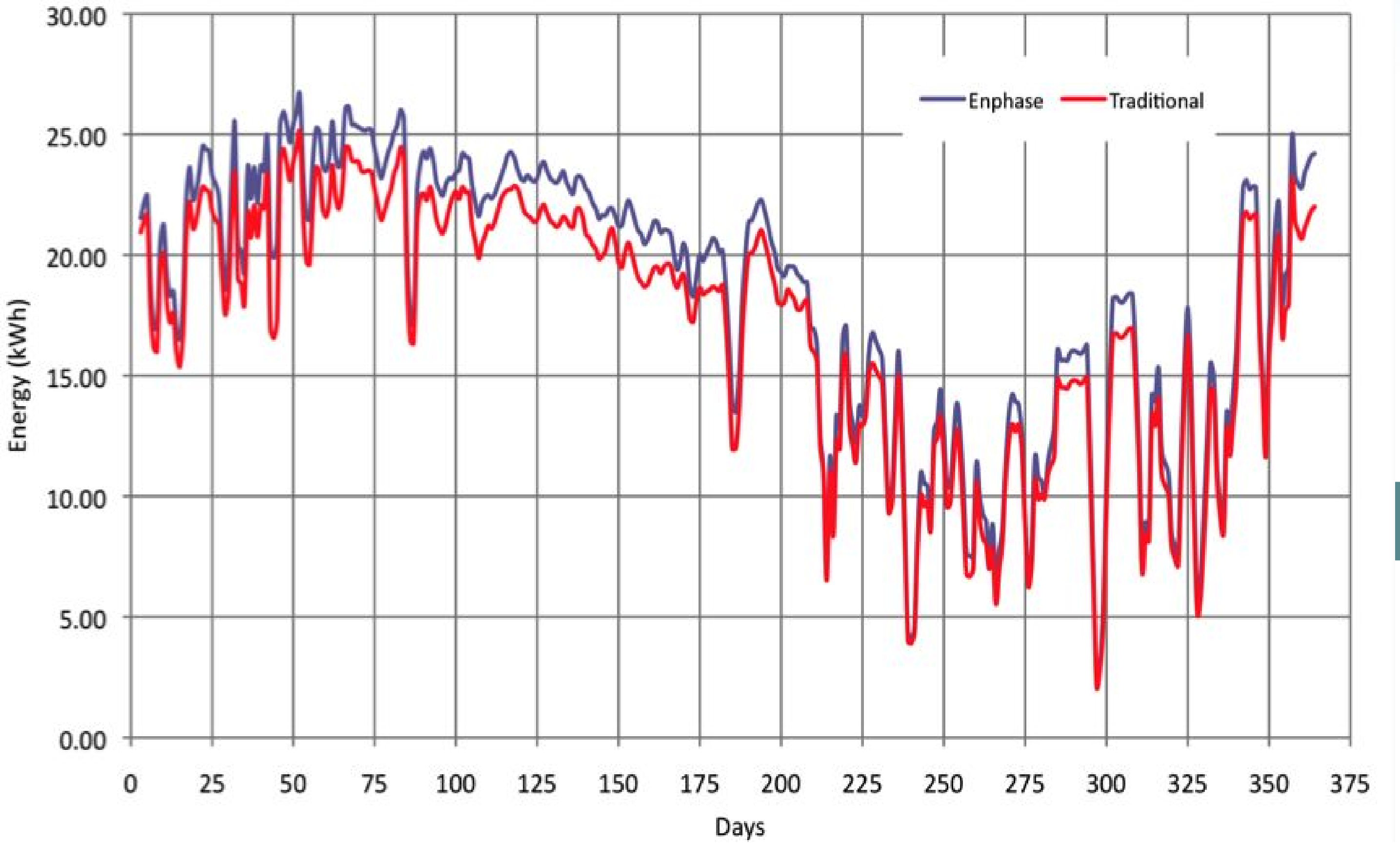


Per-module

Power Conversion

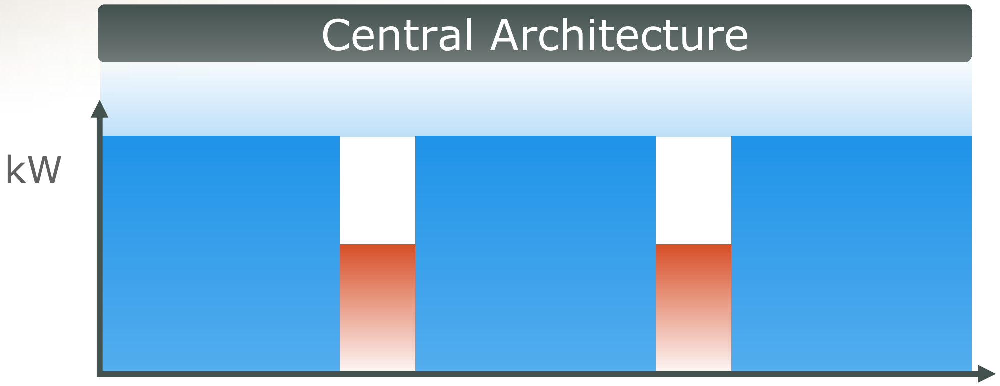
Modules are controlled independently to maximize energy harvest

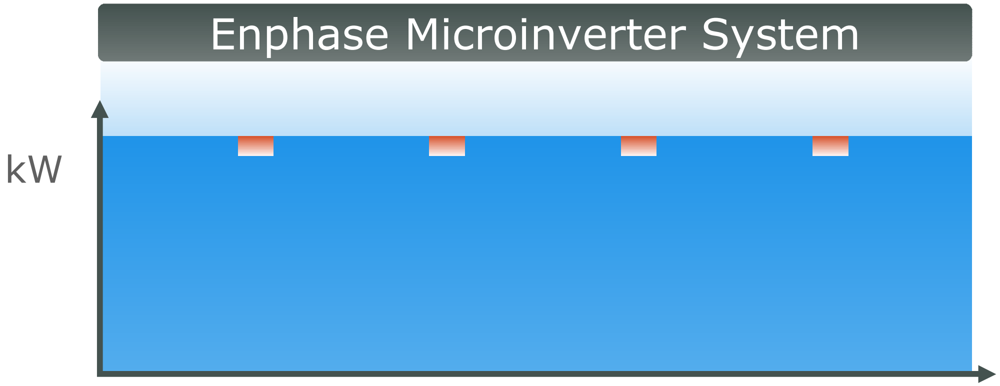
Increased Energy Harvest



Greater energy production means a better return on investment

System Availability Model





Enphase
System
Availability

>99.8%

Westinghouse Solar Reliability Data

Traditional Inverter vs. Microinverter Failure Rates

Westinghouse Solar (Residential)

	Traditional inverters	Microinverters
Installed	3,373	10,630
Replaced	318	22

*Source: Westinghouse Solar, March 2011

Standard Inverter Dangers

DC Arcs are Difficult to Suppress

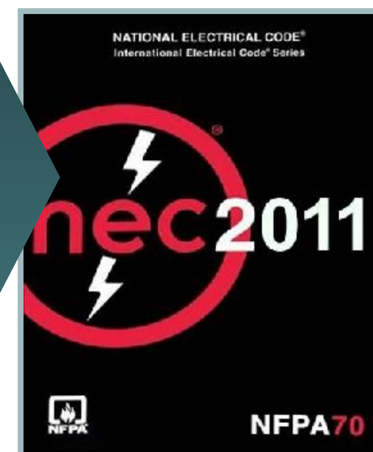
No inherent detection of wire faults

- Disconnects may not interrupt fault path
- System cannot de-energize during daytime

NEC 2011 has changes that mandate detection of – and preventative measures for – series DC arc faults in systems where the DC voltage exceeds 80VDC

690.11 Arc-Fault Circuit Protection (Direct Current)

Photovoltaic systems with dc source circuits, dc output circuits, or both, on or penetrating a building operating at a PV system maximum system voltage of 80 volts or greater, shall be protected by a listed (dc) arc-fault circuit interrupter, PV type, or other system components listed to provide equivalent protection.



Inverter Design Challenges

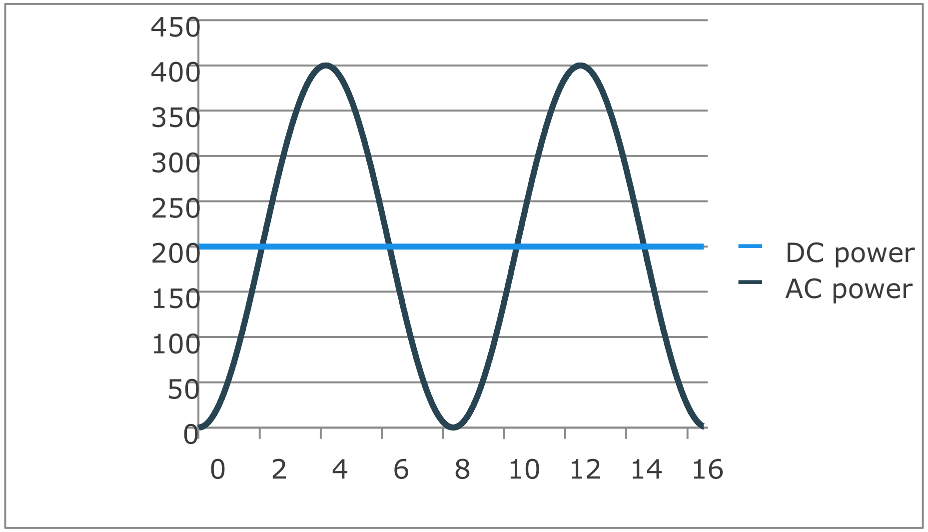
Inverter Design Challenges

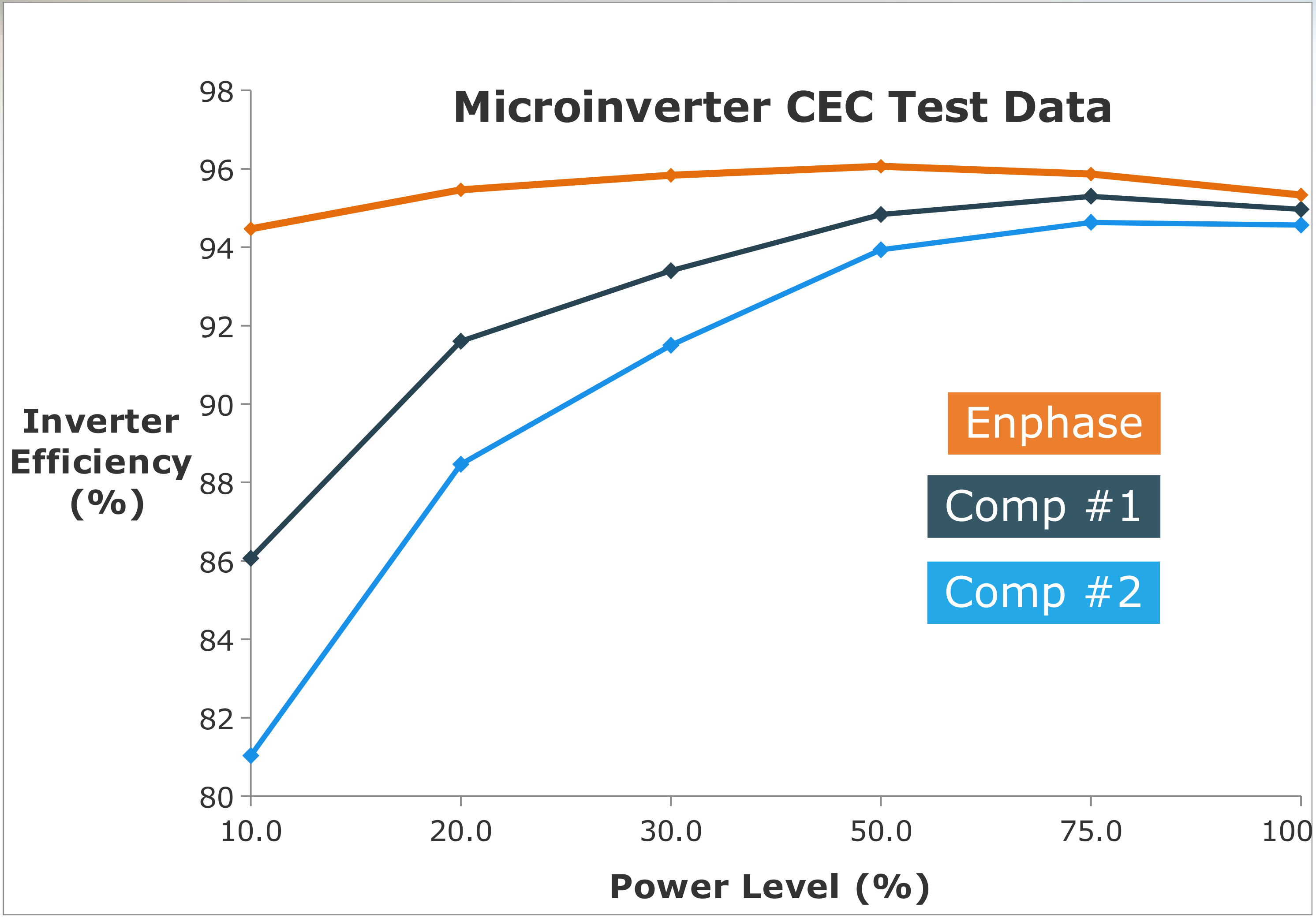
- Single-phase Energy Storage
- Efficiency
- Reliability and Robustness
- Wide operating ranges

Single-Phase Power Conversion Basics

Inherent input/output power-flow mismatch

Bulk energy storage required at 120Hz

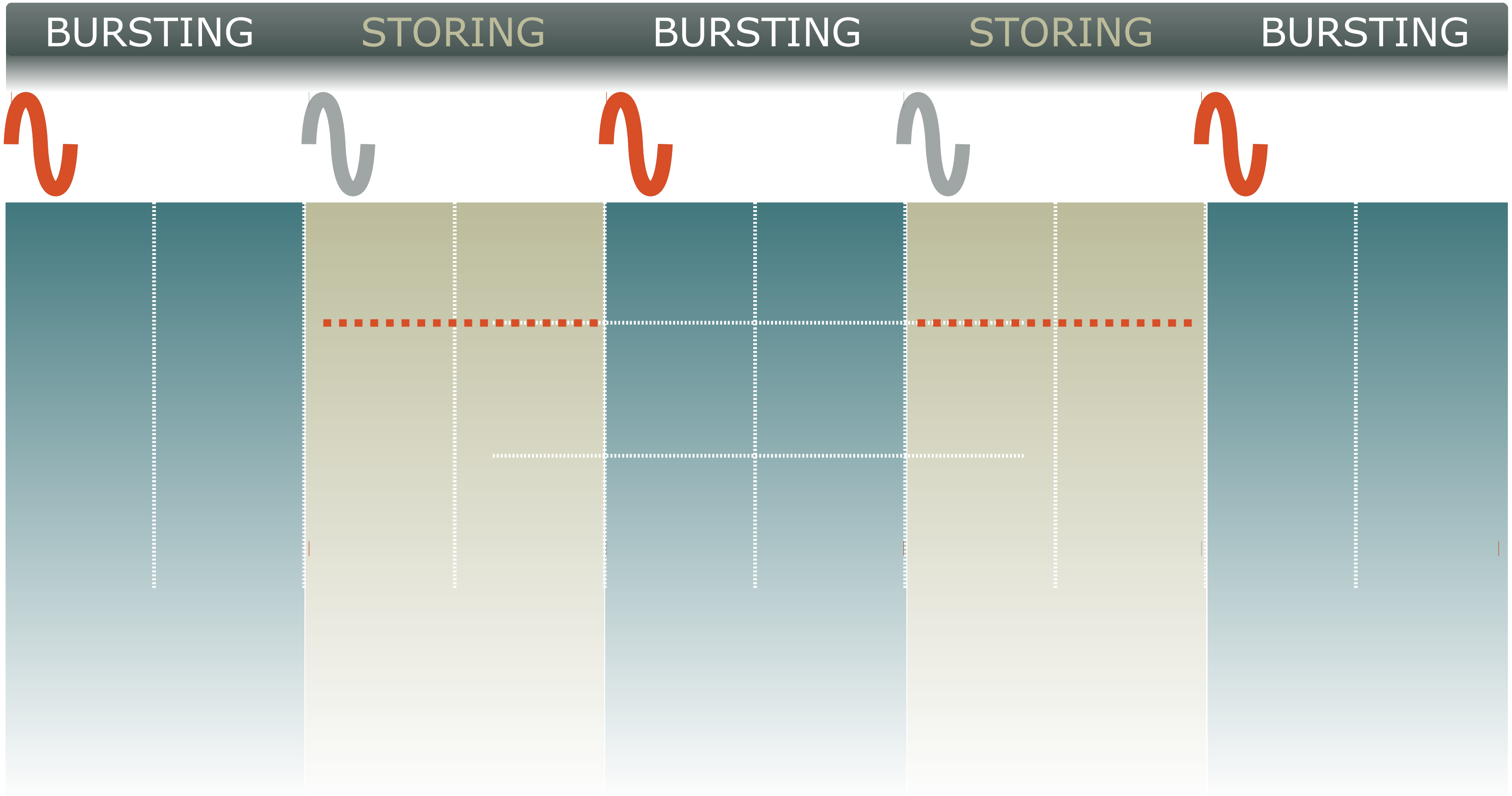




Testing using the CEC or EN 50530 definitions

Light Load Efficiency

Burst Mode: High efficiency at low irradiance



Grid Standards / Compliance

Typical US Grid, 60Hz:

- Residential: 120V/240V
- Commercial: 120V/208V, 3 phase
- Industrial LV: 277/480V, 3 phase

Typical Euro Grid, 50Hz:

- Residential: 230V, single phase
- Commercial/Industrial LV: 230V/400V 3 phase

Safety:

- NEC
- UL 1741

Interconnection:

- IEEE 1547
- FERC 661

EMI:

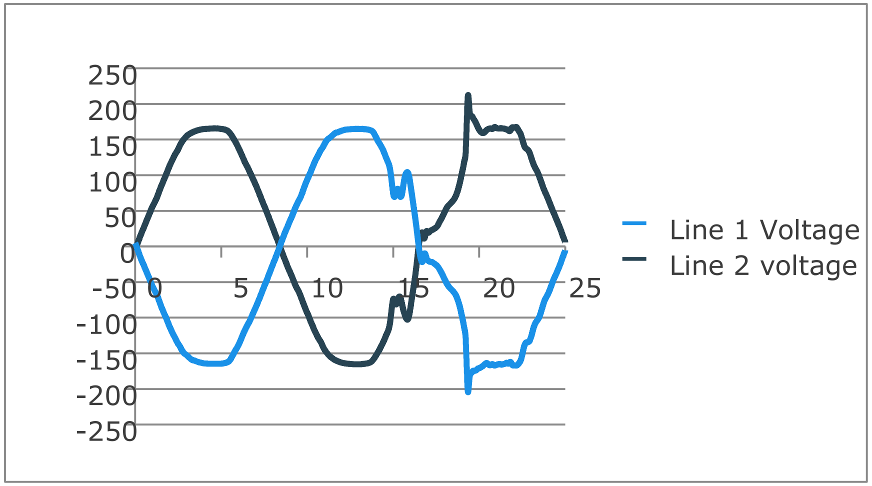
- CFR 47 Part 15

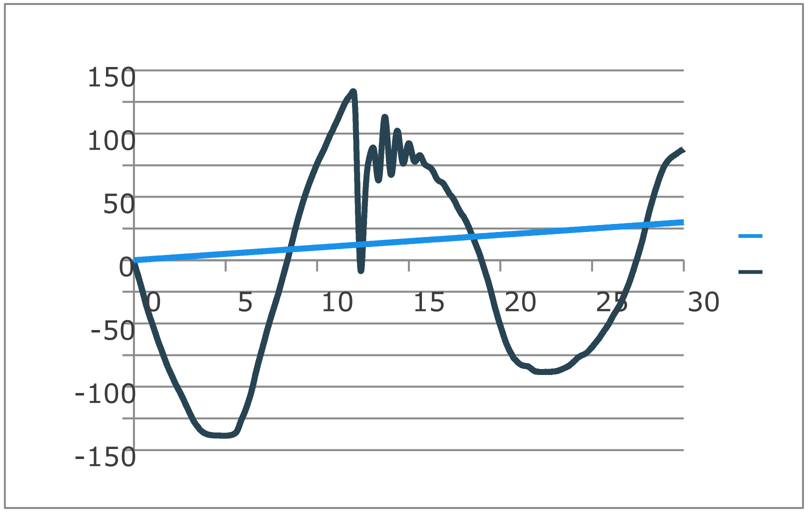
Surge testing:

- ANSI C62.41

AC Grid Realities

- It's nasty:
  - Voltage surges of >1000 V from indirect lightning strikes
  - Tap changes, misplaced zero crossings, dc offset
  - Distortion, double zero crossings
- Surviving it everyday and in all cases is very, very difficult





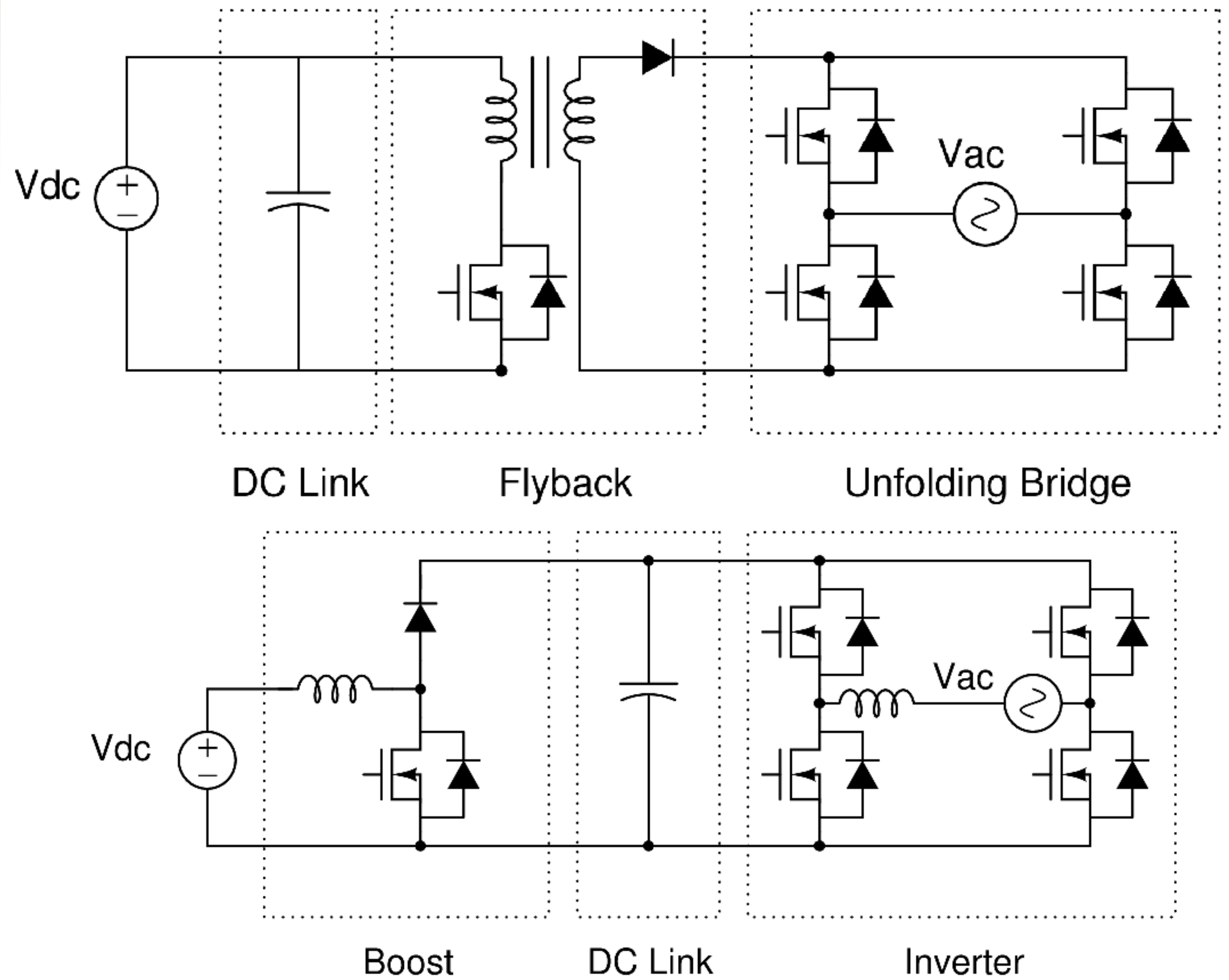
Design Challenges

- From a dc-dc perspective:
  - Wide input voltage range: 20-40 Vdc
  - Wide output voltage range: 0-340Vdc (+/-)
  - Wide power range: 0-200 W
  - Large energy storage requirement
  - Additional monitoring functions:

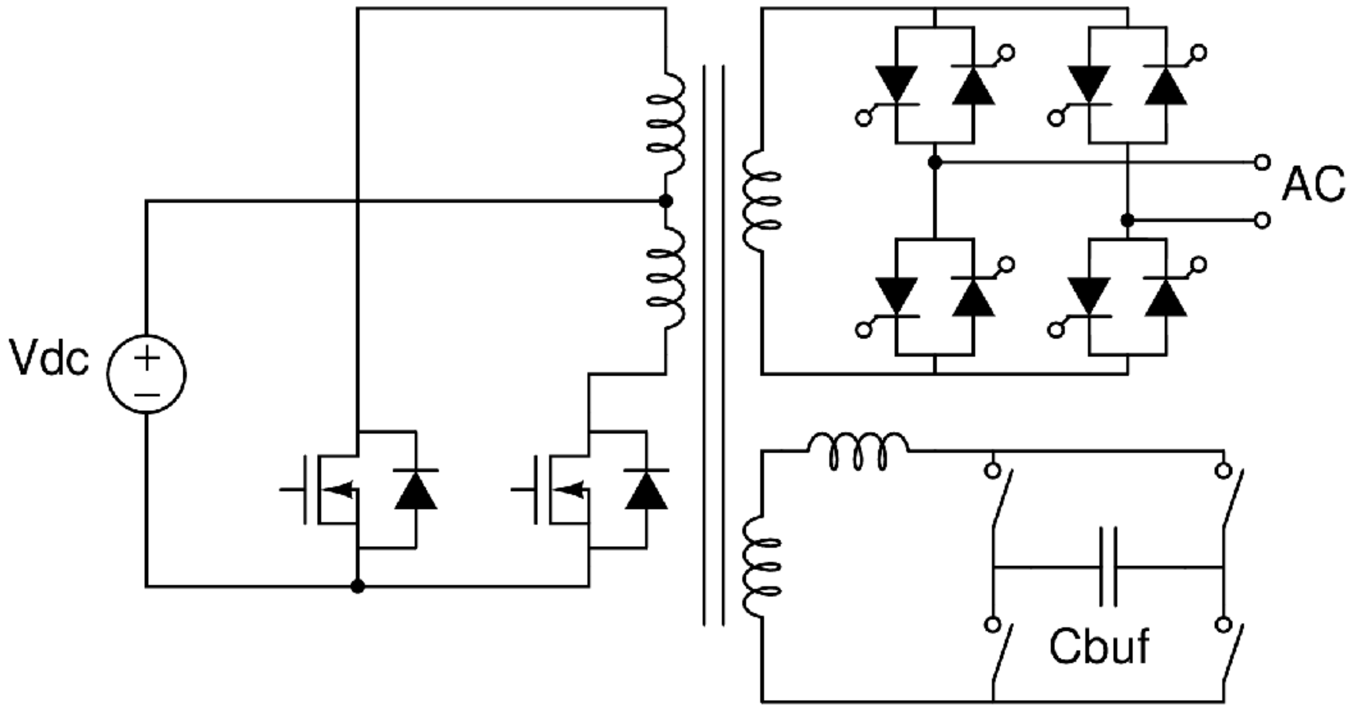
- DC Side Functions:
  - Maximum peak power tracking (speed and accuracy are important)
  - DC voltage and current reporting
  - Arc-fault detection

- AC Side Functions
  - Grid synchronization
  - Voltage and Frequency (out of range thresholds)
  - Anti Islanding (AI) checks

Some Conversion Topologies

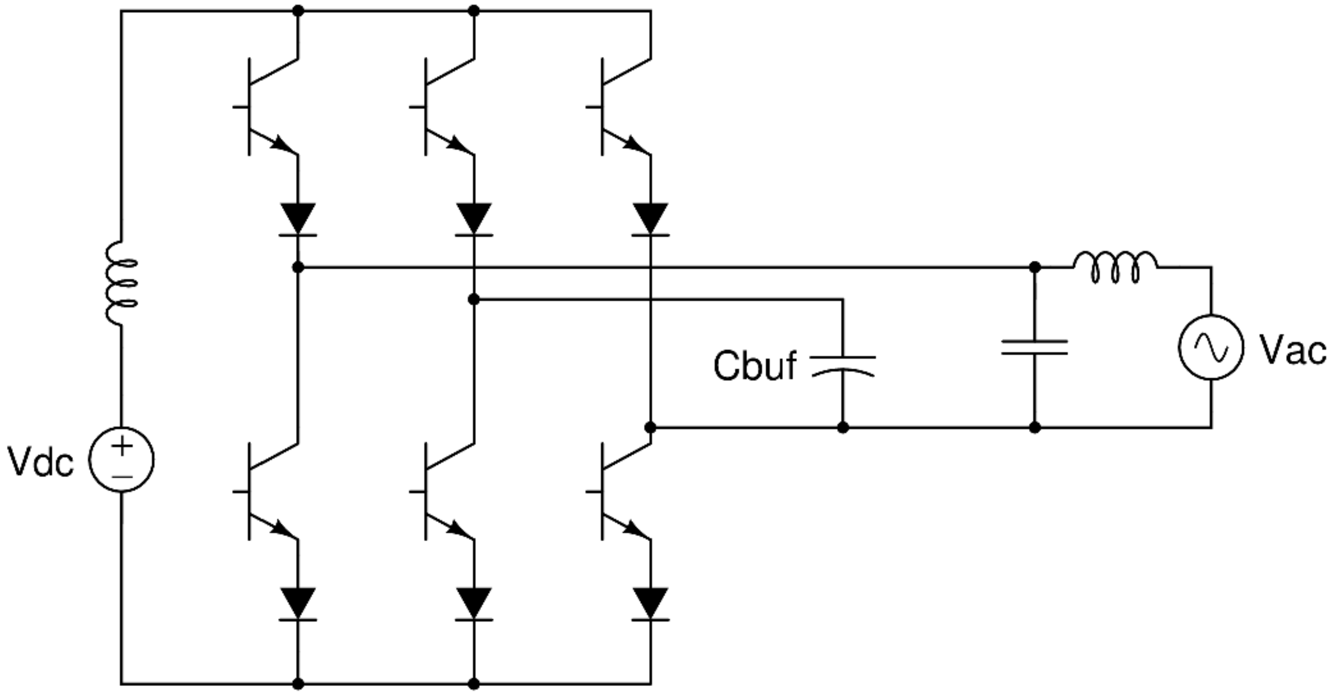


Some Conversion Topologies



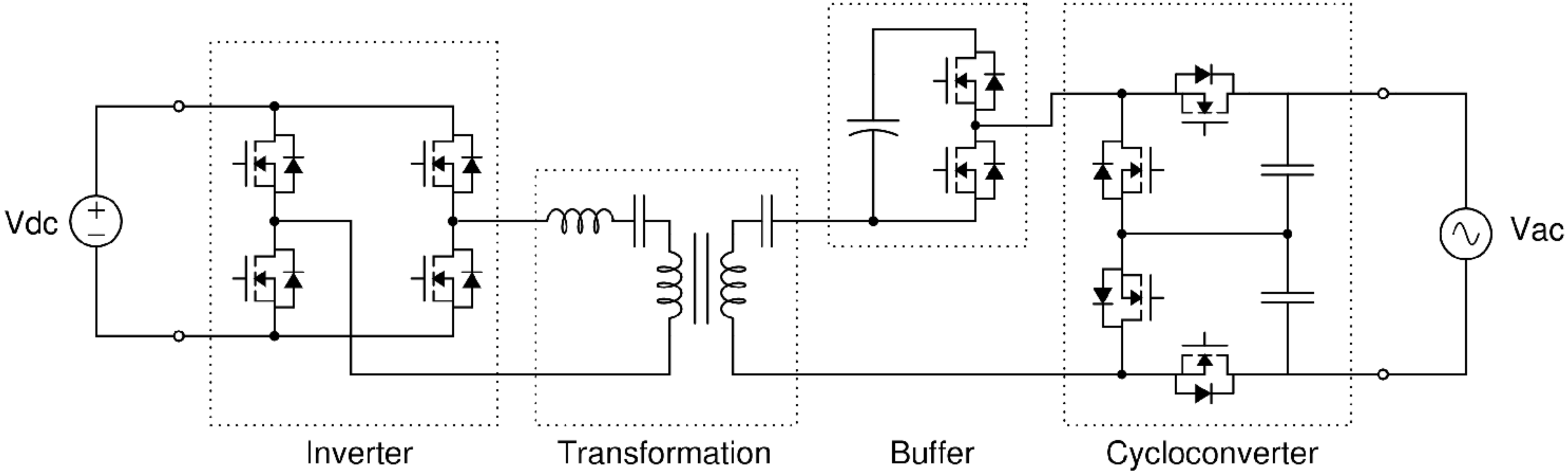
P. Krein and R. Balog

Some Conversion Topologies



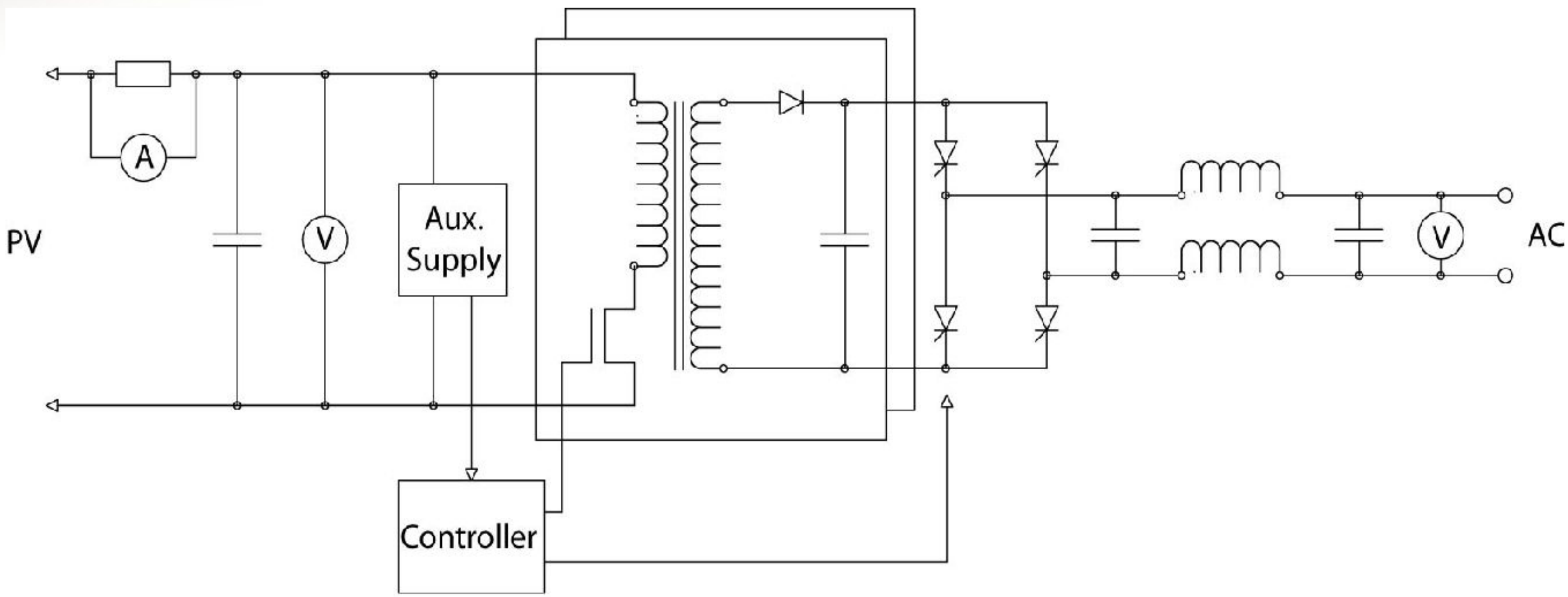
C. Bush and B. Wang

Some Conversion Topologies



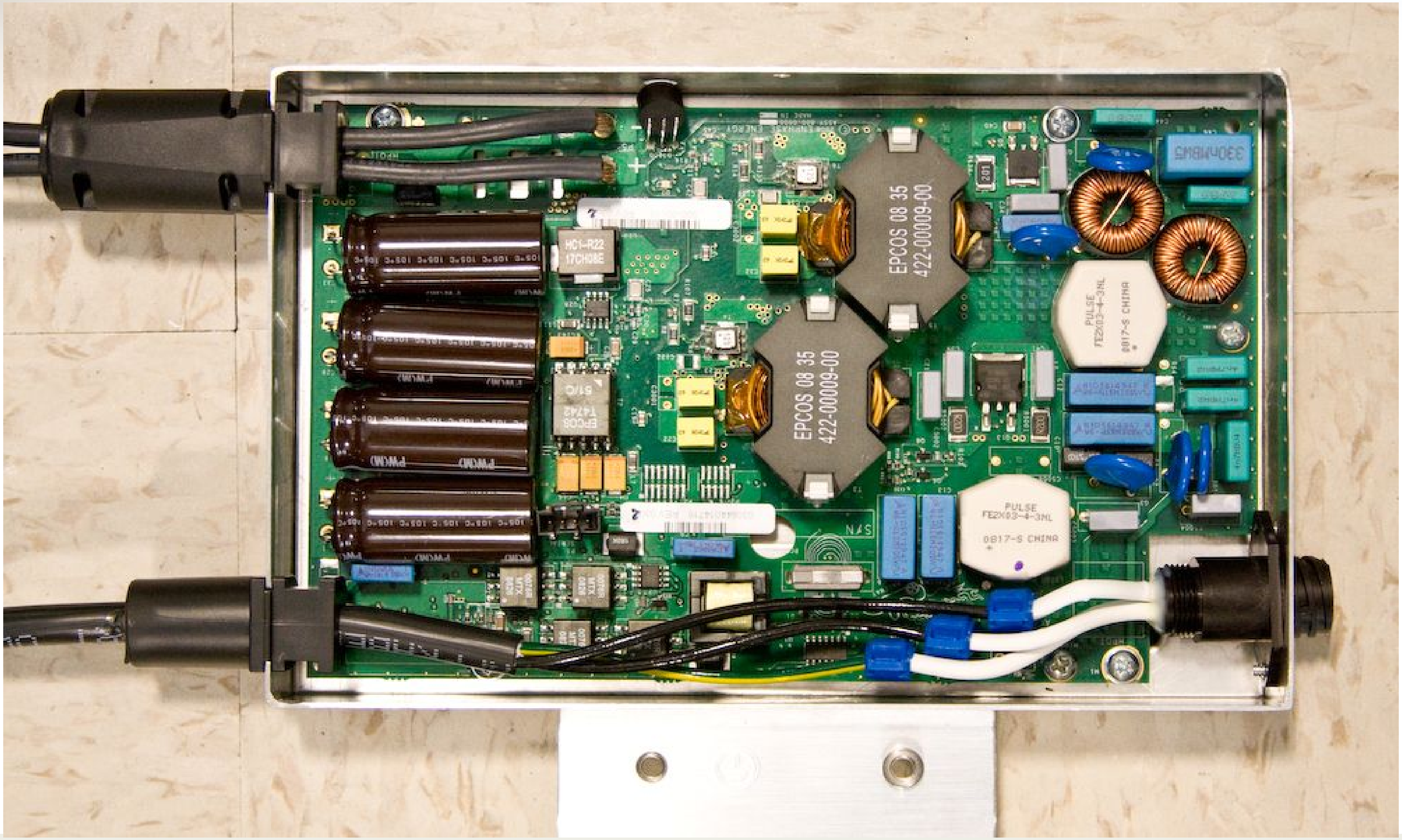
B. Pierquet, D. Perreault

One Power Conversion Topology



PCU Block Diagram

Inside the box…



Review of Advantages

- Productive
  - Harvests more energy
- Reliable
  - No single point of failure, high reliability electronics
- Smart
  - Allows for full system monitoring and analysis
  - No string calculation, regular AC wiring
  - Lowers installation time
- Safe
  - No high voltage DC: DC faults cannot lead to fires
  - No lethal power source present when AC is shutdown

Challenges

Very difficult product to get right

- Efficiency
- Cost
- Reliability
- Lifetime
- Robustness
- Ease of use
- Compliance to standards
- Communication
- Packaging
- etc.

Advanced Grid Controls

(brief)

Advanced Grid Controls

- New Islanding behavior
- VAR injection
- Power slew based on frequency / voltage
- Spinning reserve emulation / Transient compensation
- All bring stability and jurisdiction issues.
- Under discussion and very controlled trials

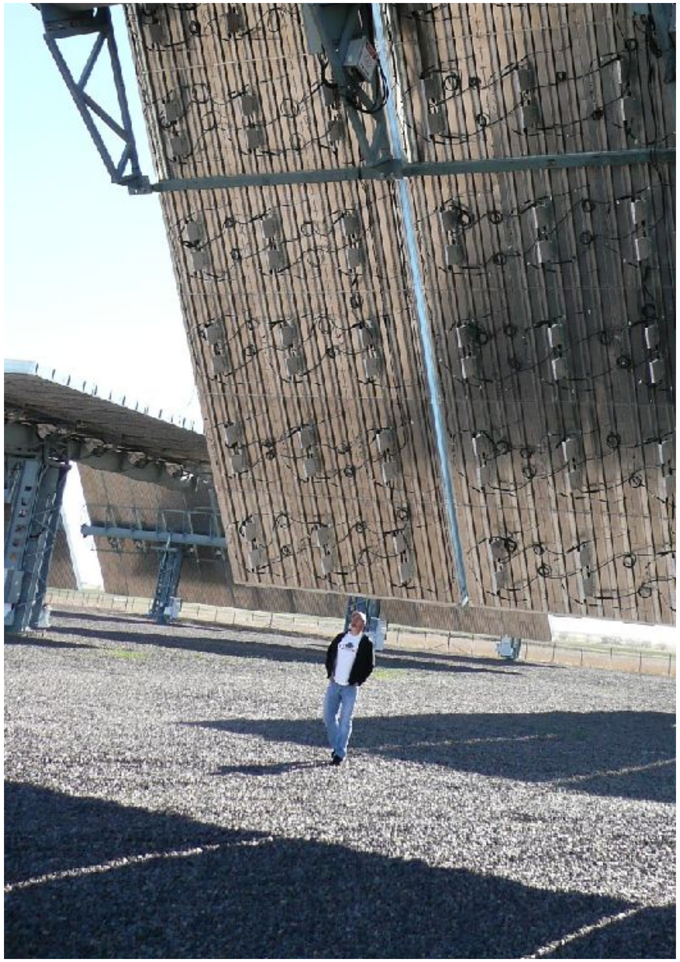
	x	x'	x"
Voltage			
Current			
Frequency			
Phase			

Conclusion

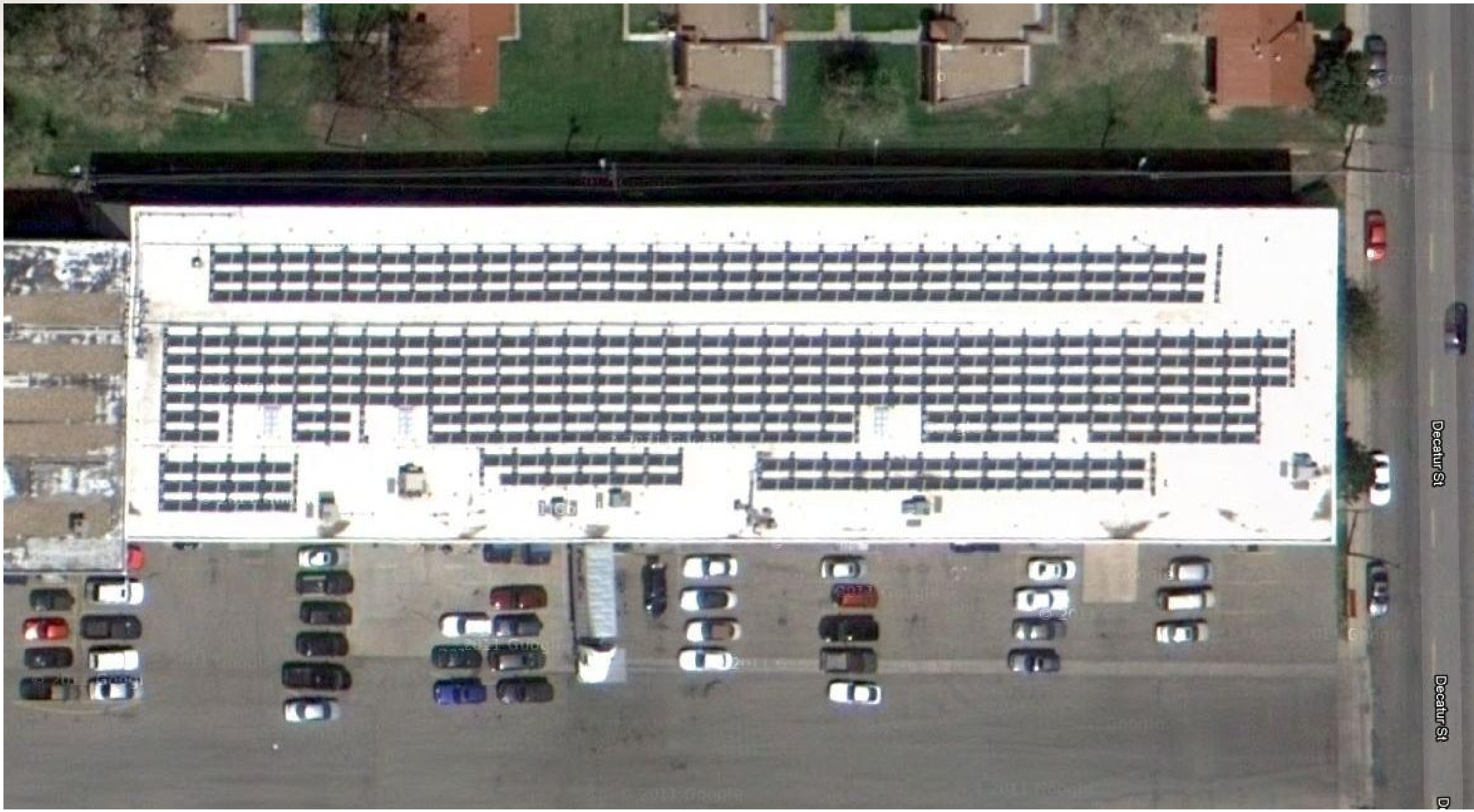
Some Example Installation Photos

Roof-mount in Hawaii

Tracker Mount (Concentrated PV), Colorado

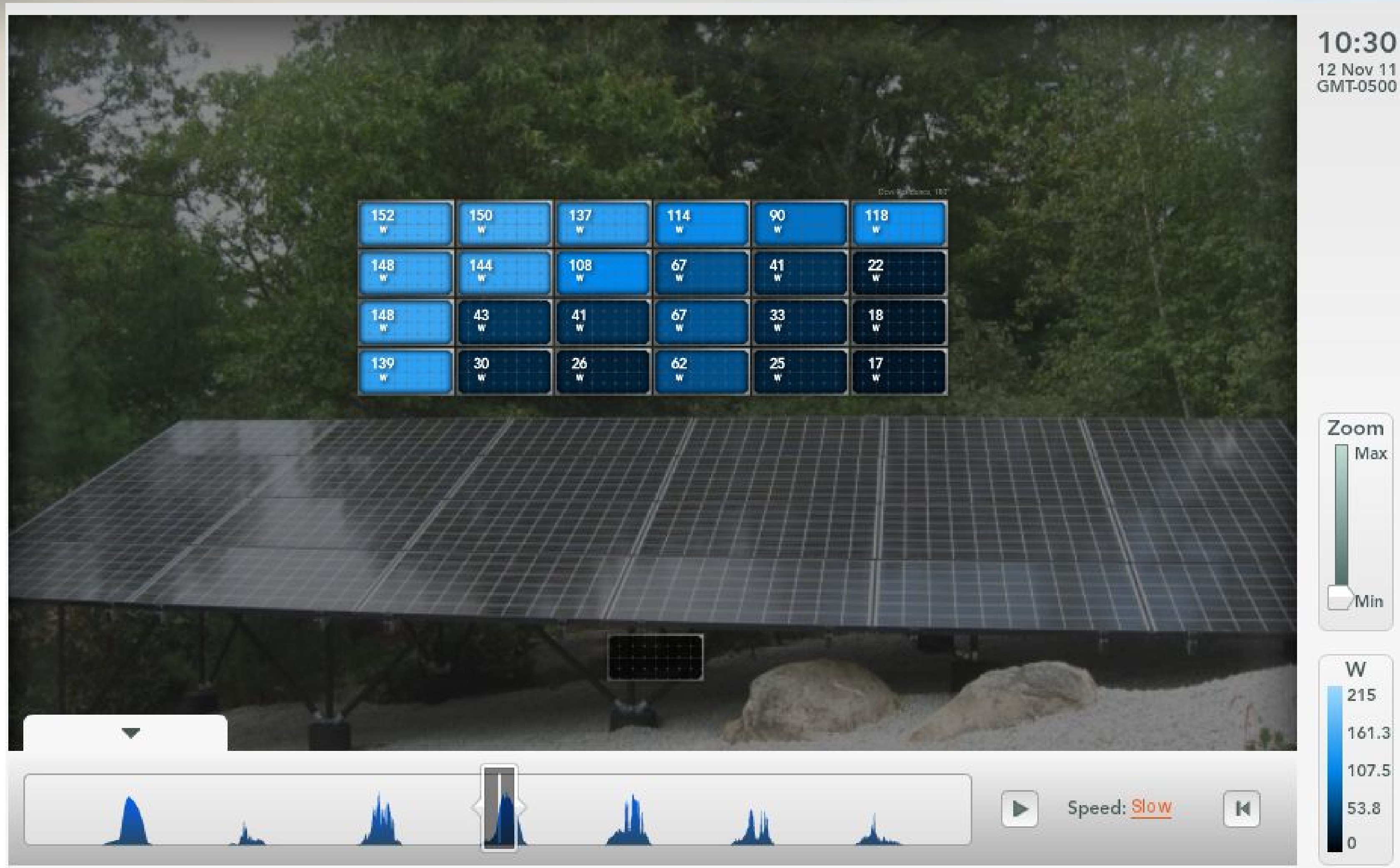


Commercial Rooftop, Colorado



Residential "Ground mount"

Energy Production



Past Month: 151kWh, Lifetime: 1.78MWh (Since 7/15/11), Peak: 34kWh/day