Renewable and Environmentally Friendly Energy Sources for Remote Locations

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QESST

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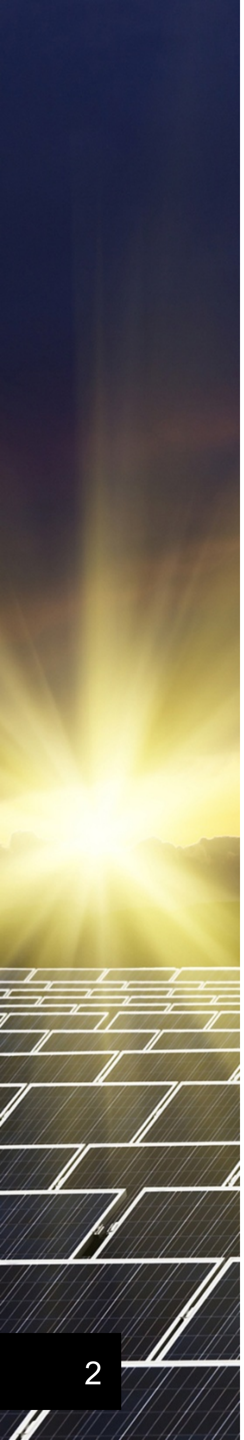


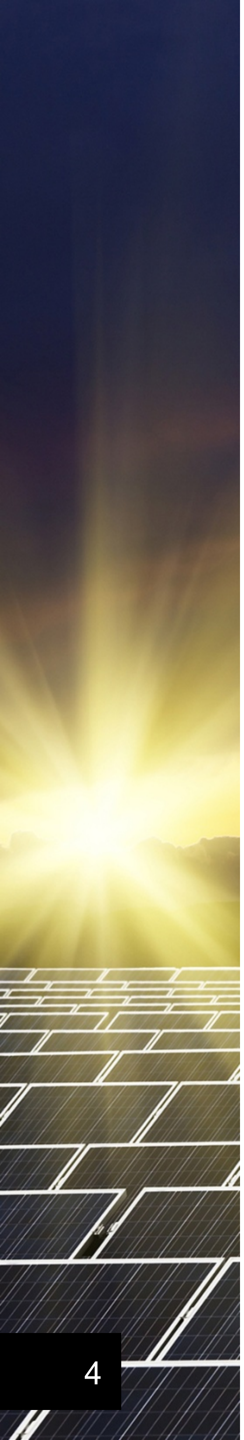
Outline

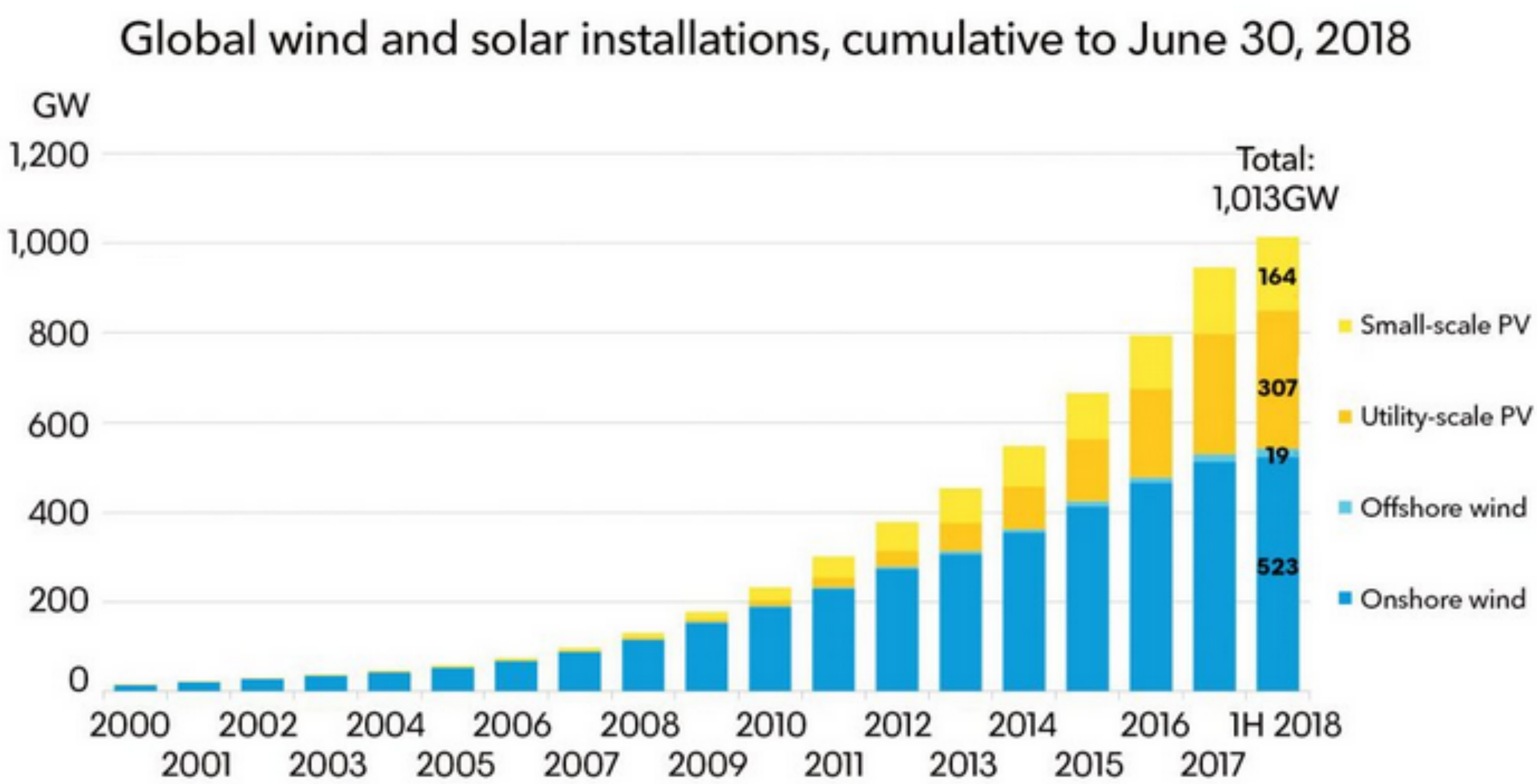
- Renewable energy
- Introduction to photovoltaics
- Photovoltaic technology
- Solar modules and solar systems
- Remote applications

Renewable Energy

<u>Renewable Sources:</u> Hydro, Wind, Solar, Bio, Geothermal

Renewable Energy: Wind & Solar

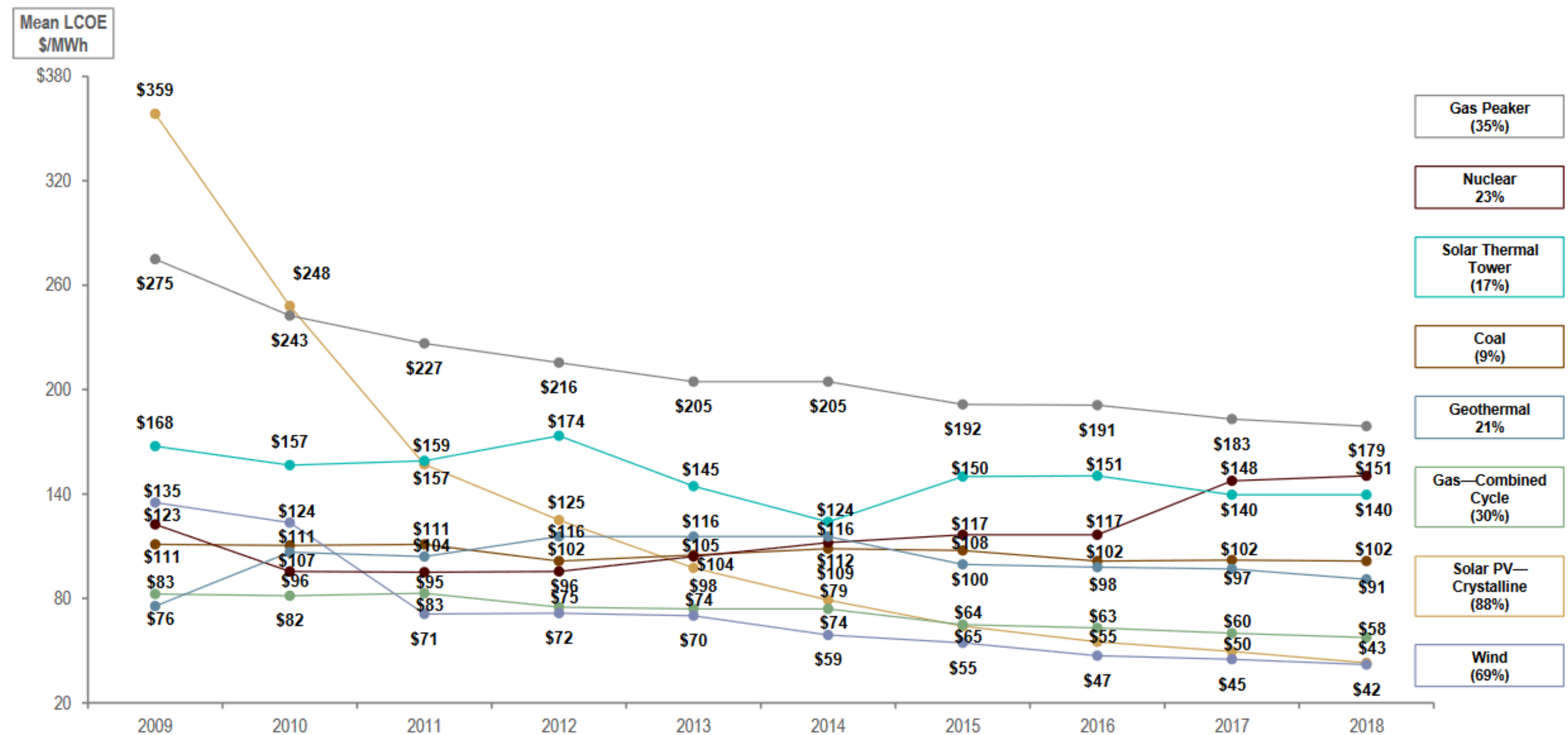




Source: Bloomberg NEF. Note: 1H 2018 figures for onshore wind are based on a conservative estimate; the true figure will be higher. BNEF tyipcally does not publish mid-year installation numbers.

Energy Costs: Wind & Solar

Selected Historical Mean Unsubsidized LCOE Values[1]



LCOE Version	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0

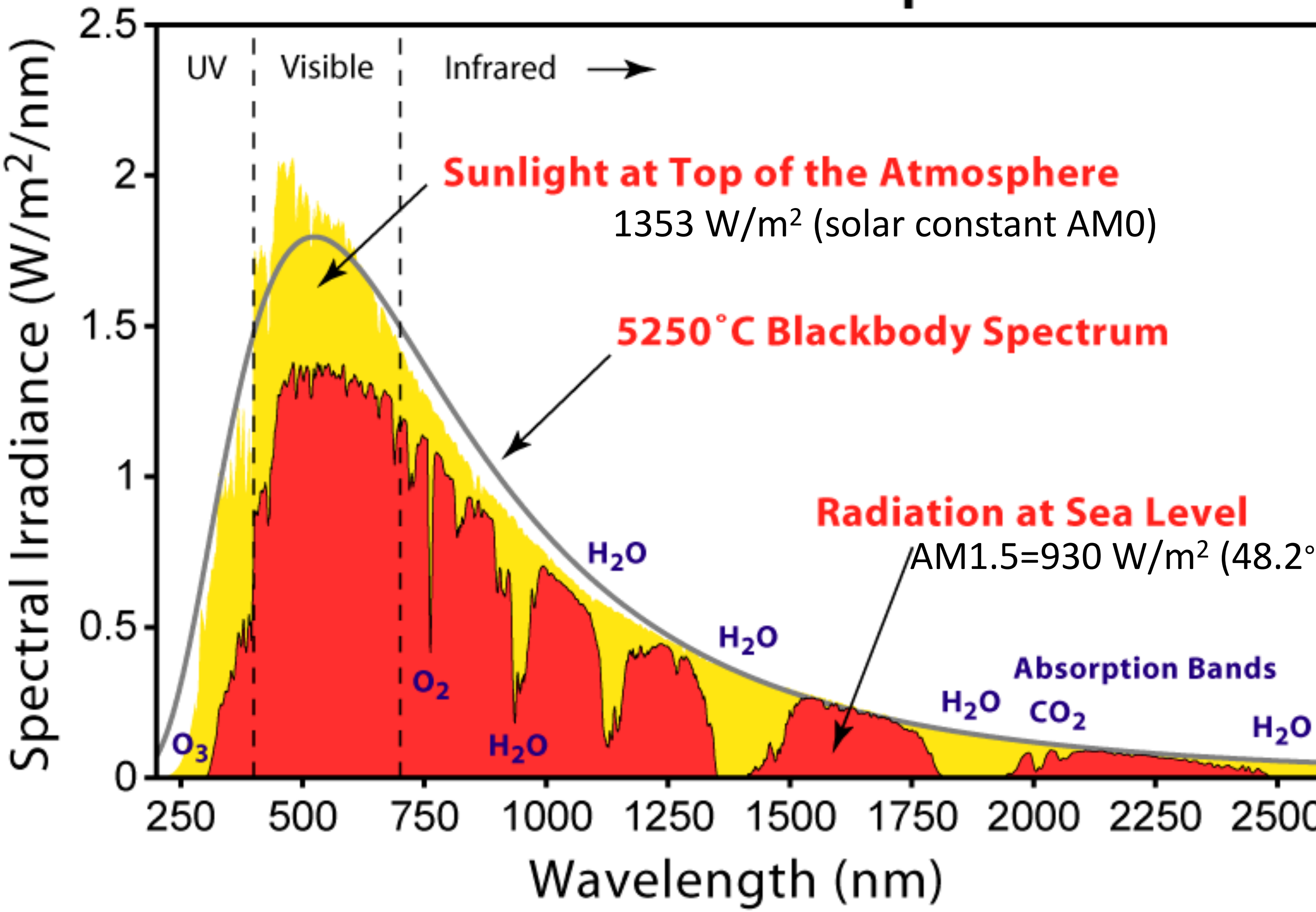
Source: Lazard estimates.

(1) Reflects the average of the high and low LCOE for each respective technology in each respective year. Percentages represent the total decrease in the average LCOE since Lazard's LCOE—Version 3.0.

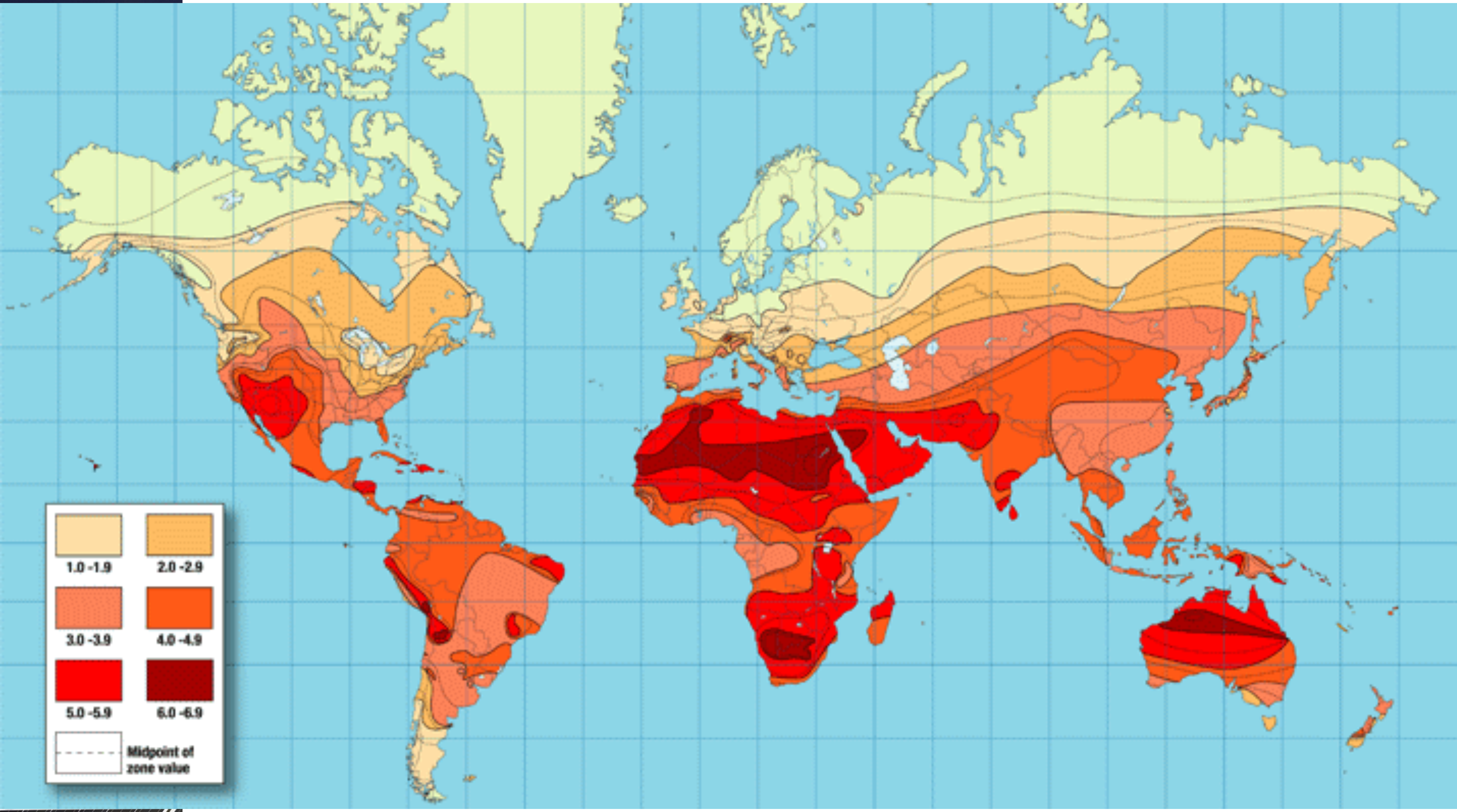
LAZARD

Solar Energy

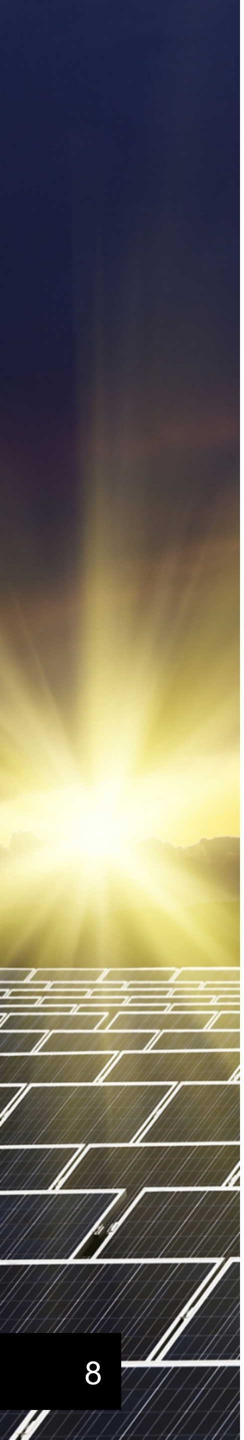
Solar Radiation Spectrum



World Solar Insolation Distribution

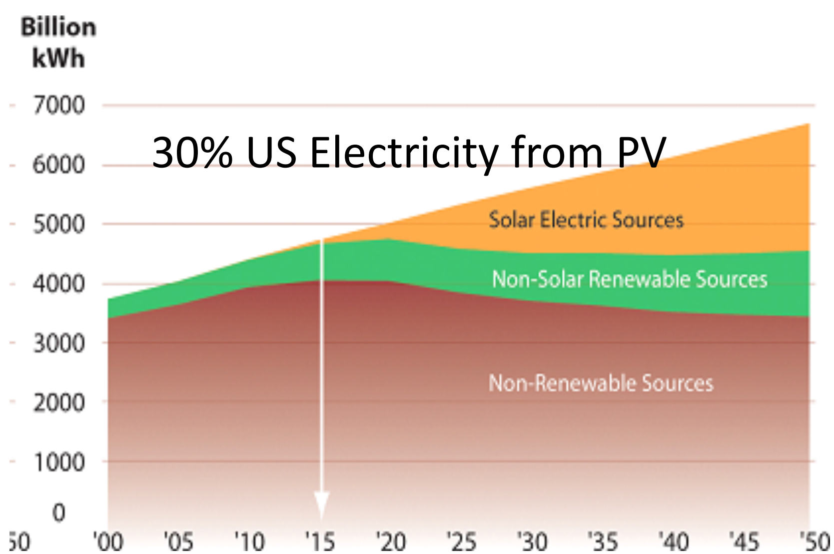


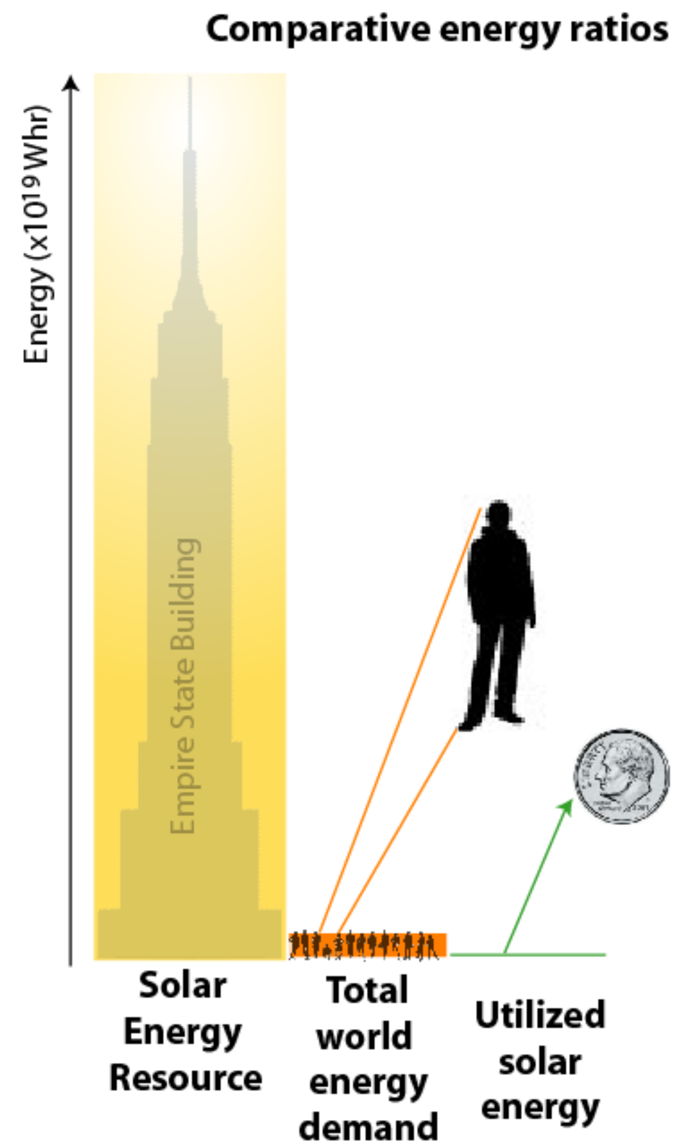
Solar Electricity Opportunity



Solar energy is a unique source of energy:

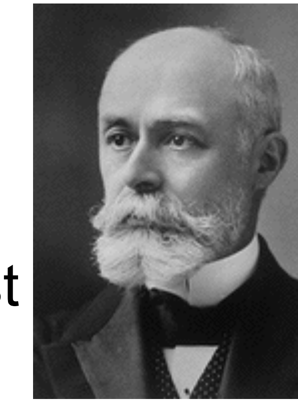
- Large resource & renewable
- Distributed generation

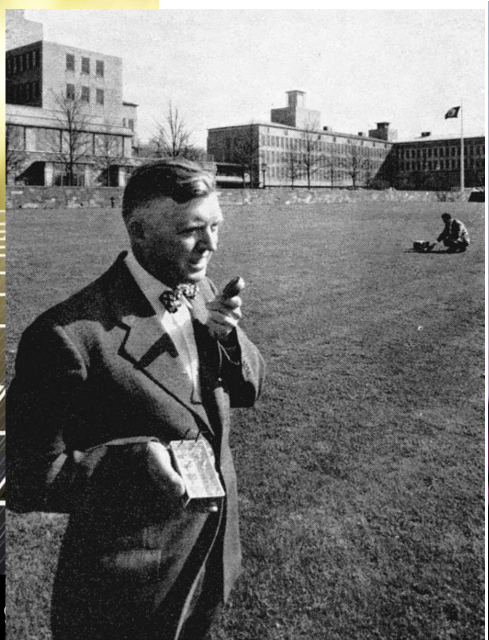


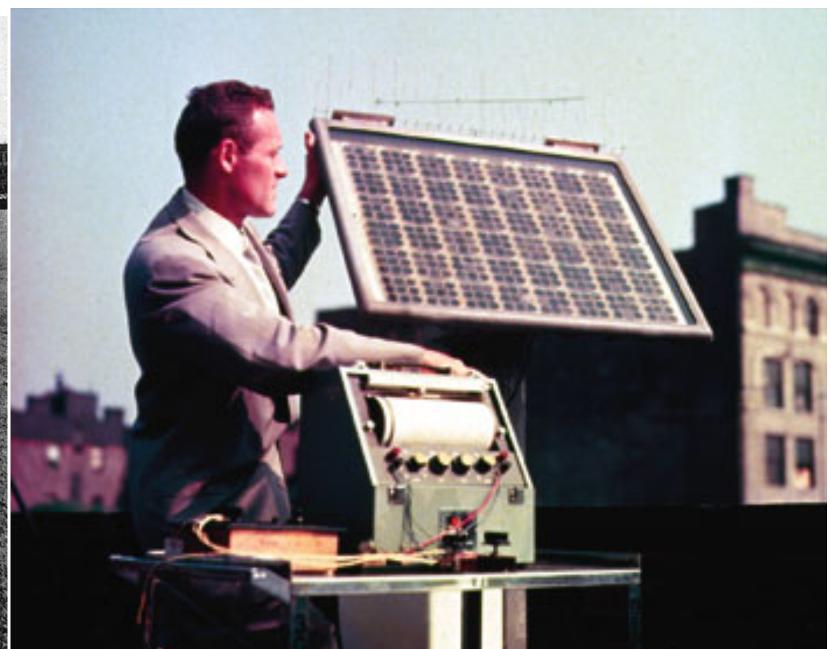


History of Photovoltaics

- Direct conversion of sunlight into electricity via the photovoltaic effect
- Photovoltaic effect first discovered by Bequerel (1839); Se/Au solar cell (C. Fritts, 1883)
- Modern junction solar cell (R. Ohl, 1946)
- Silicon junction formation allowed formation of first practical devices, at Bell Labs (1954)

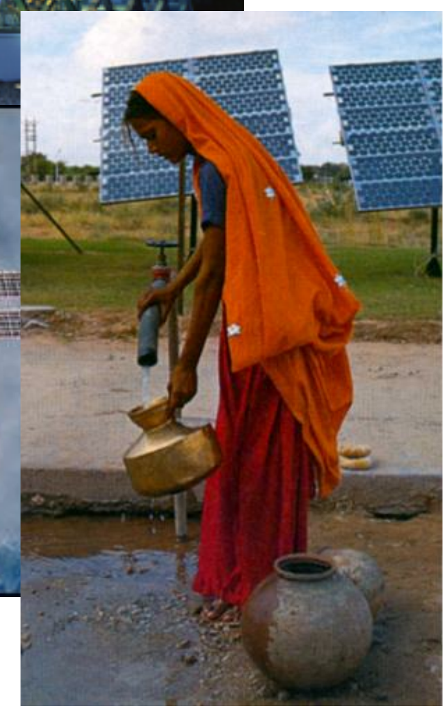






Why and Where to Use Photovoltaics

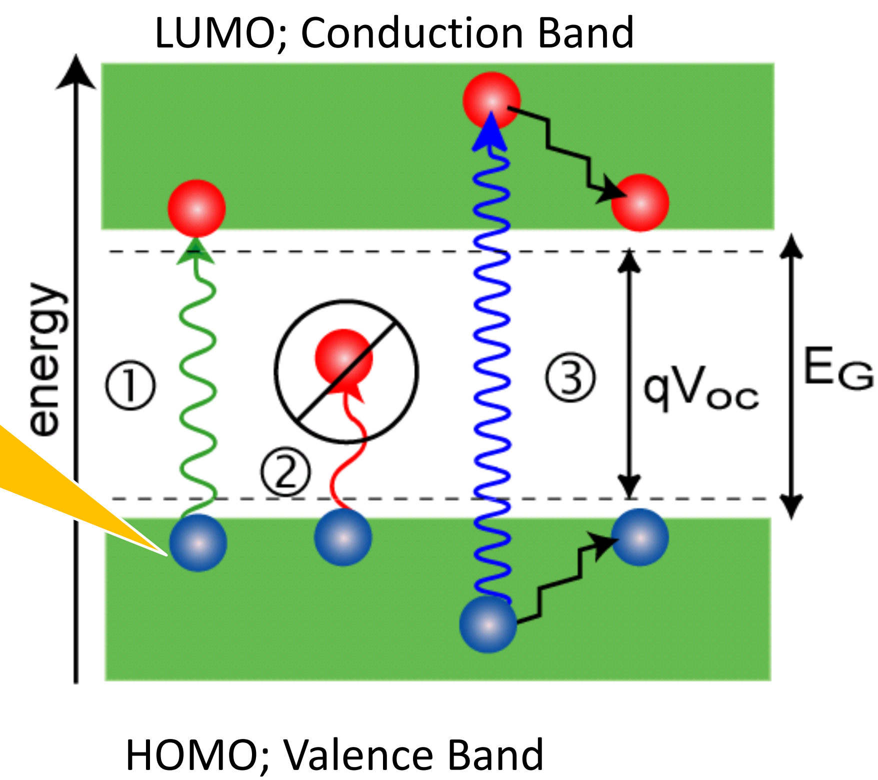
- Features of Photovoltaics
  - High efficiency
  - Short energy payback time
  - Distributed energy source
  - Low energy payback time
  - Zero carbon energy source
  - Low water usage
  - Modular
- Markets
  - Remote area power
  - Grid-connected: residential and utility
  - Space
  - Niche markets (drones, IoT, etc.)
  - Carbon sequestration



2-Level System and Optical Absorption

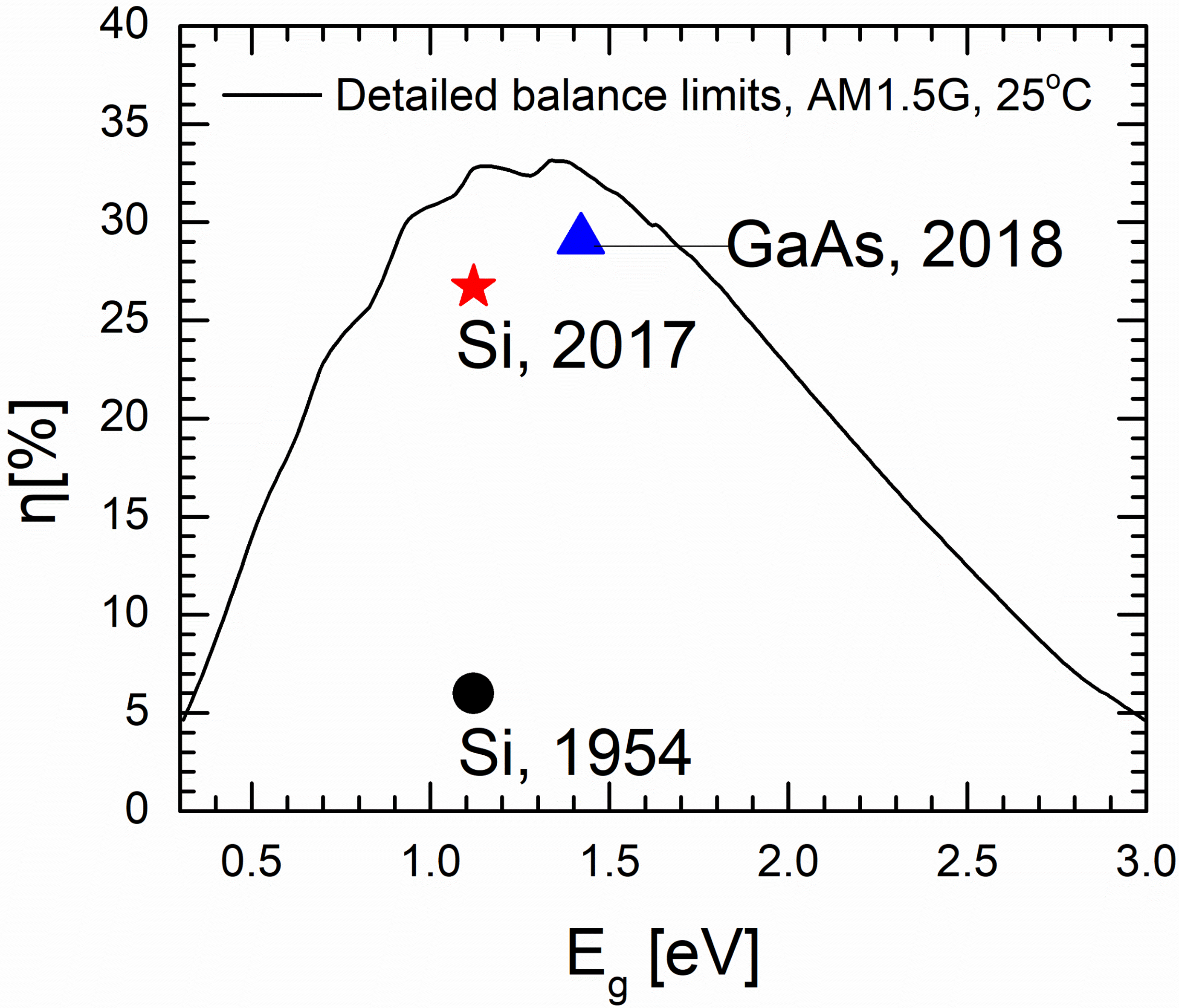
$$E_{ph} = h\upsilon$$

Photon

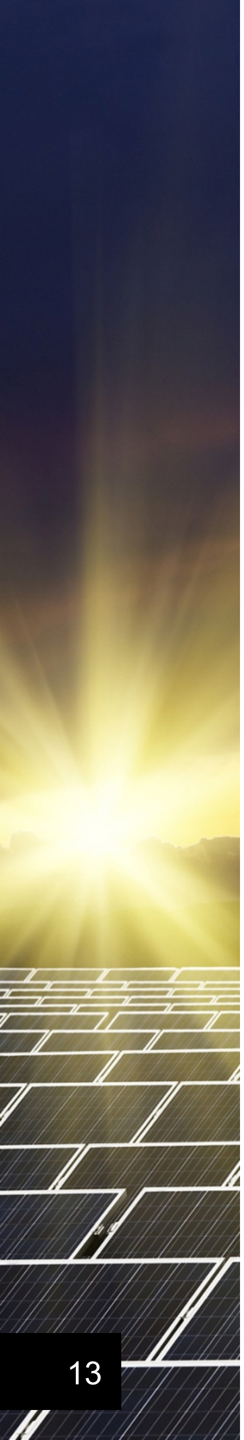


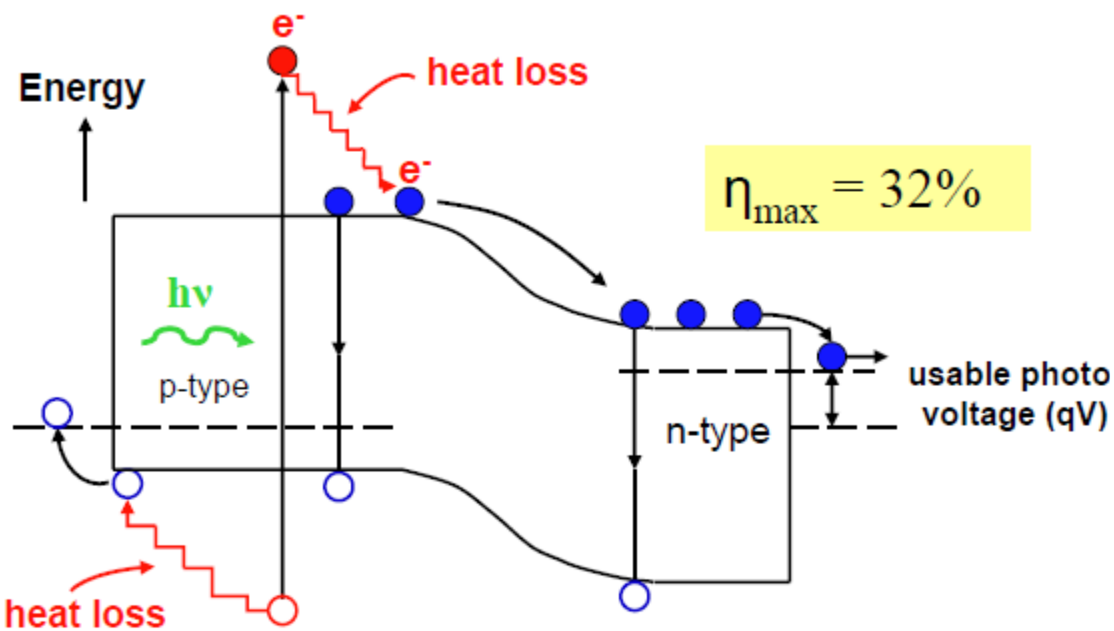
Most optical absorption processes involve excitation of an electron from a filled state, across an energy gap to an unoccupied state

Solar Energy Conversion Efficiencies



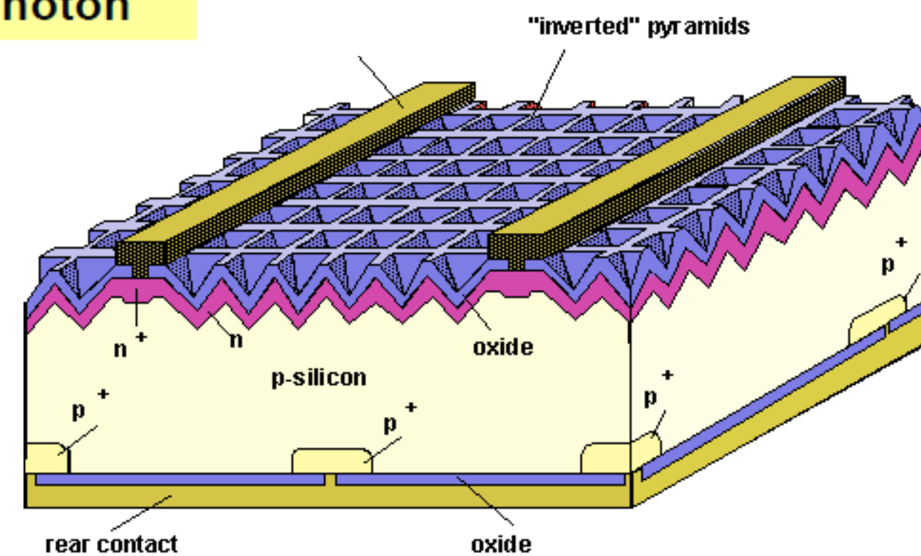
Photovoltaics (PV)



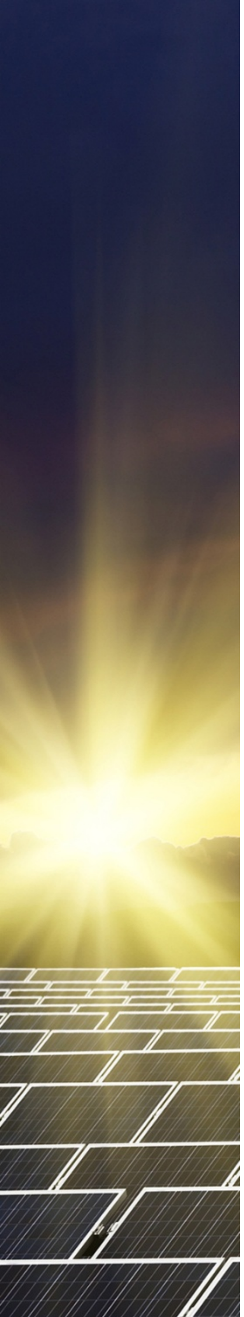


1 e^- - h^+ pair/photon

First Generation
single crystal Si PV
technology



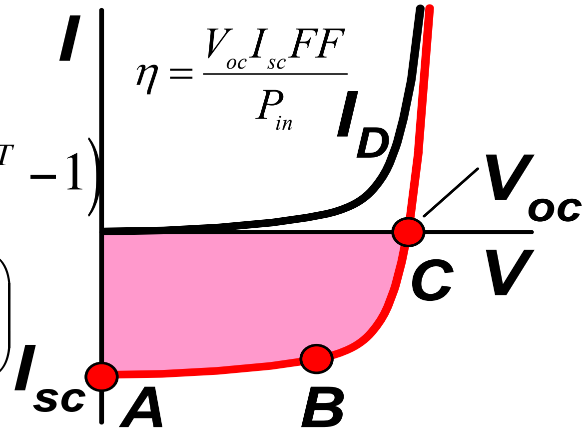
Photovoltaics



$$I_D = I_0\left(e^{qV_D/nkT} - 1\right)$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_{sc}}{I_o} + 1\right)$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$



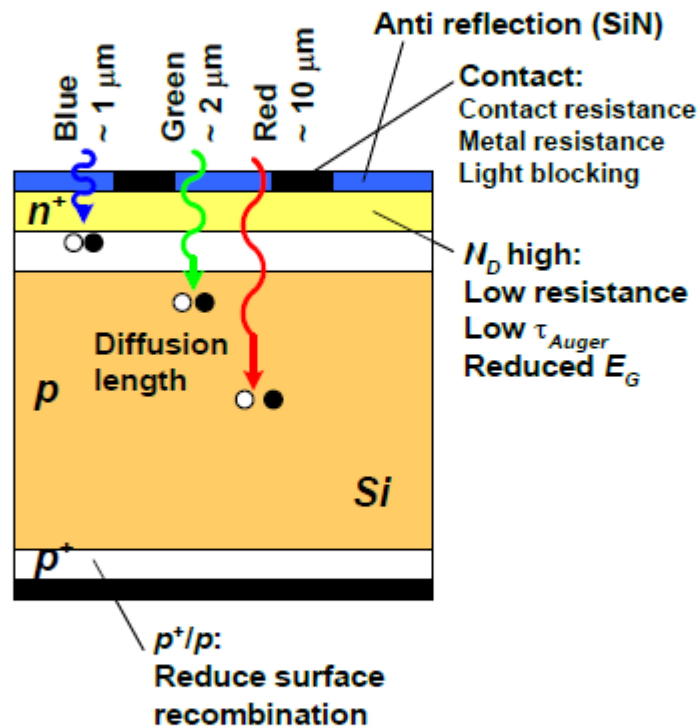
Figures of merit:

Open Circuit Voltage, V_{oc}

Short Circuit Current, I_{SC}

Efficiency, η

Top View



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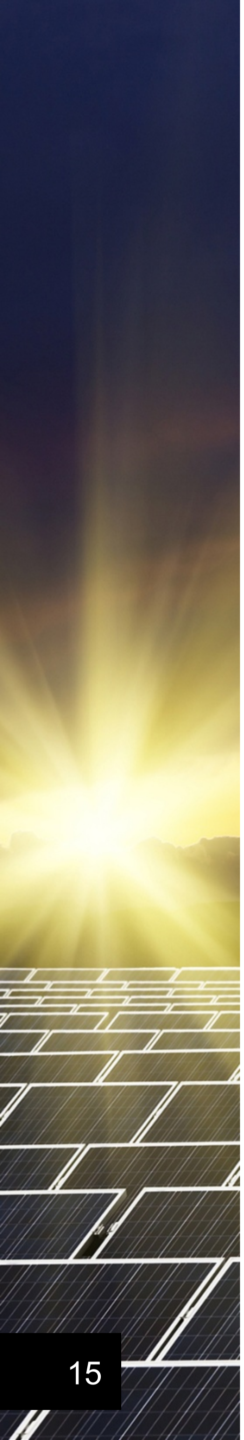


Solar Cell Technologies

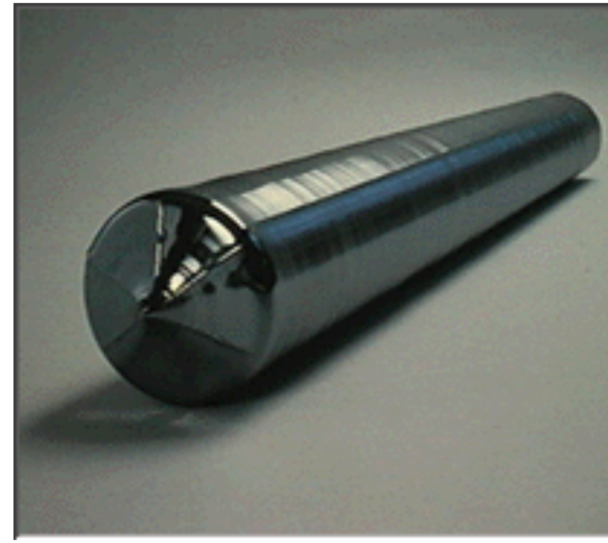
Established technologies

- *First Generation*: Silicon (single and polycrystalline) and III-V solar cells
  - GaAs/AlGaAs
  - GaAs/InGaAsP
  - InP
- *Second Generation*: Thin Film
  - $CuInSe_2$ (CIS)
  - $CuInGaSe_2$ (CIGS)
  - CdTe
  - Amorphous Si (a-Si)
  - Organic

IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

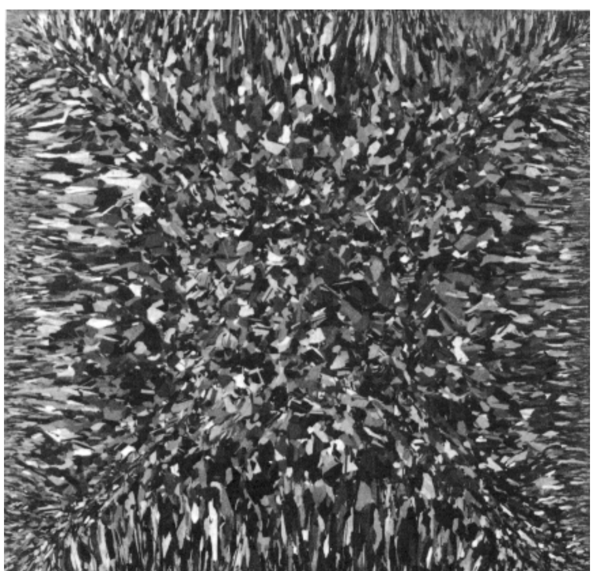
- *Third Generation*
  - Multijunction
  - Advanced concepts
  - Organic/Perovskite
  - Dye sensitized solar cells

Commercial Si Solar Cells



<u>Si Technology</u>: 95% of world market for photovoltaics

<u>Single Crystal</u>: Czochralski growth of single crystal Si ingot, sliced into wafers



<u>Multi- or polycrystalline Si</u>: Slicing multi-crystalline silicon into blocks (followed by slicing into wafers)

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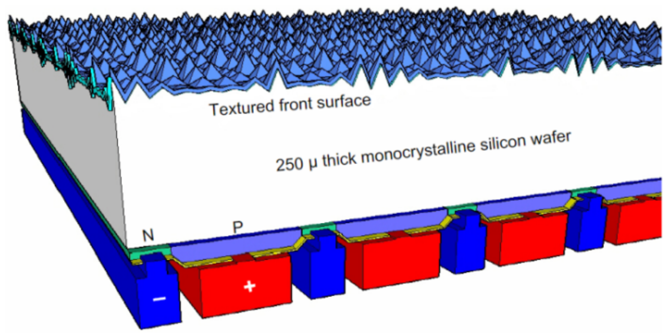
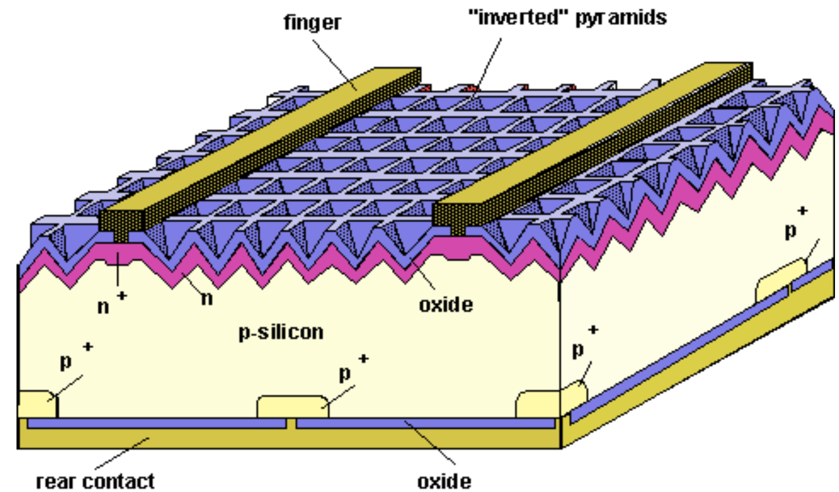
High Efficiency Si Technology

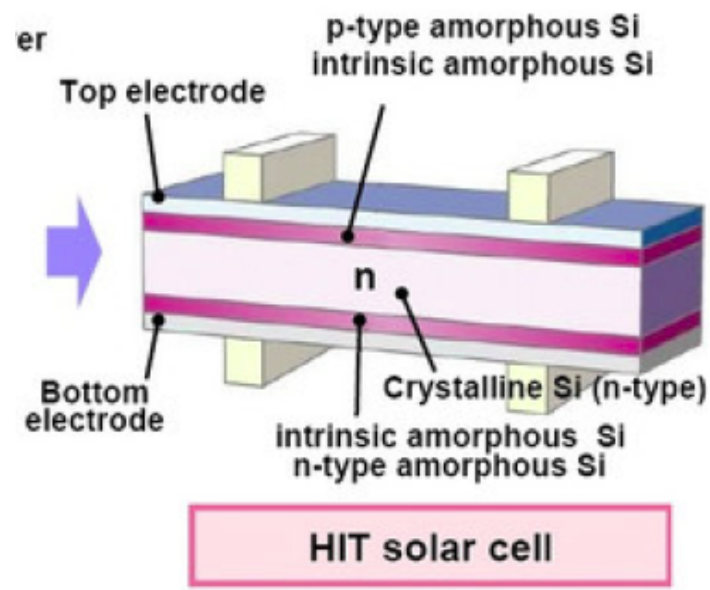


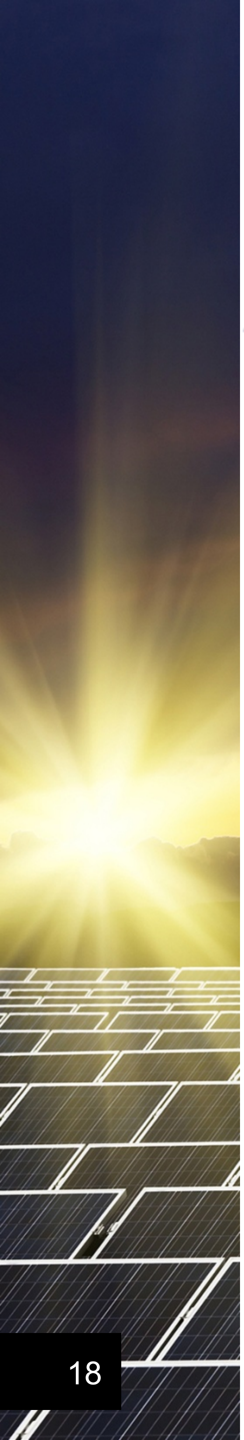
Interdigitated back contact



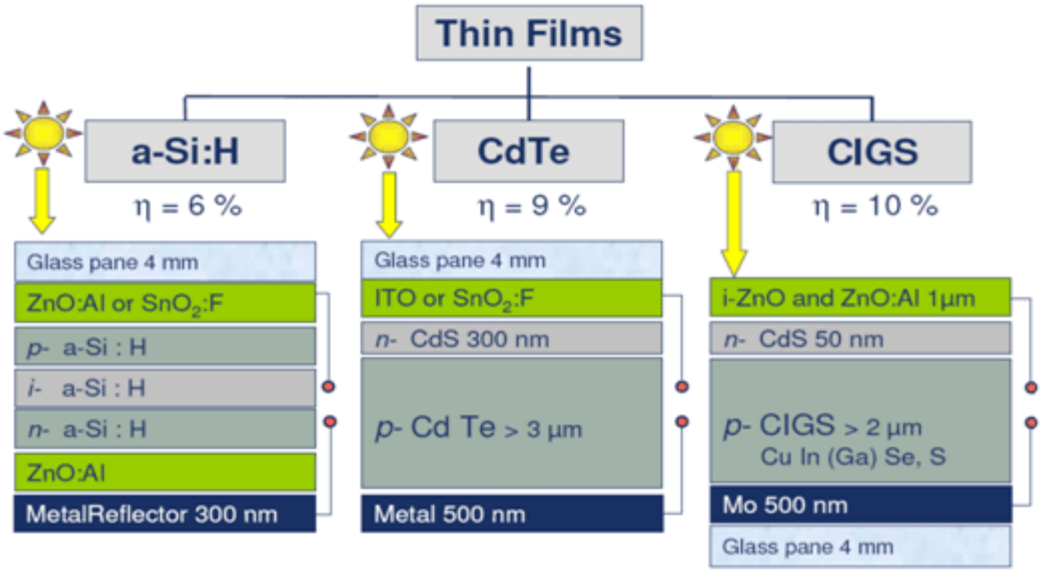
PERL Cell (UNSW)

- **Panasonic HIT® Solar Cell Achieves World's Highest Conversion Efficiency of 24.7% at Research Level (Jan. 2013 press release, now > 26.7%)**
- **Record open circuit voltage of 0.75 V**



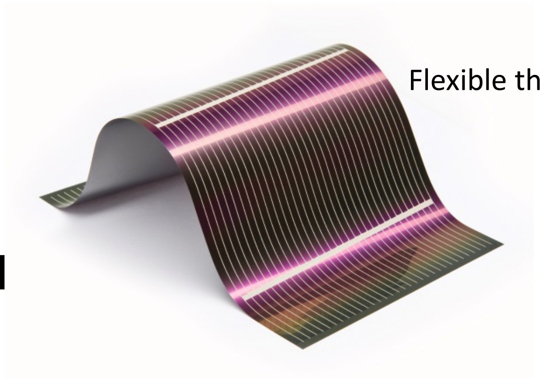


Thin Film Solar Cells




CdTe Modules
From First Solar,
Blythe Solar Project

- **In large scale production, cost of the materials dominates the overall solar cells cost.**
- **Goal of thin film approaches is to reduce the materials and processing costs while retaining acceptable efficiency**
- ***Heterojunction* solar cells are typically used**


Flexible thin film

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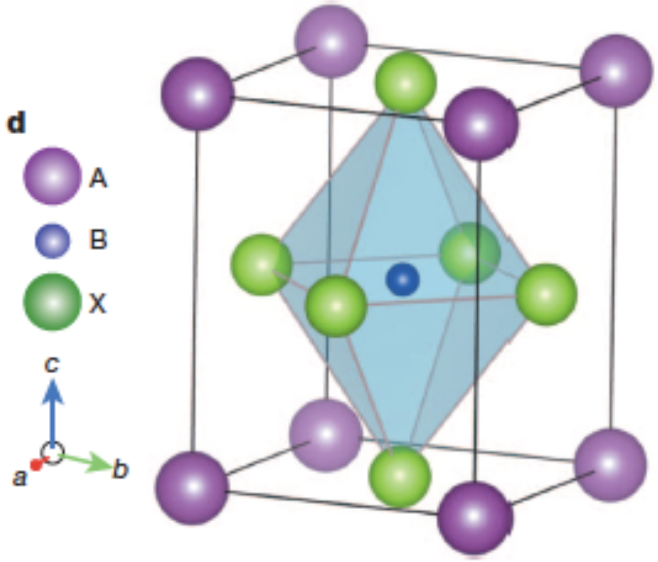
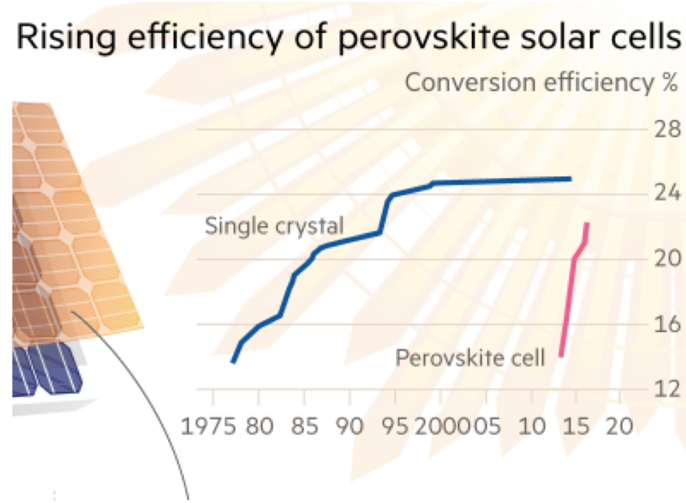
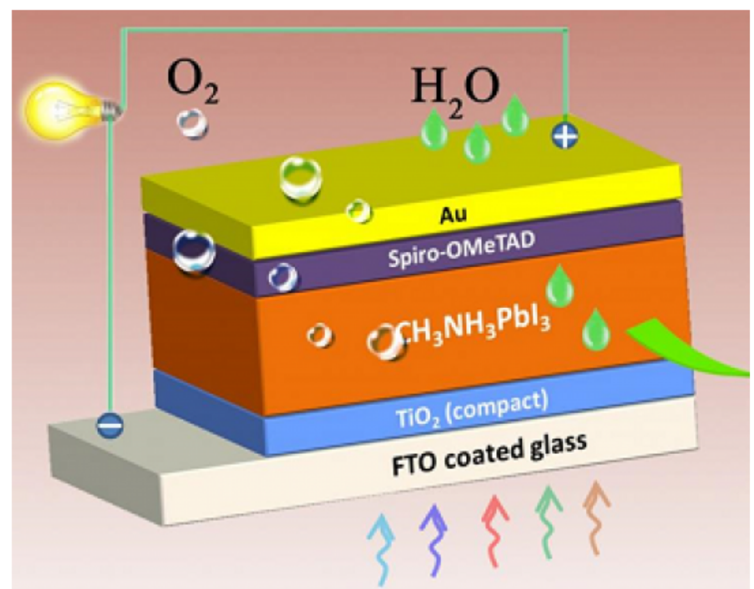
Perovskite Solar Cells



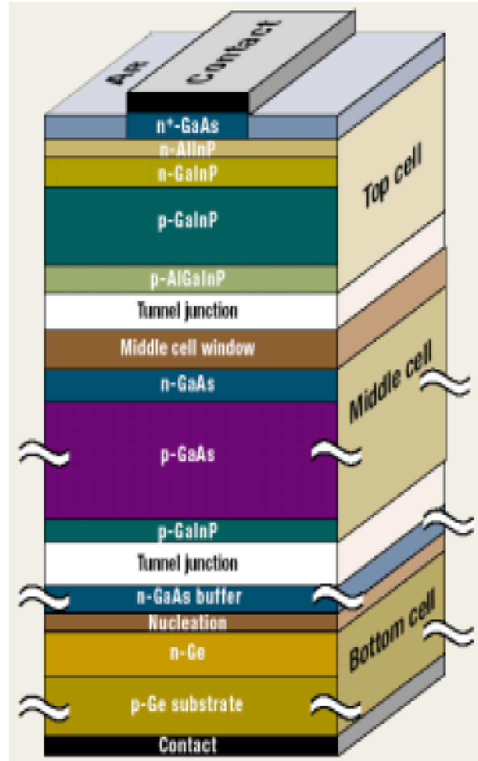


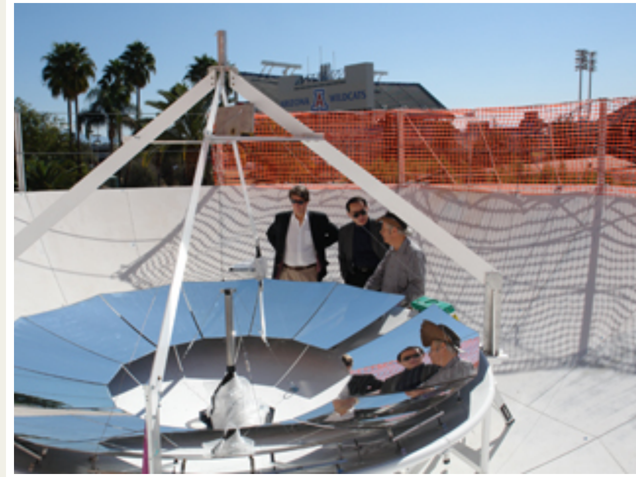
- **Hybrid organic metal halide perovskites: ABX_3- A=CH_3NH_3, B=Pb, X=I or Cl**
- **Bandgap of 1.55 eV**
- **Low cost materials, thin film processing**
- **Lifetime and reliability are main barriers to commercialization**

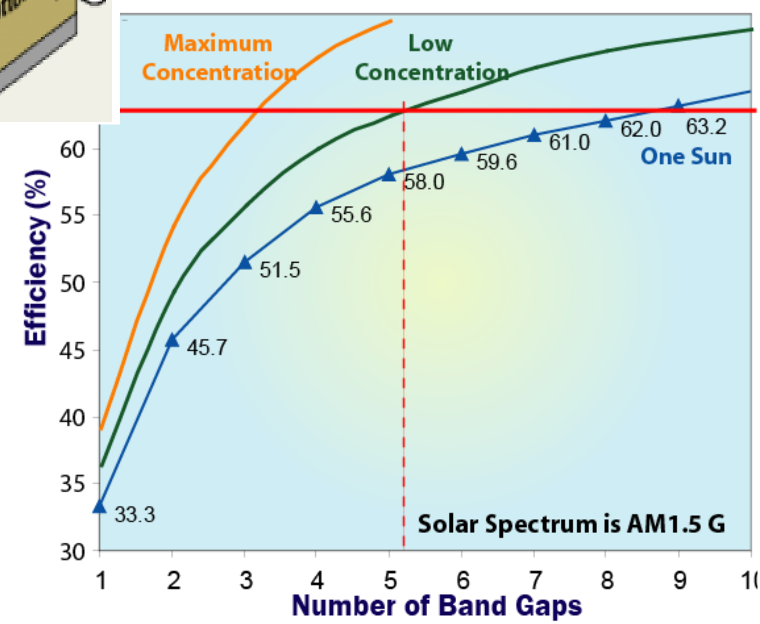


Multijunction (Tandem) Solar Cells

- Stacking multiple bandgap solar cells increases efficiency (46.5% current record)
- Material and fabrication costs very high
- Space power
- Concentrating photovoltaic (CPV)

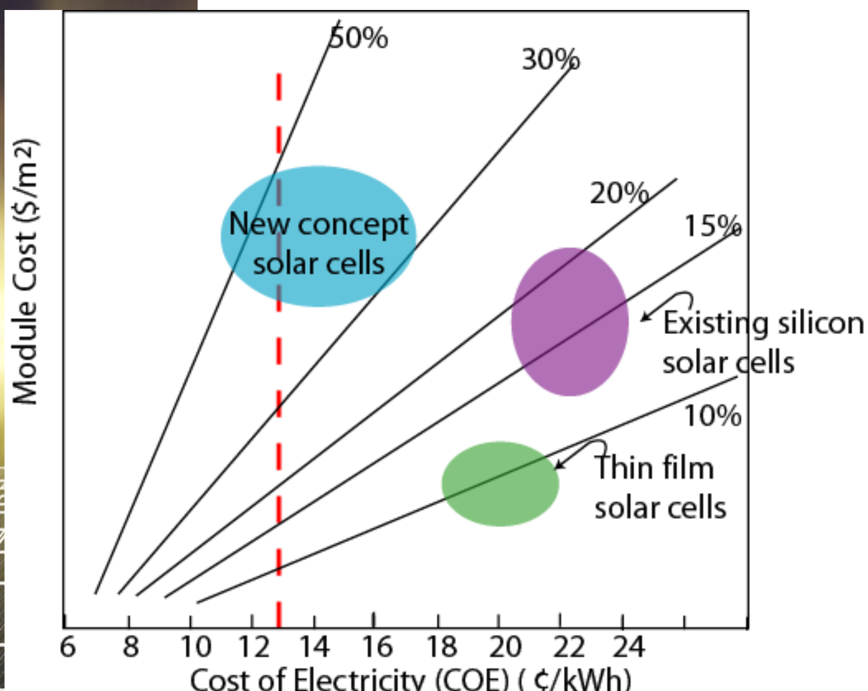


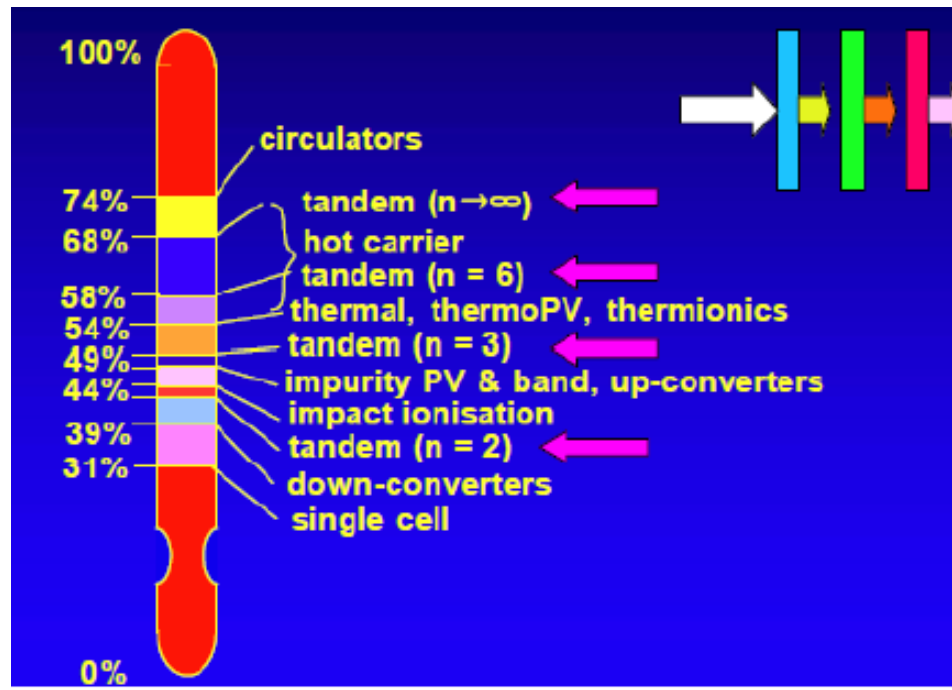




Third Generation (3G) Solar Electric

- New physics concepts to take PV efficiencies closer to thermodynamic limits
- Nanotechnology solutions





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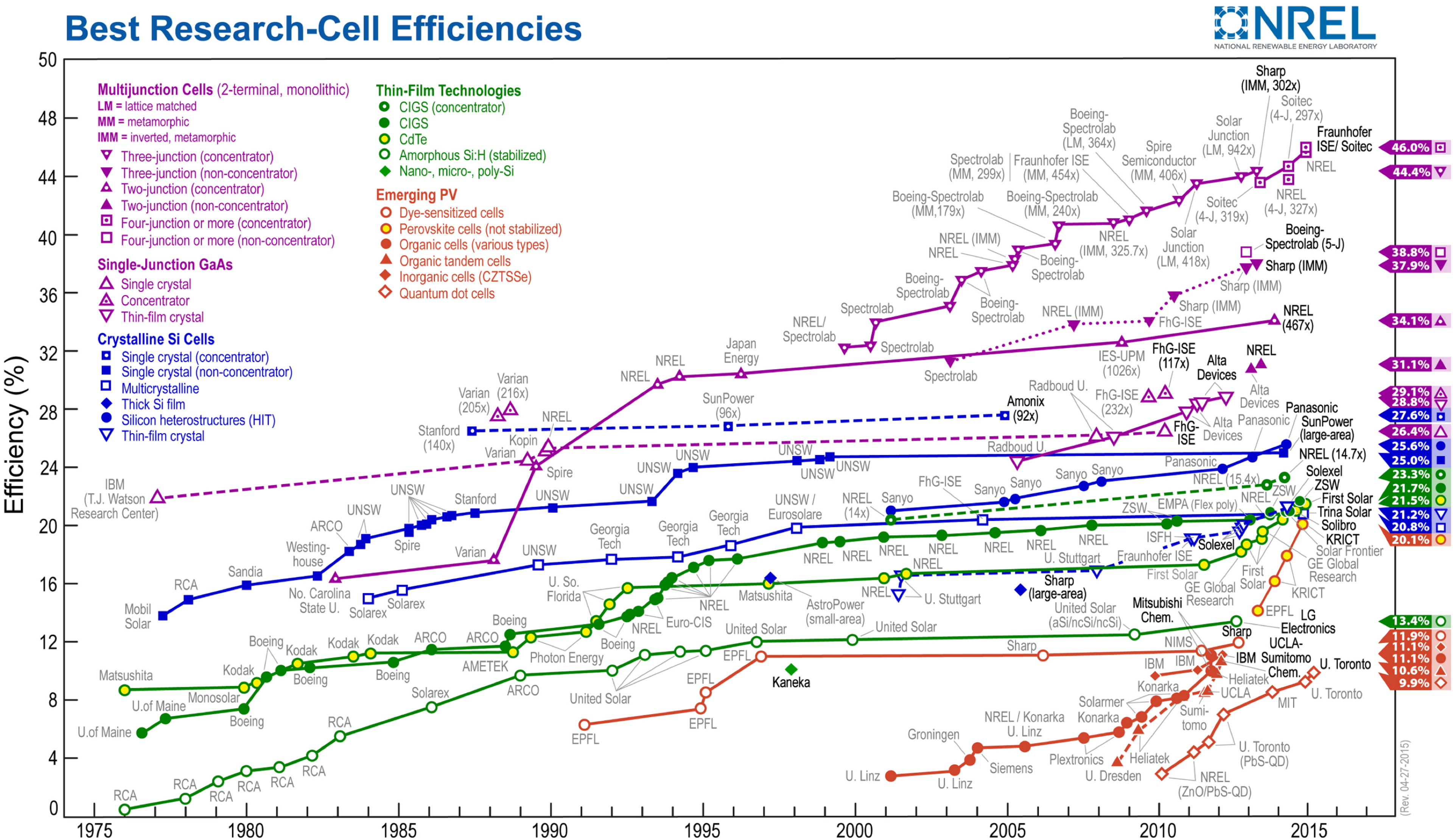
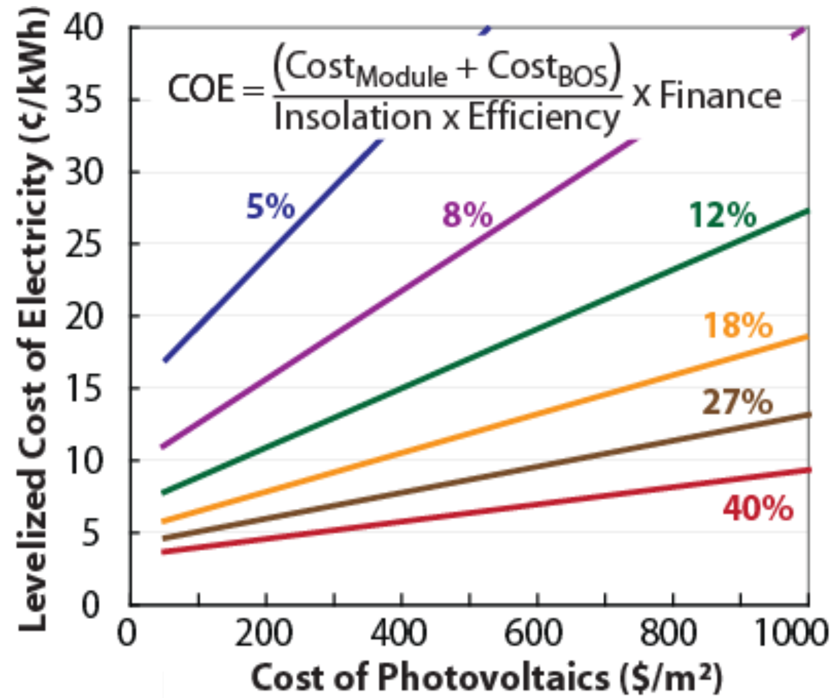
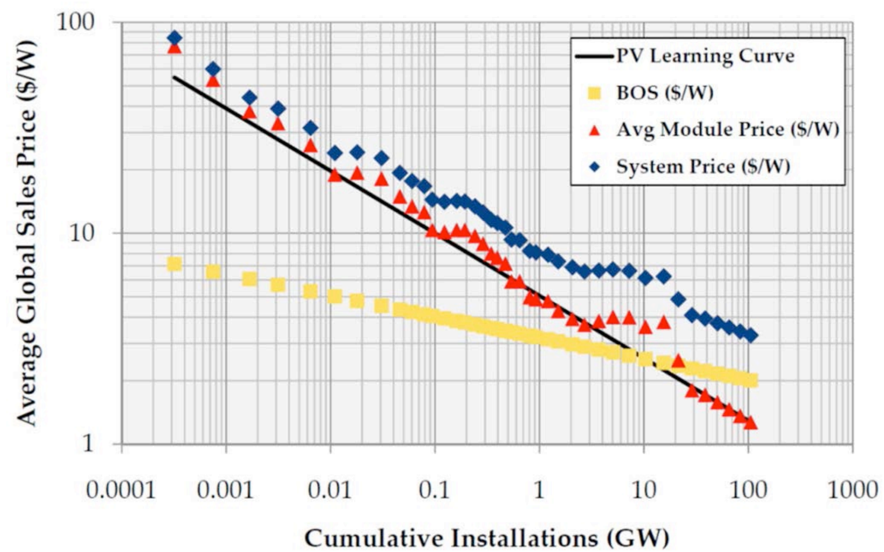
Solar Cell Efficiencies

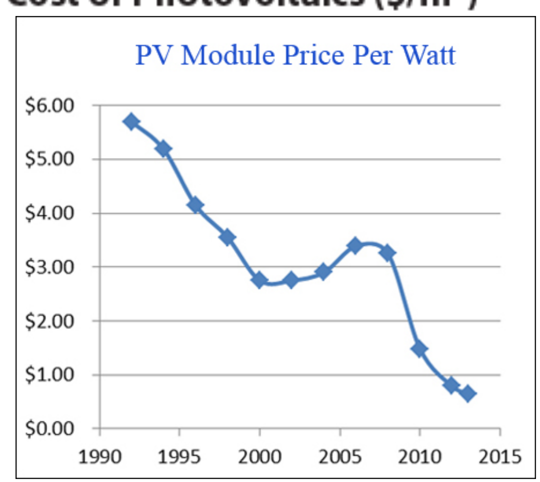


Efficiency as Critical Metric

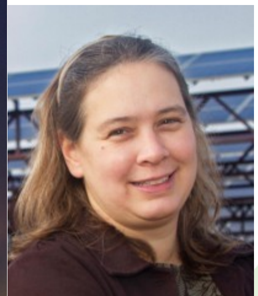
- Why is efficiency important?
- Cost of electricity
- Reducing PV costs ineffective if PV costs go below BOS costs

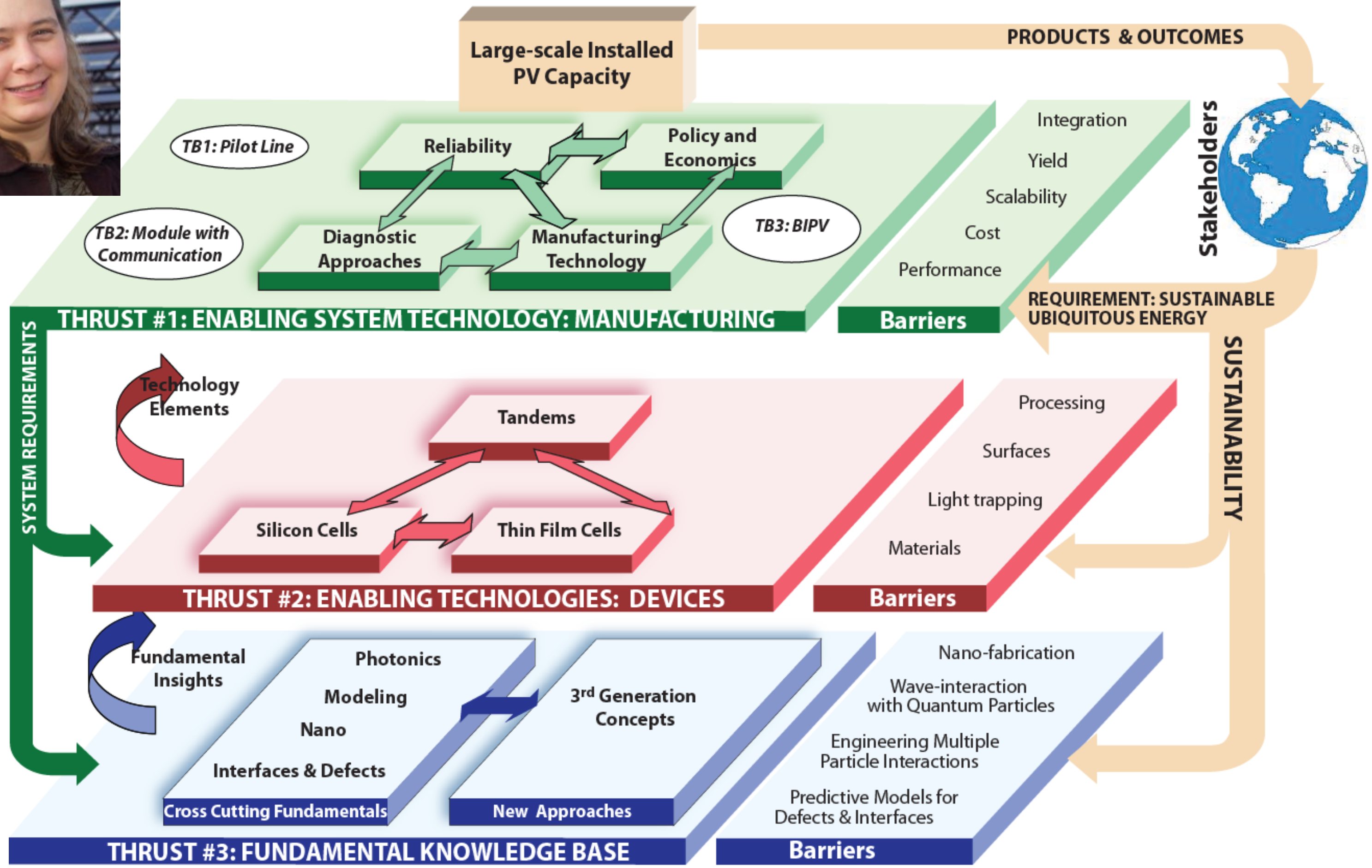






NSF/DoE Quantum Energy for Sustainable Solar Technologies (QESST) Engineering Research Center





Si Solar Modules

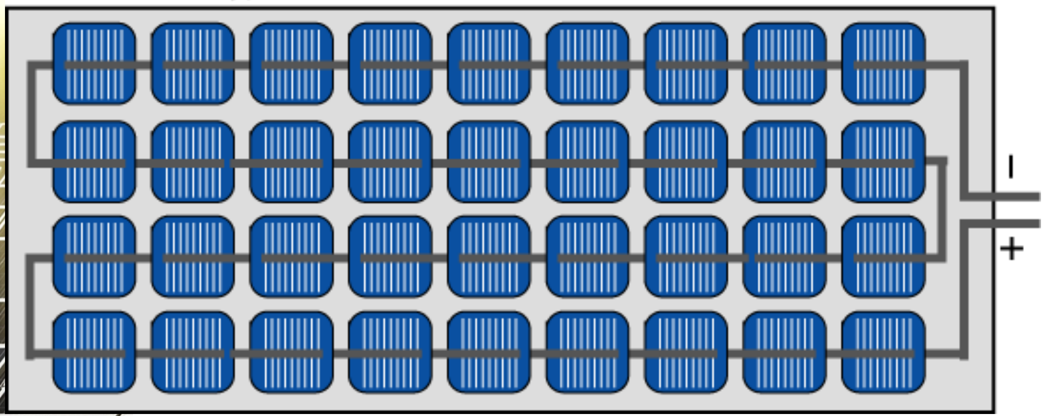
Historically, modules consisted of 36 series connected cells for battery charging (15-16V required):

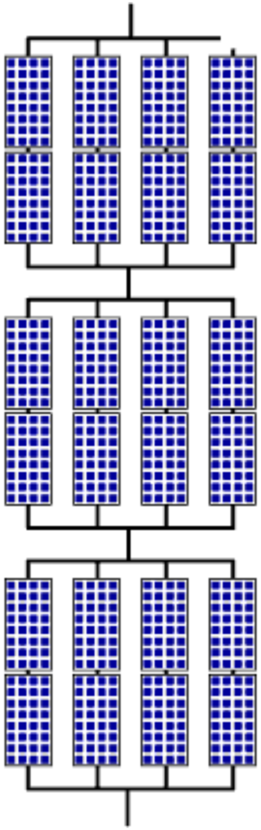
V≈ 36x0.6 = 21 volts max, and 17-18V at max power and operating temperature

I ≈ 30 to 36 mA/cm^2 x 100cm^2 = 3-3.5A

Power ≈ 70 watts

A typical module has 36 cells connected in series



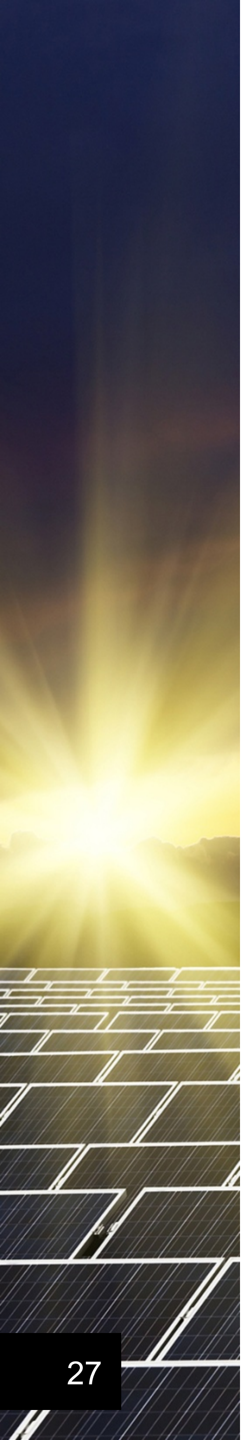


Module Structure

≈ 36 individual cells are encapsulated in a single stable unit
- mechanical protection
- protection from the environment (water vapor)
- protect the user from electrical shock

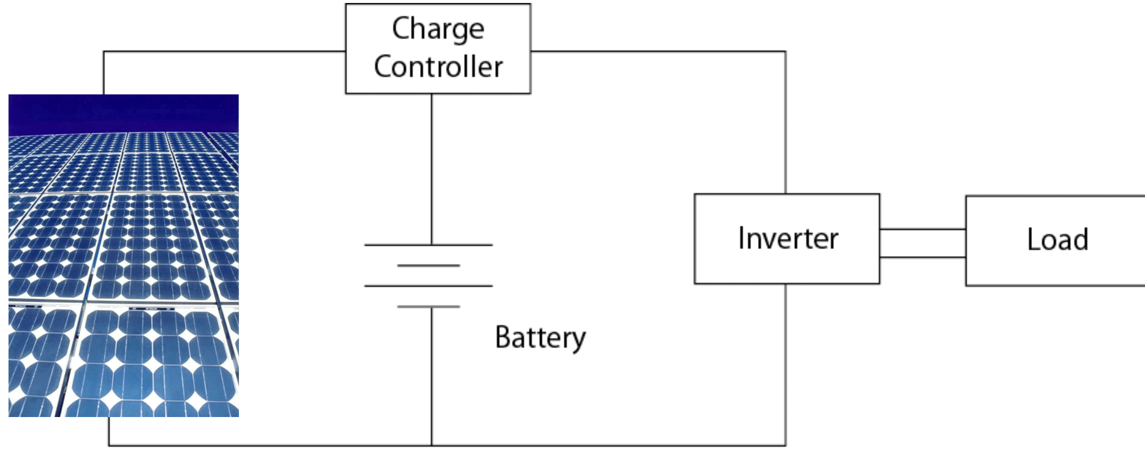
Rear view of PV module before encapsulation.

The module consists of the solar cell sandwiched between EVA (a clear polymer), with glass on the front and Tedlar on the rear.



Photovoltaic Systems

- PV System requirements:
  - PV Modules
  - Storage
  - Power elect.
  - Installation
  - Permitting

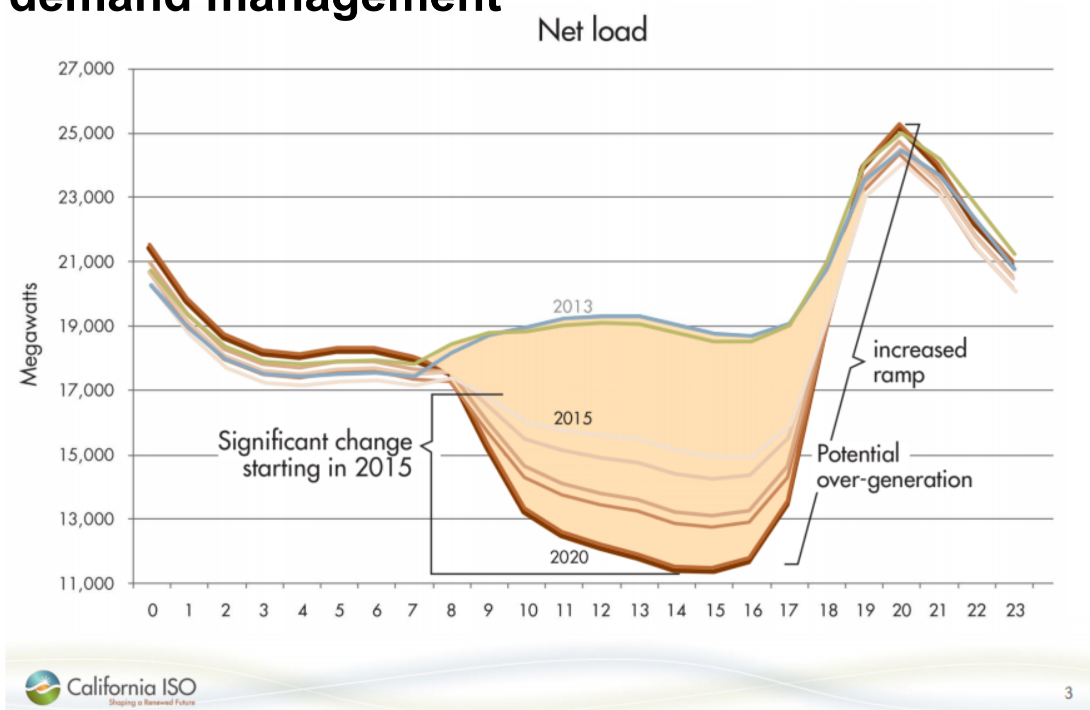


- Cost Issues:
  - Main costs are usually Module, Inverter, and BOS
  - $1/Peak Watt ($1/Wp) for the system is usually stated as overall price to reach ‘grid parity’
  - However, the Levelized Cost of Electricity (LCOE) depends on several assumptions regarding system lifetime, maintanance, financing costs, etc.

Challenges for PV: Intermittency

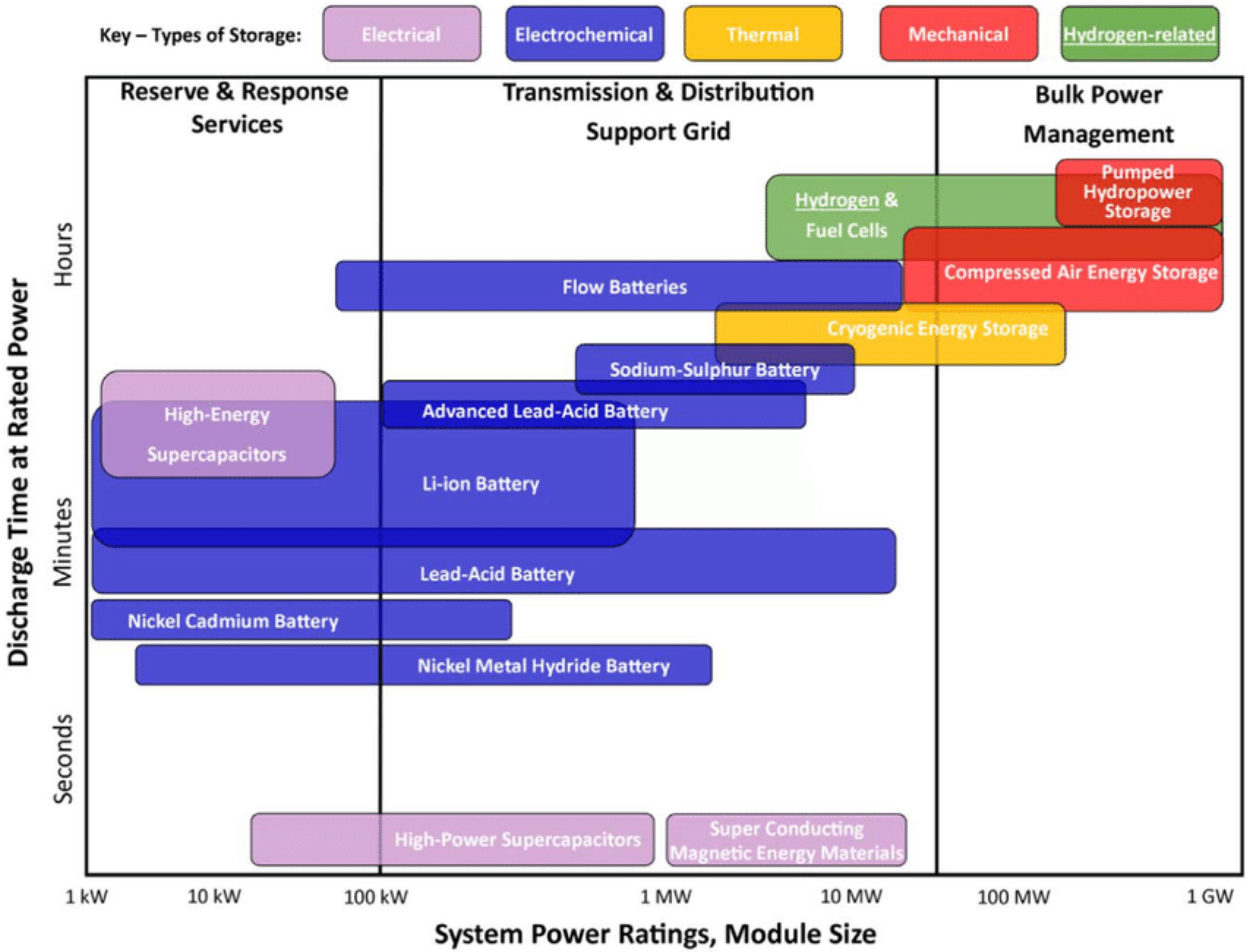
Intermittency (rapid fluctuations, diurnal) limit penetration solar onto current grid without:

- **Storage**
- **Geographic averaging, mixed renewables**
- **Load demand management**

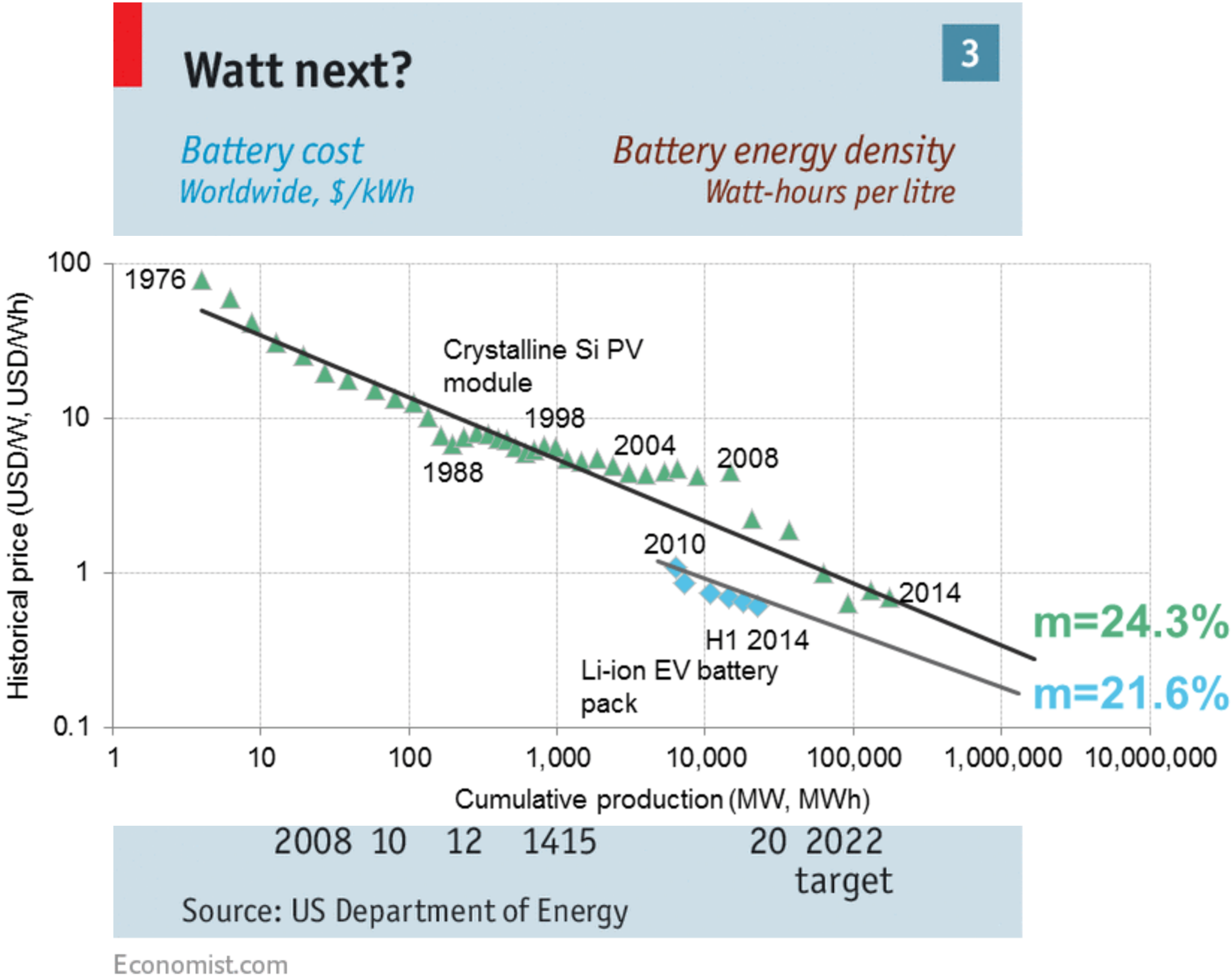


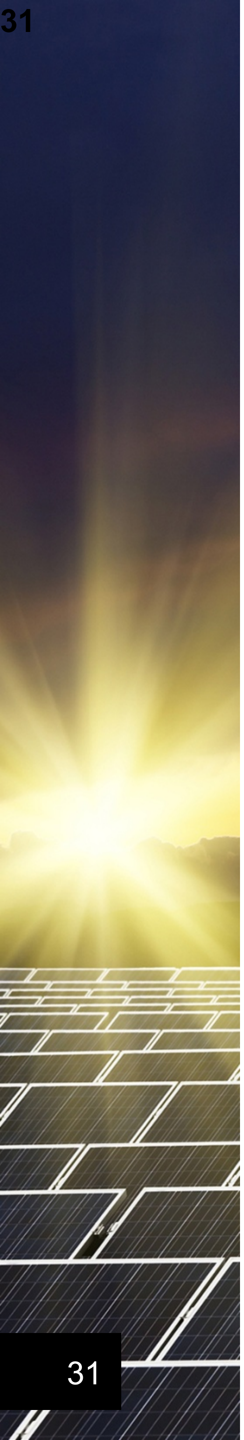
"Duck curve", showing hourly system load for a typical March day for the California ISO, less projected yearly rise in renewable (including PV) generation. Problems of increased renewables include potential over-generation in late afternoon and high ramp rates (14000 MW in ~1 hour).

Electrical Energy Storage Technologies



Electrical Energy Storage Technologies





PV for Remote Systems

- Remote PV Systems:
  - Off grid
  - Battery storage required
  - No existing energy infrastructure
  - Transportation
  - System cost increases nonlinearly with % availability

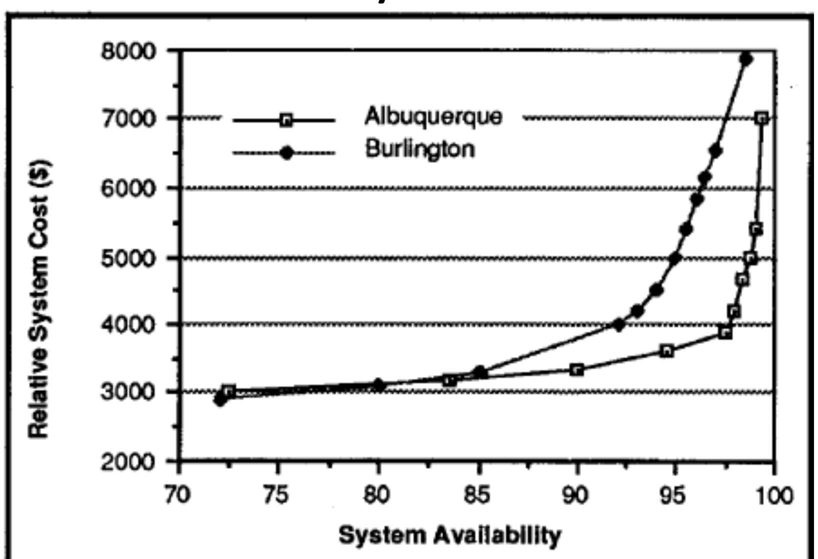
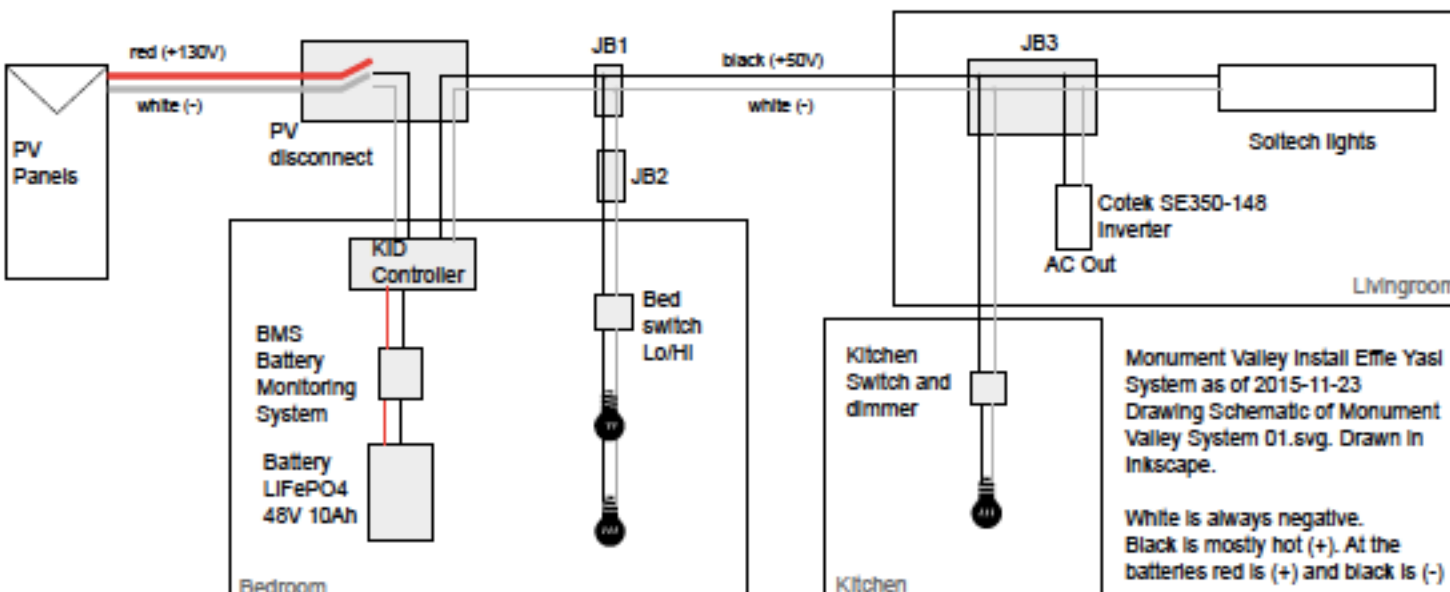


Figure 8. Cost vs. Availability--Albuquerque, New Mexico, and Burlington, Vermont.

Monument Valley

Monument Valley PV Install

Top view, Google Maps



Summary

- Photovoltaics is the fastest growing renewable energy technology
- Present cost is now lowest of all energy technologies in terms of LCOE
- Intermittancy of wind and solar is the main barrier to increased penetration of renewables
- Low cost energy storage technologies are emerging such as Li-batteries, hydrogen production, etc.
- Photovoltaics provides many advantages for remote, off-grid locations, and only source in some cases.

Acknowledgements

U.S. DEPARTMENT OF ENERGY

TUM

QESST

NSF

Concentrating Solar Power

CSP-Concentrating solar thermal

- **Currently more expensive than PV in $/watt**
- **Thermal storage in molten salts**