Solar Energy and a Zero-Carbon Future for the US Southwest and Beyond

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Outline

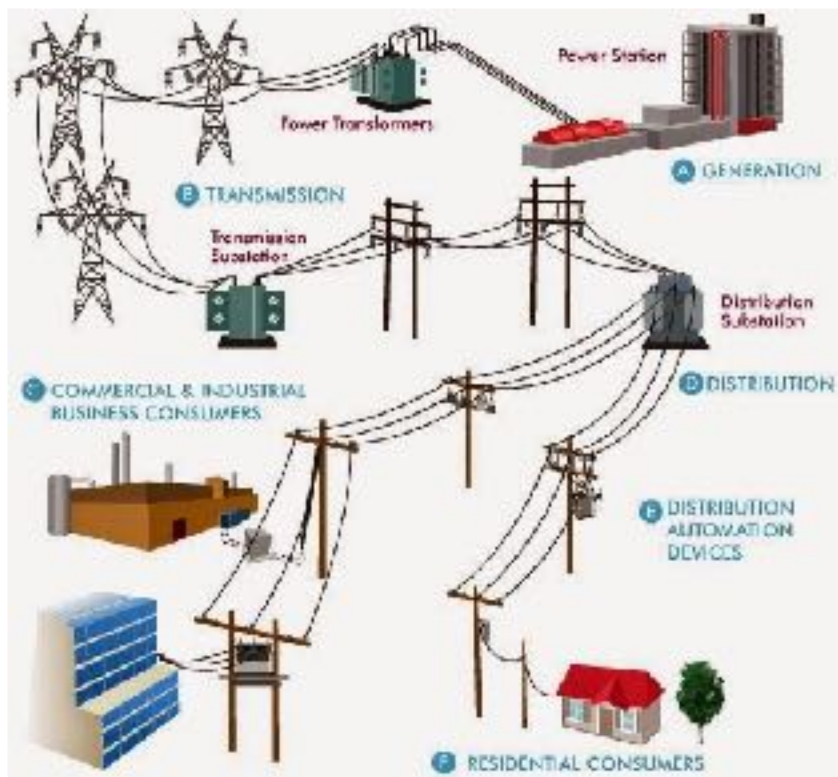
- Renewable energy
- Introduction to photovoltaics
- Photovoltaic technology
- Solar modules and solar systems
- Intermittancies and storage
- Approaching zero carbon by 2050

Renewable Energy

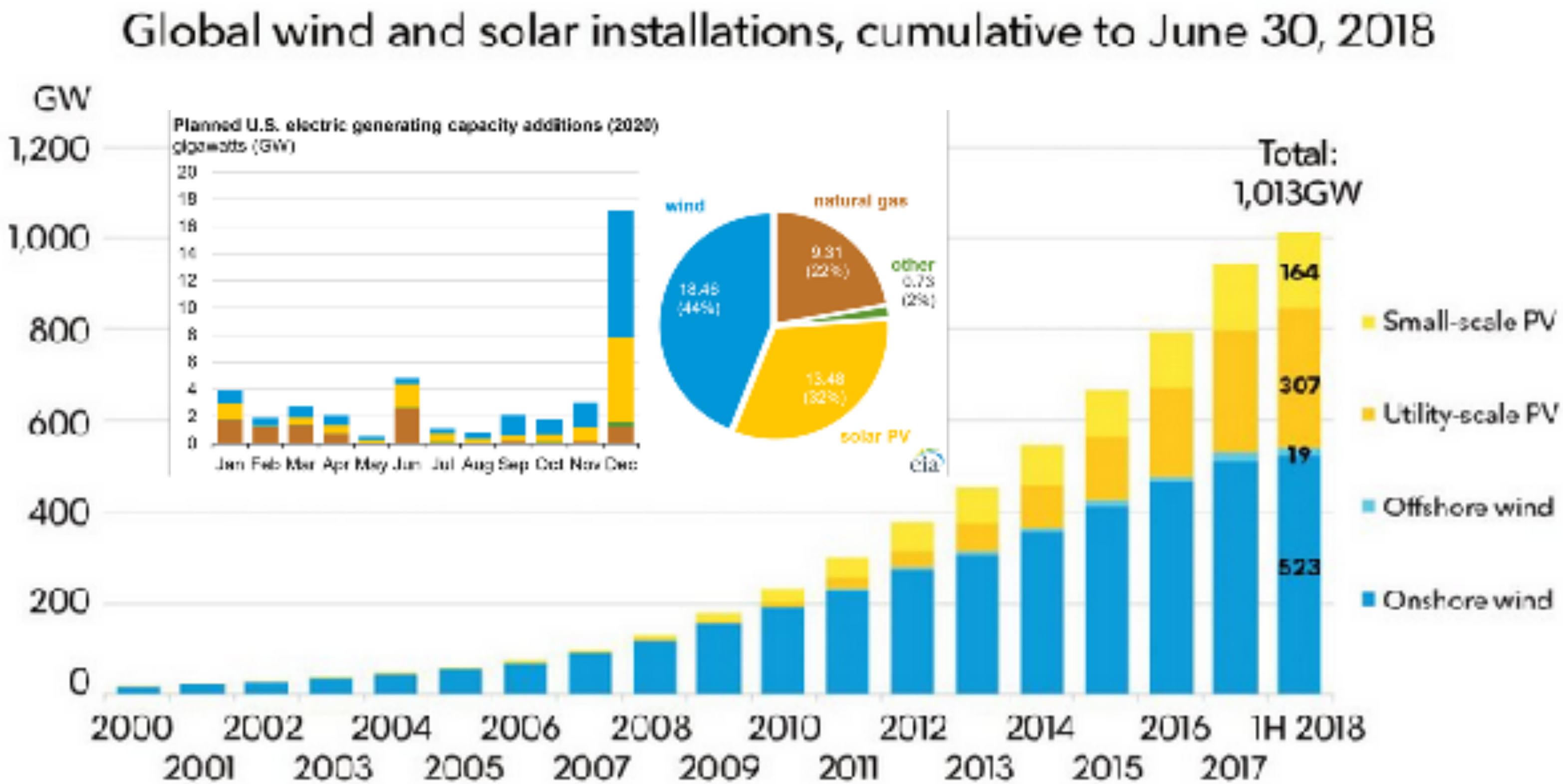
<u>Renewable Sources:</u> Hydro, Wind, Solar, Bio, Geothermal

Electrical System

- Electrical grid system is a complex, consisting of many interacting components.
- Broadly consists of:
  - Generation sources (main categories: thermal generation, nuclear, hydro, wind and solar).
  - Transmission system (high voltage lines, generally 100 kV or above)
  - Distribution Systems



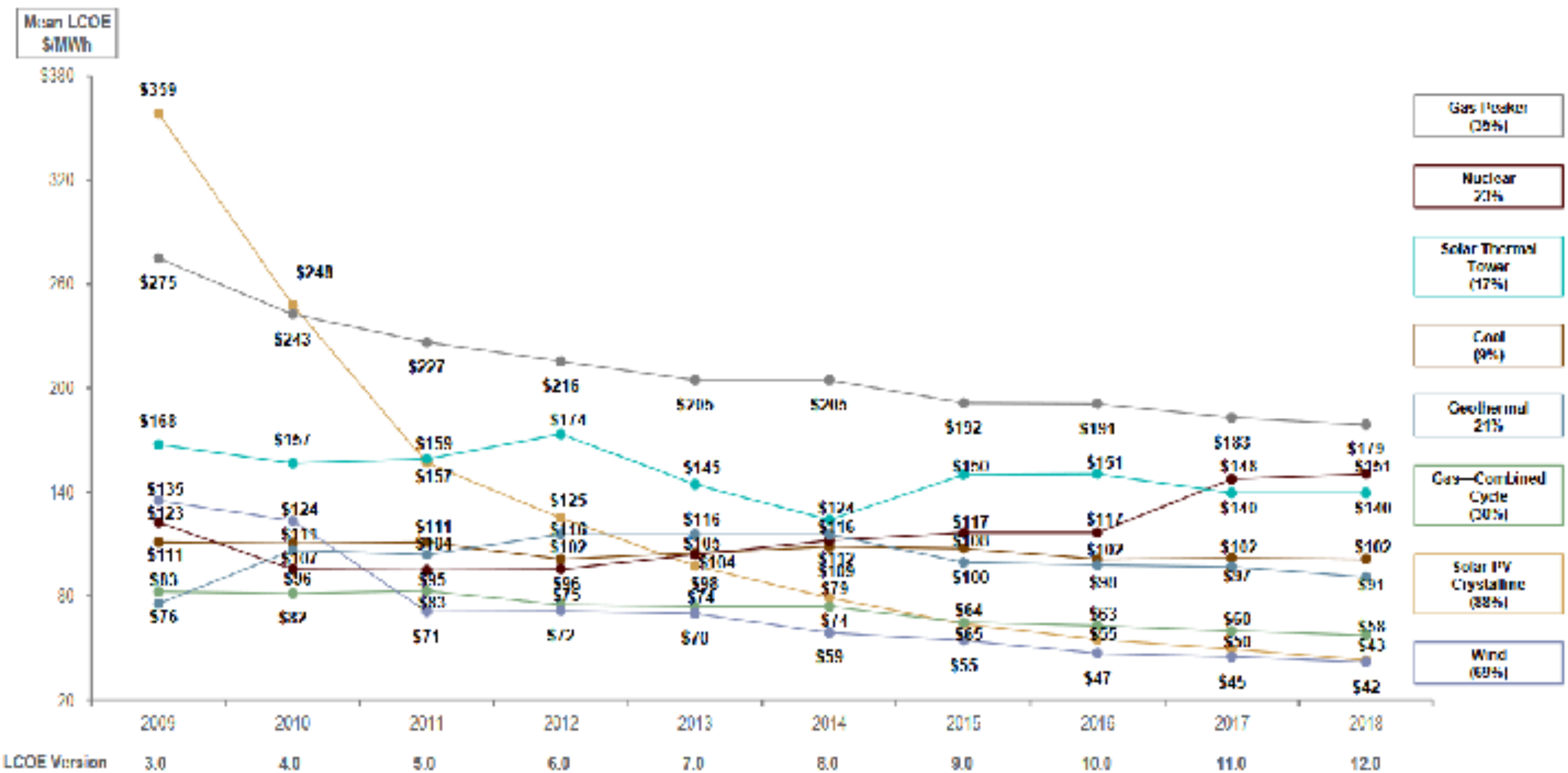
Renewable Energy: Wind & Solar



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)]



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

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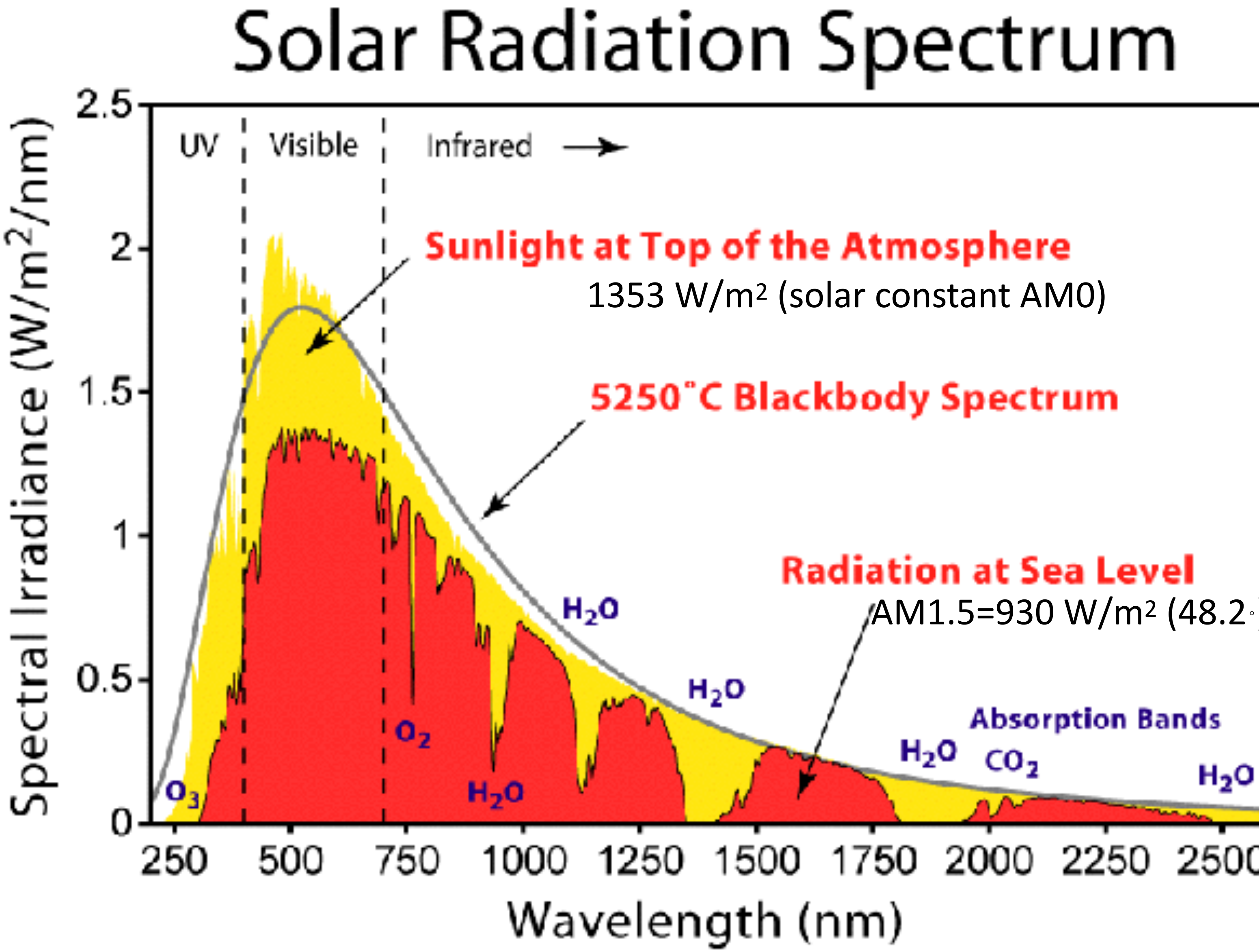
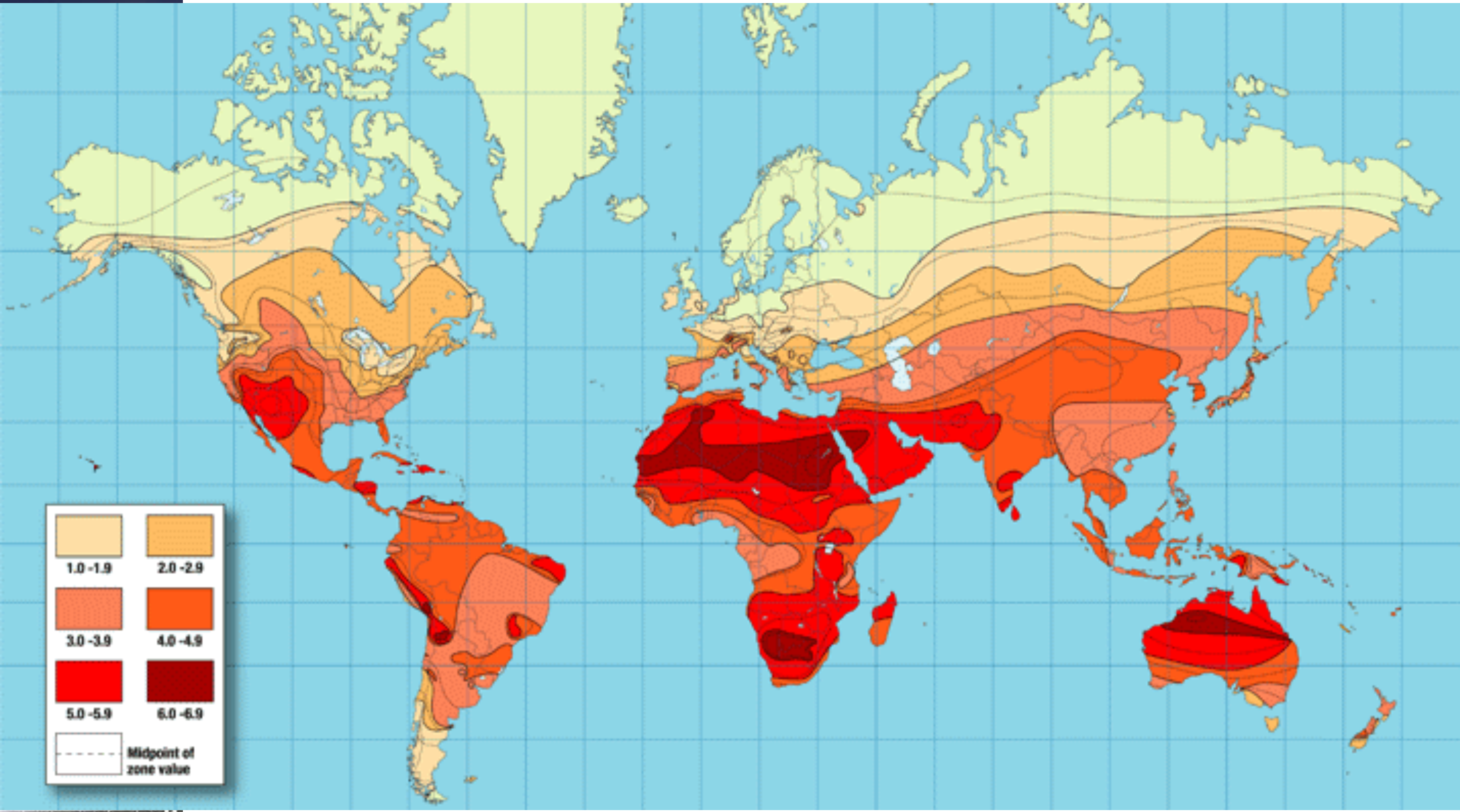
Solar Energy



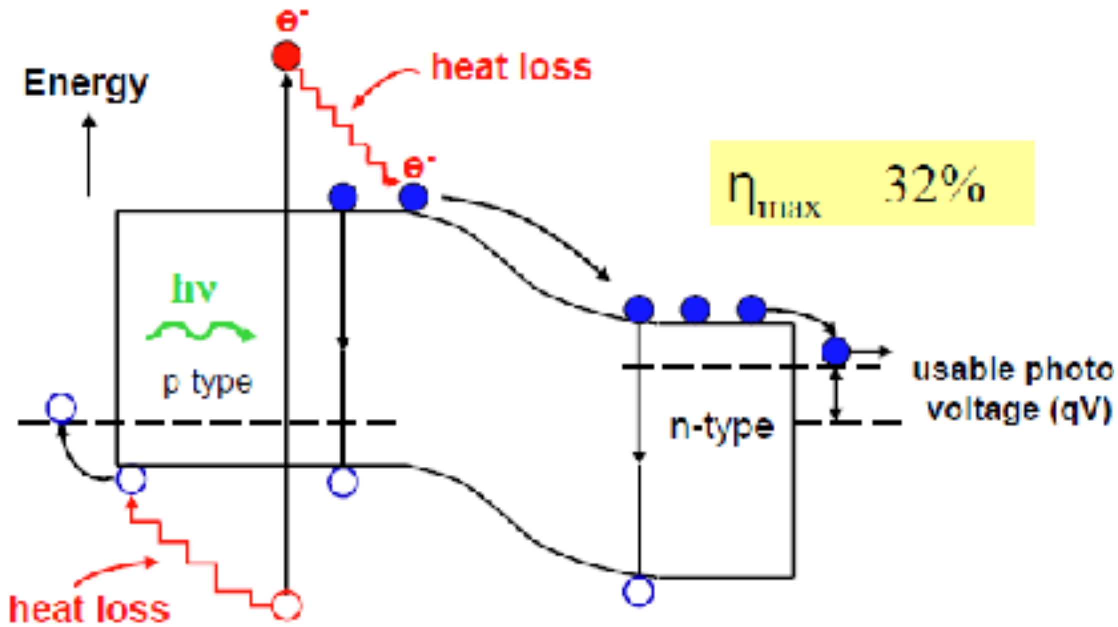
World Solar Insolation Distribution



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

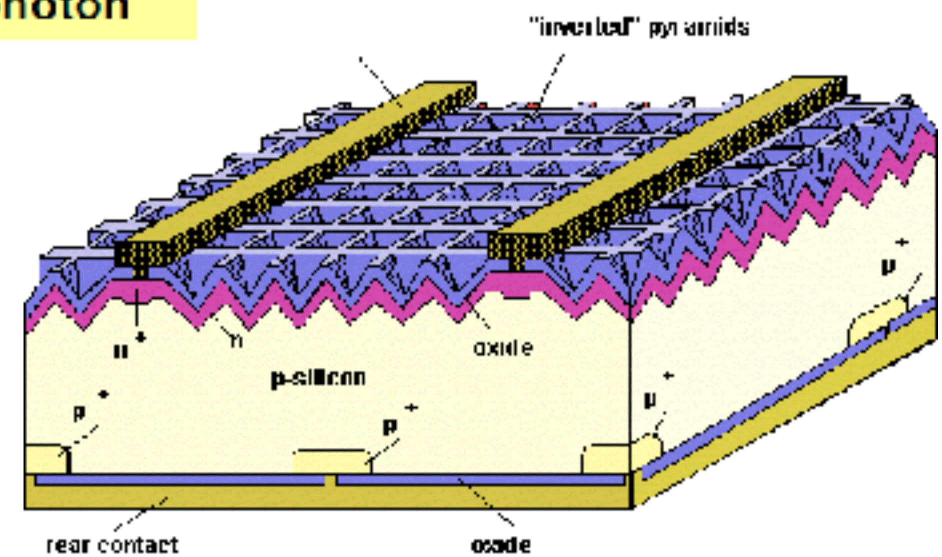
Photovoltaics (PV)



η_{max} 32%

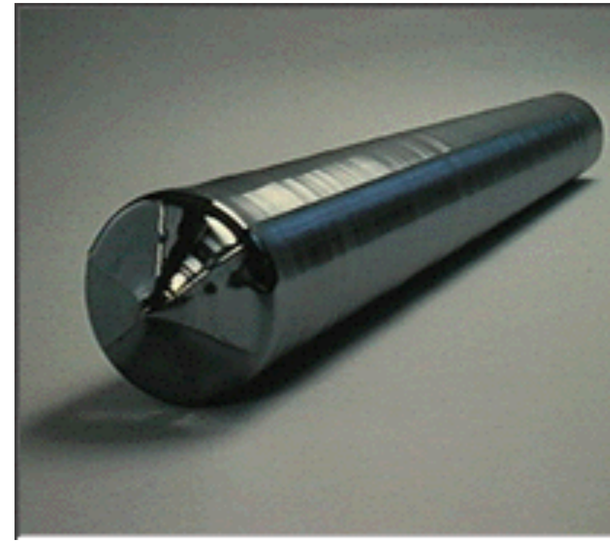
1 e$^-$ - h$^+$ pair/photon

First Generation single crystal Si PV technology

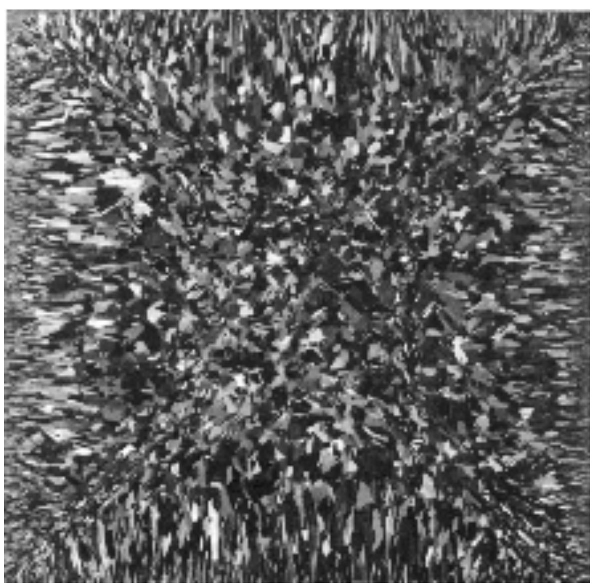


Commercial Si Solar Cells

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

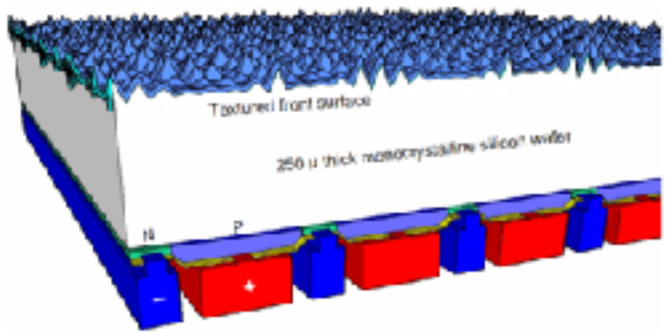


<u>Single Crystal</u>: Czochralski growth of single crystal Si ingot, sliced into wafers

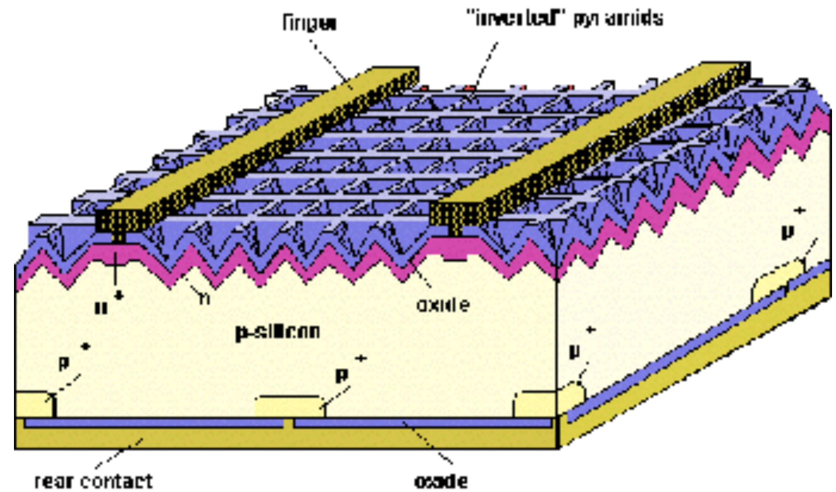


<u>Multi- or polycrystalline Si</u>: Slicing multi-crystalline silicon into blocks (followed by slicing into wafers)

High Efficiency Si Technology

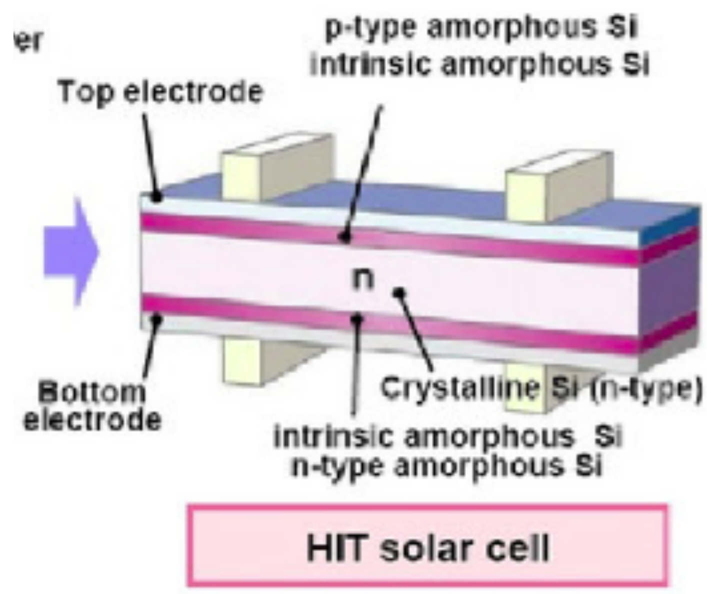


Interdigitated back contact



PERL/PERC 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**



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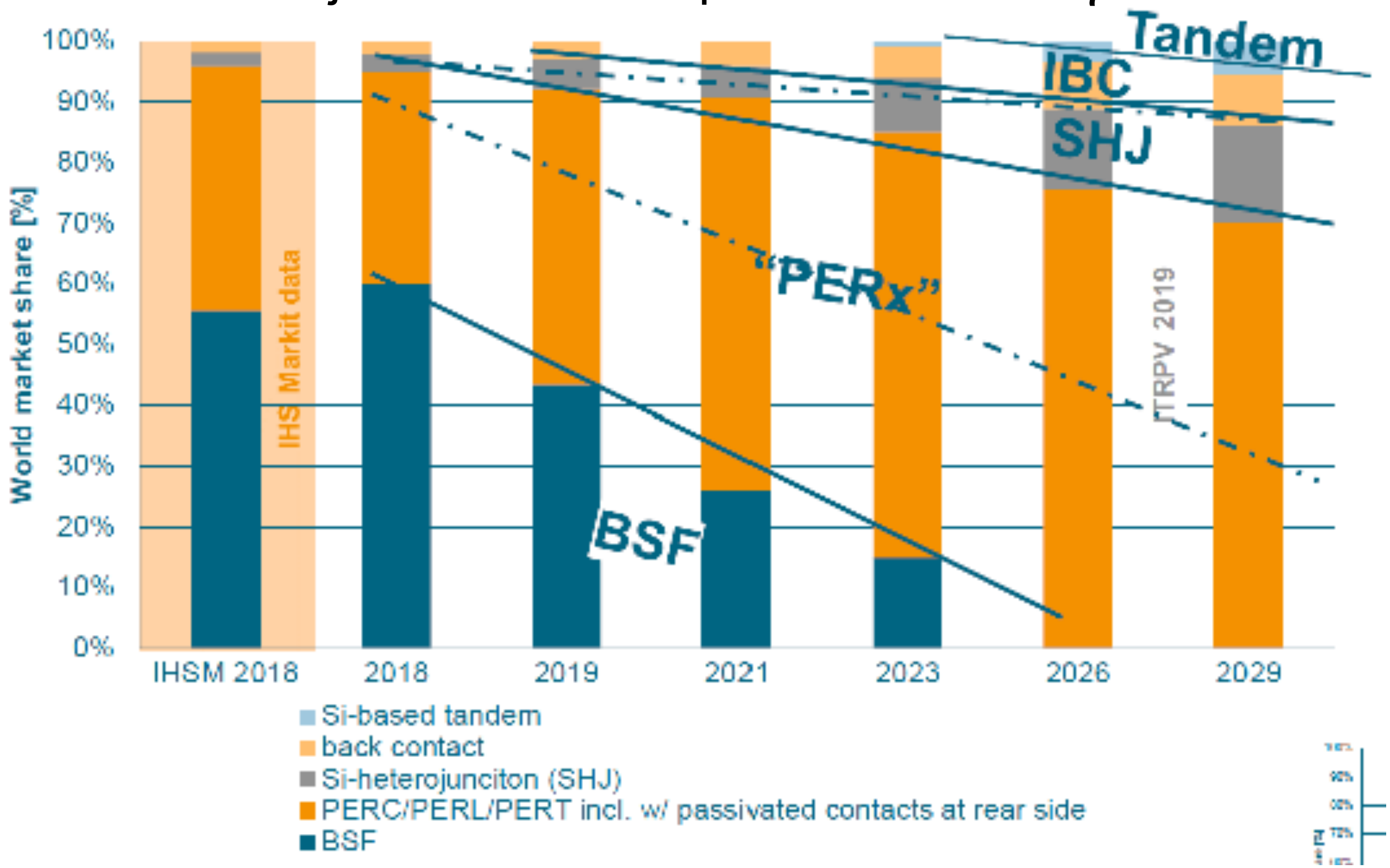
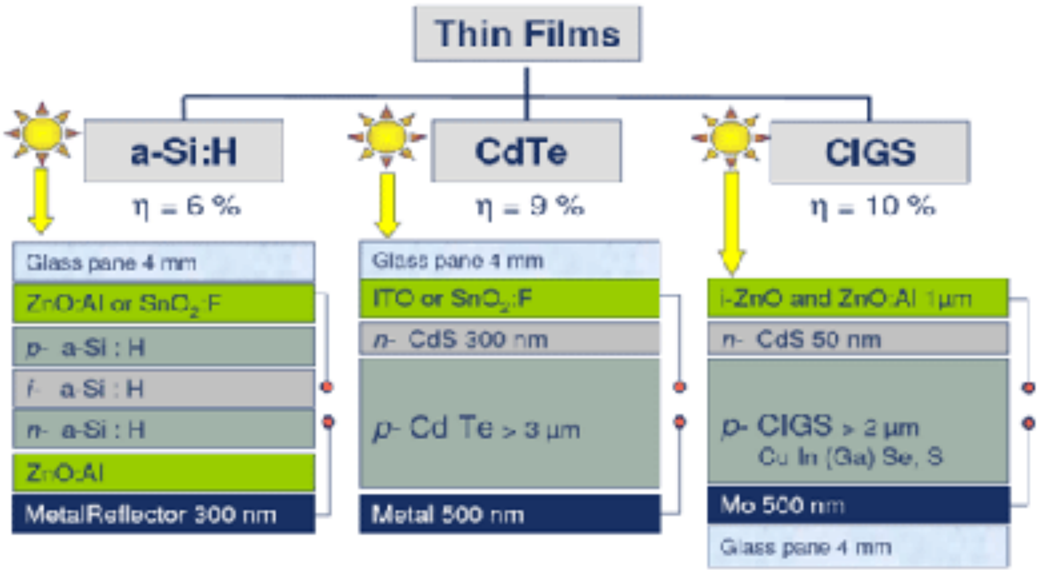
Si Photovoltaics

- Currently 95% of the world market
- Recent advances involve c-Si/a-Si heterostructures $\eta > 26.5\%$
- Approaching its theoretical efficiency limit including Auger
- Si based multijunction cells required to exceed $\eta = 30\%$



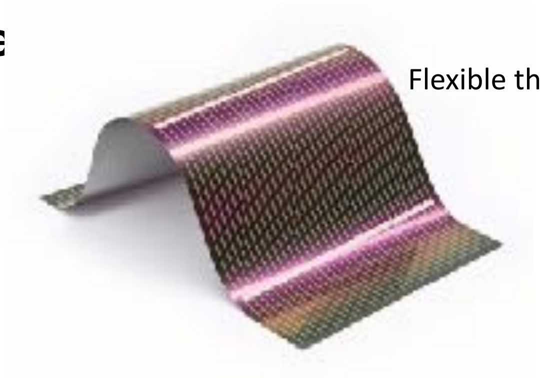
ITRPV 2019

Thin Film Solar Cells

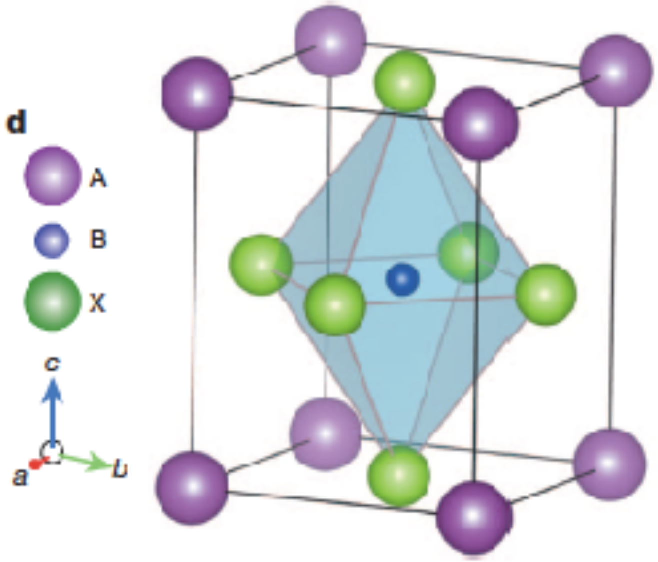


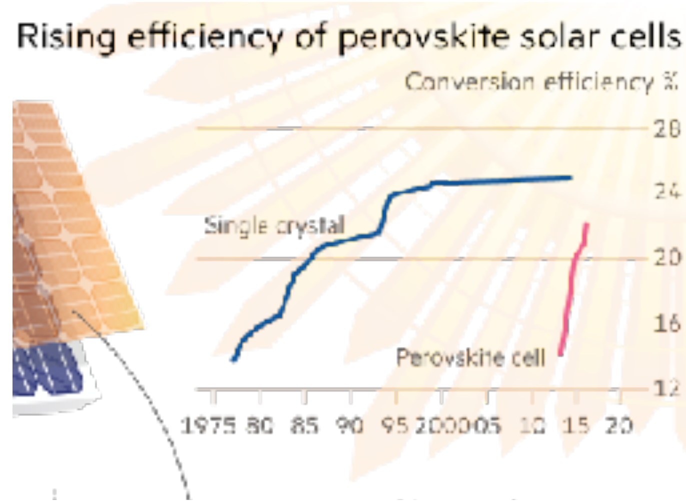

CdTe Modules
From First Solar,
Blythe Solar Project

- **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**

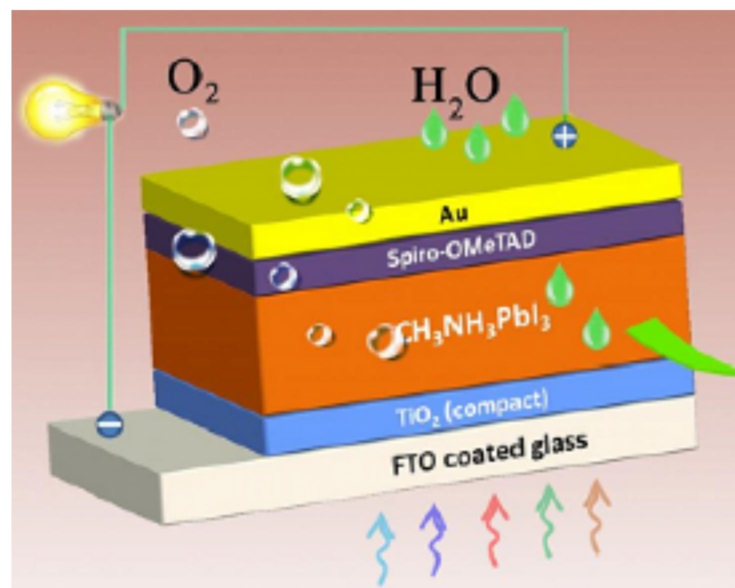

Flexible thin film

Perovskite Solar Cells

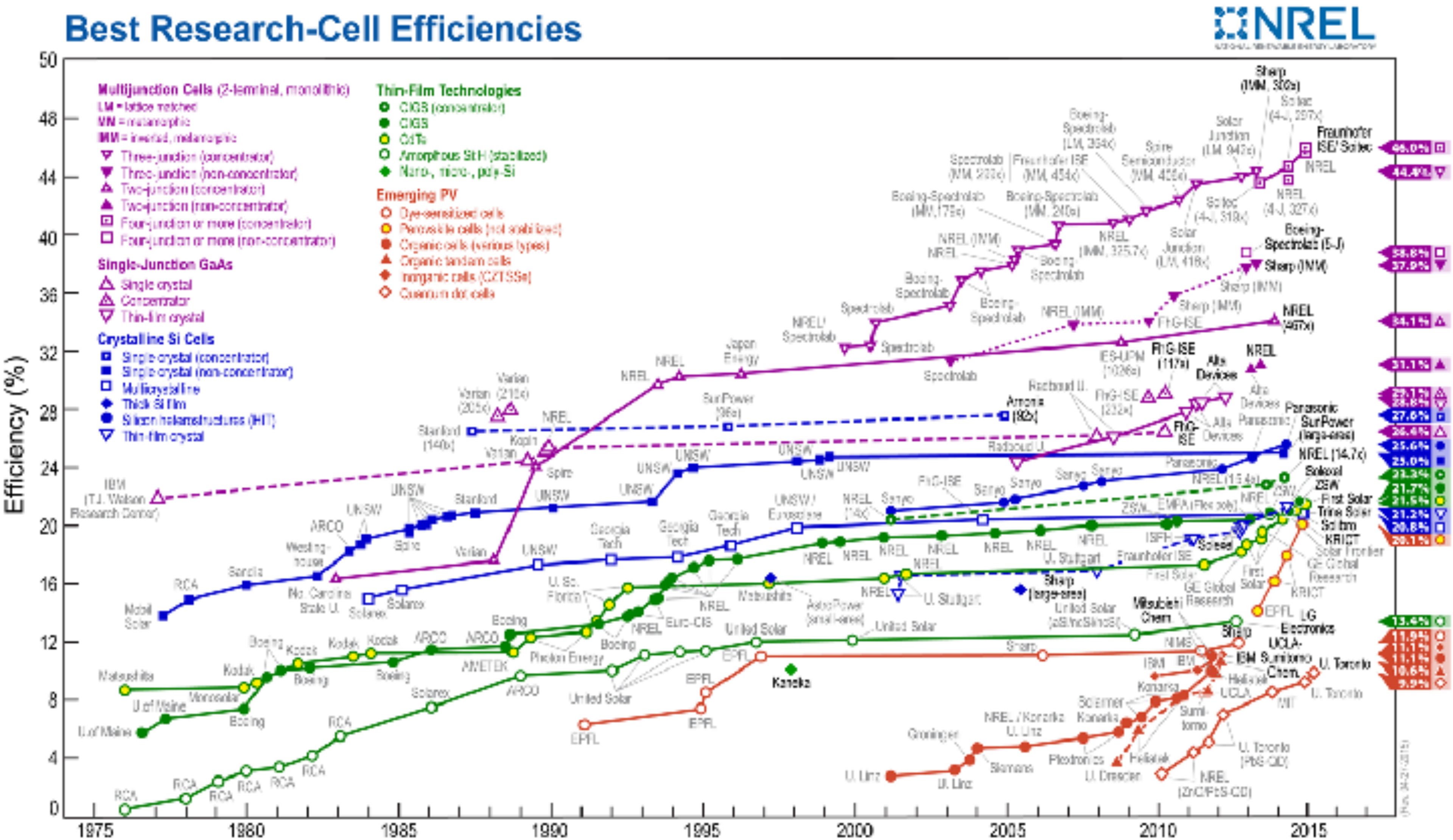




- **Hybrid organic metal halide perovskites: ABX_3- A=CH_3NH_3, B=Pb, X=I or Cl**
- **Bandgap of 1.55 eV**
- **Low cost materials, thin film processing**
- **Lifetime and reliability are main barriers to commercialization**

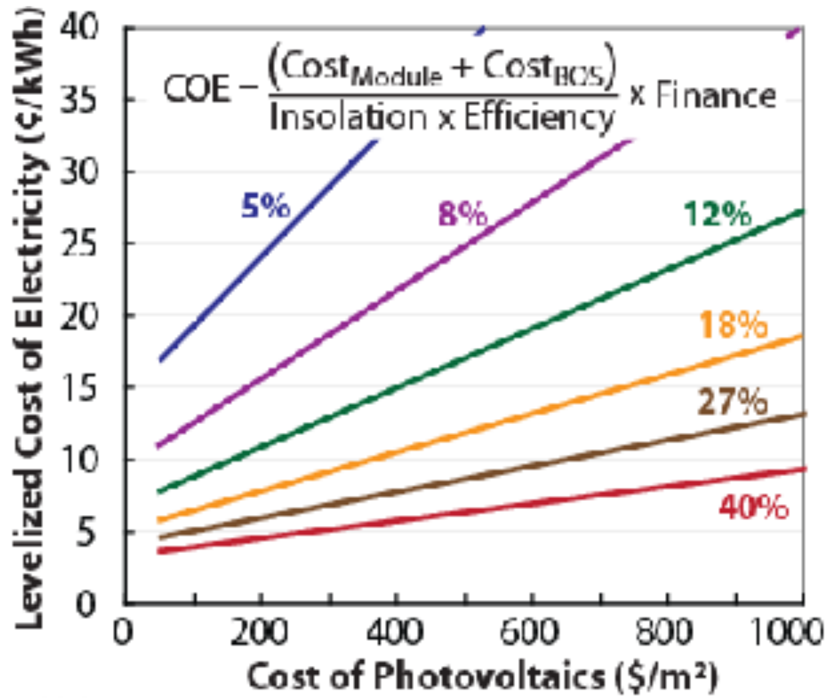


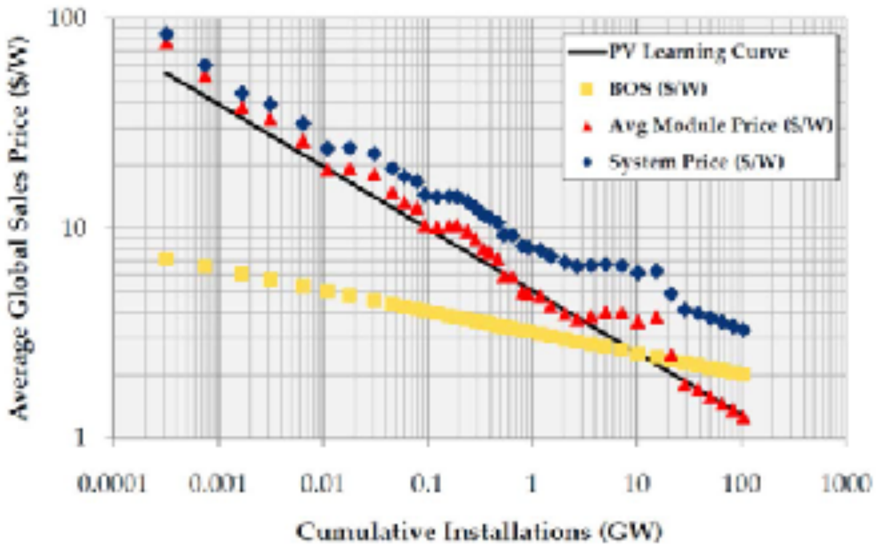
Solar Cell Efficiencies

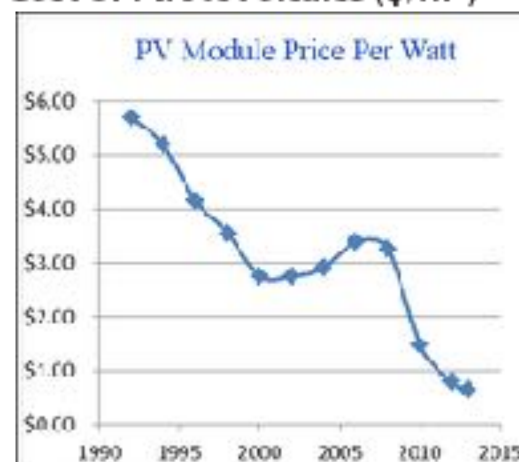


Efficiency as Critical Metric

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







Solar Modules

≈ 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.

Si Solar Modules

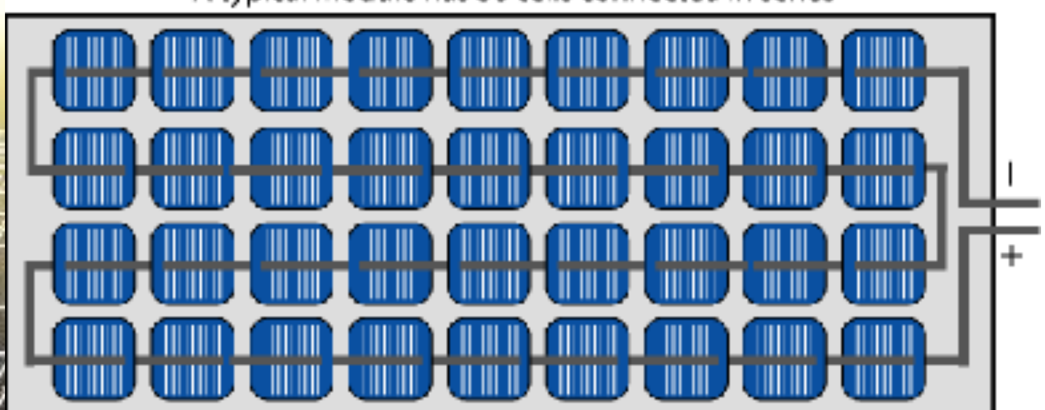
Historically, modules consisted of 36 series connected cells for battery charging (15-16V required):

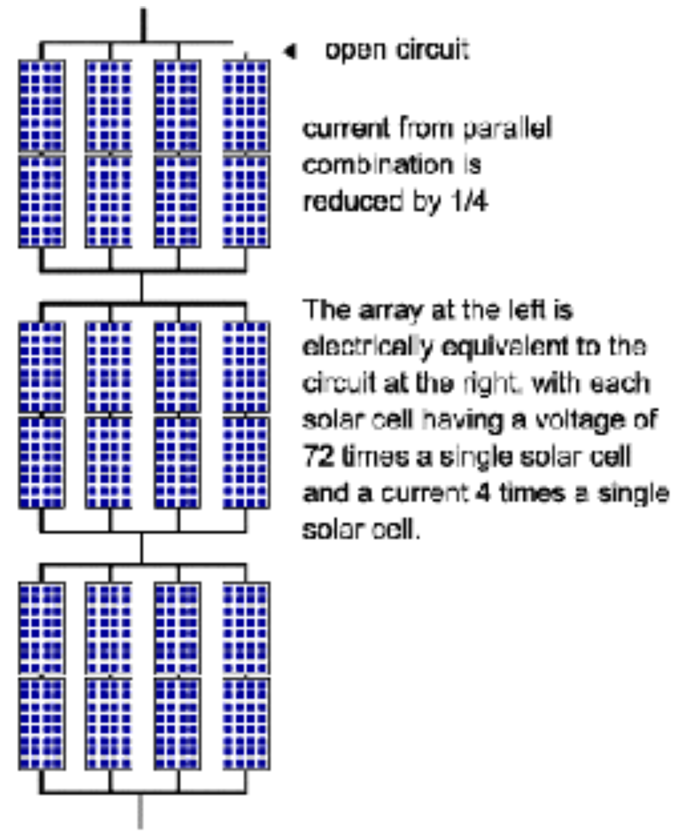
V≈ 36x0.6 = 21 volts max, and 17-18V at max power and operating temperature

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

Power ≈ 70 watts

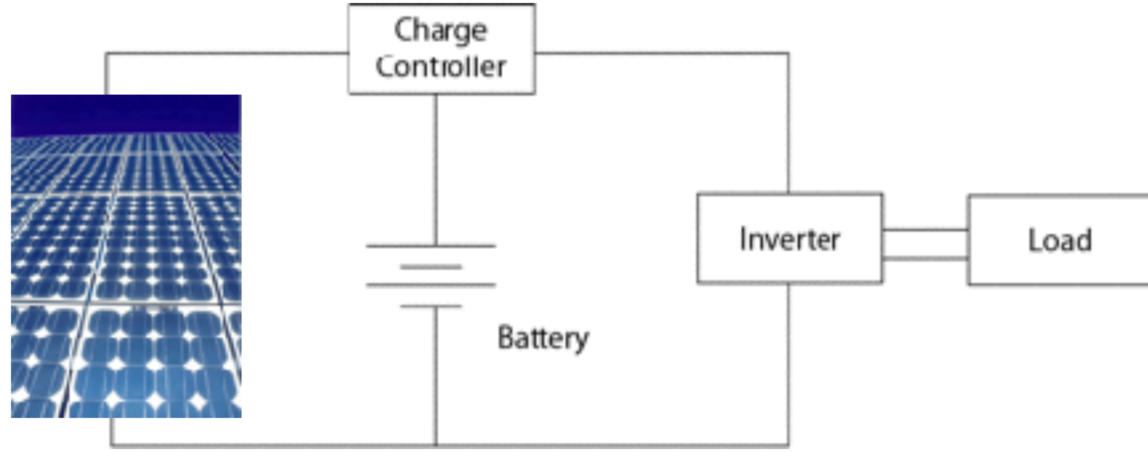
A typical module has 36 cells connected in series





Photovoltaic Systems

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

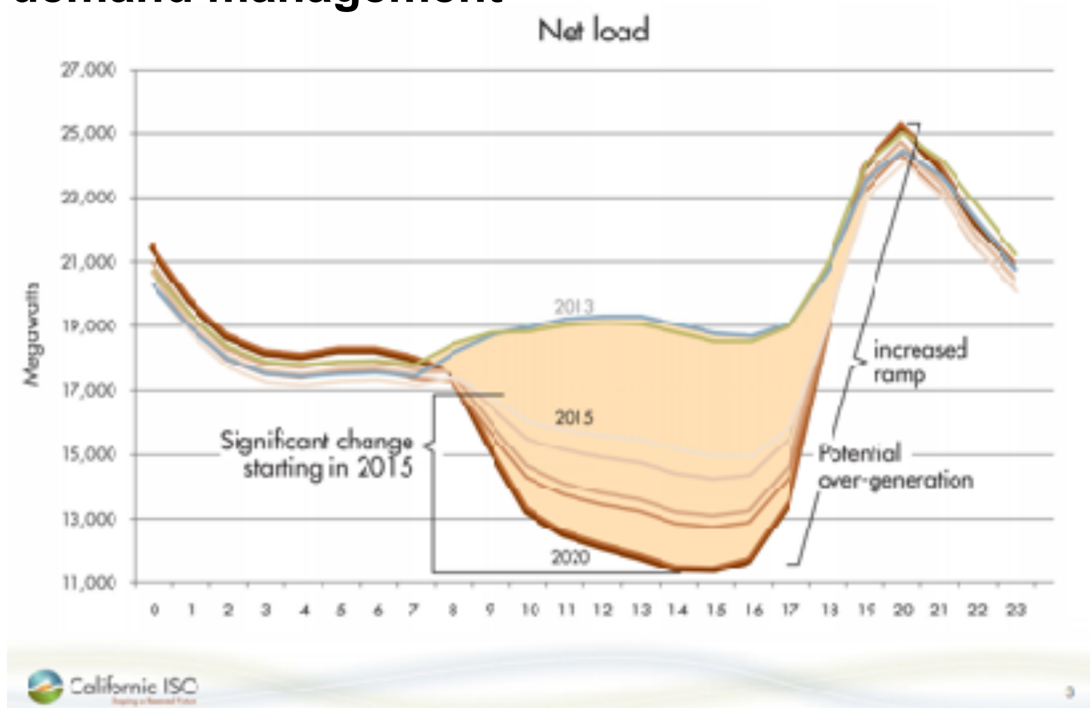


- Cost Issues:
  - Main costs are usually Module, Inverter, and BOS
  - $1/Peak Watt ($1/Wp) for the system is usually stated as overall price to reach 'grid parity'
  - However, the Levelized Cost of Electricity (LCOE) depends on several assumptions regarding system lifetime, maintanance, financing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

Challenges for PV: Intermittency

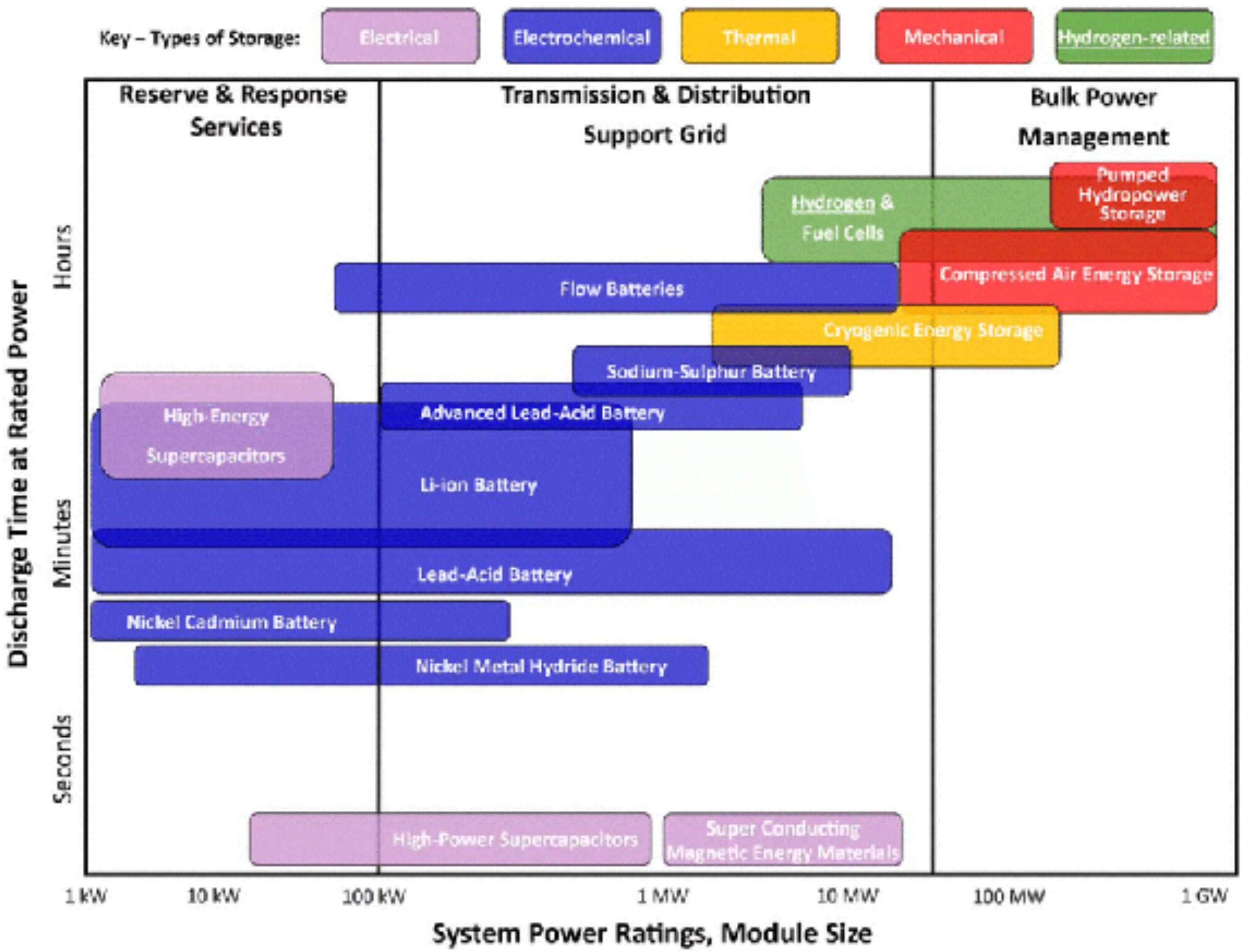
Intermittency (rapid fluctuations, diurnal, seasonal) limit penetration solar onto current grid without:

- **Storage (short term, long term)**
- **Geographic averaging, mixed renewables**
- **Load demand management**

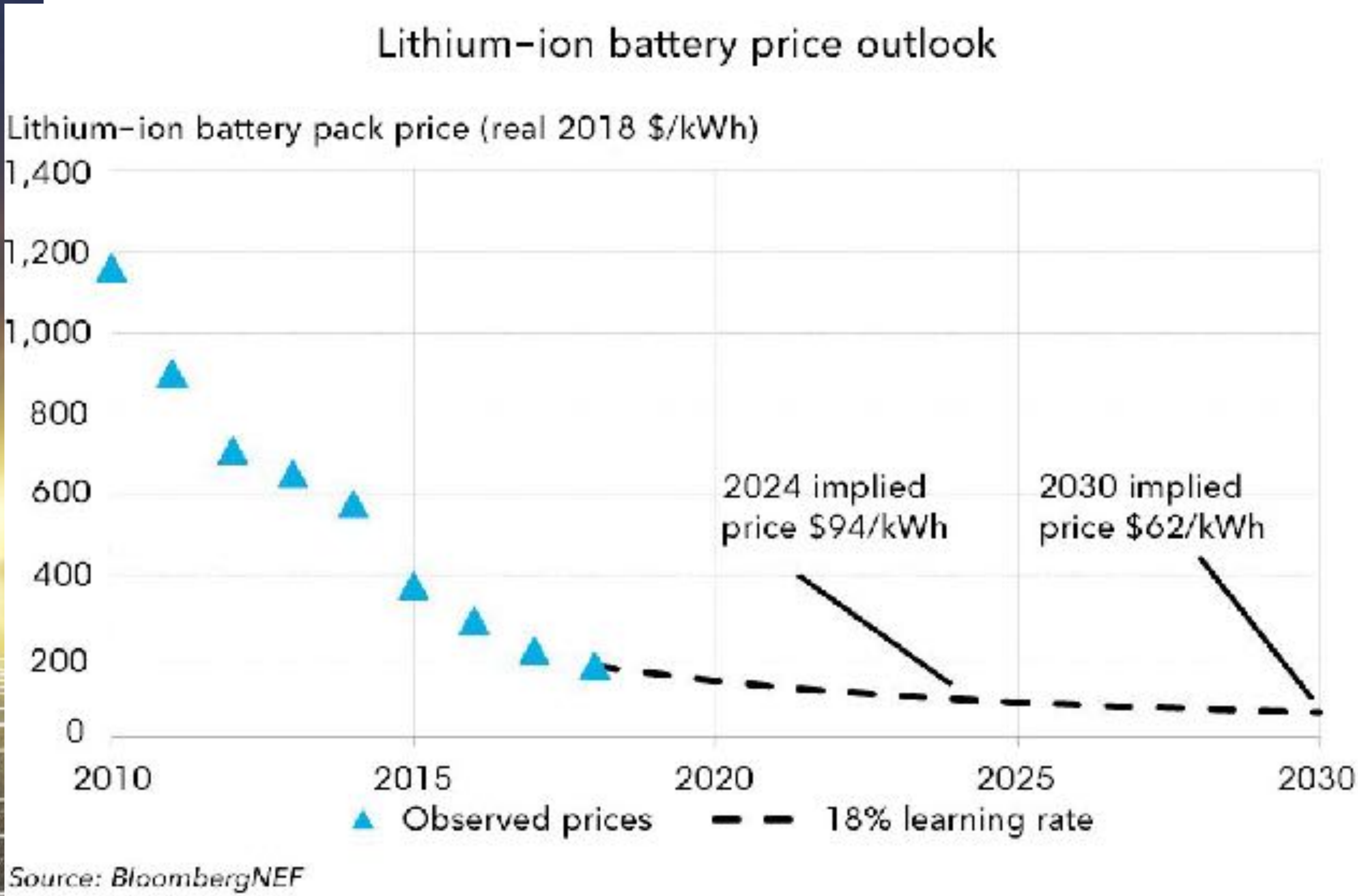


"Duck curve", showing hourly system load for a typical March day for the California ISO, less projected yearly rise in renewable (including PV) generation. Problems of increased renewables include potential over-generation in late afternoon and high ramp rates (14000 MW in ~1 hour).

Electrical Energy Storage Technologies



Electrical Energy Storage Technologies



Source: US Department of Energy

Economist.com

PV + Battery Cheaper than Gas Peakers

SOLAR-PLUS-STORAGE (/ARTICLES/CATEGORY/SOLAR-PLUS-STORAGE)

APS Plans to Add Nearly 1GW of New Battery Storage and Solar Resources by 2025

The Arizona utility says it will deploy 850 megawatts of battery storage and at least 100 megawatts of new solar generation in the coming years.

JULIA PYPER | FEBRUARY 21, 2019

The announcement provides more evidence that battery storage can beat out new gas peakers.

Arizona Utilities Commit to Zero Carbon Future

Our Clean Energy Commitment

APS January 2020

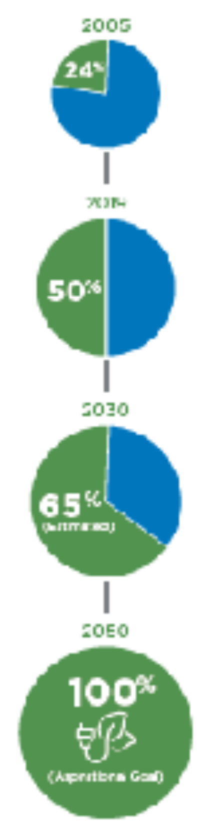
Our clean energy commitment consists of three parts:

- A **2050 goal** to provide 100 percent clean, **carbon-free electricity**
- A **2030 target** of achieving a resource mix that is **65 percent clean energy**, with 45 percent of our generation portfolio coming from renewable energy
- A commitment to **end our use of coal-fired generation by 2031**

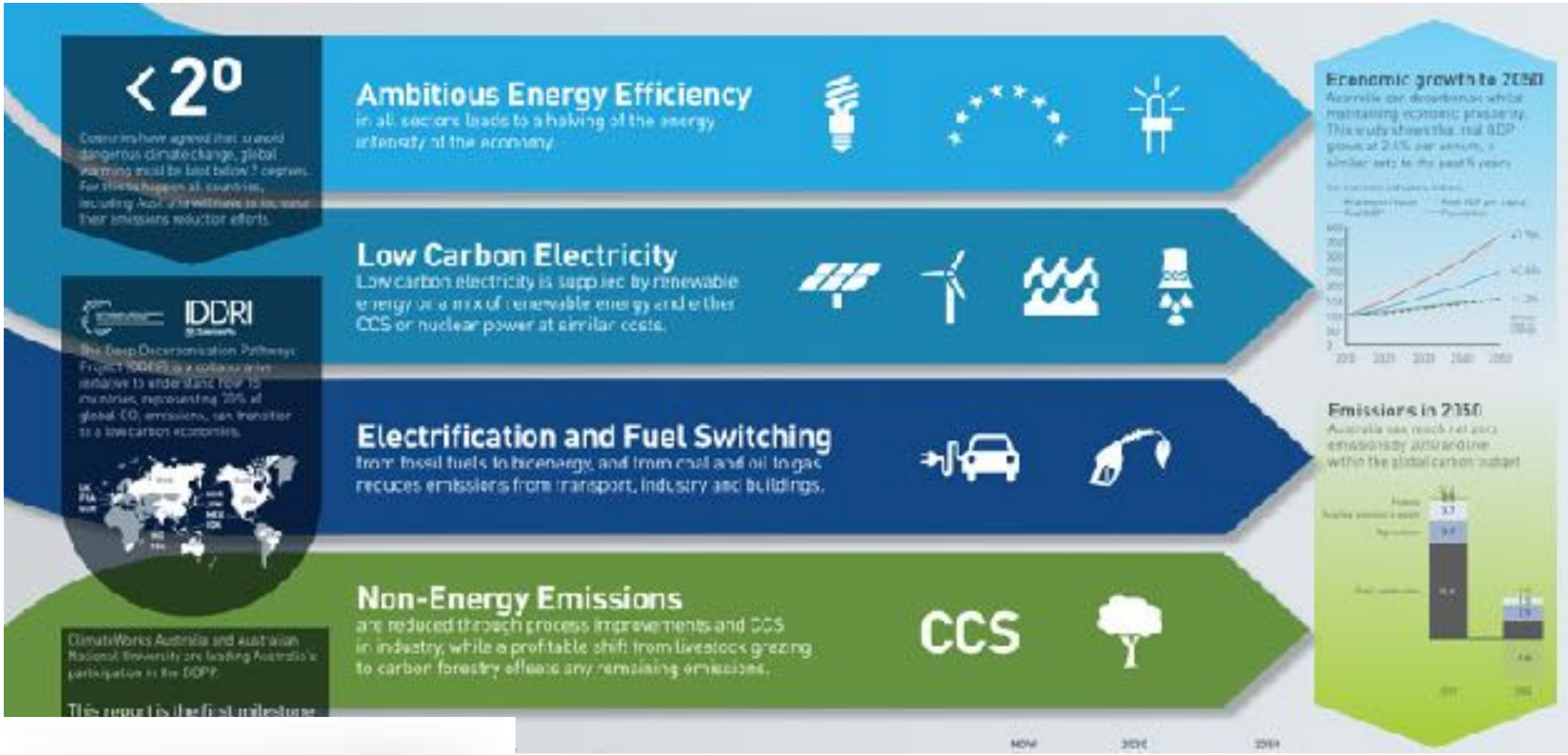
Our Goal: 100 Percent Clean, Carbon-Free Electricity

Our customers and stakeholders want clean energy, and we are listening. Working together, we are advancing Arizona's clean energy future. We plan to achieve a fully clean, carbon-free energy mix by 2050 to ensure Arizona remains a healthy and beautiful place to live and work. This goal is science-based and supports continued growth and economic development while maintaining affordable prices for our customers.

CLEAN ENERGY PATHWAY



Zero Net Carbon Future



Low Carbon Electricity

Renewables + Storage

- Short term- batteries
- Long term, seasonal- solar fuels, e.g. H

Nuclear

Summary

- Photovoltaics and wind are the fastest growing renewable energy technology
- Photovoltaics 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., and characterized in terms of storage time
- Zero-carbon goals being increasingly adopted in electricity generation sector, particularly in western US
- Advances in renewables + storage needed to meet zero carbon goals

Acknowledgements

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