The Sun Is Ready to Make Your Electricity Greener and Cheaper in Wisconsin

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Advanced Materials for Energy and Electronics Group

@ UW-Madison

Why doesn't my electricity come from the sun?

Future materials for harnessing solar energy

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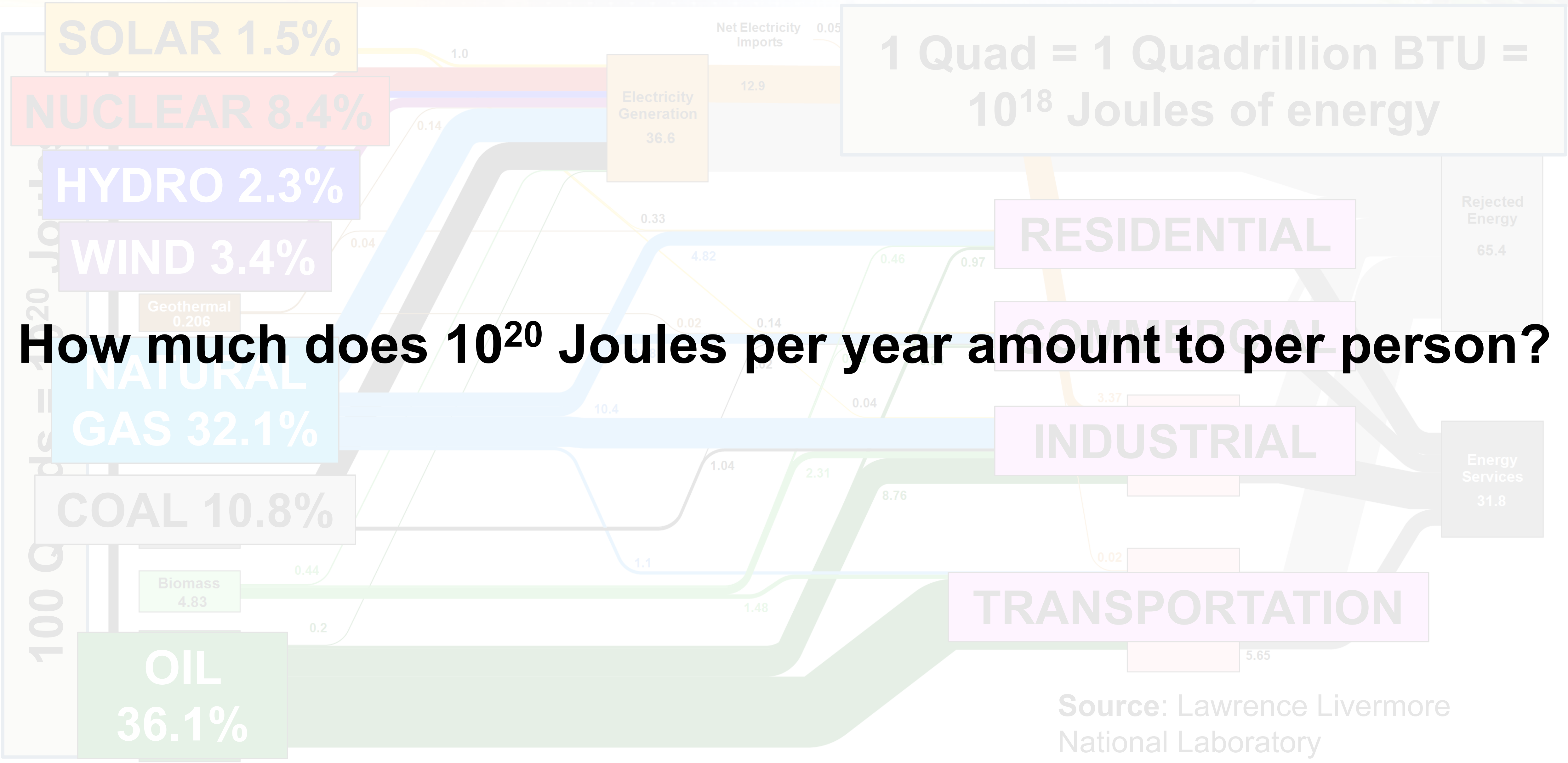
Outline

- **The sun as a source of energy**
- How does a photovoltaic solar cell work?
- Types of solar cells and their efficiencies
- Economics of solar cells then and now
- Solar in Wisconsin
- The future

2019 U.S. energy production (Quads)



How much does 10^{20} Joules per year amount to per person?

Source: Lawrence Livermore National Laboratory

Energy consumption per person

- Per person = **3×10^{11} Joules per year per person**

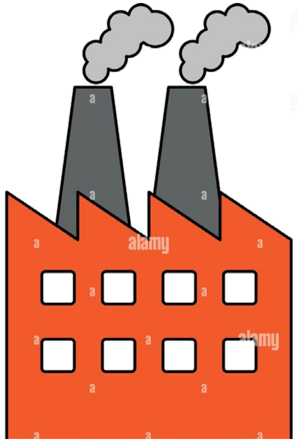
  QUESTION: When you curl a 20 lb. dumb-bell and lift it about 3 feet, how much energy does it gain?

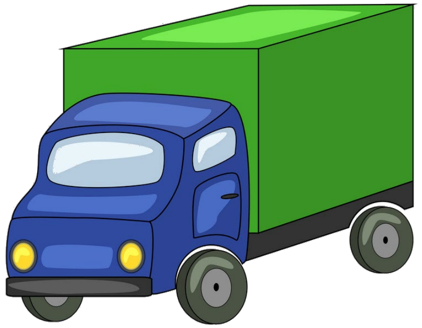
  ANSWER: About 100 Joules.

Your energy consumption

100 Joules

300,000,000,000 Joules





Your energy consumption

- You would need to lift this 20 lb. dumb-bell **3 billion times** a year in order to supply your own energy (assuming your efforts could be harnessed with 100% efficiency).

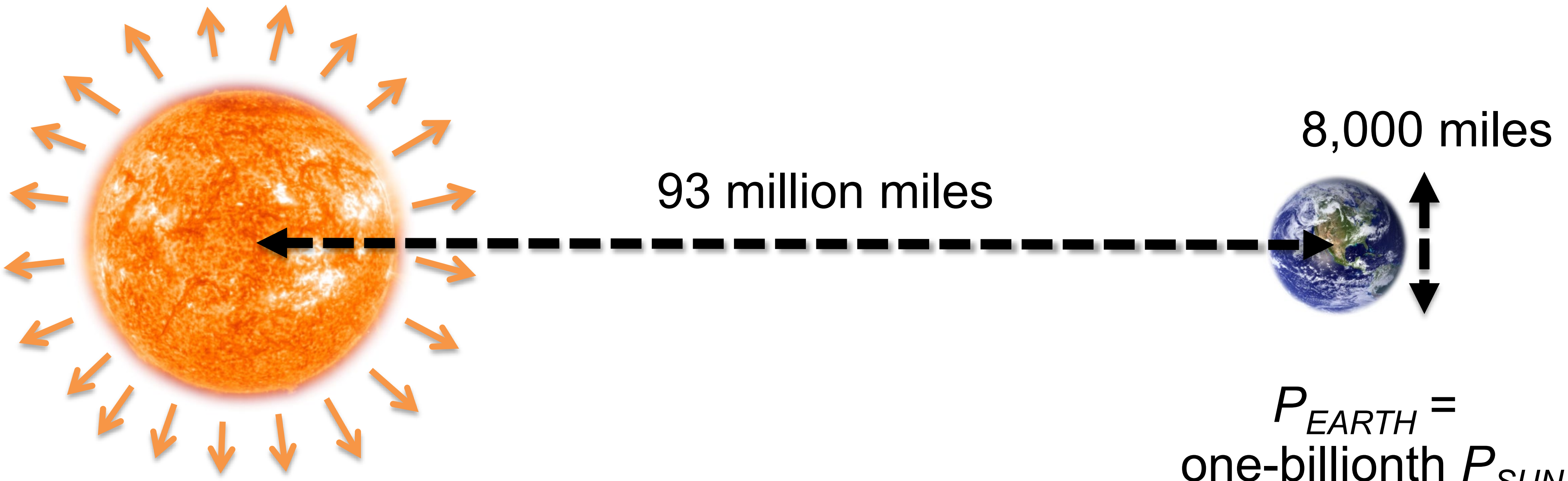
340,000 times an hour

Power = energy per time

- U.S. Energy consumption
  = 10^{20} Joules per year
  = 10^{20} Joules per 31.6 million seconds
  = 3×10^{12} Joules per second
  = 3 Trillion Watts
  = **3 TW** (3,000,000,000,000 Watts)
- Worldwide
  = **18 TW** (18,000,000,000 Watts)

Is the sun a viable source for supplying humankind with 18 TW of power?

Yes. The energy from the sun is enormous.

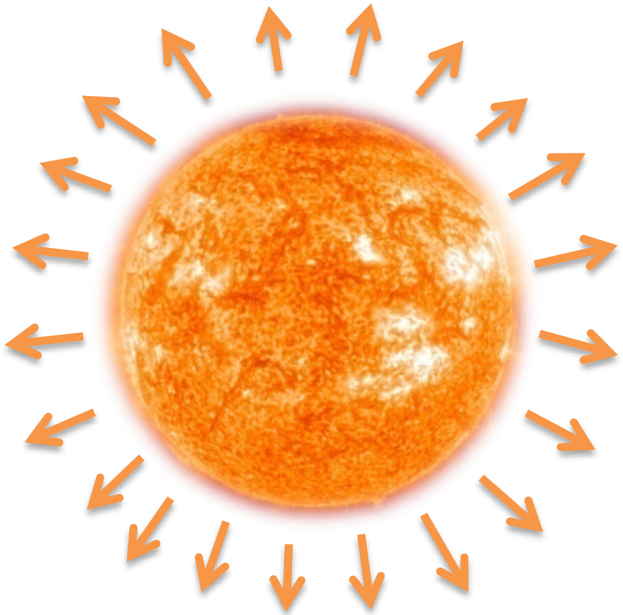


T = 6000 K
P_{SUN} = 3.9×10^{26} Watts

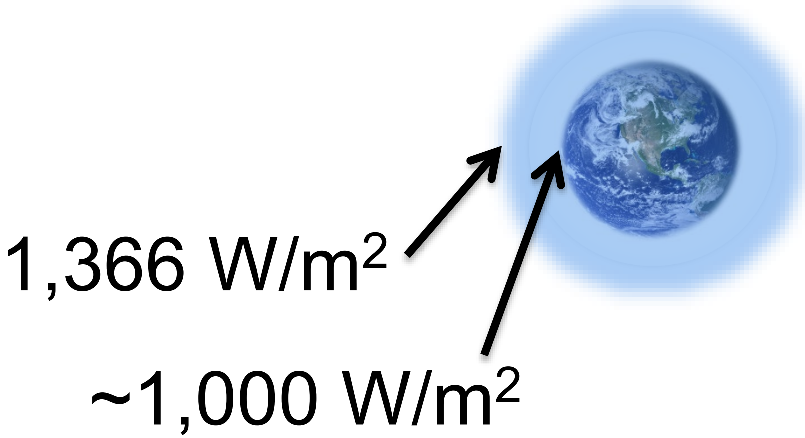
P_{EARTH} =
one-billionth P_{SUN}
= 3×10^{17} Watts
= 300,000,000,000,000,000 Watts
Global needs = 18,000,000,000,000 Watts

Image of sun:
http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

~1000 Watts per meter-by-meter area on sunny day



Peak intensities:



Averaging over the seasons and day and night?

- **Geography and climate-dependent**: considering clouds, four seasons, day and night

Peak intensity:

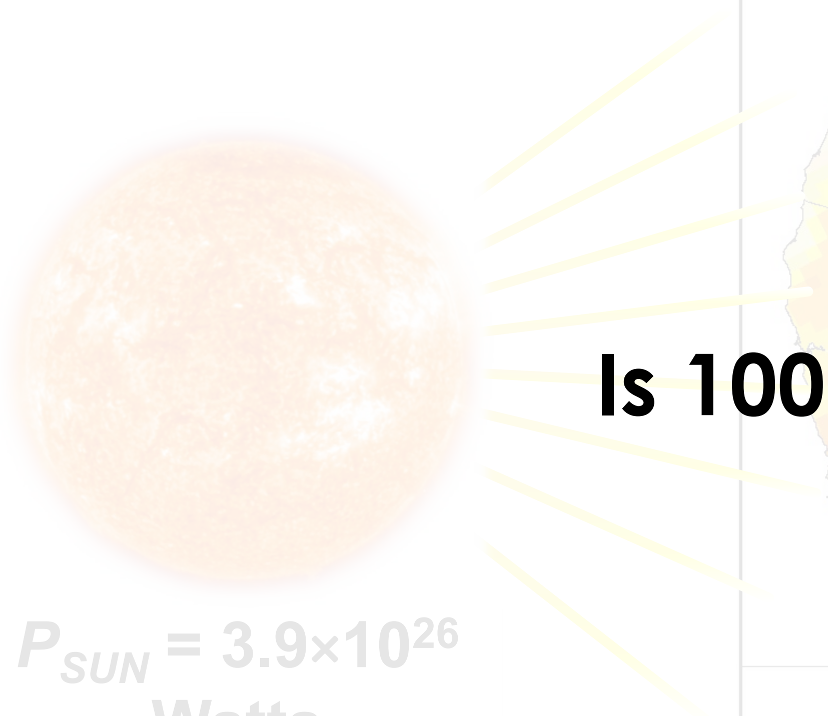
~1,000 W/m^2

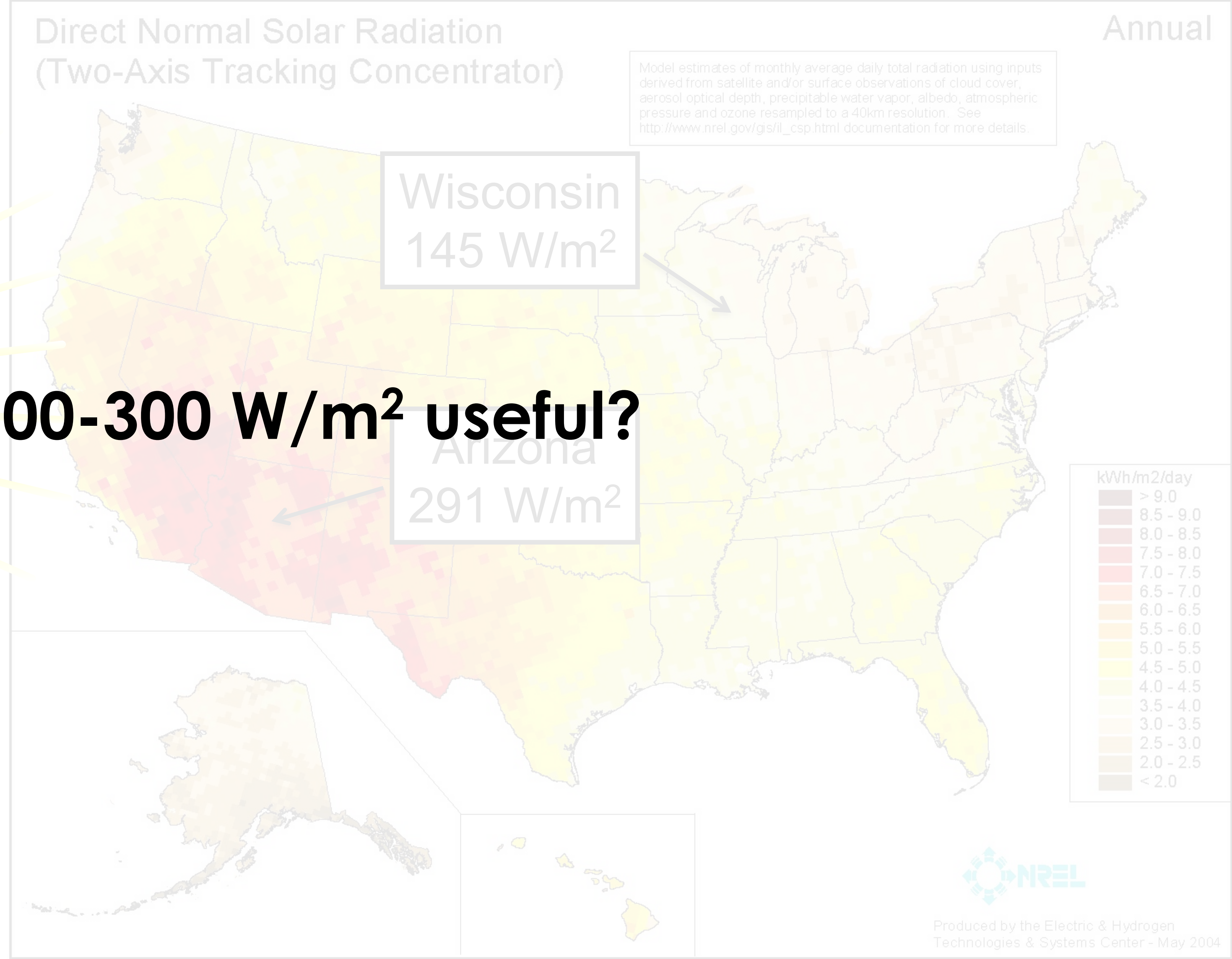
Average intensity:

~100-300 W/m^2

Image adapted from: https://science.howstuffworks.com/nature/climate-weather/atmospheric/climate-change-four-seasons-redefine.htm

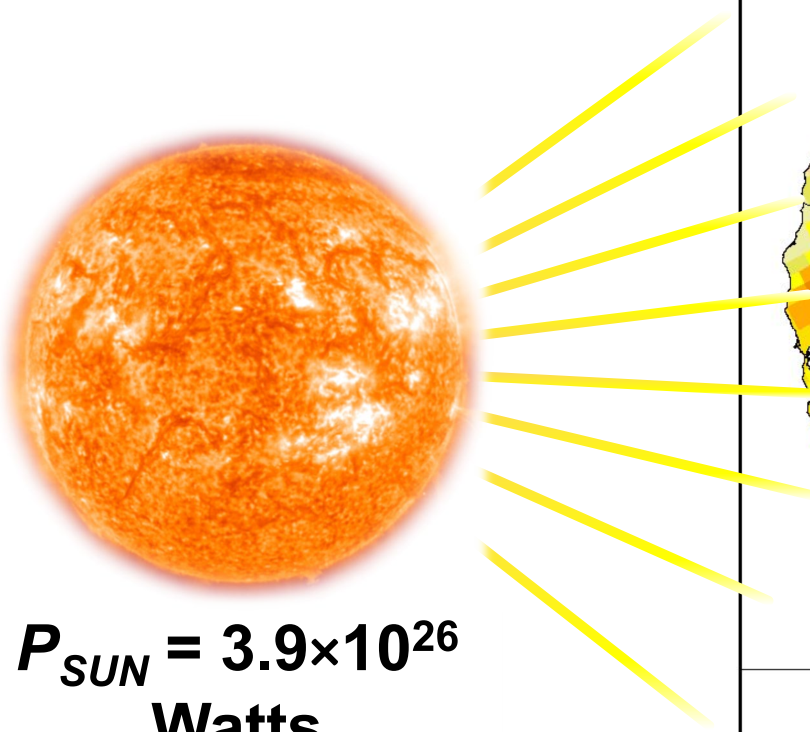
Map of average intensity in U.S.



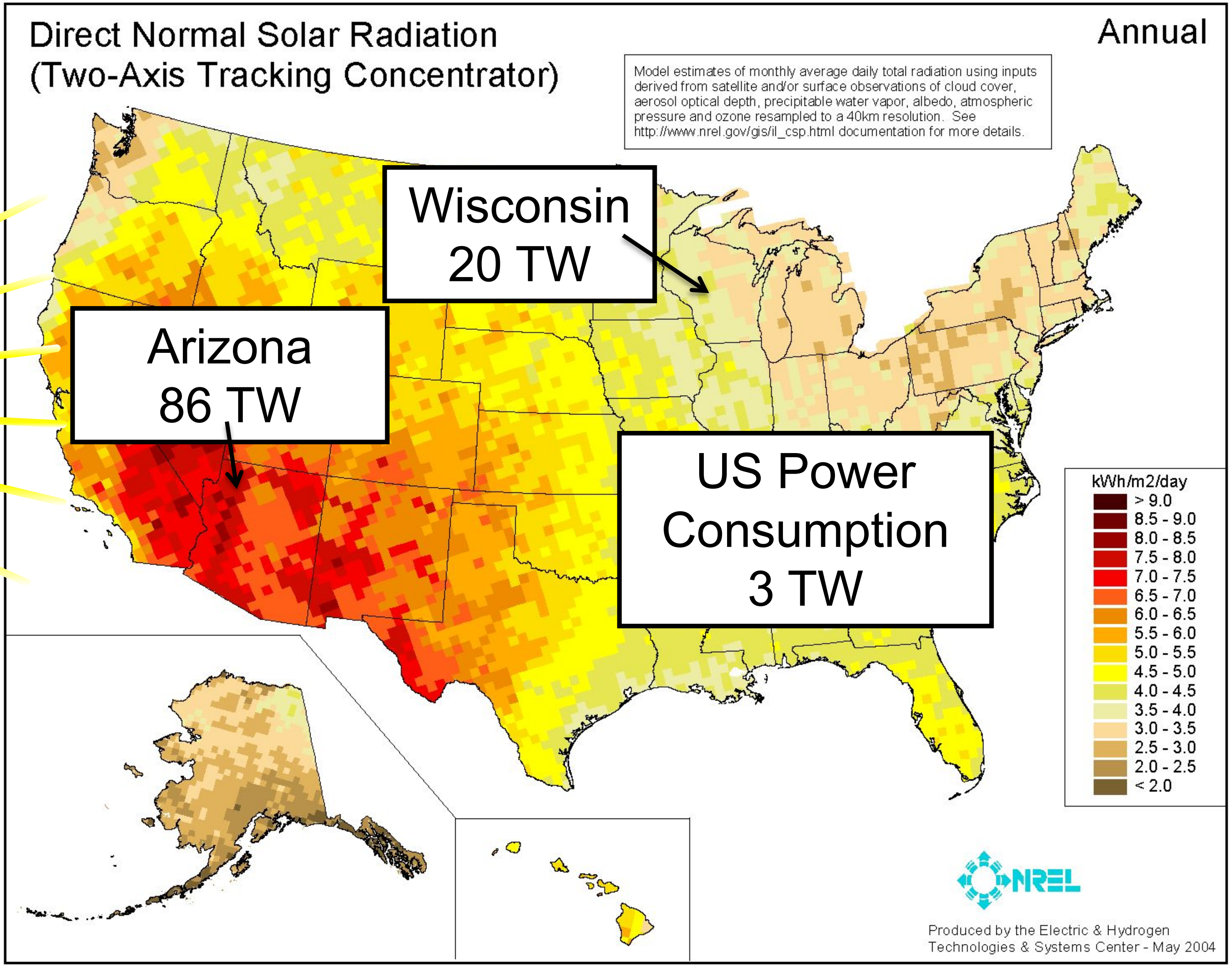


Is 100-300 W/m^2 useful?

Yes, when summed over the entire state.



$P_{SUN} = 3.9 \times 10^{26}$ **Watts**



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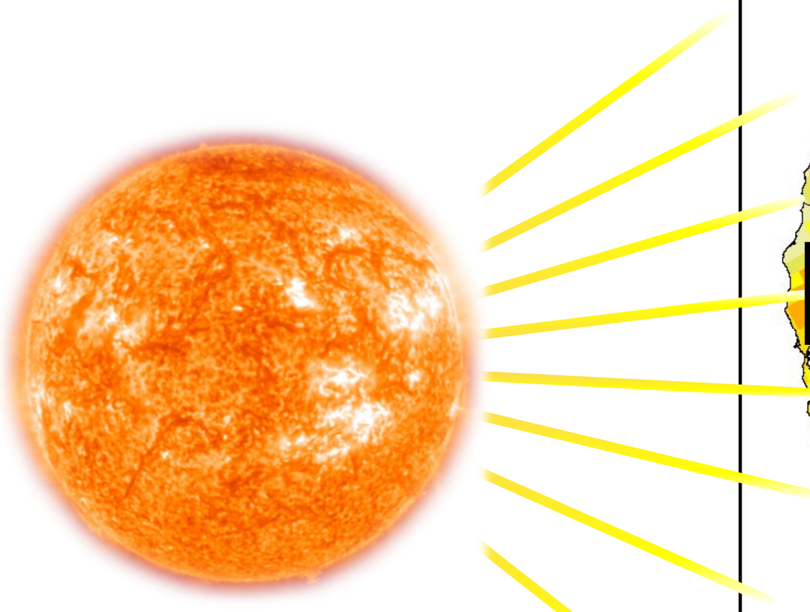
Small fraction of land-area needed to cover energy needs.



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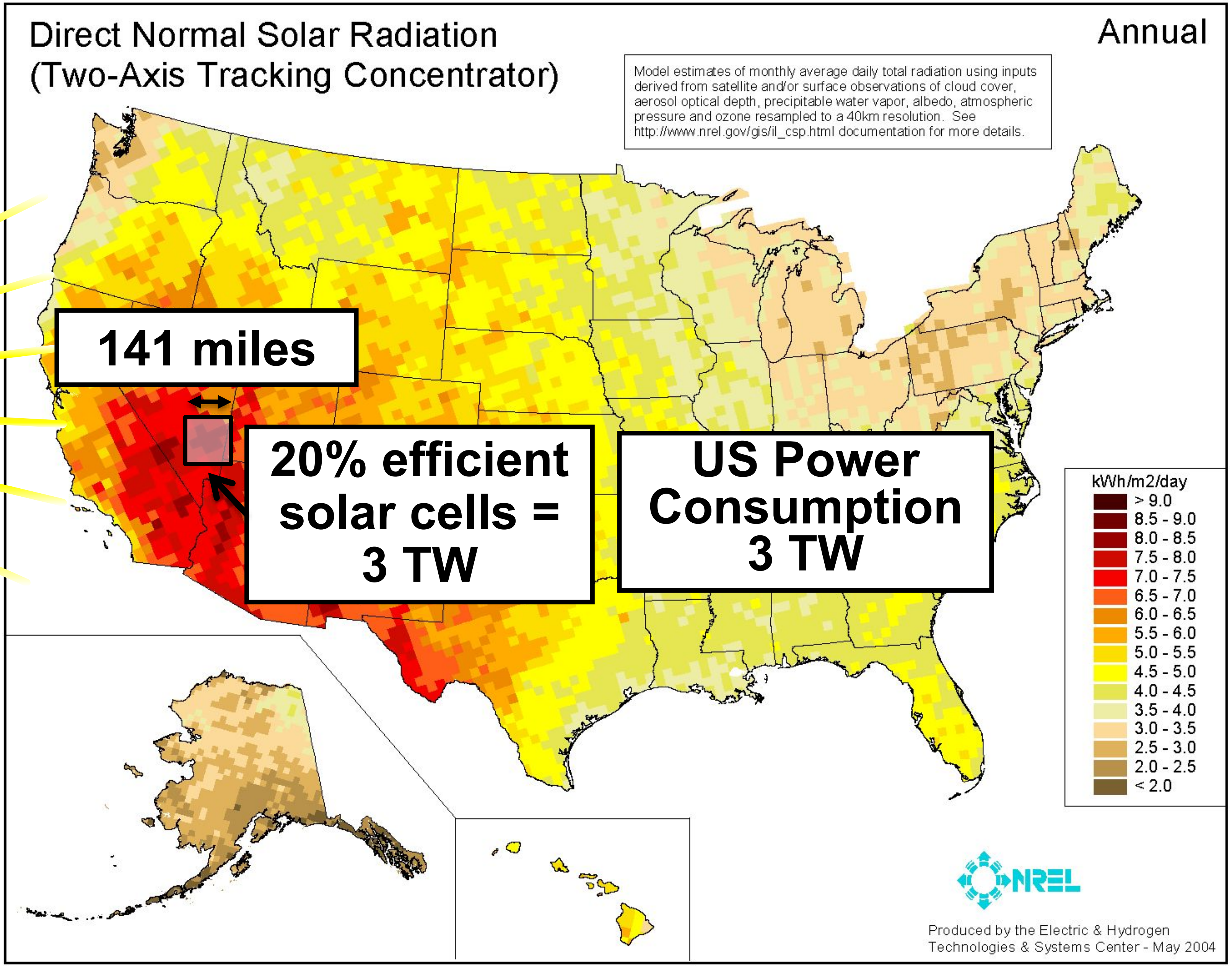

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Conclusions about solar resources

- Humankind's energy needs are enormous.
- The energy we receive from the sun is more enormous.
- Sunlight could power our society if the proper technology were available and affordable.

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- Types of solar cells and their efficiencies
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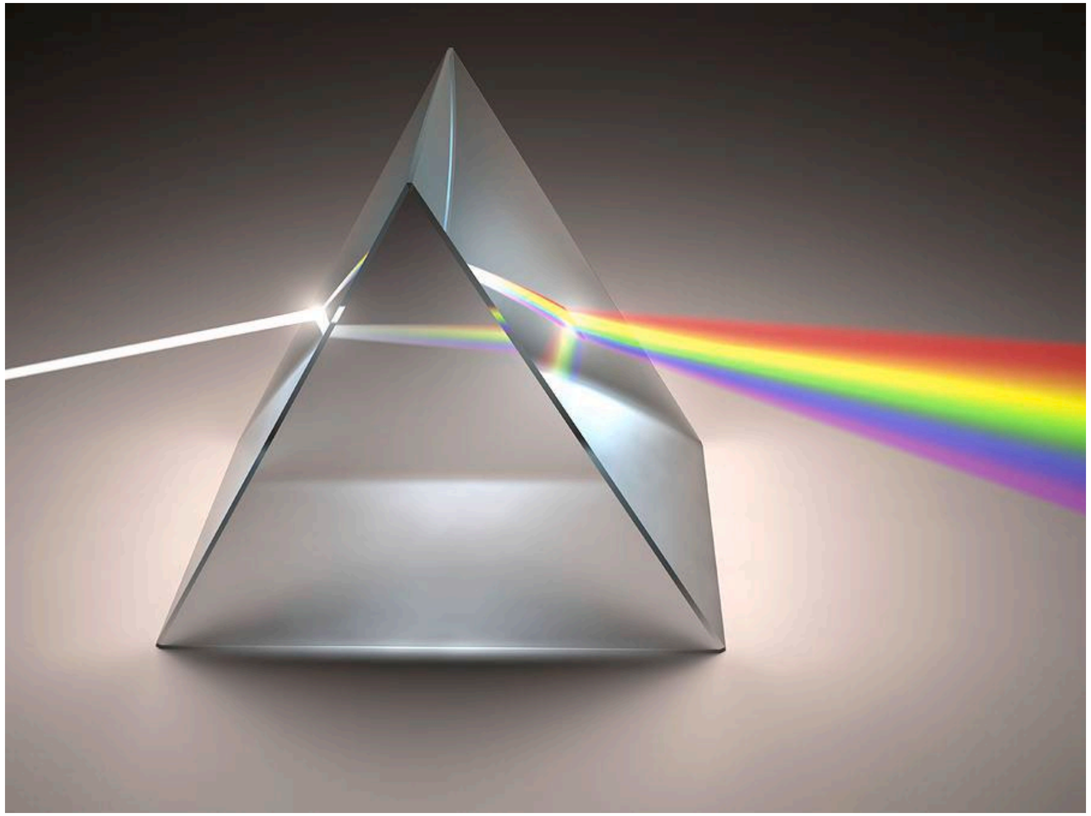
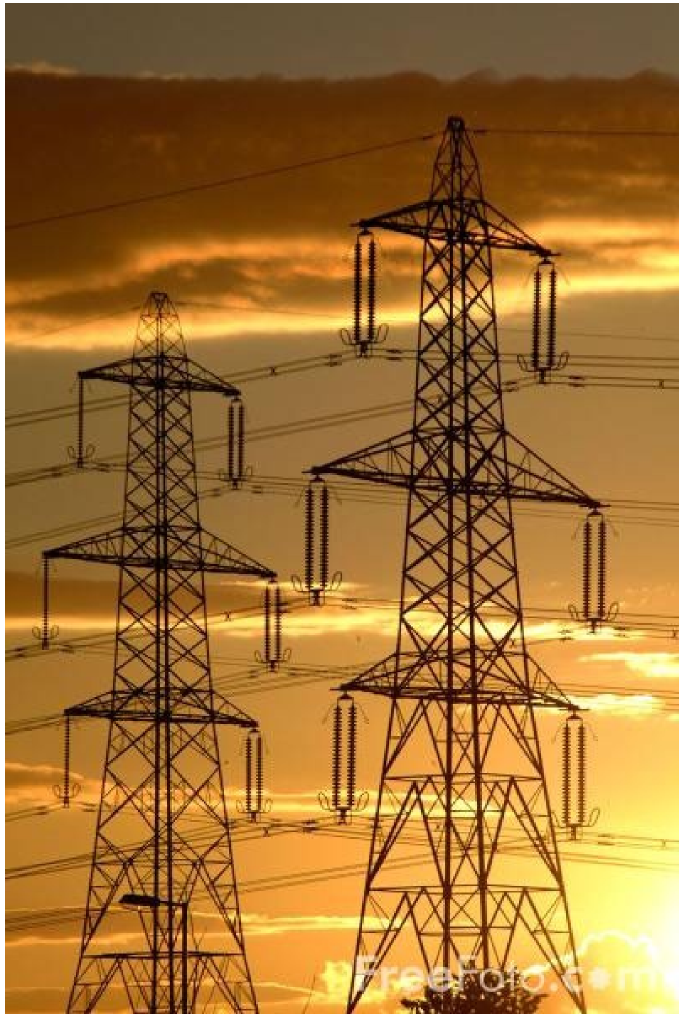
Photovoltaic solar cells are the technology we need to convert sunlight into electricity.



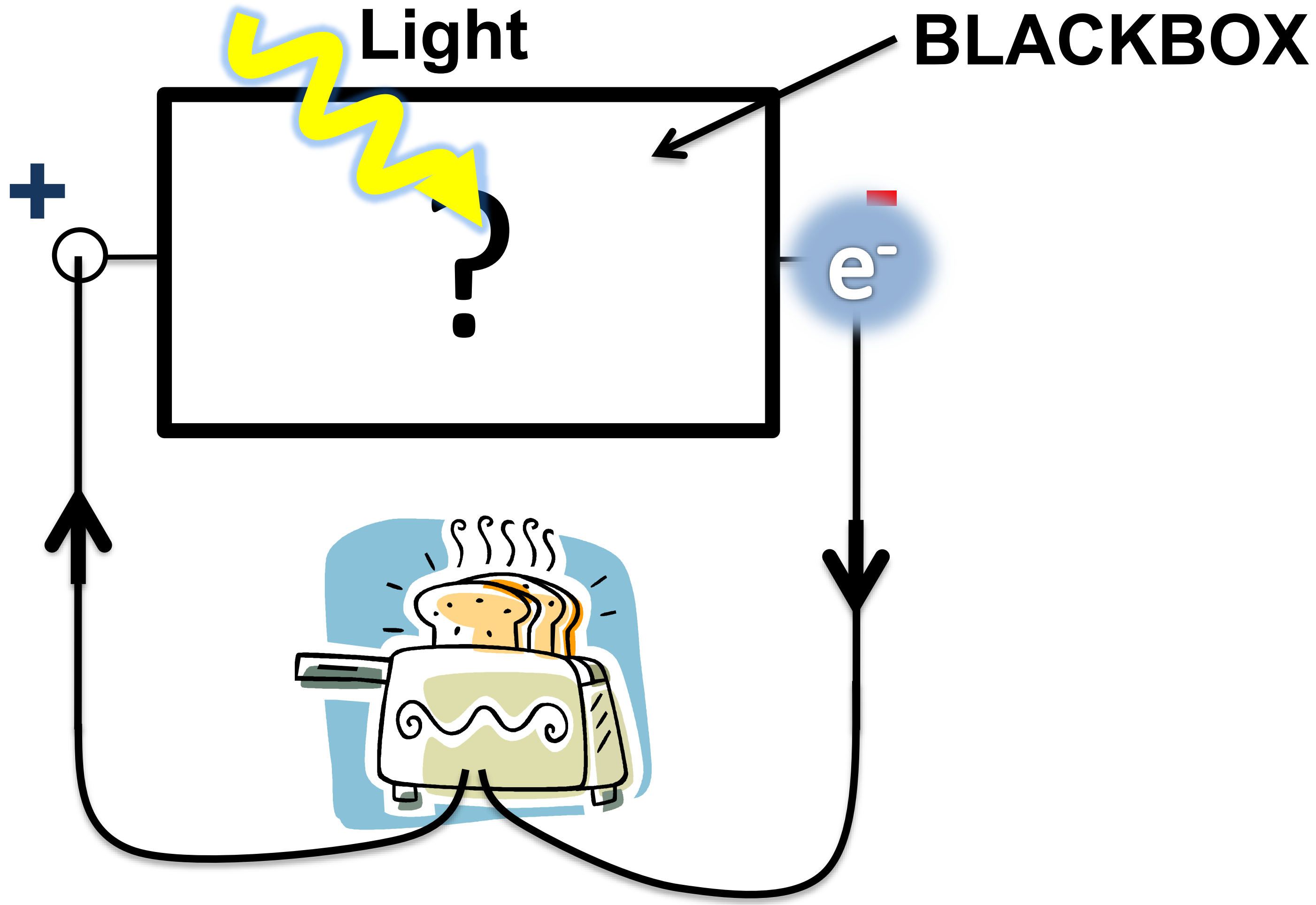
Light



Electricity

www.freefoto.com

What is a solar cell made from?



What is a solar cell made from?

- At heart: **<u>a semiconductor</u>**
  - Silicon is most common
- Also: inactive components such as metal, glass, structural materials

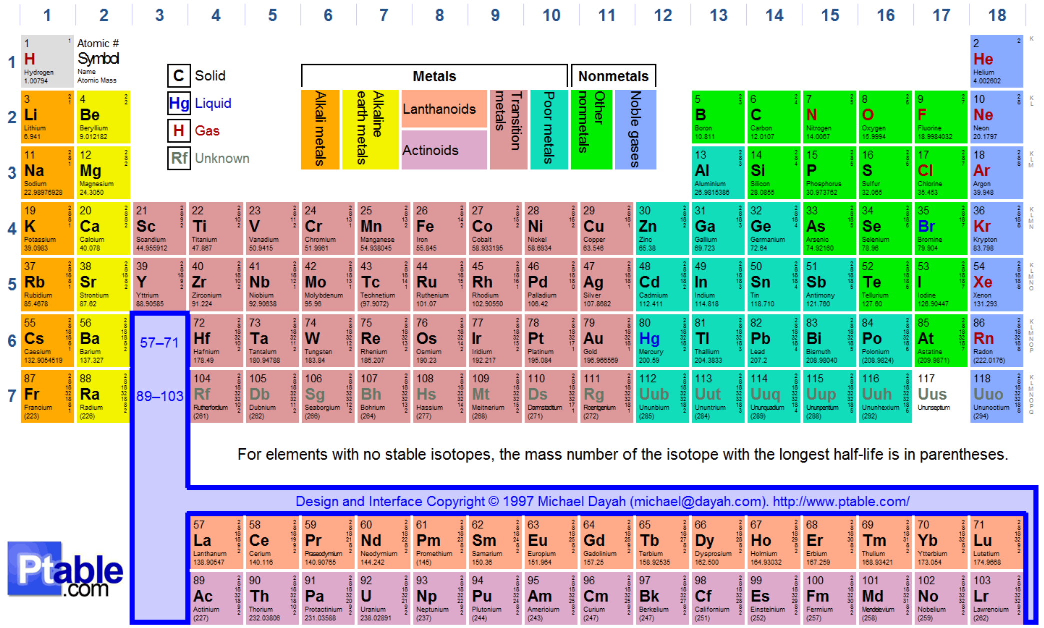
A computer chip and a solar cell are both made from semiconductors.

Ample silicon on earth

http://www.dailygalaxy.com/.a/6a00d8341bf7f753ef0168eafb3053970c-pi

Other semiconductors useful for solar cells

- GaAs
- CdTe
- CuInGaSe (CIGS)
- Organic molecules (C)
- PbI2 + Organic molecules (Organic-inorganic hybrid perovskite)



Many elements and compounds are semiconductors.

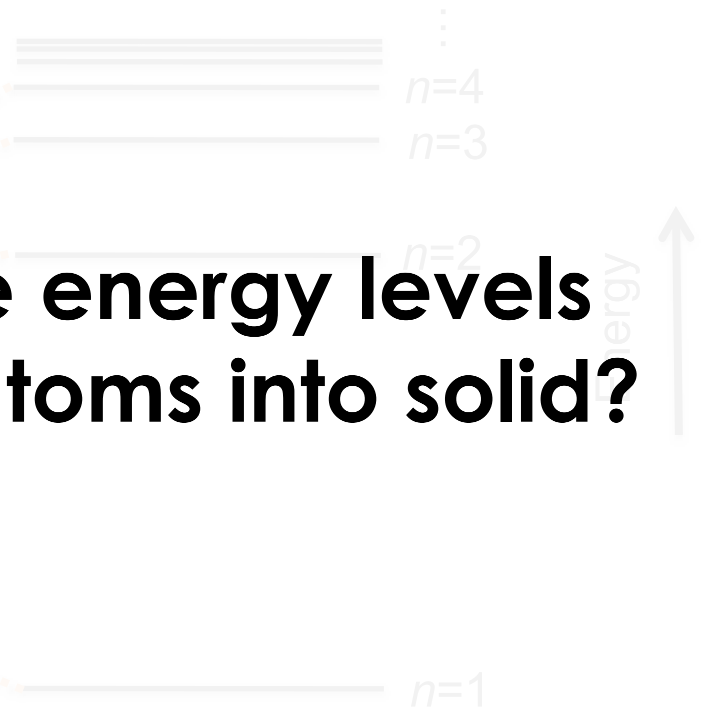
What makes a semiconductor a semiconductor?

- It can act like both a conductor or an insulator.
- It can be doped to conduct negative charge (electrons) or positive charge (holes).
- It has an "energy gap" or "band gap".

Conductor

Insulator

Concepts of band gap and energy levels of isolated atoms and materials

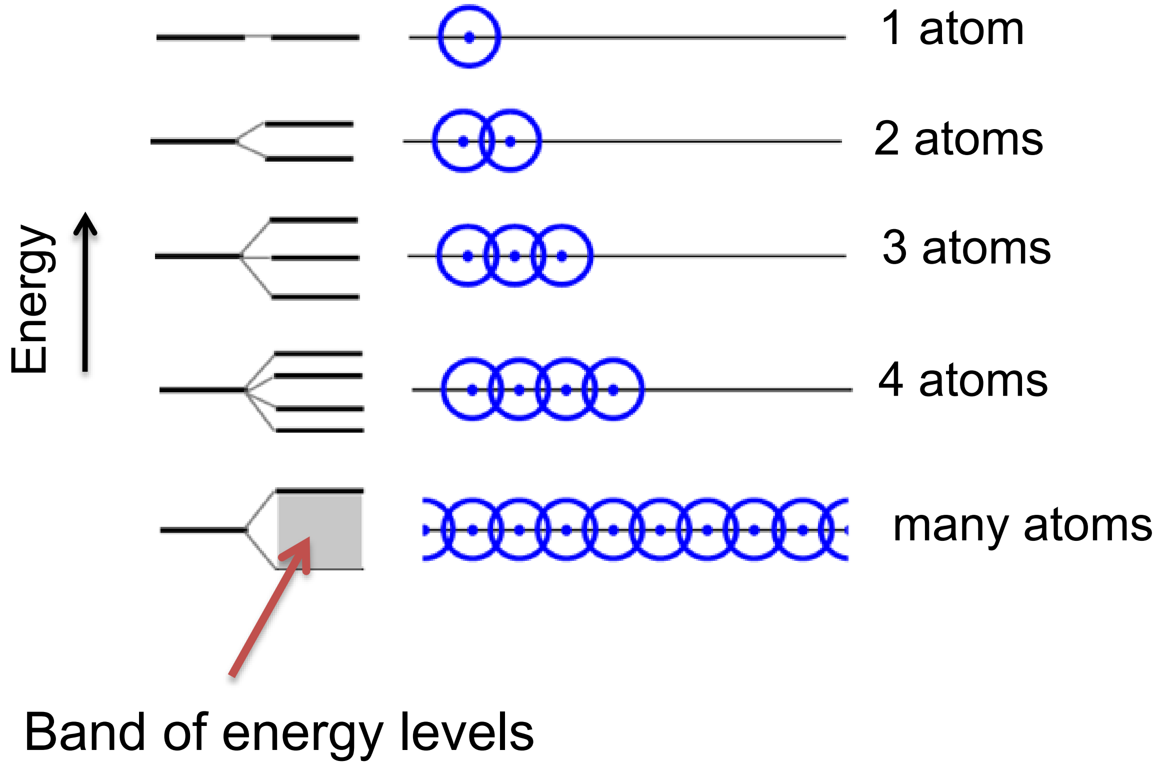


What happens to these energy levels when you pack many atoms into solid?

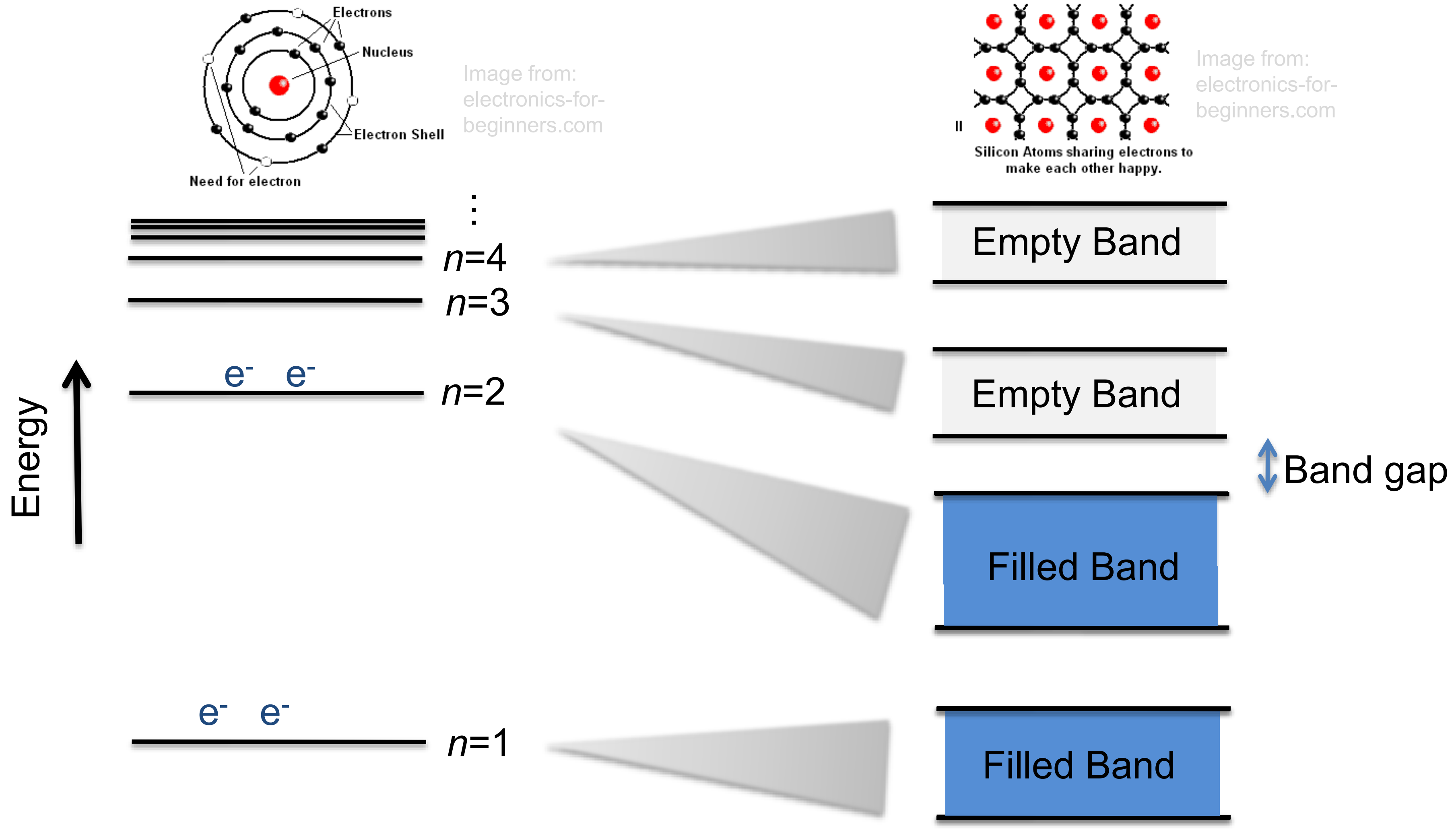
Image from: http://spiff.rit.edu/classes/phys301/lectures/spec_lines/Atoms_Nav.swf

Energy levels split in a solid to form bands

Look at effect on lowest *n*=1 orbital.



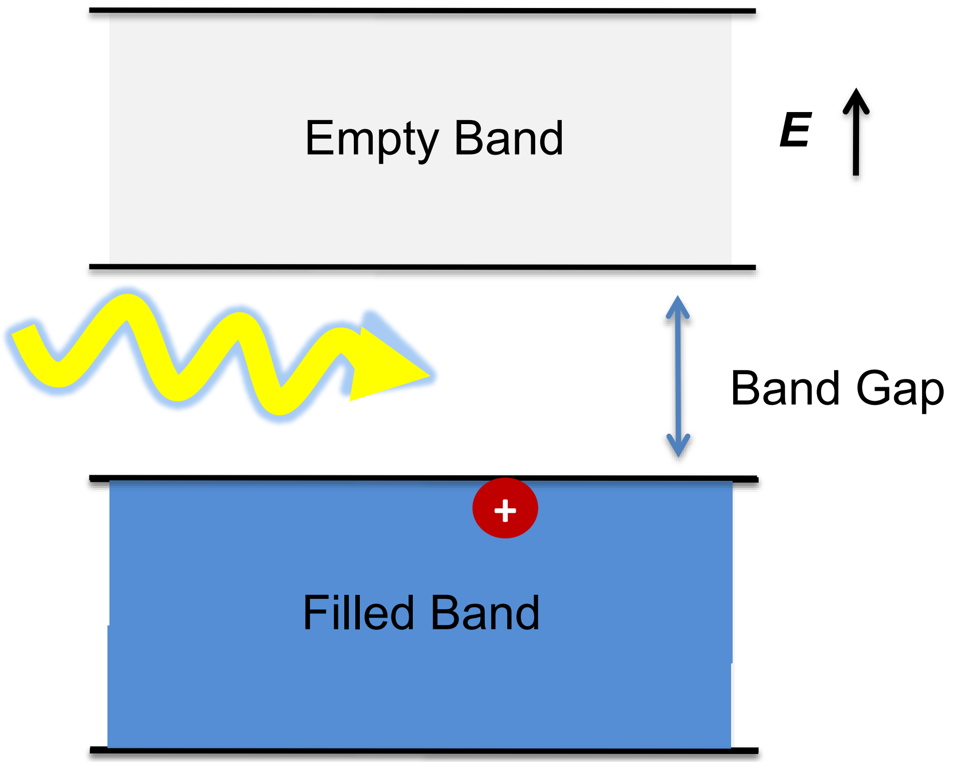
Semiconductor has gap between bands



1 isolated atom

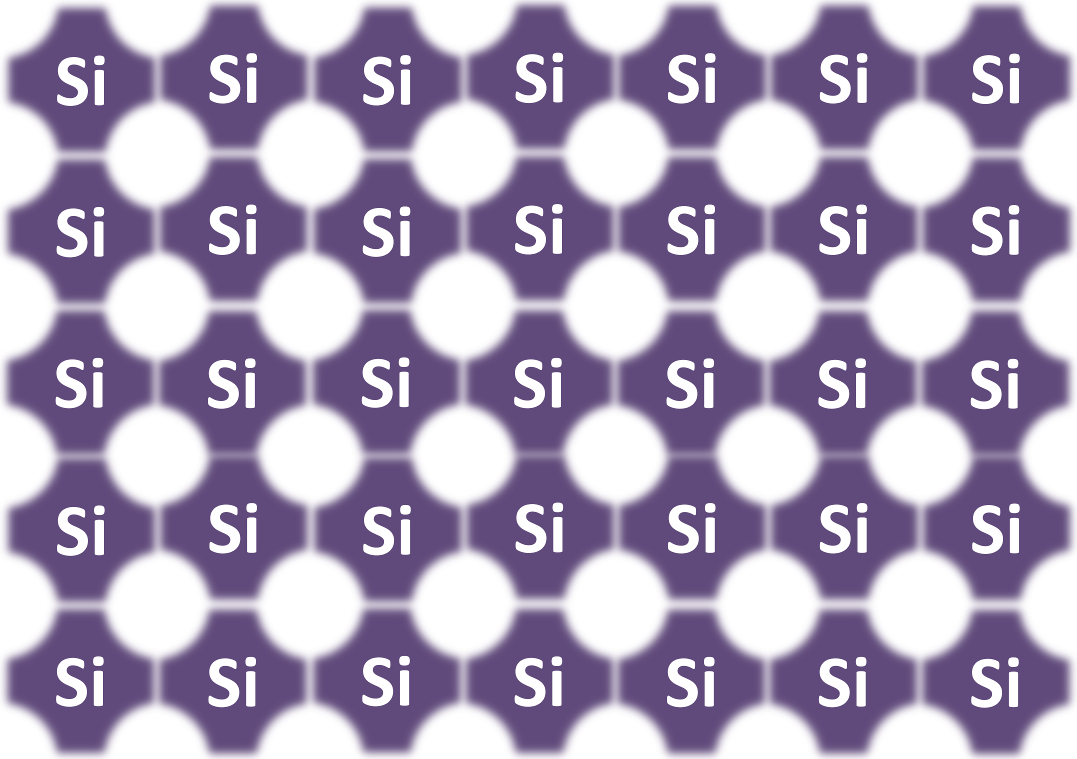
solid of many atoms

Light excites electrons across band gap



Challenge is to next separate negative and positive charge to opposite sides of a solar cell before the electron falls back down to the filled band and turns into heat!

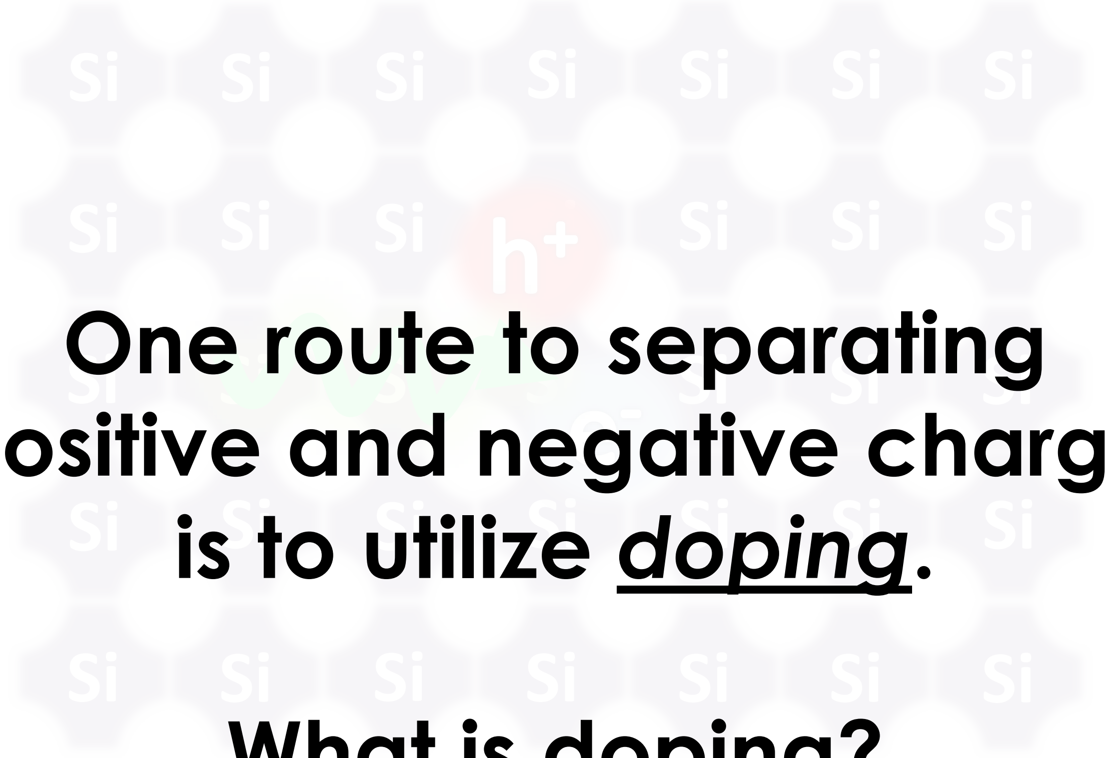
How can charge be spatially separated?



Example 2D Representation of Si:

- Each Si atom is covalently bonded to 4 other Si atoms.
- All 4 electrons in the outer-shell are in covalent bonds.
- **No free charges to move around – low conductivity.**

Absorption of light



One route to separating positive and negative charge is to utilize *<u>doping</u>*.

What is doping?

- When a semiconductor absorbs light → positive (holes) and negative (electrons) charges are created.
- But, how can you induce their spontaneous separation?

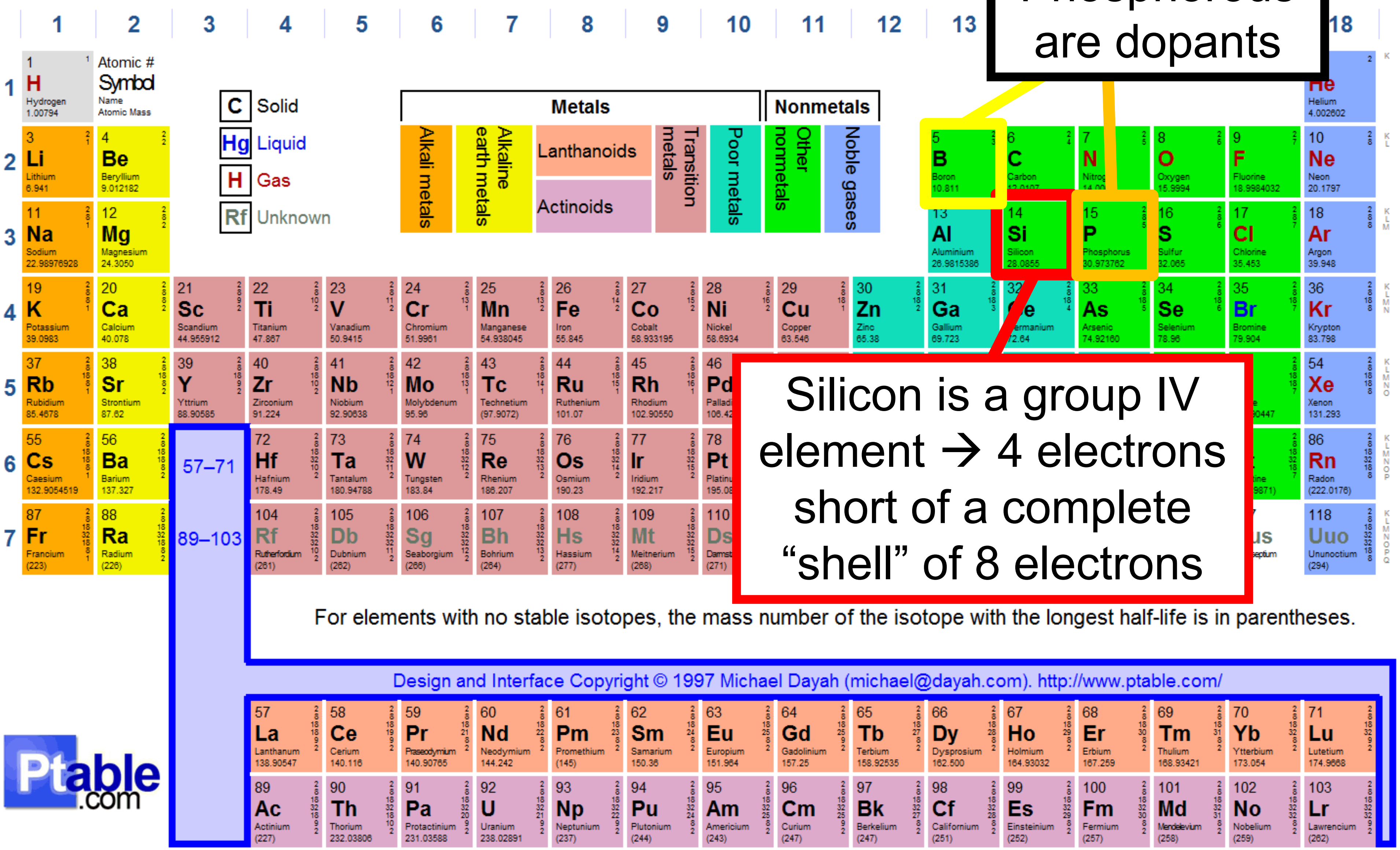
Not this kind of doping!!!

www.independent.co.uk: *Was London 2012's 1500m Olympic final the dirtiest race in history?*

What is doping?

- Doping results from the ***intentional*** or ***unintentional*** addition of impurities to a semiconductor.

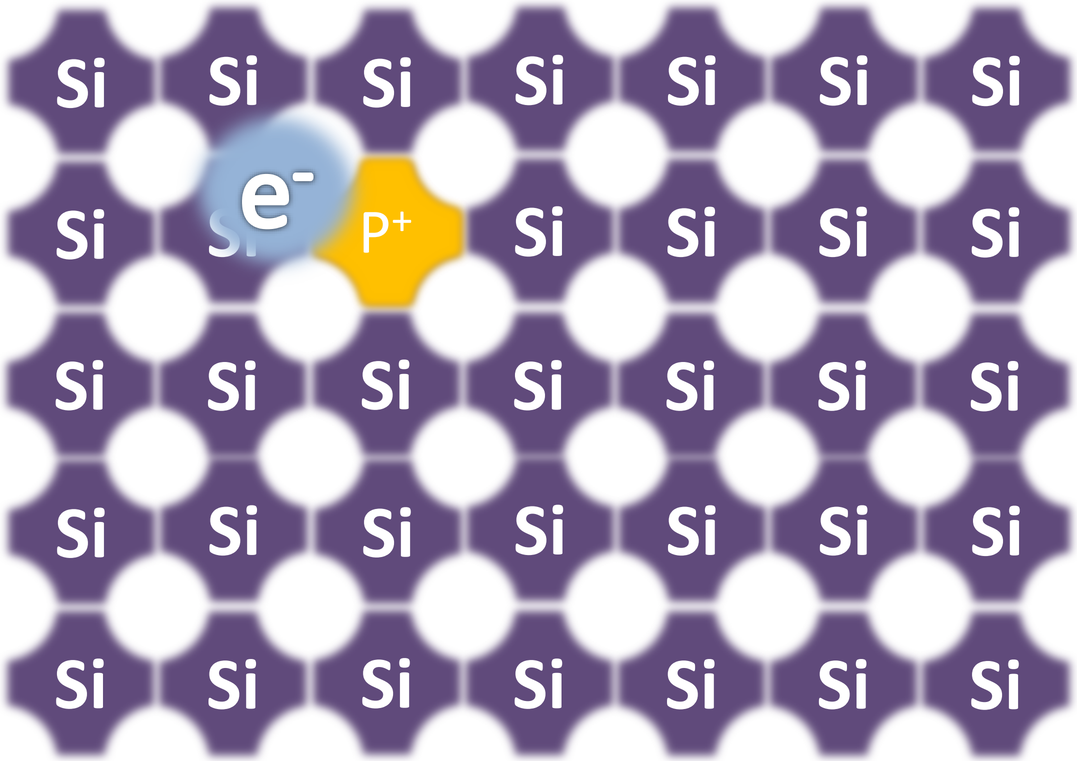
Periodic Table of Elements



Boron and Phosphorous are dopants

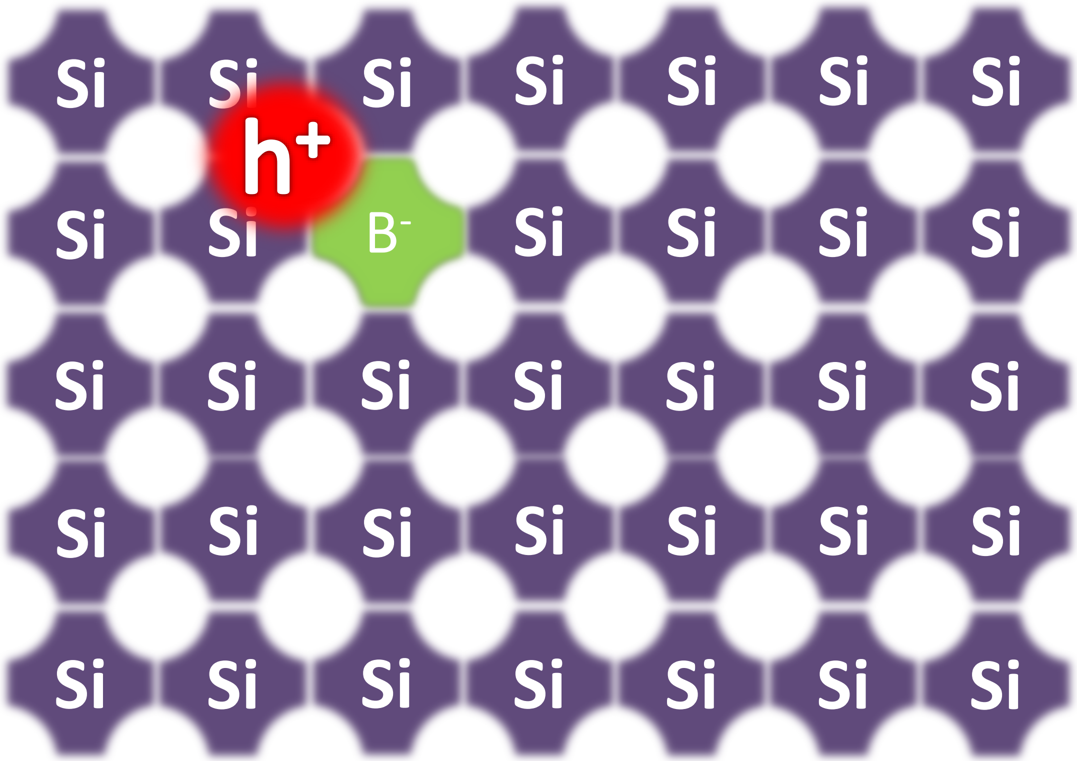
Silicon is a group IV element → 4 electrons short of a complete "shell" of 8 electrons

N-type (electron doped) silicon (Si)



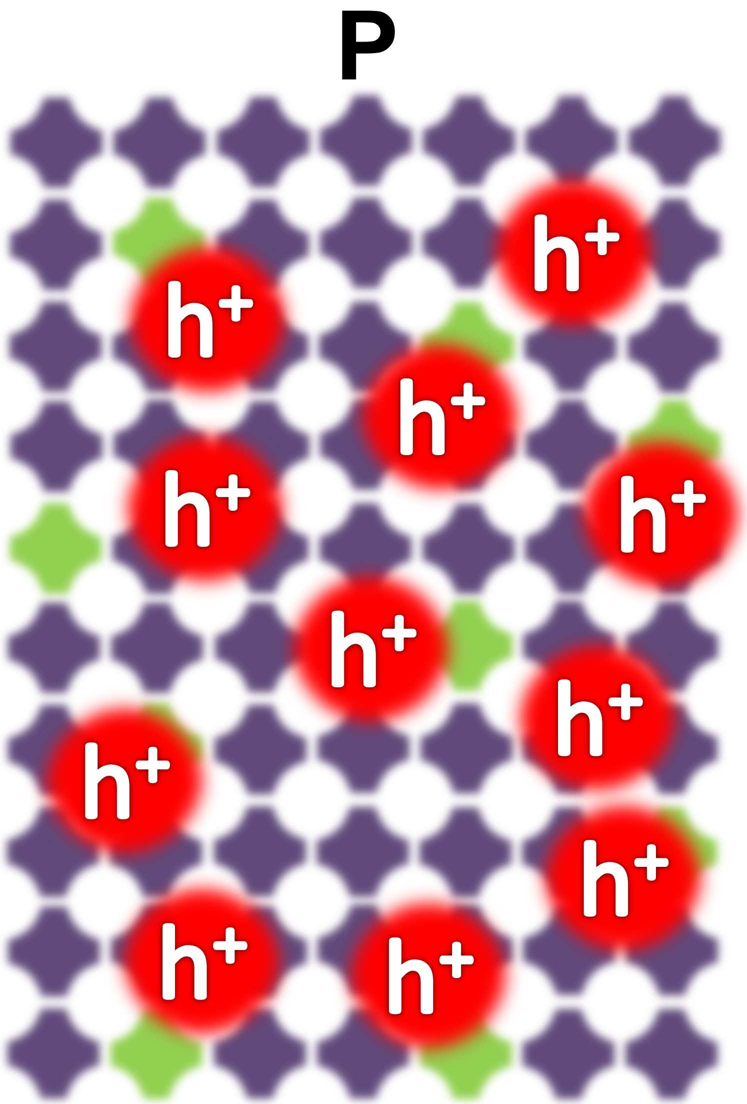
- Replacement of group IV Si atom with group V P atom
- P atom becomes positively ionized, releasing free electron that can move and conduct.

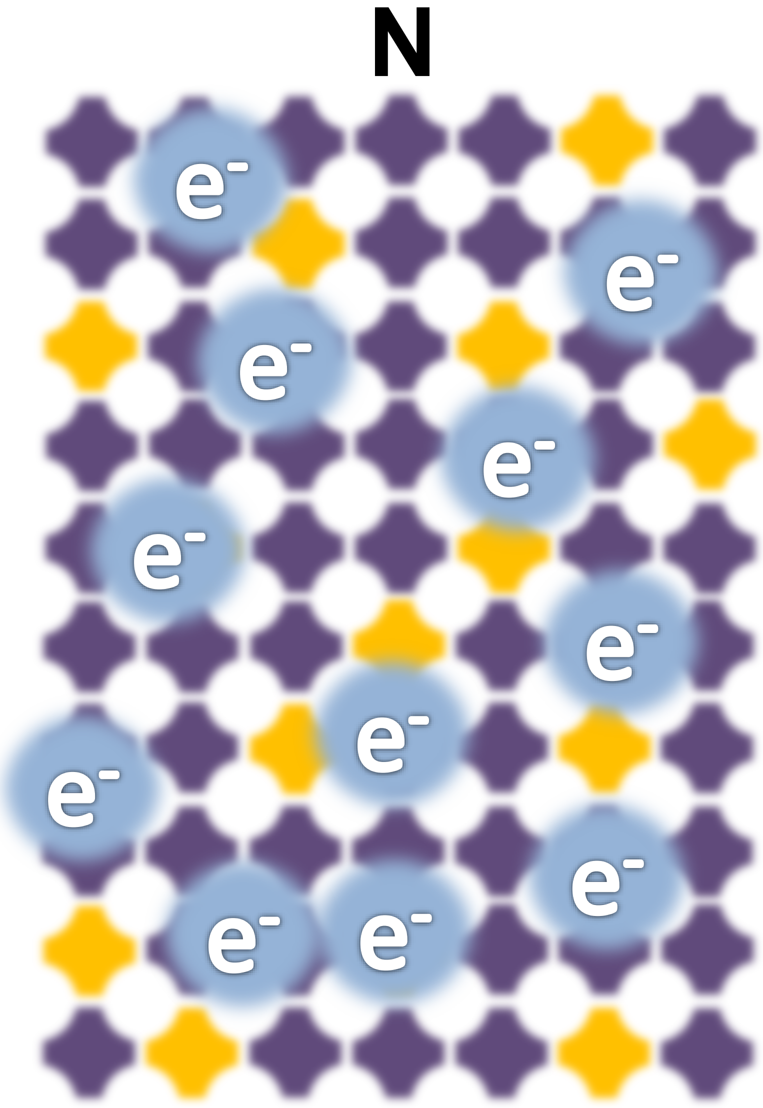
P-type ("hole" doped) silicon (Si)



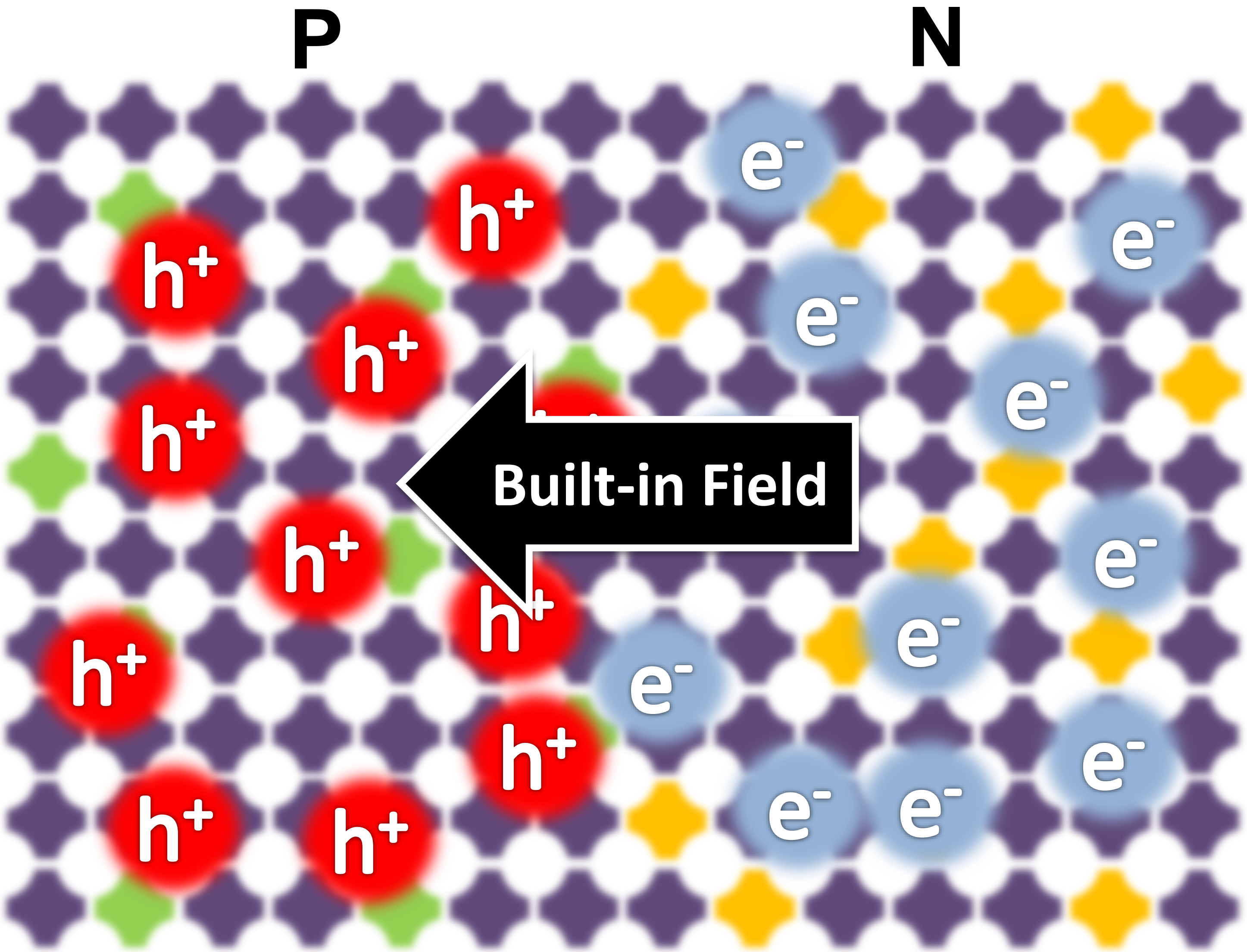
- Replacement of group IV Si atom with group III B atom
- B atom becomes negatively ionized, effectively releasing positive charge called a hole that can move and conduct.

A common device is: P-N junction

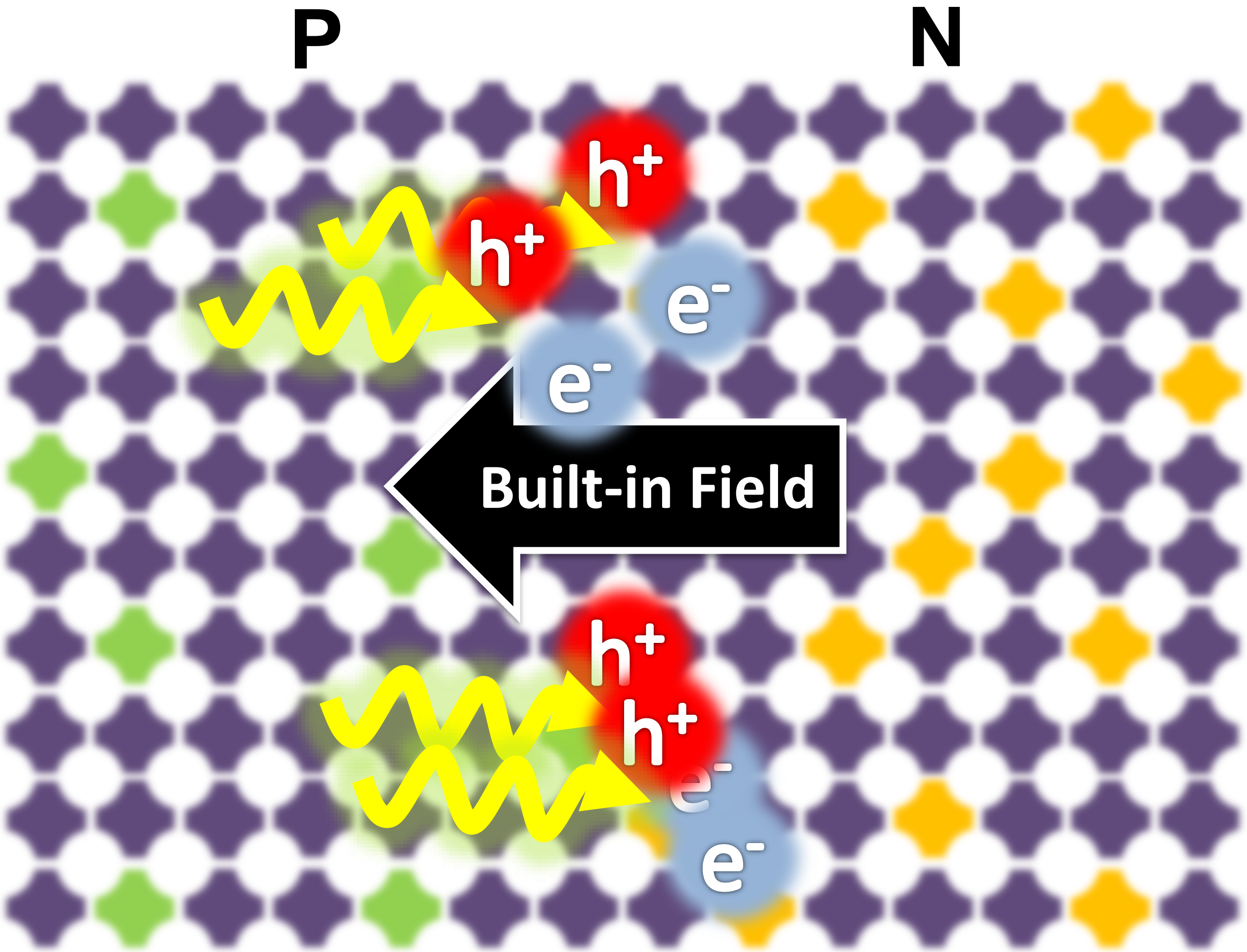




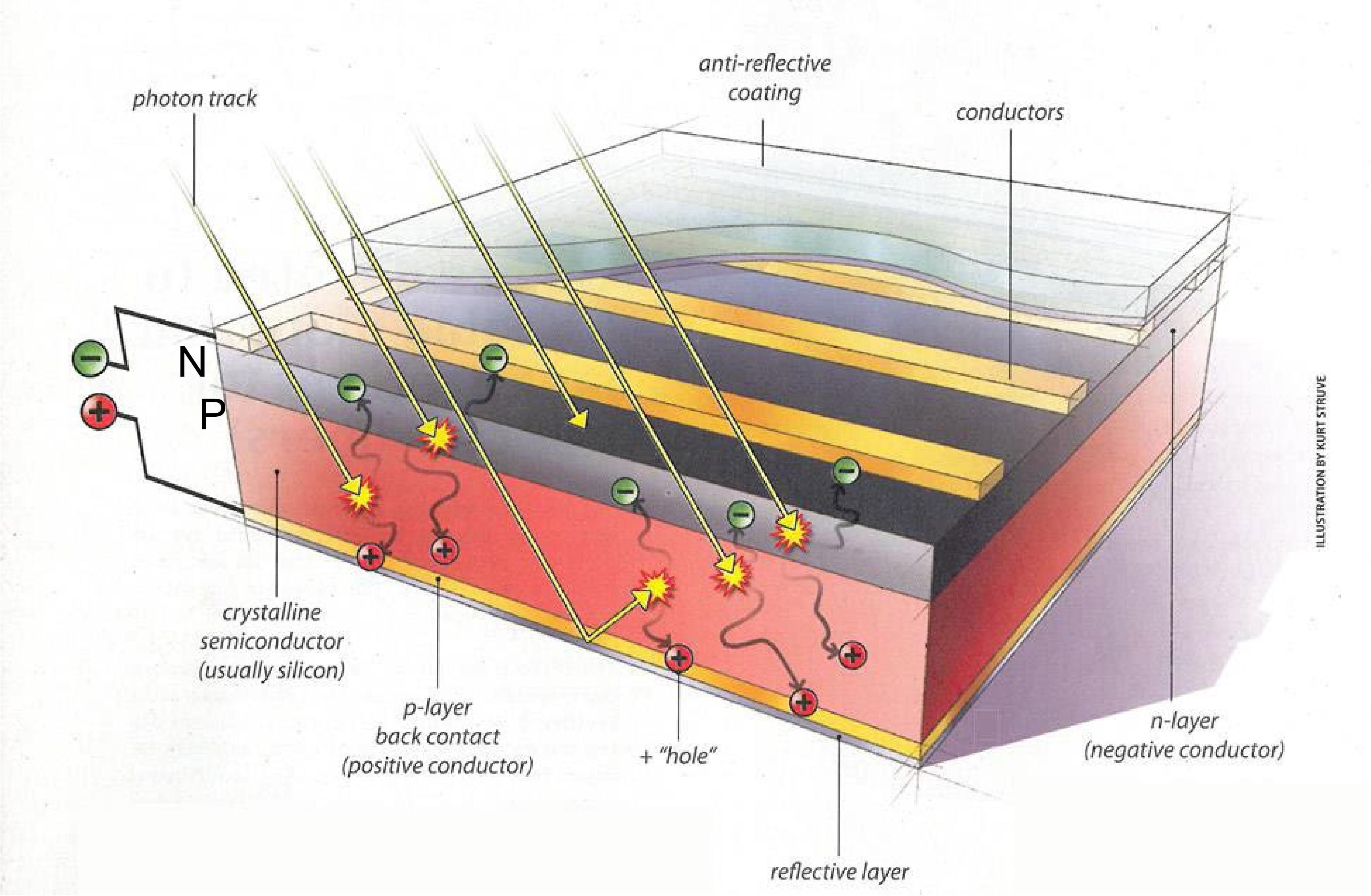
P-N junction



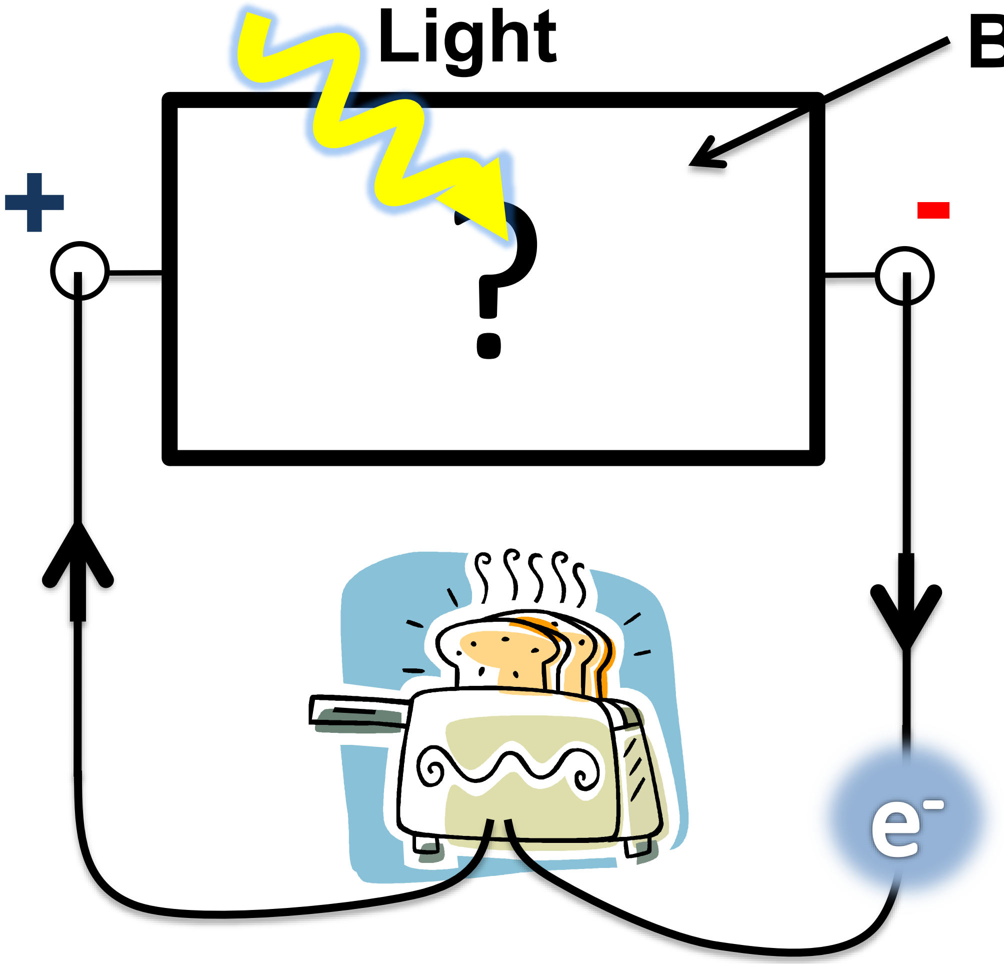
P-N junction

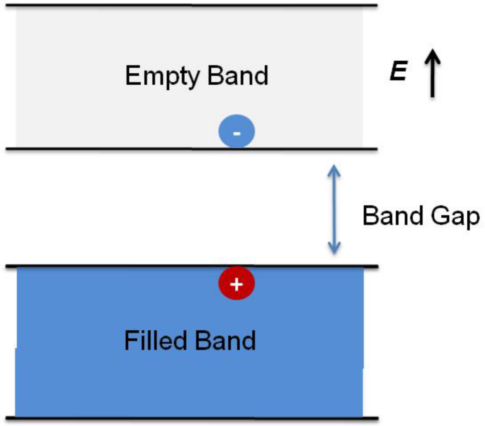


Other components: electrodes, coatings



Our blackbox





Conclusions about how a solar cell works on the level of electrons and atoms

- The active materials in a photovoltaic solar cell are semiconductors.
- Light excites negative charge (electrons) higher in energy across the band gap.
- A junction between P-doped and N-doped semiconductors (PN junction) is used to separate the positive and negative charges → electricity.

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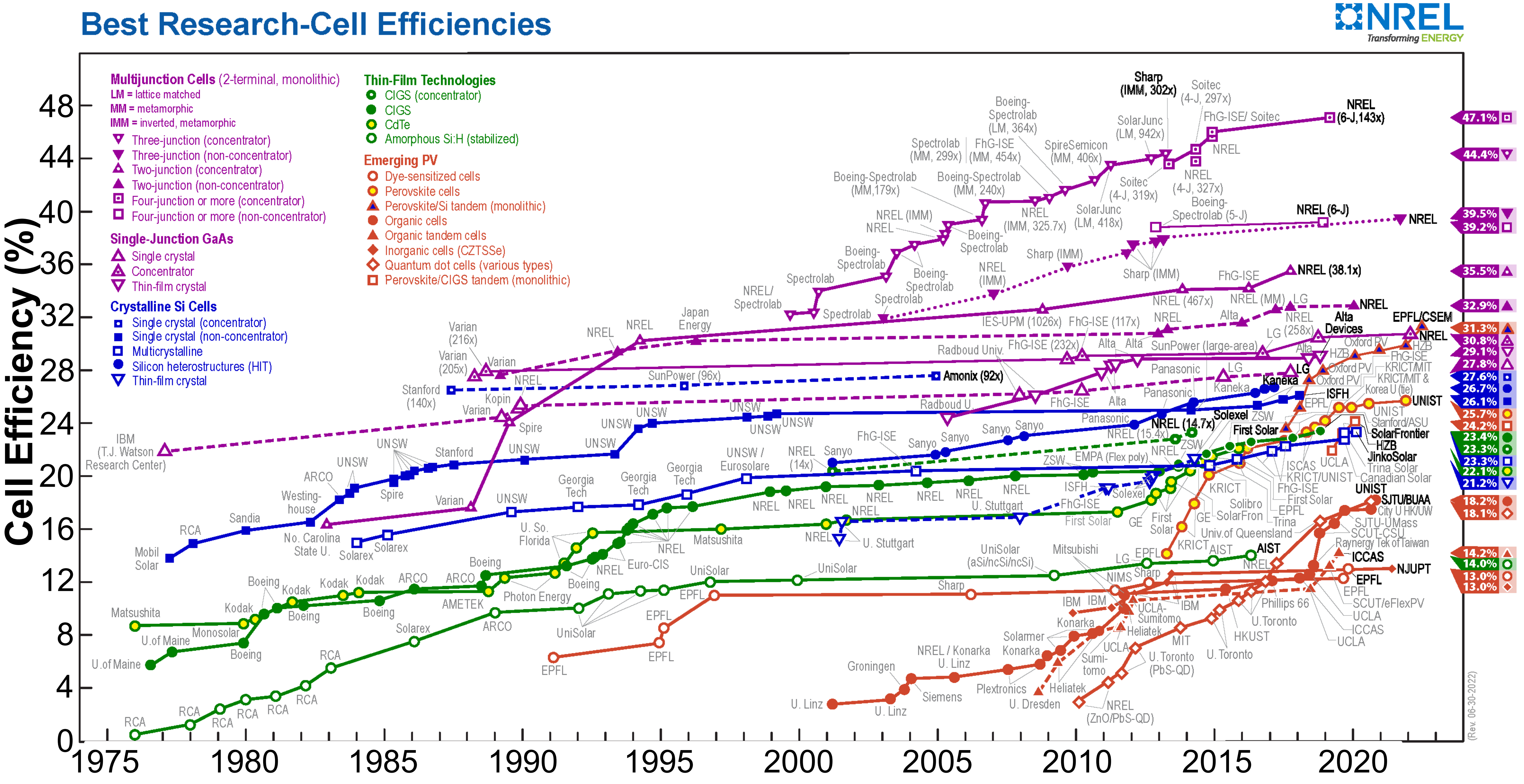
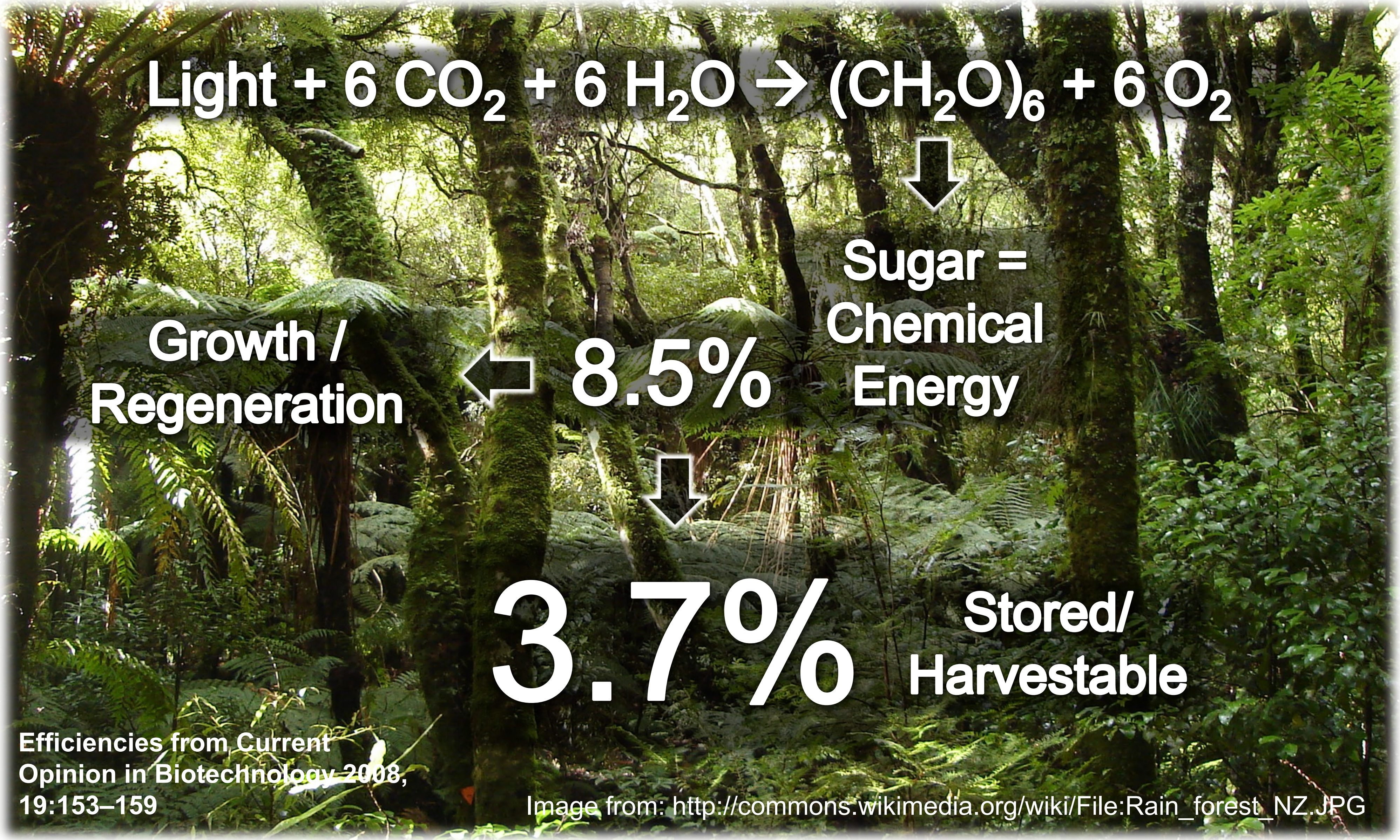


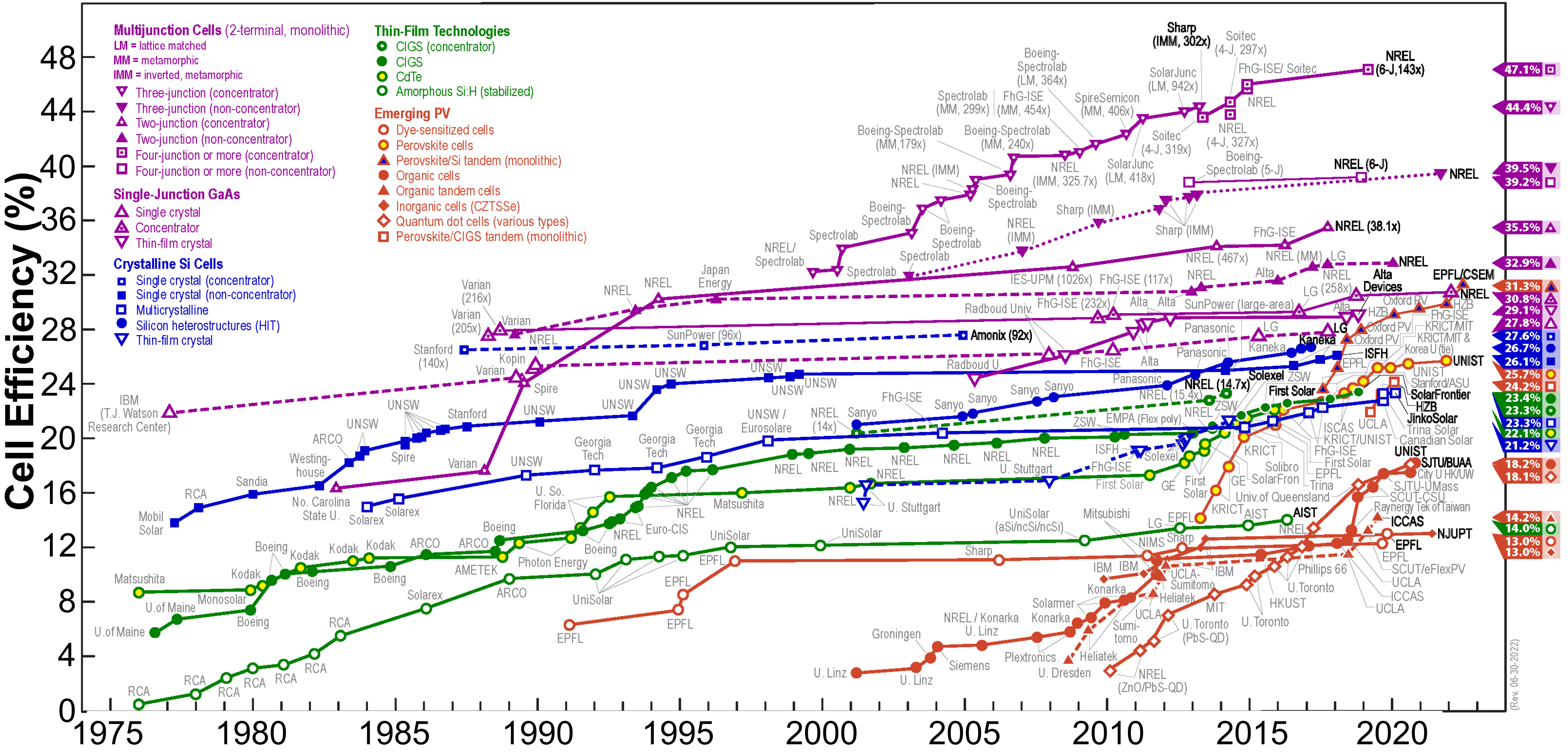
Observation #1: Efficiency up with time! Ranges from 10-47%!!!

Aside: How efficient is photosynthesis?



Best Research-Cell Efficiencies

NREL Transforming ENERGY



Observation #2: Lots of different cell-types!

Cell-type classifications

Crystallinity

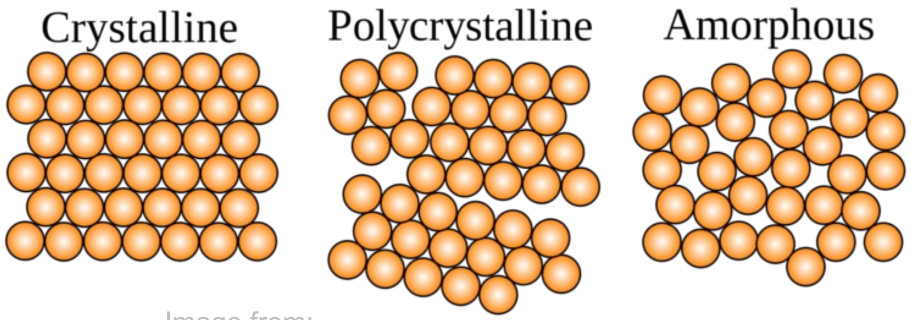


Image from: https://commons.wikimedia.org/wiki/File:Crystalline_polycrystalline_amorphous.svg

Thick Crystal or Thin Film

Thin-Film

Semiconductor Thin Film

Substrate (Glass / Plastic)

Thick Crystal

Semiconductor Crystal

Number of Junctions

Single-Junction:

P
N

Multi-Junction:

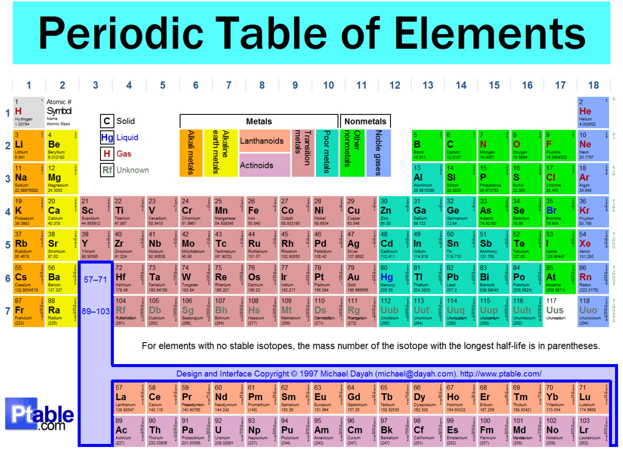
P
N
P
N
P
N

Small Band gap

Medium Band gap

Large Band gap

Composition



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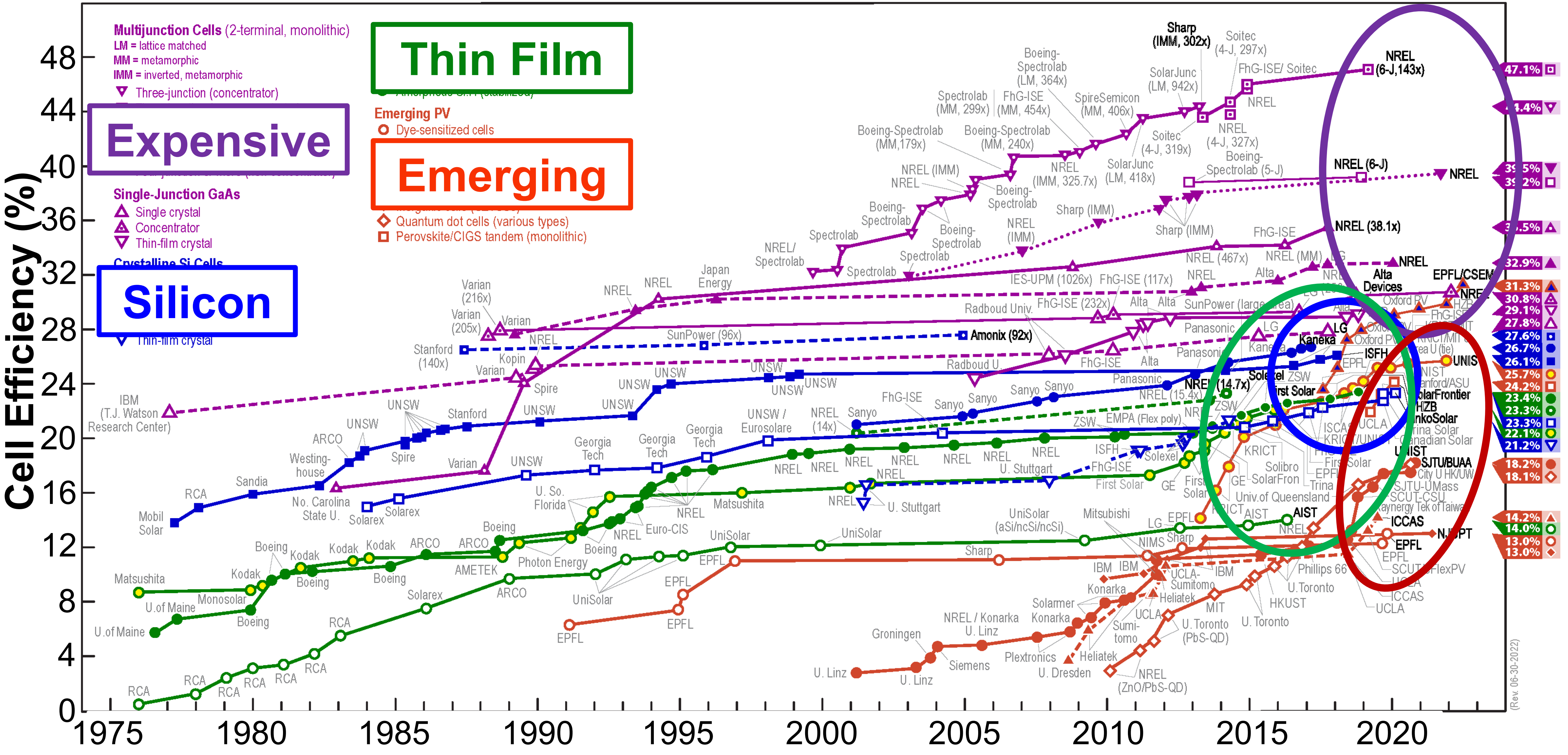
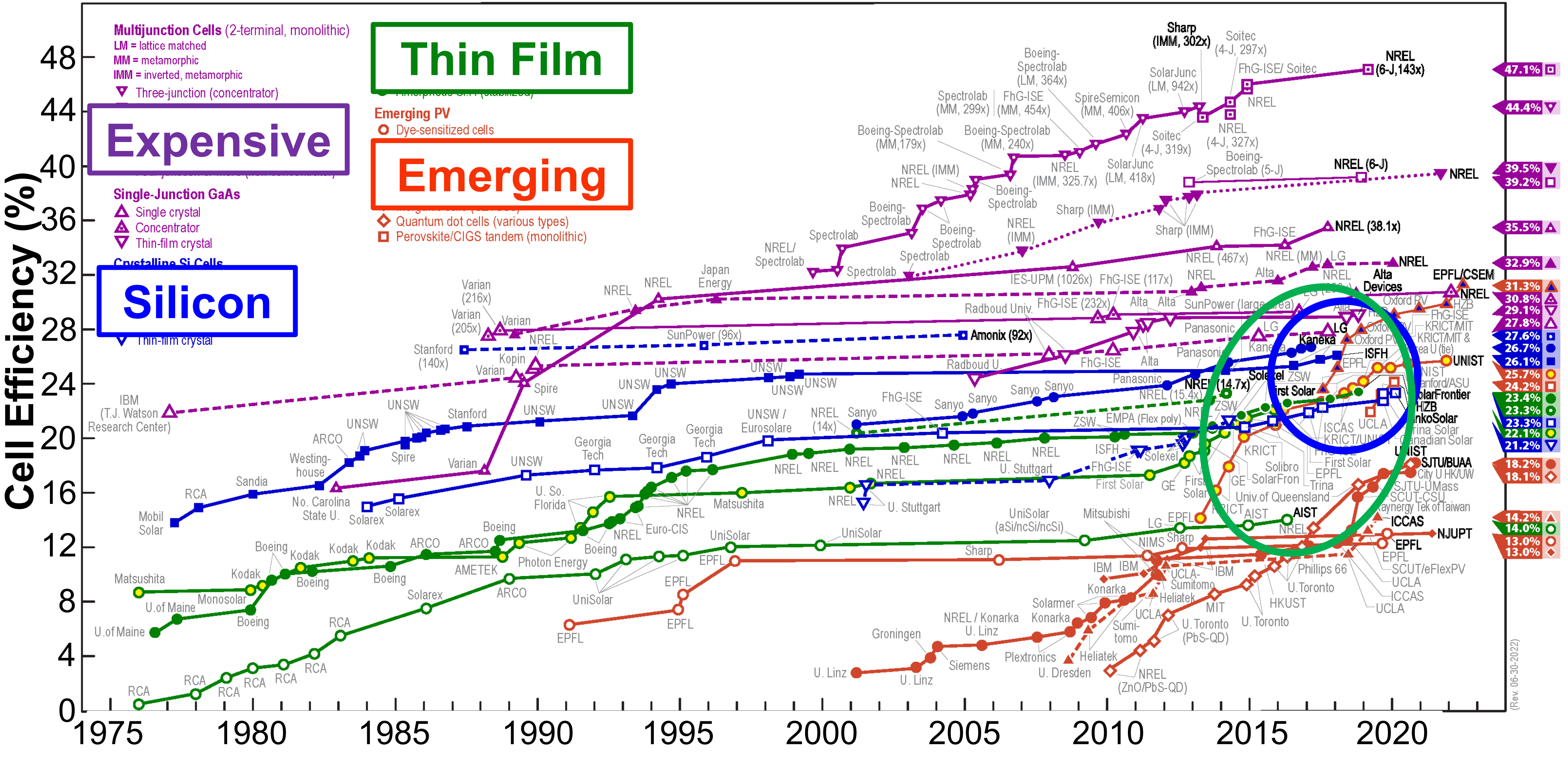


Observation #2: Lots of different cell-types!

Best Research-Cell Efficiencies



Observation #2: Lots of different cell-types!

Single crystal silicon

Crystallinity

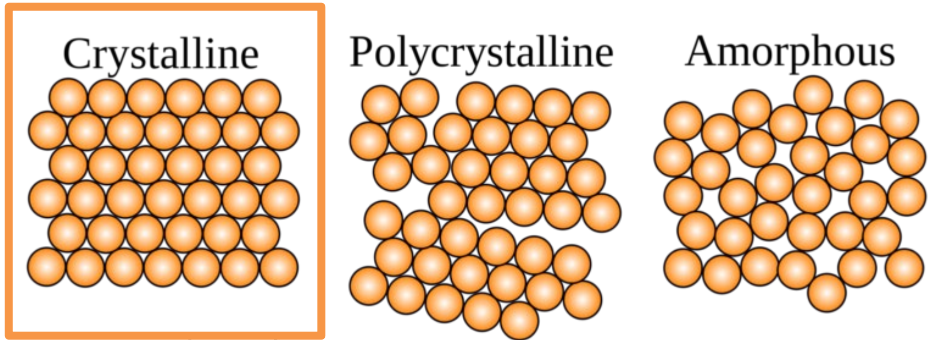
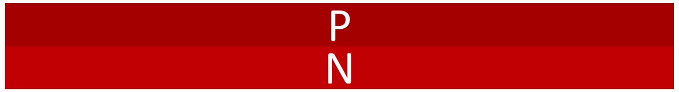


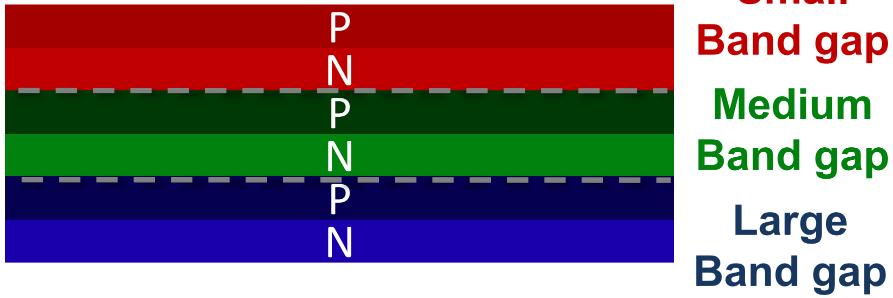
Image from: https://commons.wikimedia.org/wiki/File:Crystalline_polycrystalline_amorphous.svg

Number of Junctions

Single-Junction:



Multi-Junction:



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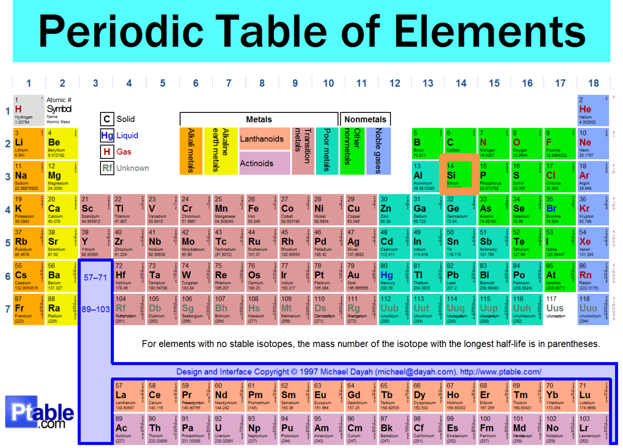
Thin-Film

Thick Crystal

Composition



Single crystal silicon manufacturing

Polycrystalline Si
> 99.9999%

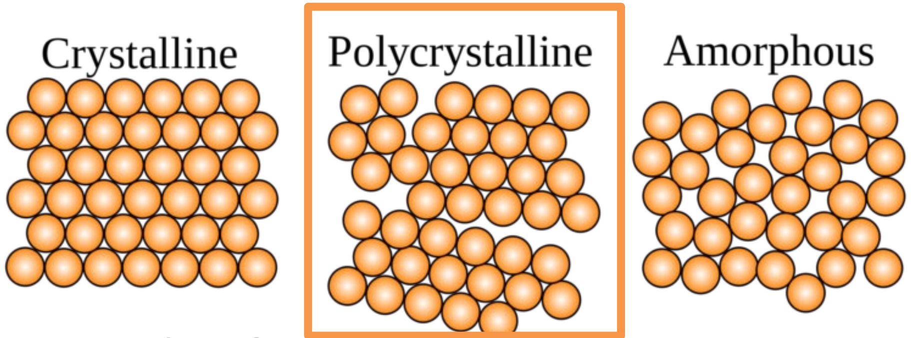
1400 ºC

Single crystalline Si

http://www.youtube.com/watch?v=aWVywhzuHnQ&NR=1
(start @ 1:48)

Polycrystalline silicon

Crystallinity



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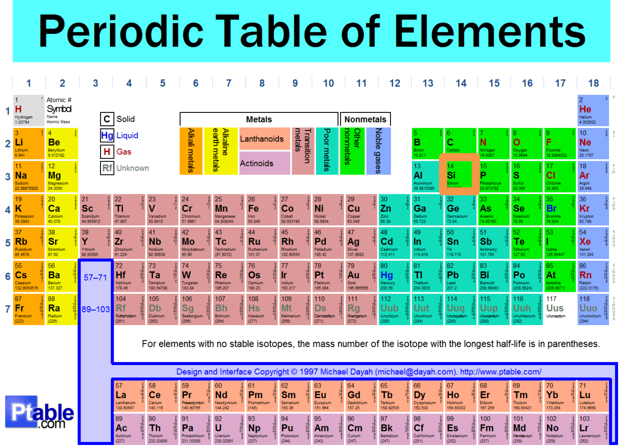
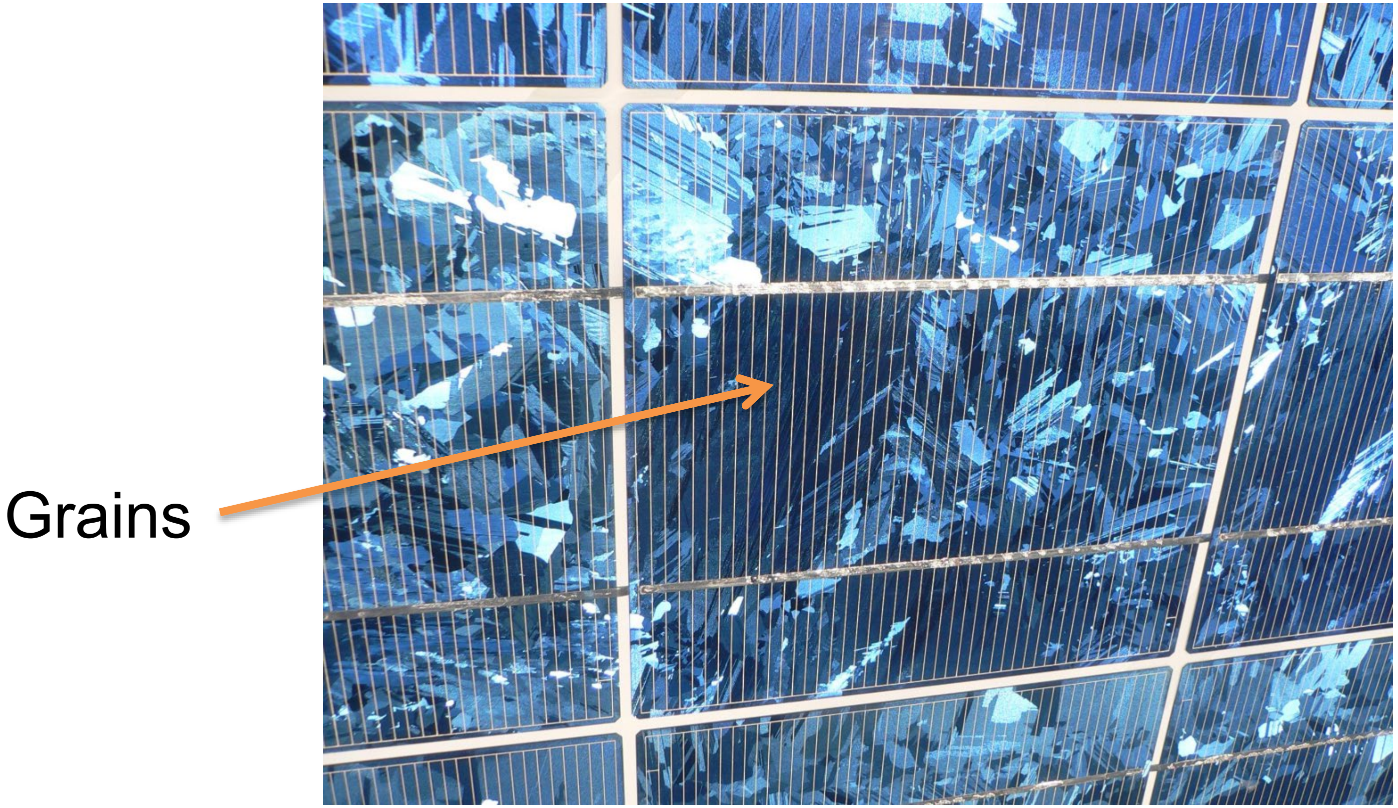


Polycrystalline silicon manufacturing

Deposition by chemical vapor deposition: SiH_4 (g) → Si (s) + $2H_2$ (g), 650 °C

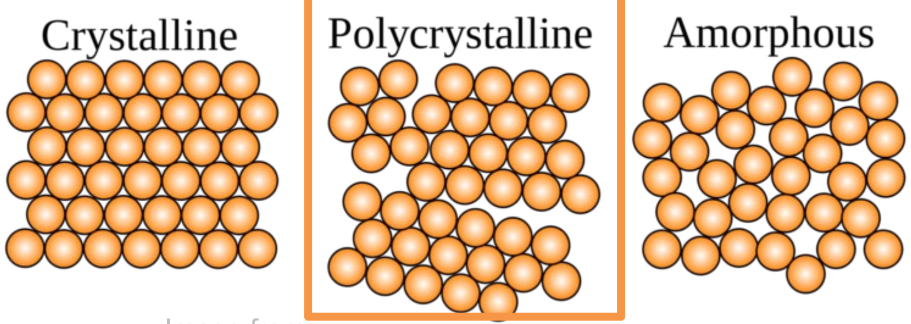


- Lower cost due to lower temperature processing but lower efficiency due to loss at grain boundaries.

Image from: http://upload.wikimedia.org/wikipedia/commons/1/15/Polycristalline-silicon-wafer_20060626_568.jpg

Thin film

Crystallinity



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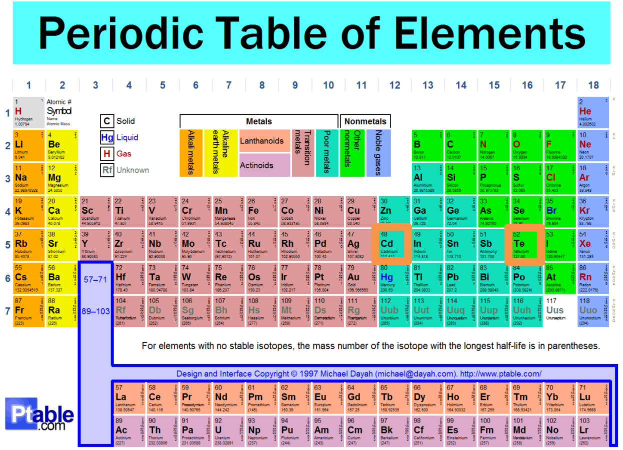
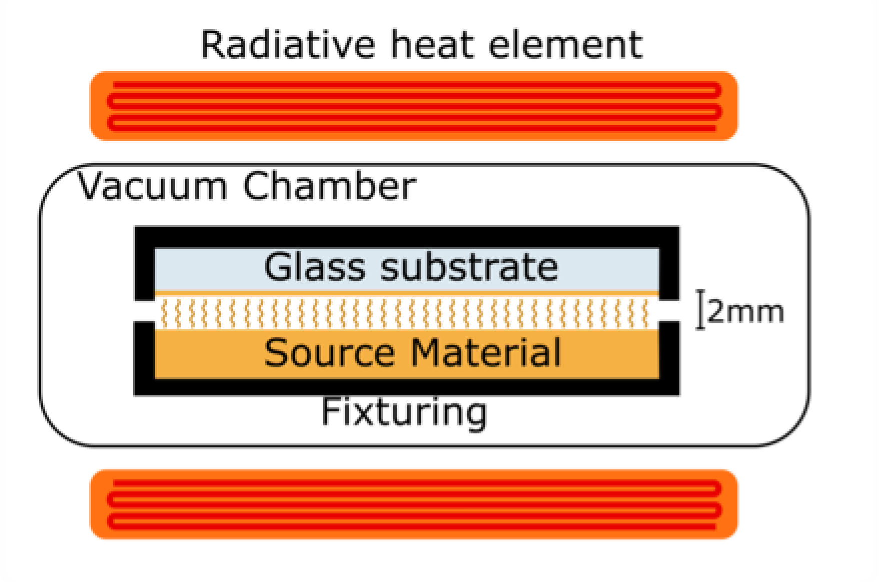
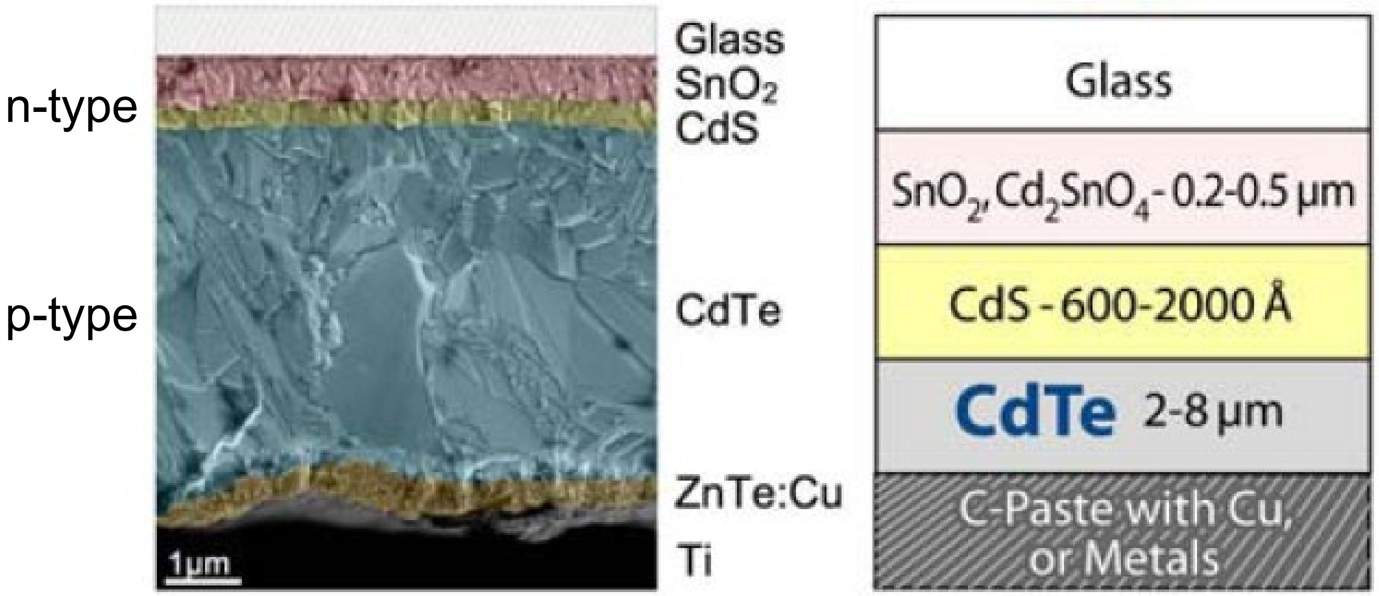


Thin film manufacturing (CdTe)

Sublimation

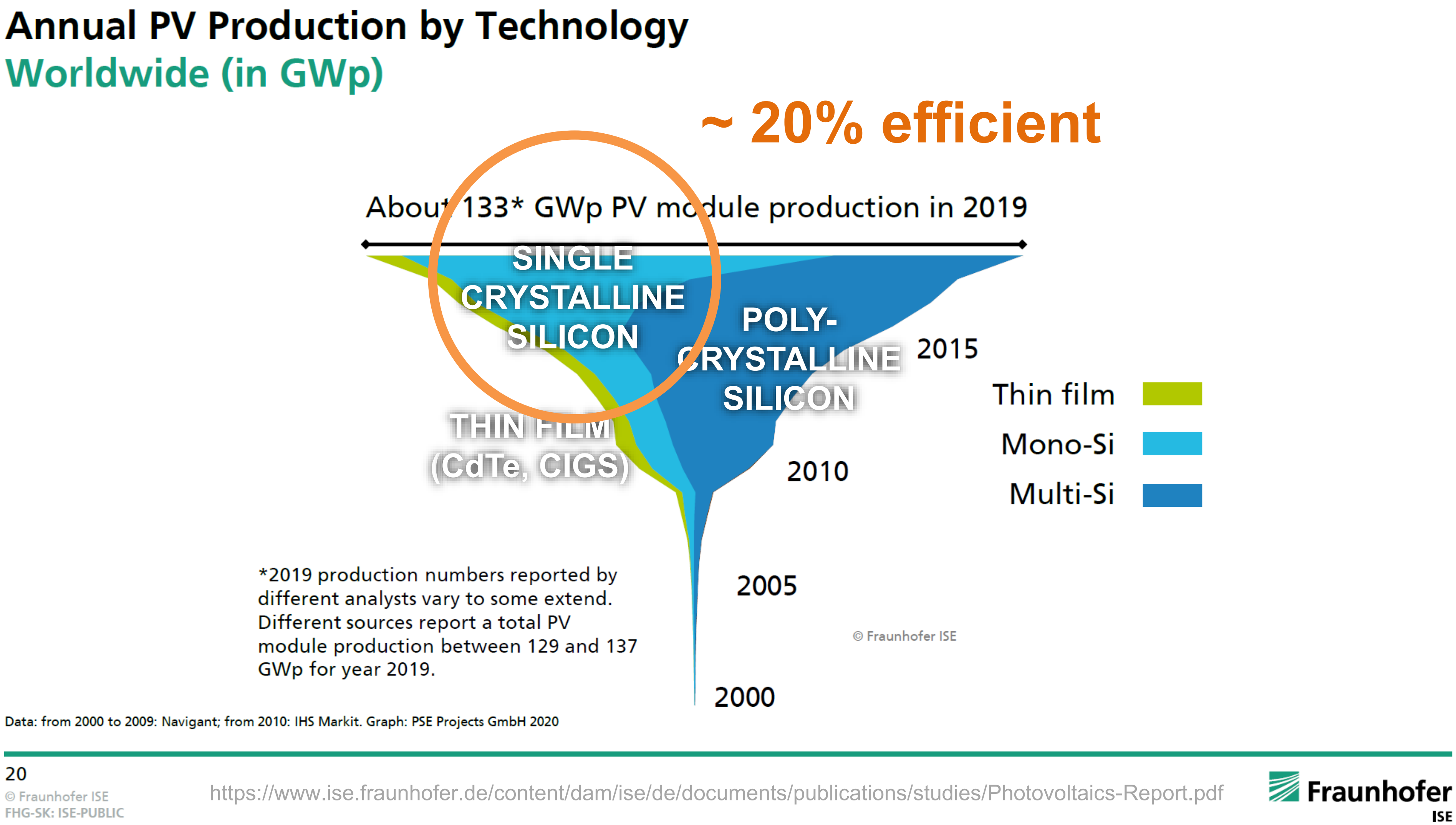


650 ˚C



from: Noufi and Zweibel, IEEE 4th WCPEC-4 (2006)

Single crystal silicon is most prevalent.



https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Outline

- The sun as a source of energy
- How does a photovoltaic solar cell work?
- Types of solar cells and their efficiencies
- **Economics of solar cells then and now**
- Solar in Wisconsin
- The future

Economics on both residential and utility scales

Residential

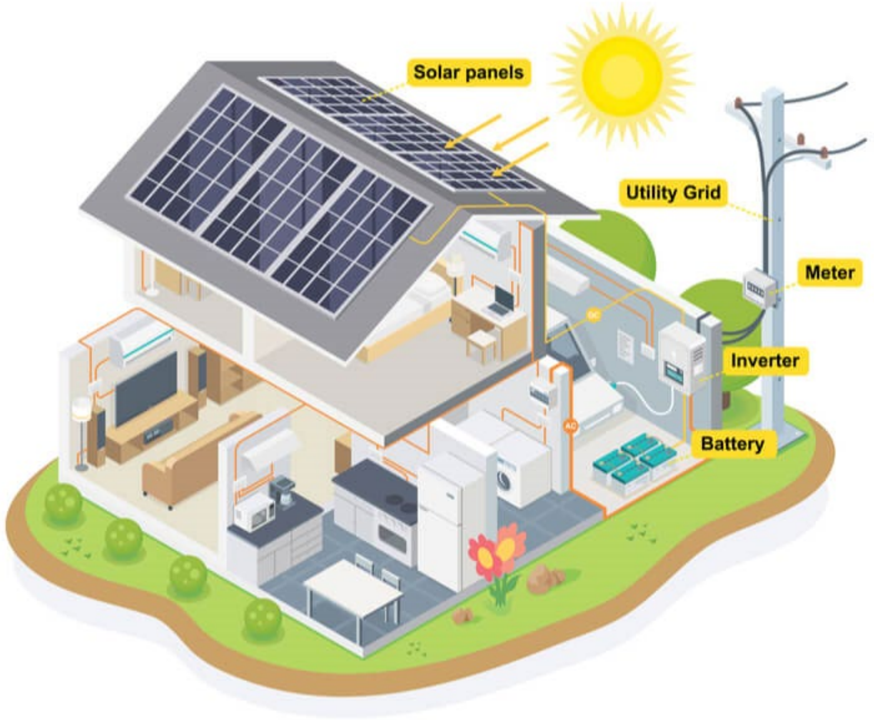


Image from: https://www.saveonenergy.com/solar-energy/solar-panels-for-home/

Utility-Scale (Solar Farms)

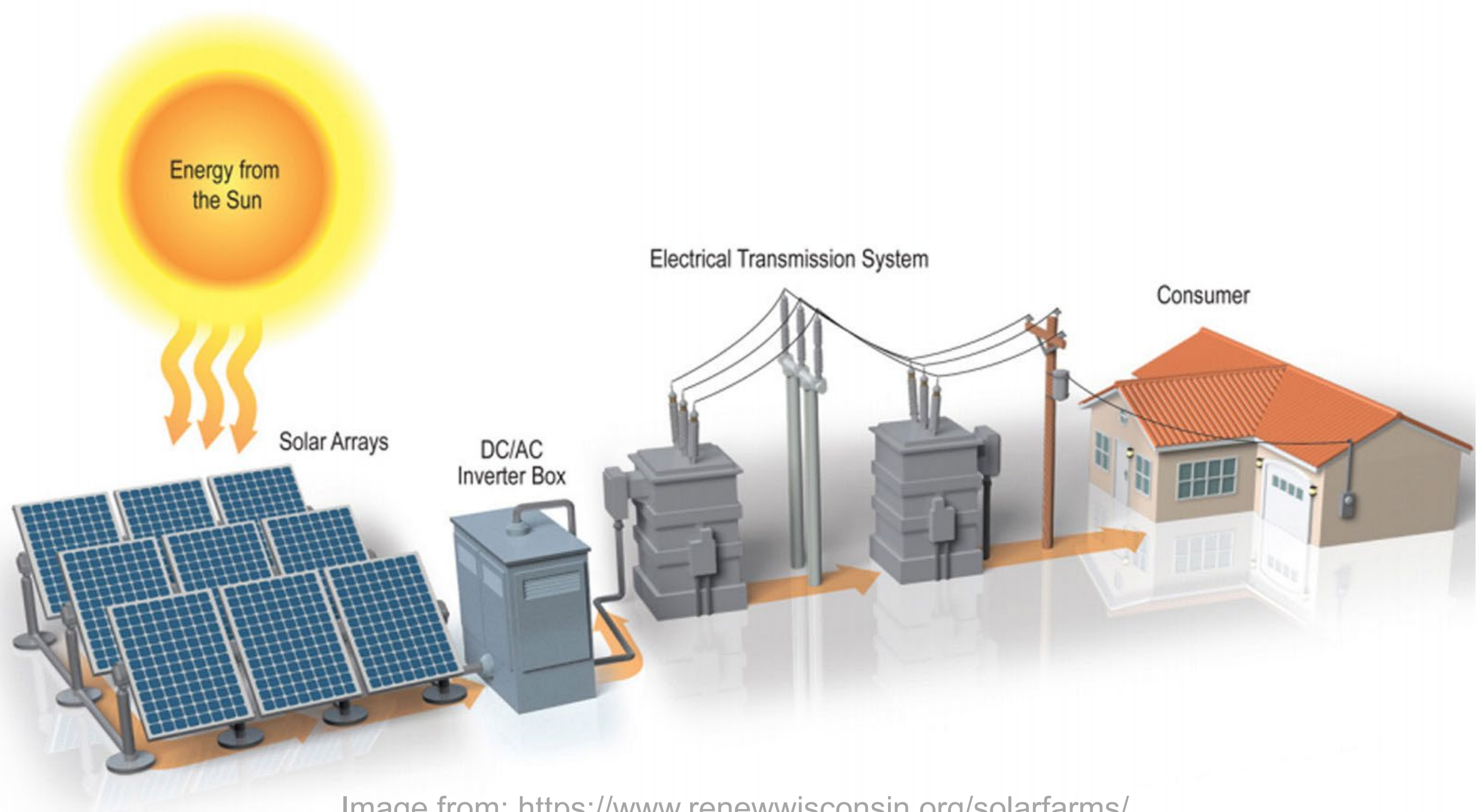


Image from: https://www.renewwisconsin.org/solarfarms/

Installed cost: *residential*

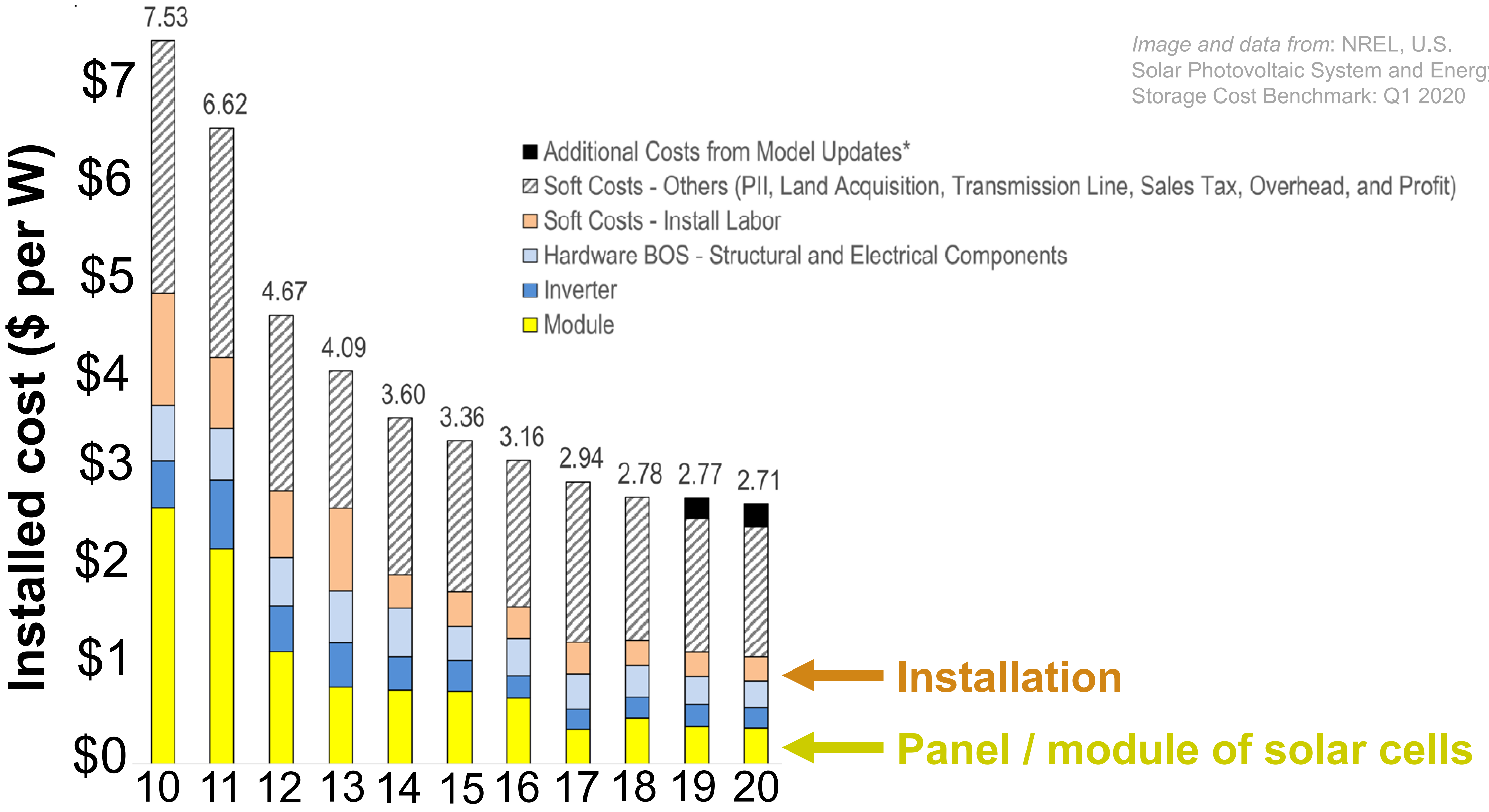
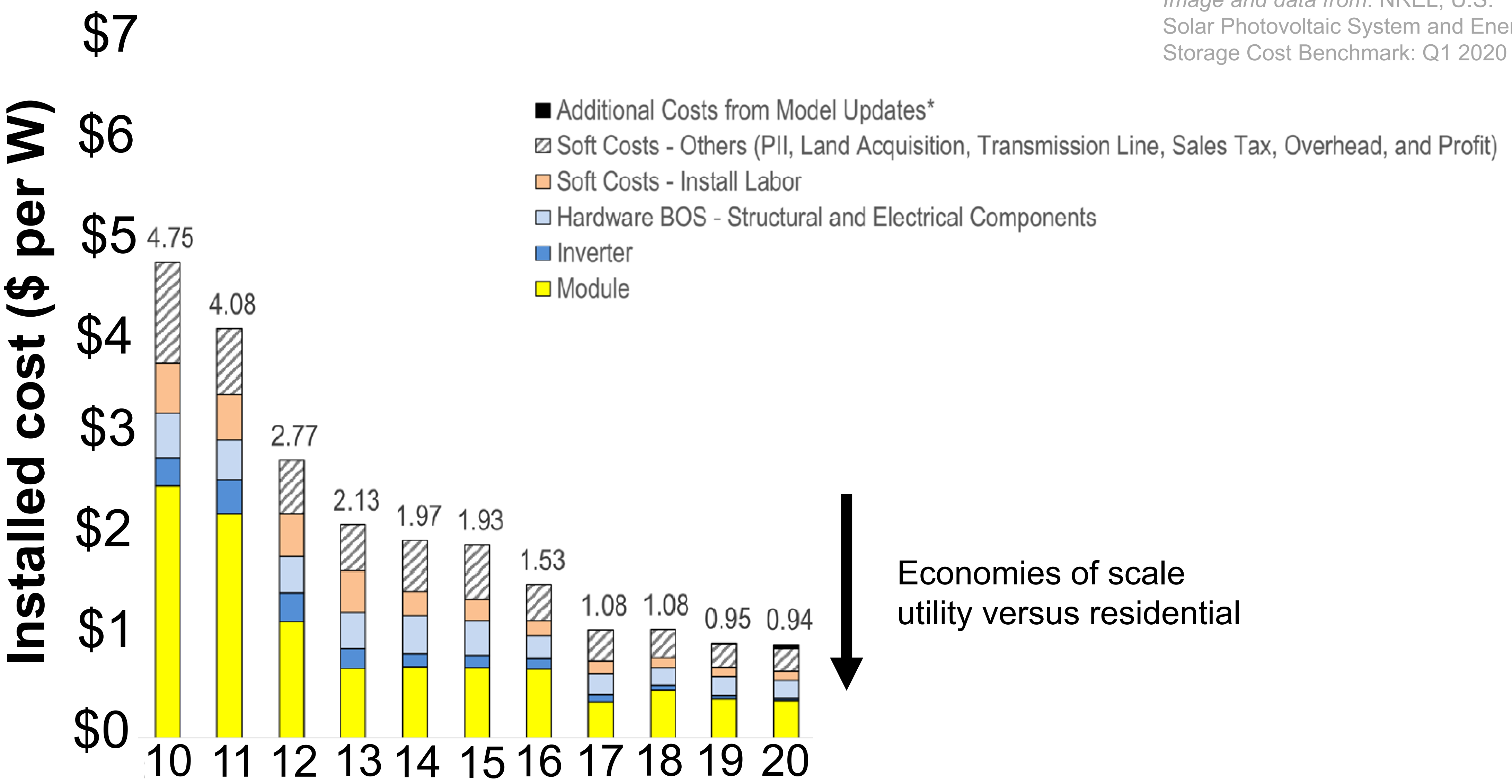


Image and data from: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

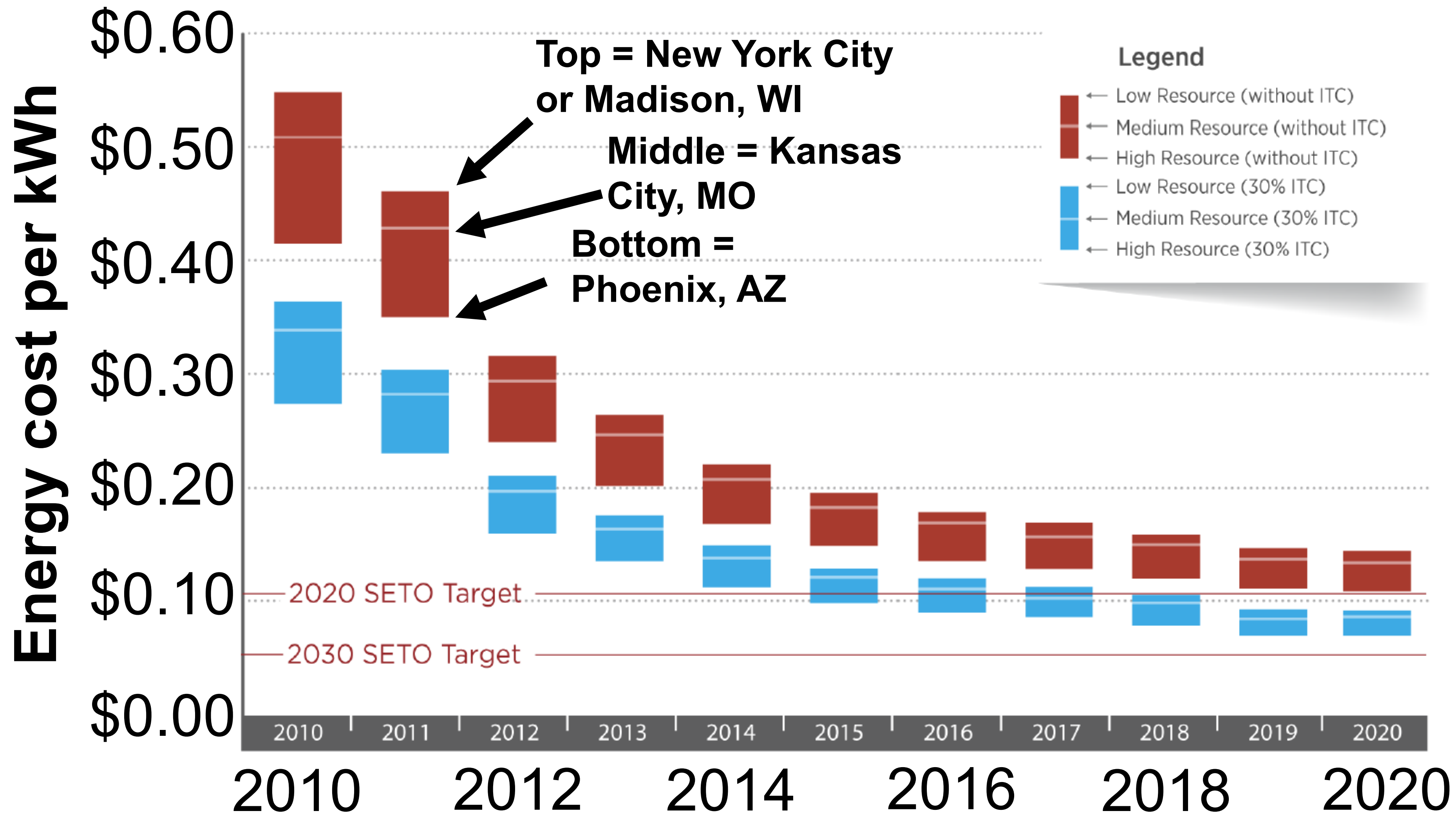
Installed cost: *utility-scale*

Image and data from: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

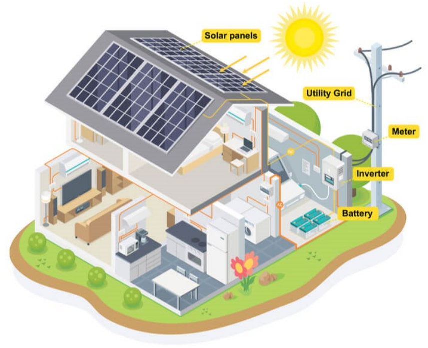


Economies of scale
utility versus residential

Energy cost per kWh (30 years)



Residential

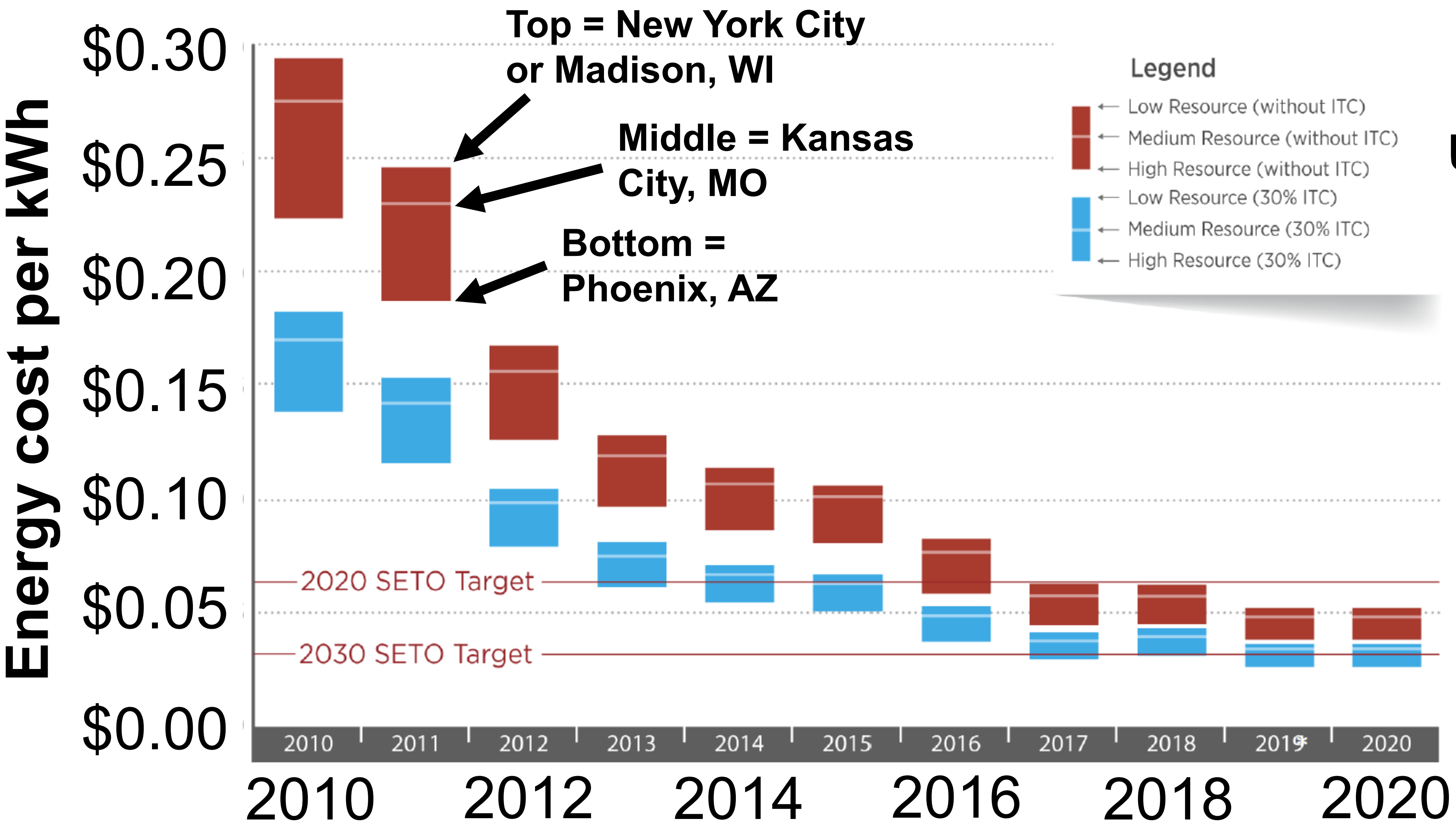


Red = without tax credit

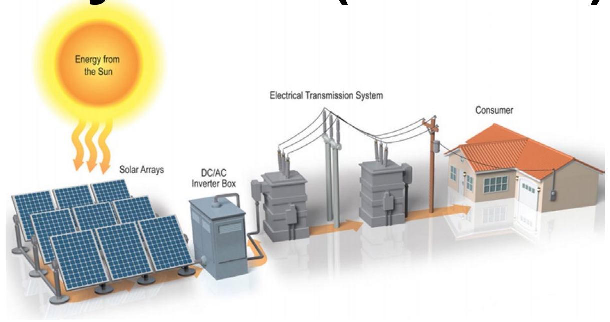
Blue = with tax credit

Data / image source: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

Energy cost per kWh (30 years)



Utility-Scale (100 MW)

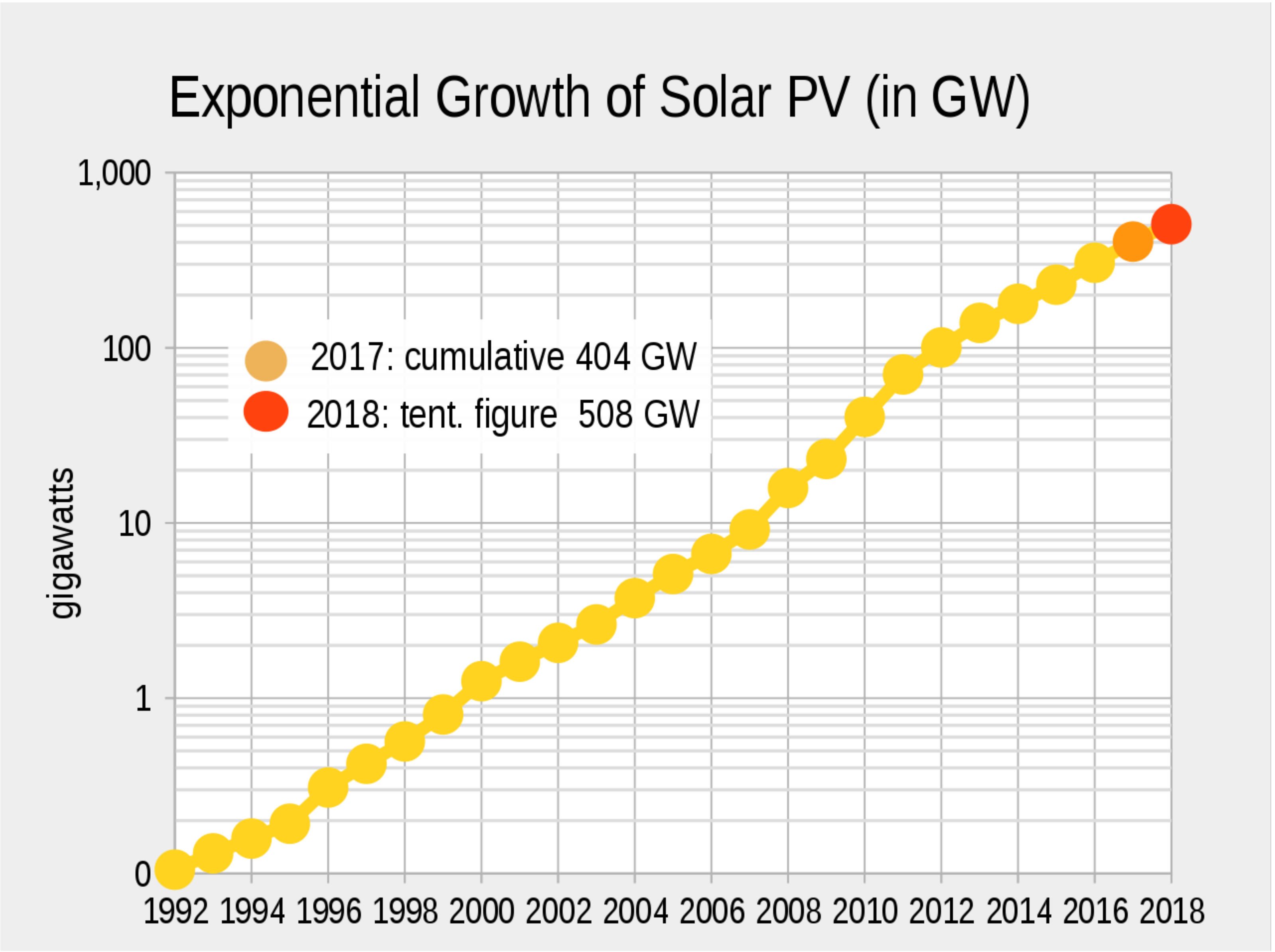


Red = without tax credit

Blue = with tax credit

Data / image source: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

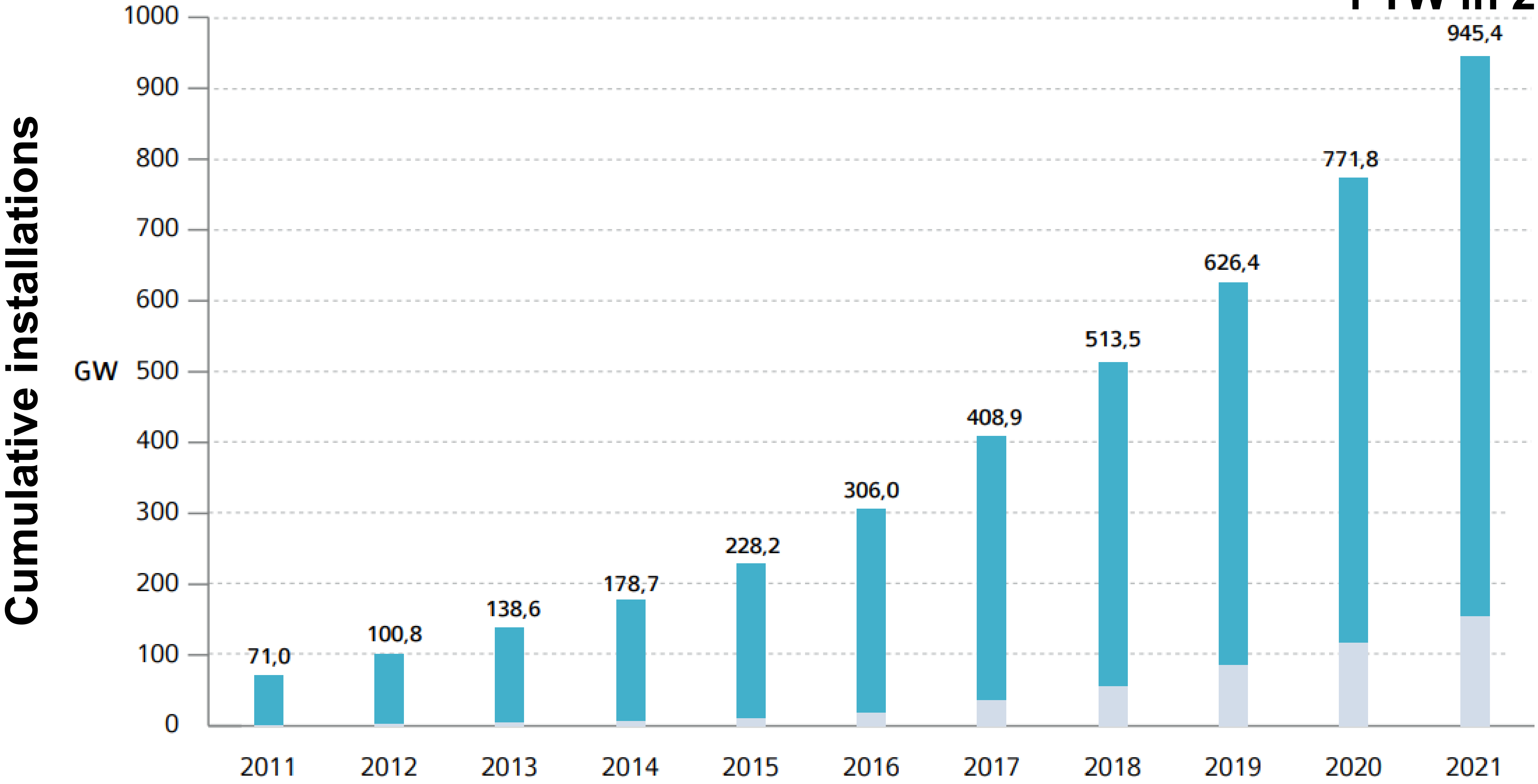
Global PV market grown exponentially in 30 years.



Data source: iea-pvps.org

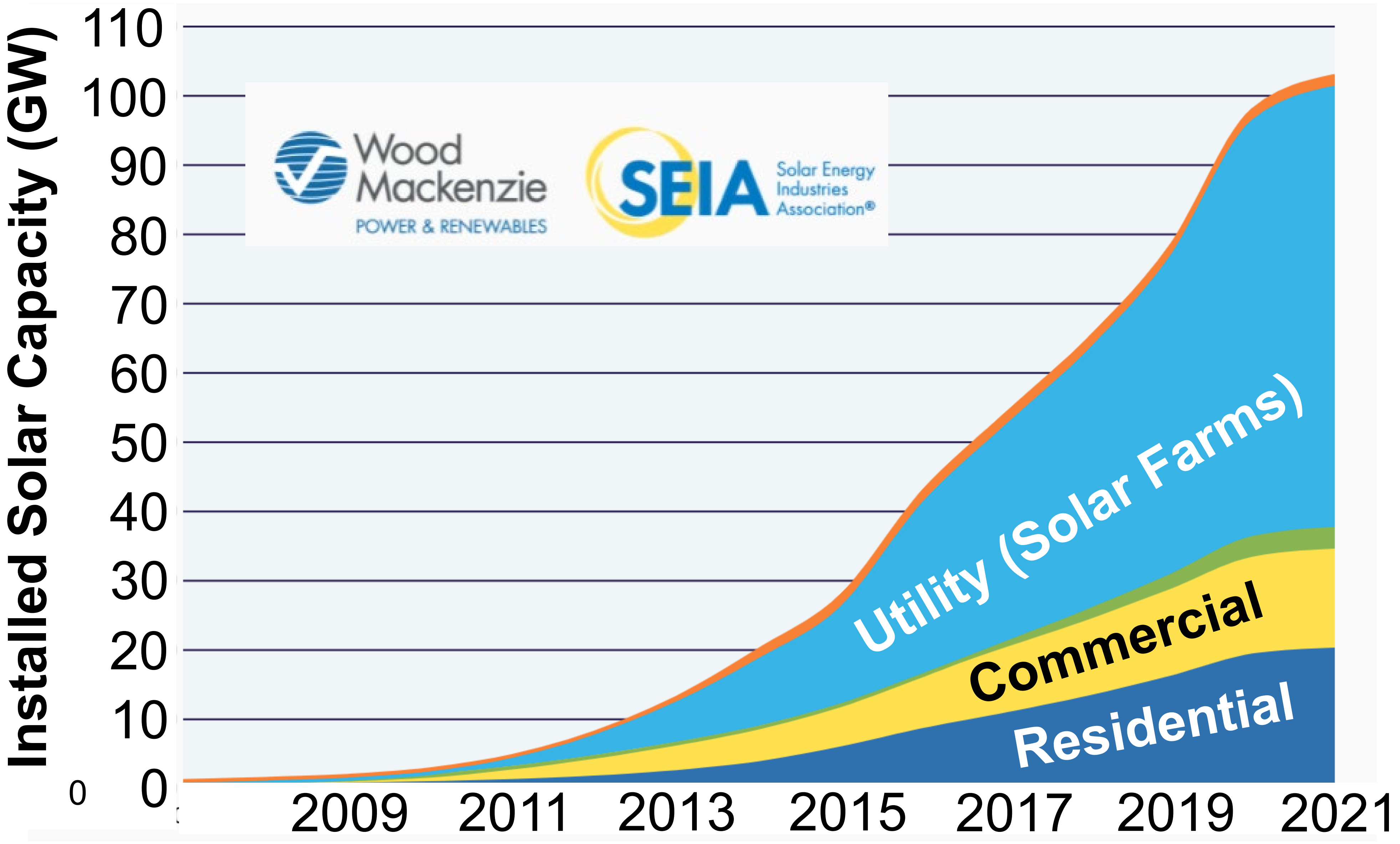
Closer look at last 10 years

~1 TW in 2021



Data/image source: iea-pvps.org

U.S. installations have also dramatically grown.



Reasons for dramatic growth

- **Capitalism and economies of scale**
  - Business of manufacturing and installing solar have become dramatically more efficient.
- **R&D**
  - Improved cell efficiency and decreased materials processing costs
- **Government policy**
  - Tax credits
  - Inflation Reduction Act of 2022 extends ITC of 30% through 2032

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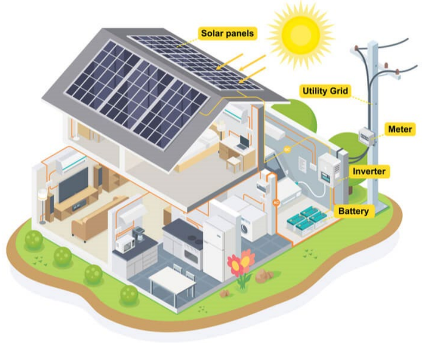
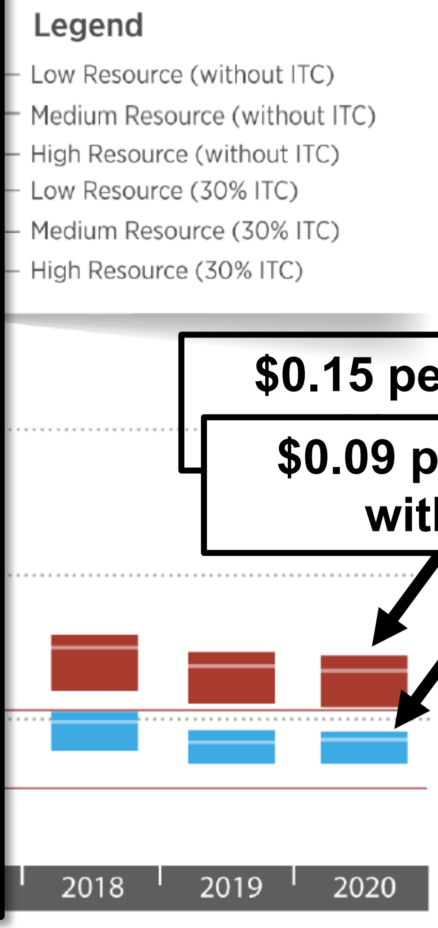
Energy cost per kWh (30 years)

- Current MGE rate is $0.15 per kWh.
- MGE rate will inflate with time to much greater than $0.15 per kWh.
- Fixed cost of solar now will lock in price of $0.09 kWh.
- Significant savings over 30 years.
- Break even point < 15 years.

Residential





$0.15 per kWh in 2020

$0.09 per kWh in 2020 with tax credit

Red = without tax credit

Blue = with tax credit

Data / image source: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

Payback time of < 15 years

solarreviews.com/solar-panel-cost/wisconsin

SolarReviews | Solar Calculator | Reviews | Your Utility | Blog | Learn About Solar

Current solar panel cost near you in WI

Showing data for:

Change

ric Co Change

Change

- Investment of $10,000 now will return a "profit" of $20,000+ in 30 years.
- Reduce pollution and save money at the same time!!!

Prices based on a 5.8kW system, after 30% federal tax credit

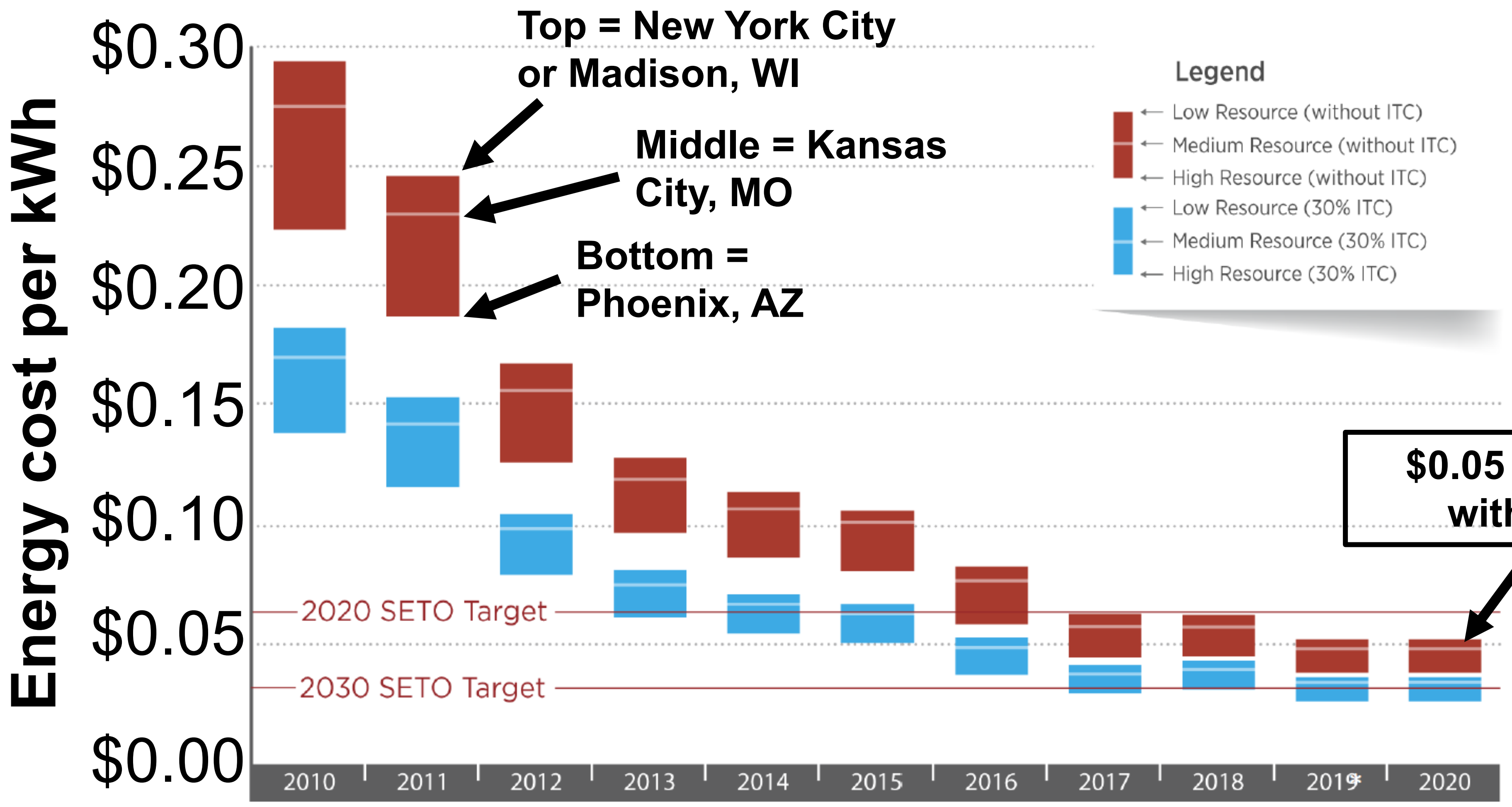
(*with tax incentives*)
Cost range of local prices
$9,113-$11,138

Net profit (savings less system cost)
$21,843-$26,698

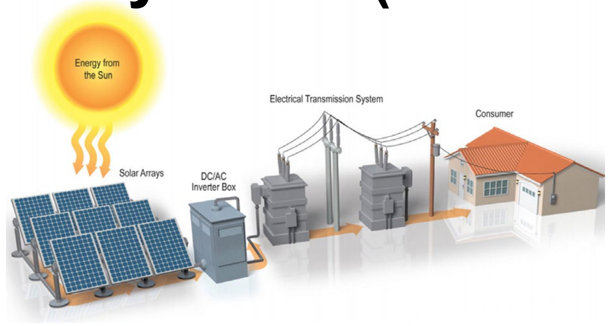
with tax incentives

Payback period
8.8-10.8 years

Energy cost per kWh (30 years)



Utility-Scale (100 MW)



Red = without tax credit

Blue = with tax credit

Data / image source: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

Utility solar in development across Wisconsin

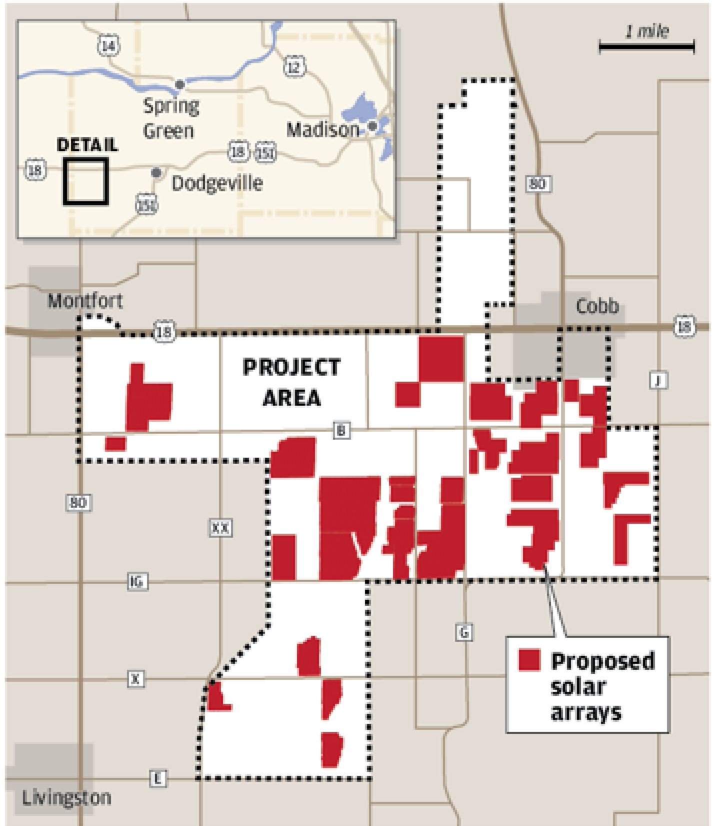
PROJECT NAME	LOCATION	SIZE OF PROJECT	PROJECT STATUS
Two Creeks Solar	Manitowoc County	150 MW	Operational November 2020
Badger Hollow Solar 1	Iowa County	150 MW	Operational December 2021
Badger Hollow Solar 2	Iowa County	150 MW	Online March 2023
Point Beach Solar	Manitowoc County	100 MW	Operational September 2021
Wood County Solar	Wood County	149 MW	Online November 2022
Bear Creek Solar	Richland County	49 MW	Online October 2022
North Rock Solar	Rock County	50 MW	Online March 2023
Paris Solar	Kenosha County	200 MW	Online June 2023

Alliant Energy has proposed 1100 MW and WEC+MGE 350 MW of solar utility projects.

RENEW WISCONSIN

Badger Hollow Solar Farm

Construction is underway on a 300-megawatt solar farm in Iowa County that would be the largest in Wisconsin. The first 150 megawatts are scheduled to go in service in April, but import tariffs have delayed the second half until December 2022.



Outline

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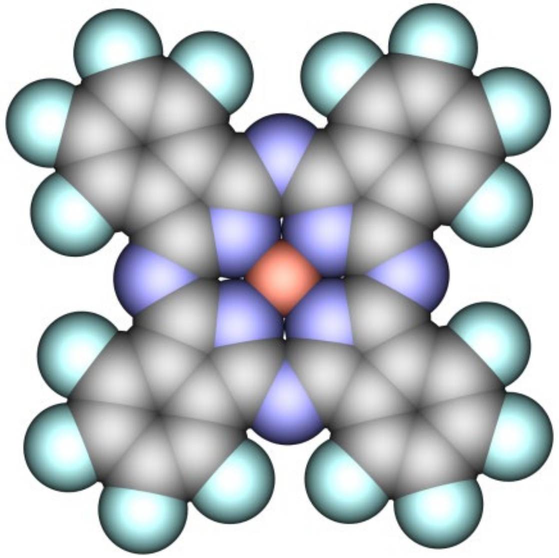
- Solar in Wisconsin
- **The future**

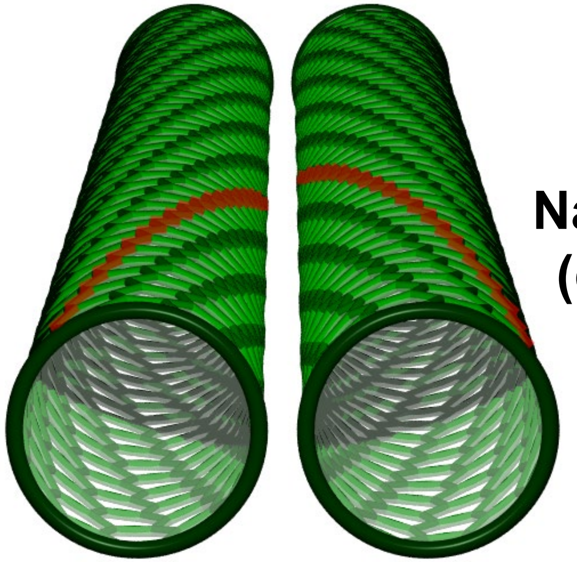
Looking forward

- Economies of scale will continue to push down price.
- R&D of new materials and processes will continue to improve the $ / W ratio.
- Challenges
  - Energy storage
  - Existing fossil fuel infrastructure already in place… will take time to transition and retire existing plants
  - Land usage conflicts

Exploratory cells: new materials

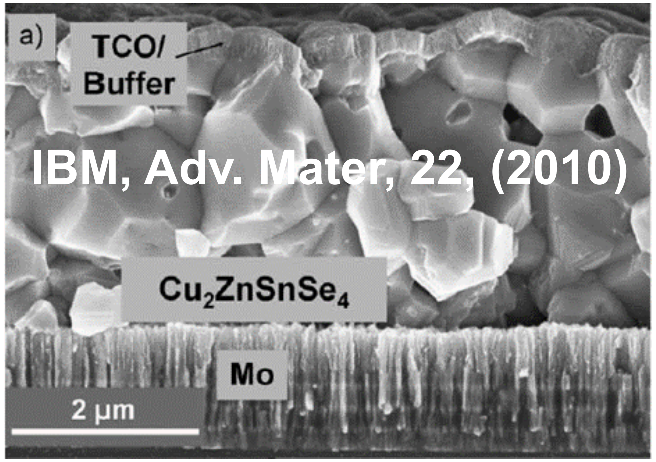
Organic molecules & polymers

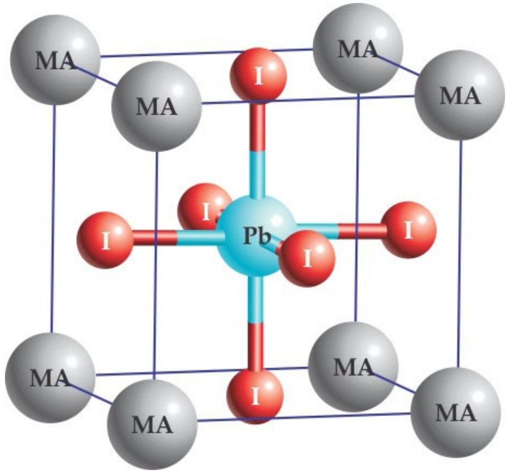




Nanotechnology (quantum dots and carbon nanotubes)

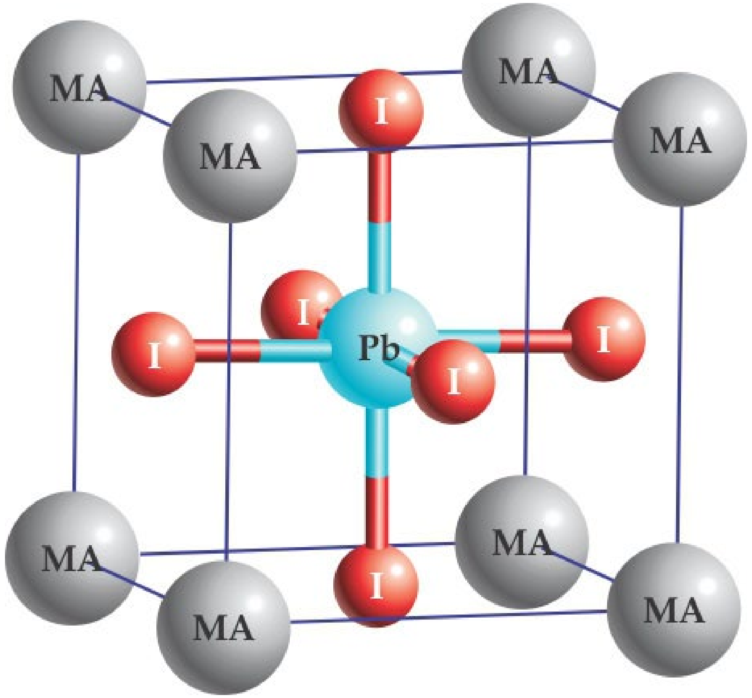
New inorganic semi-conductors





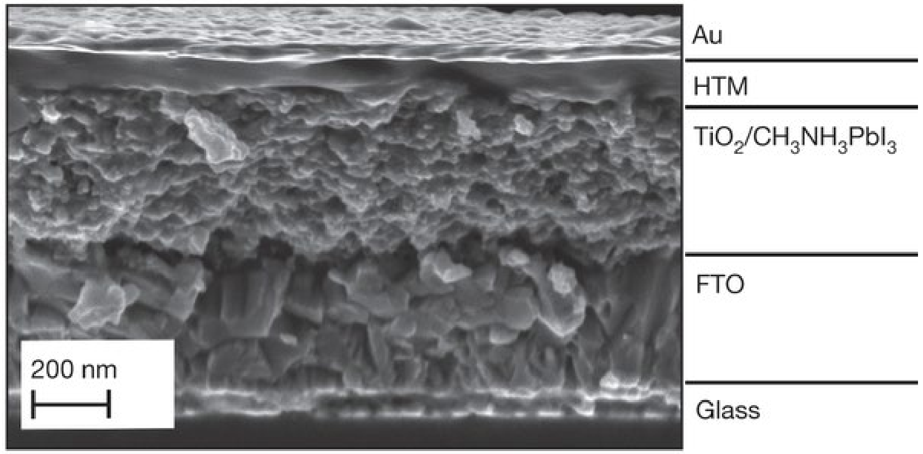
Inorganic /organic hybrid perovskites

Organic-inorganic hybrid perovskites



MA = methylammonium

http://scitation.aip.org/docserver/fulltext/pt.5.7058figure1.jpg



http://www.nature.com/nature/journal/v499/n7458/images_article/nature12340-f2.jpg

- ❑ Discovered just a few years ago
- ❑ Solution-processable → Inexpensive
- ❑>20% already!!!
- ❑Stability and lifetime still an issue

Economic conclusions

- Technology has rapidly matured.
- Scale of manufacturing has grown exponentially.
- Price has plummeted.
- Solar is now cost- competitive or superior.

Thank you!

- **Wisconsin specific resources**
  - REWEW Wisconsin
    www.renewwisconsin.org/solar-energy/
  - Solar Energy Industries Association (SEIA)
    https://www.seia.org/state-solar-policy/wisconsin-solar
- **More information on solar technologies**
  - Solar Photovoltaics Technology Basics
    https://www.energy.gov/eere/solar/solar-photovoltaic-technology-basics
  - Copy of these slides
    https://arnold.engr.wisc.edu/outreach.html

Science and engineering summary

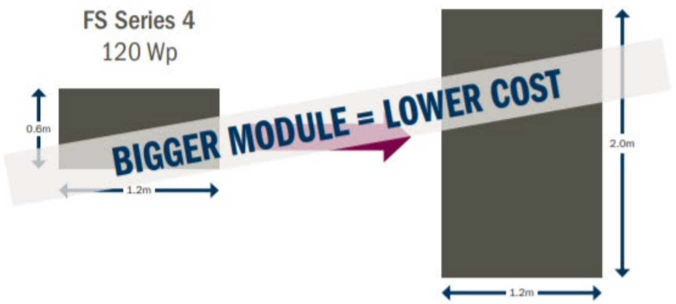
- The active materials in a photovoltaic solar cell are semiconductors.
- A junction between P-doped and N-doped semiconductors (PN junction) is used to separate the positive and negative charges generated by light → electricity.
- Single- and polycrystalline single-junction Si and polycrystalline thin film single-junction CdTe are currently the most commonly installed photovoltaic technologies.
- Efficiency is about 20%.

First Solar Thin Film CdTe Series 4 versus Series 6… Improvements in manufacturing and efficiency

THIN FILM SCALES

- Unit of process for CdTe is the glass; scaling benefit
- Unit of process for c-Si is the wafer; no scaling benefit
- Same manufacturing process as the previous technology
- Highest power utility-scale modules in the market

Thin film cost scales non-linearly…



…similar to LCD screens.

No cost benefit from scaling c-Si

Source: FirstSolar.com

What makes a semiconductor a good semiconductor?

- Proper band gap
  - Determines energies of light waves absorbed and PV voltage
- Abundance of materials
- Economics of processing / scale-up / toxicity / cost of disposal
- “Speed” of charges
- Thermal and chemical stability / lifetime / reliability
- Electronic nature of atomic-scale defects and imperfections in semiconductors

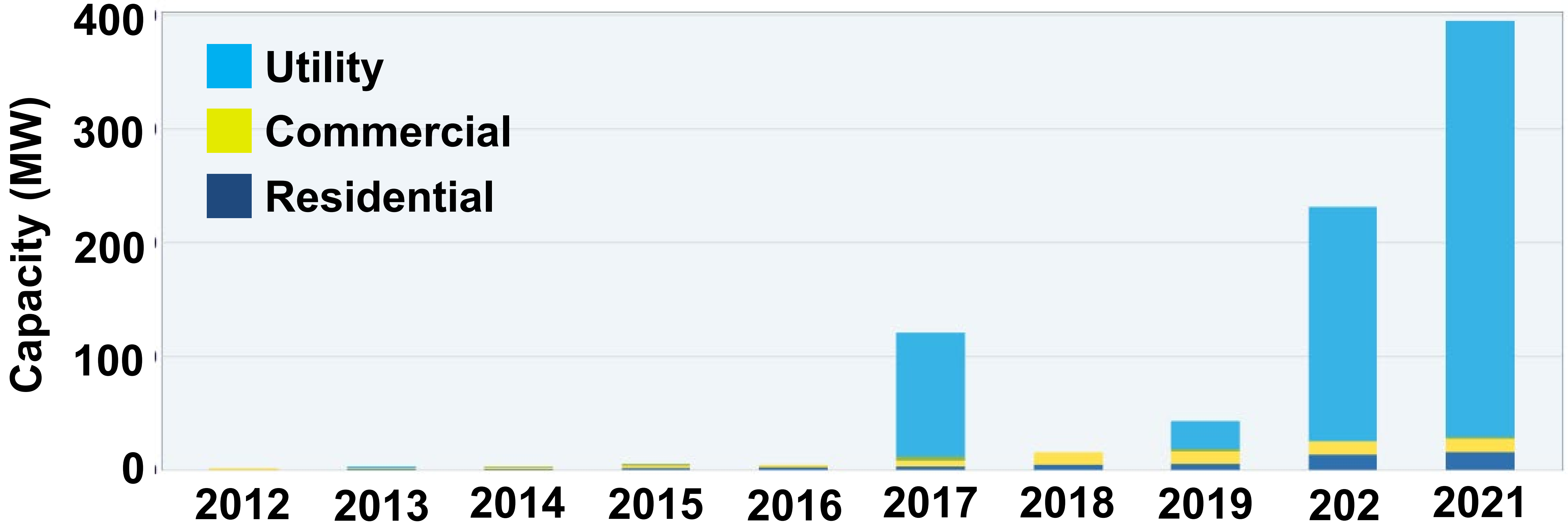
Is there enough land? Yes.

- “Wisconsin could produce about 50% of our annual electricity needs through the use of solar panels on only 125,000 acres of land.
- For comparison, according to the USDA, as of 2021 the total land in farms for Wisconsin was approximately 14,300,000 acres.”

https://www.renewwisconsin.org/solar-energy/

RENEW WISCONSIN

Result of favorable economics:
Solar installations rapidly growing in WI!



SEIA.ORG/states

What about storage?

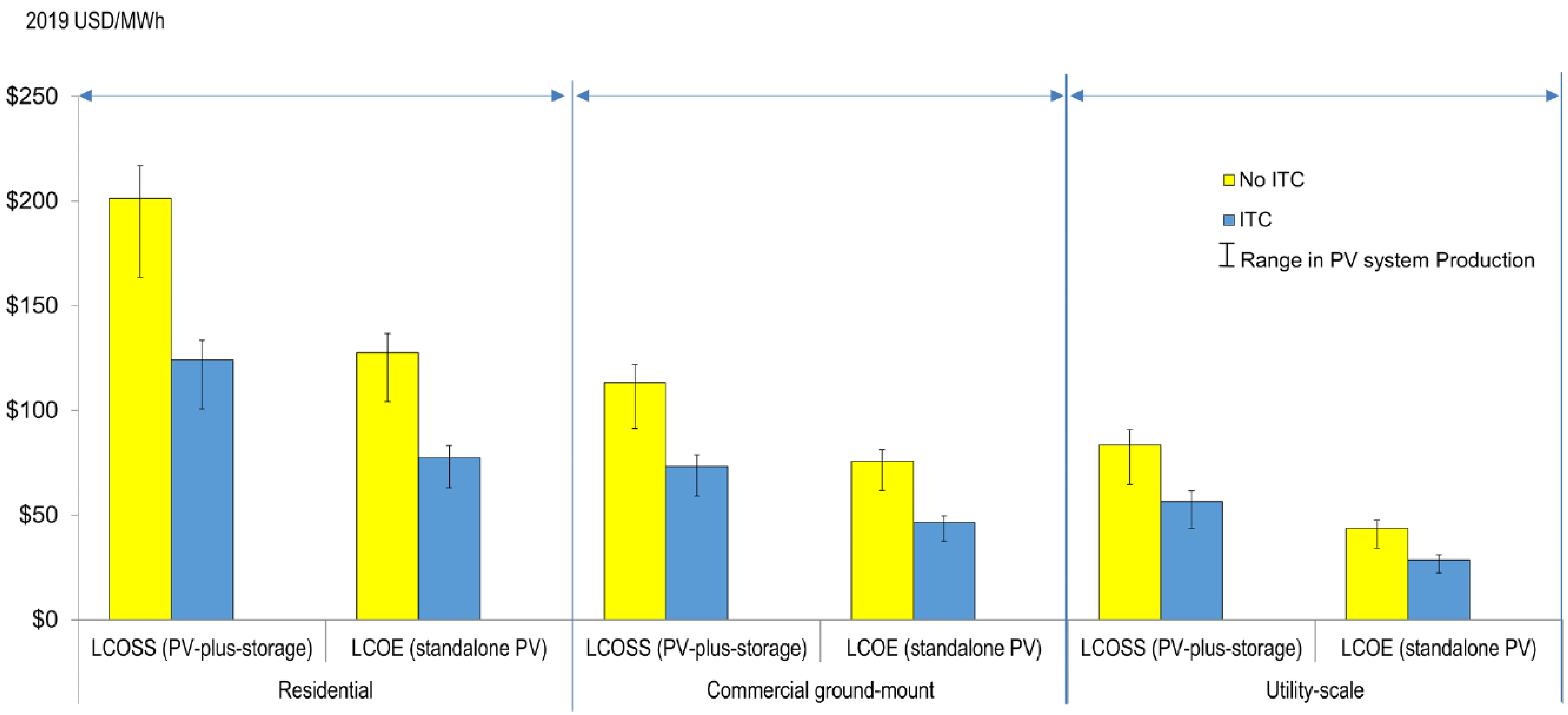


Image and data from: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

Storage costs decreasing with time as well...

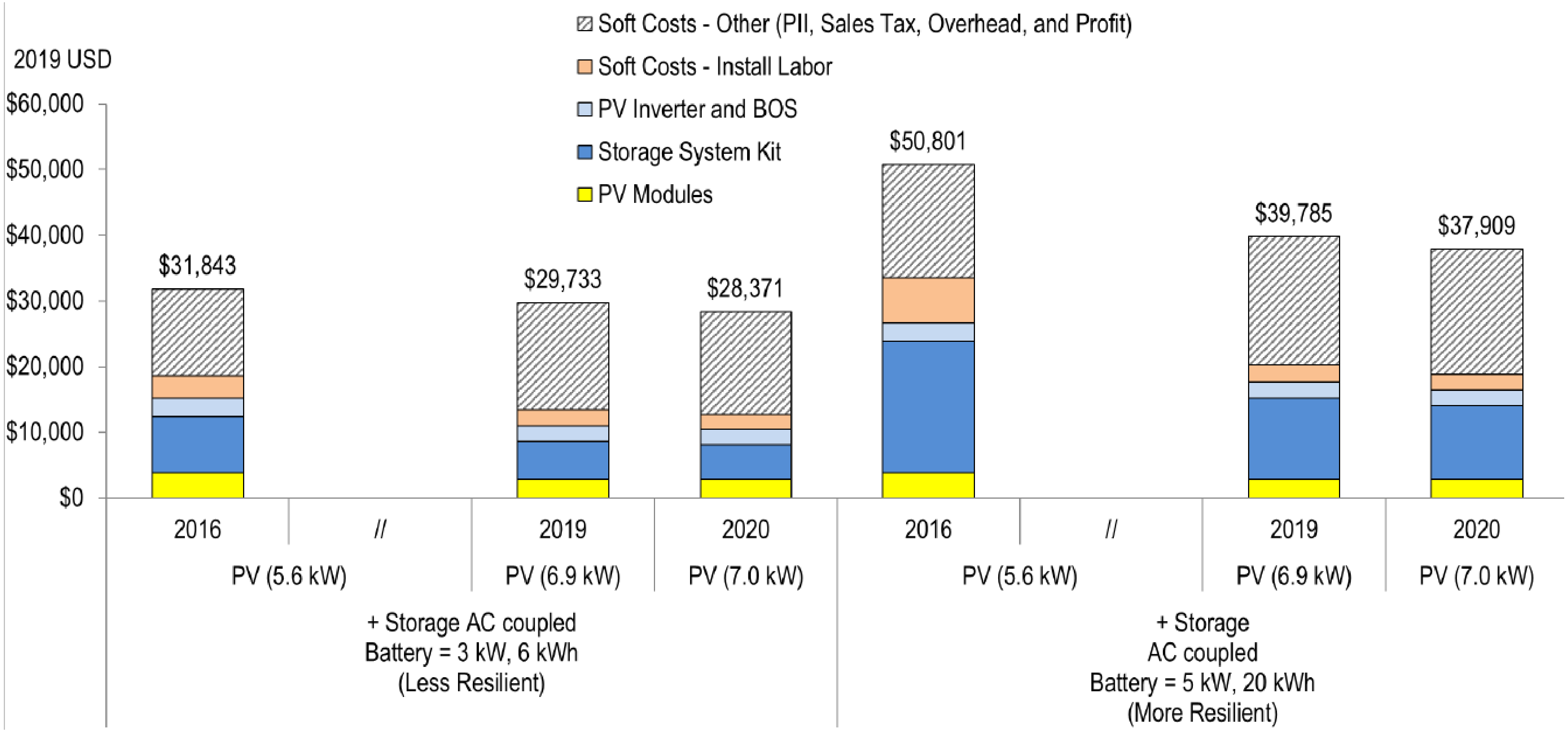
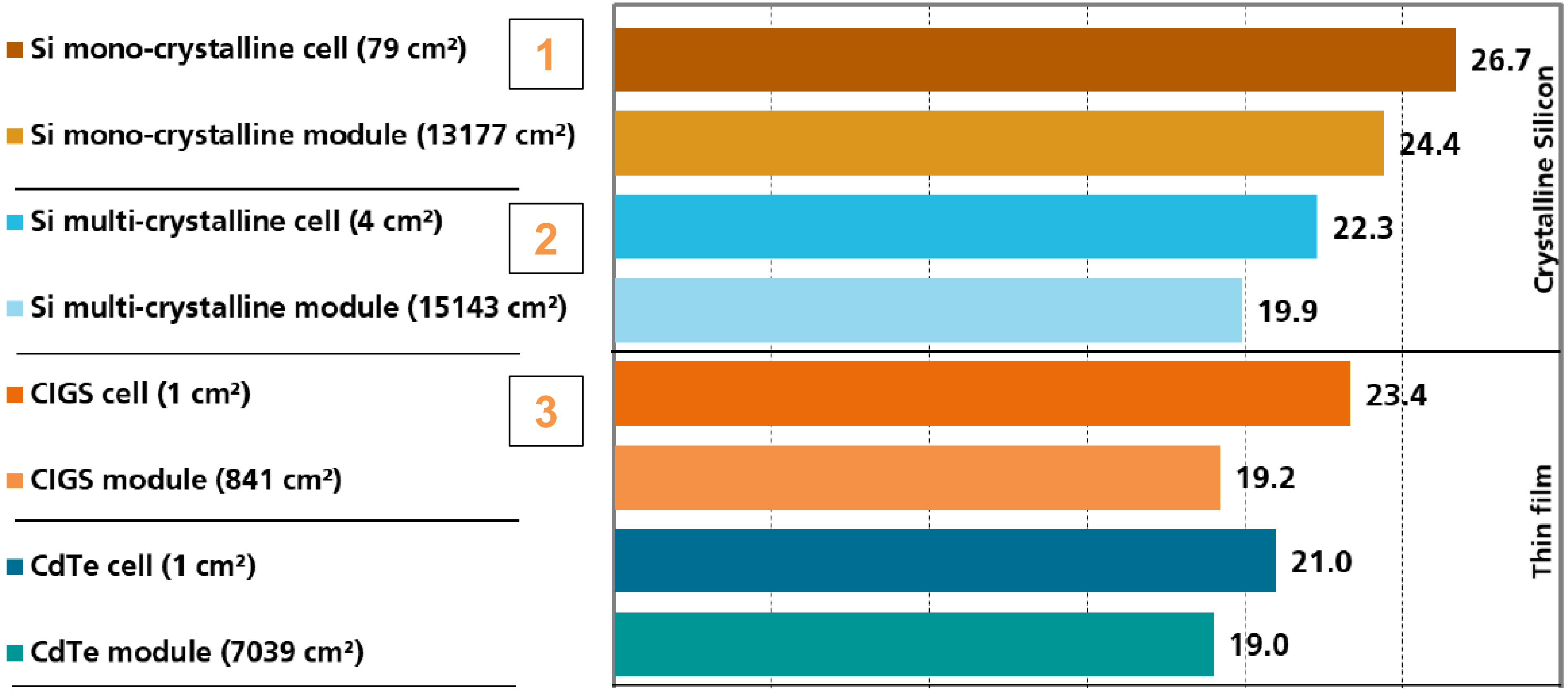


Figure ES-5. Residential PV-plus-storage system cost benchmark summary (inflation-adjusted), 2016, 2019, and 2020

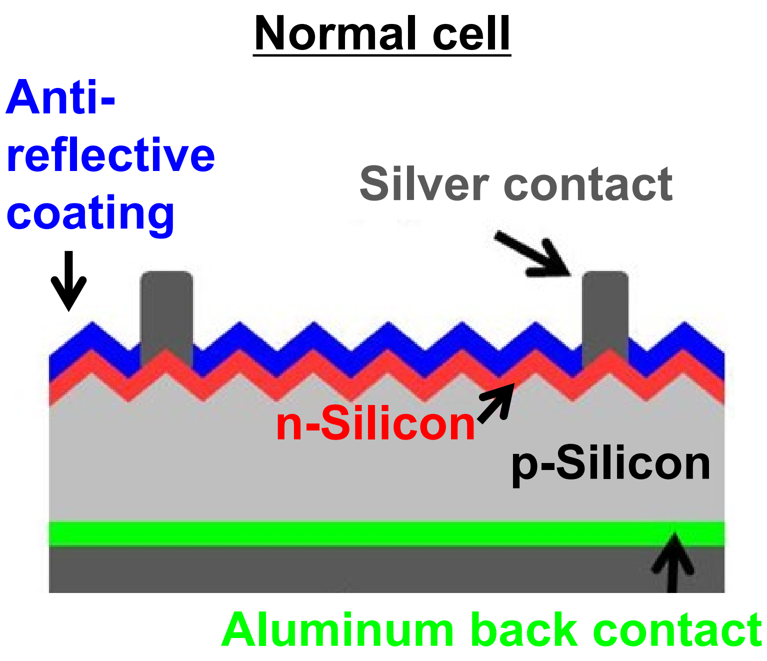
Image and data from: NREL, U.S. Solar Photovoltaic System and Energy Storage Cost Benchmark: Q1 2020

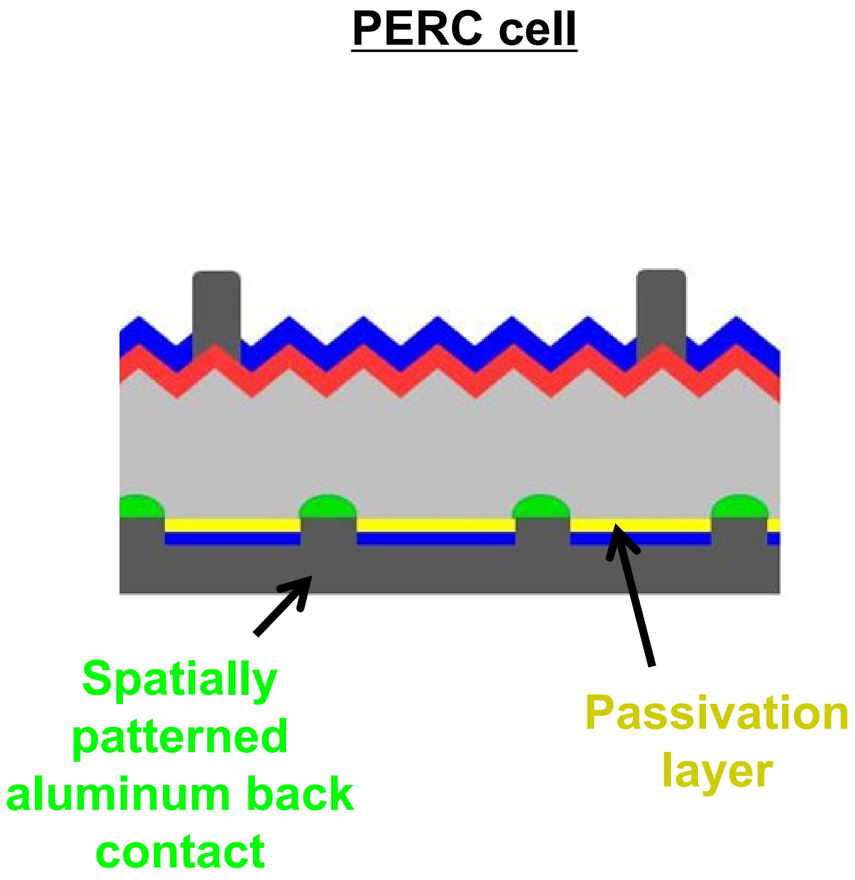
More Detailed Comparison



https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Passivated Emitter Rear Contact (PERC) Single Crystal Silicon Cells

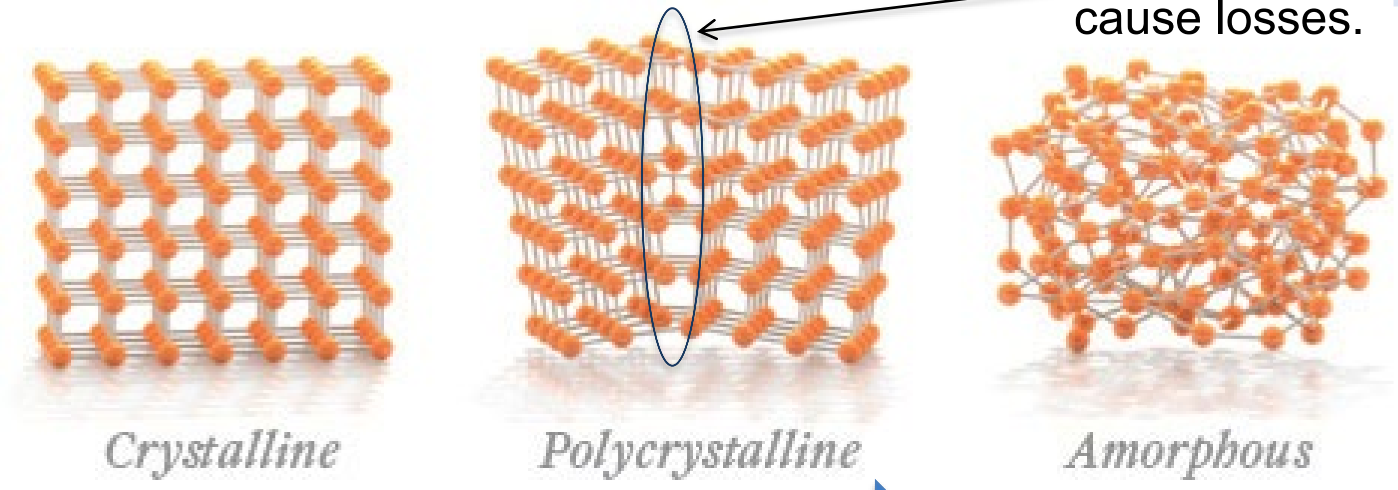




Source: Institute for Solar Energy Research Hamelin (ISFH)

Crystallinity

Defects slow charges and cause losses.



More Economical →

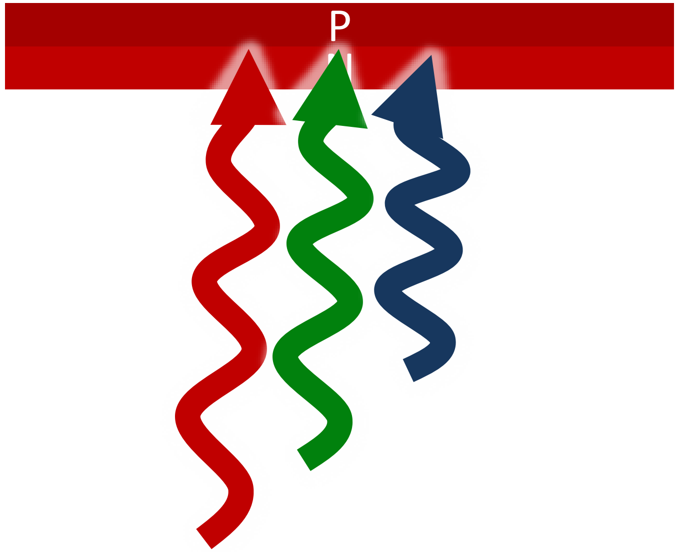
← Faster Charge Collection

Faster Charge Recombination →

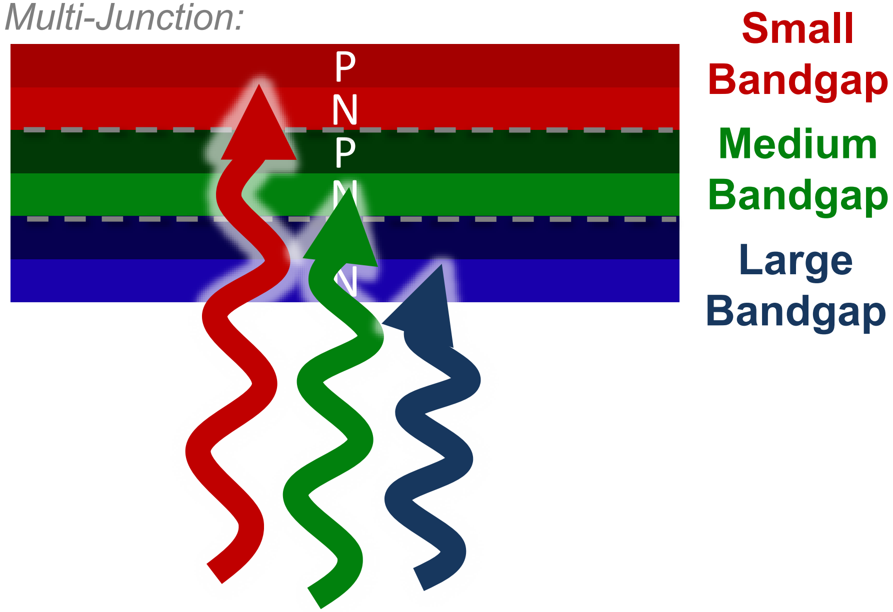
Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:



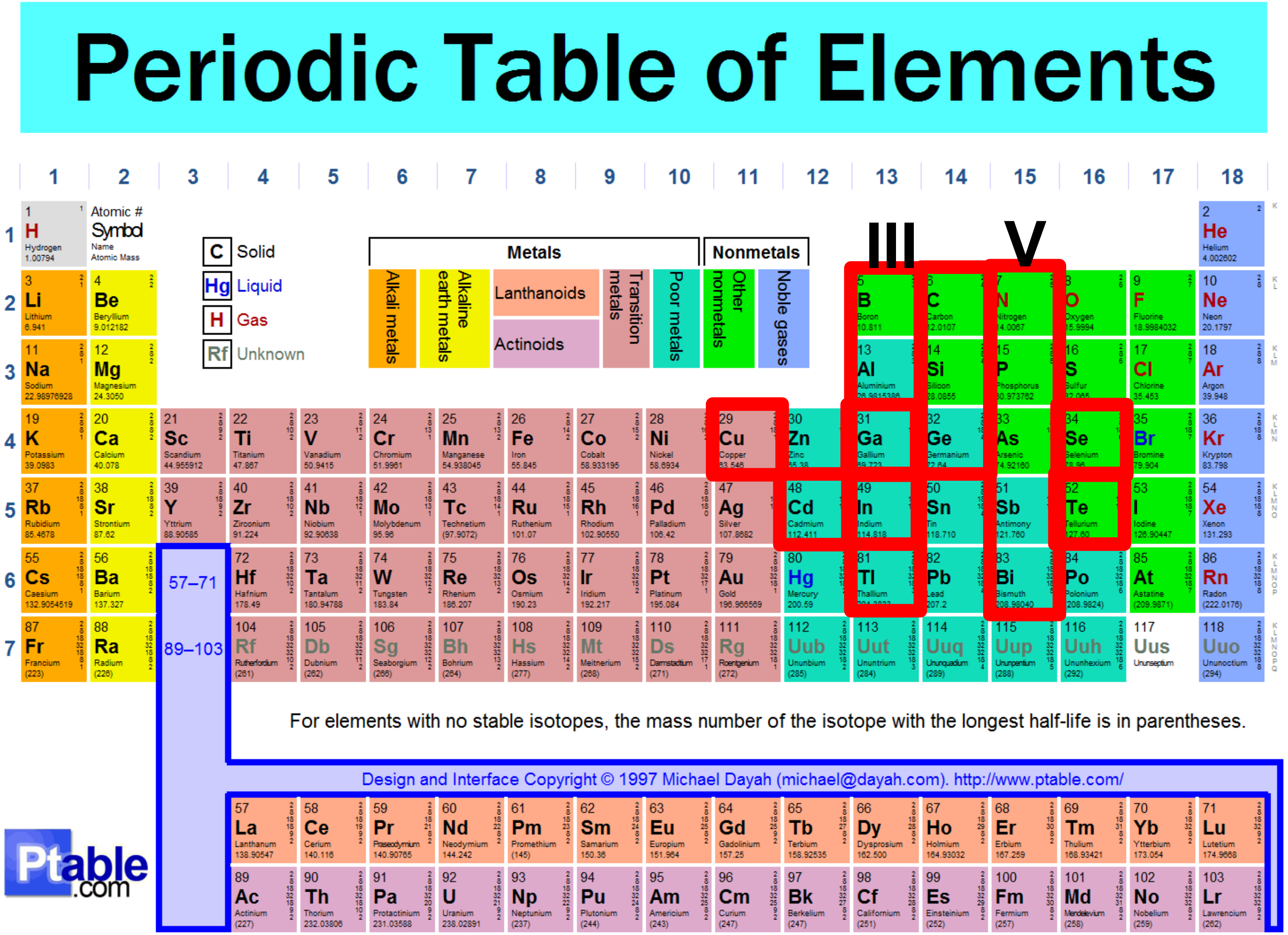
Multi-Junction:



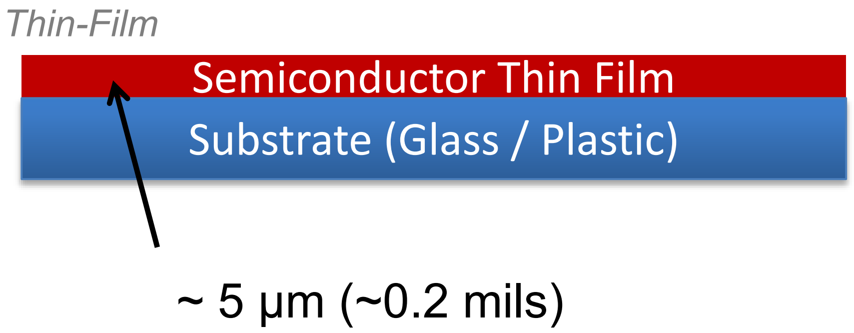
- ❑ When the photon energy > band gap, extra energy is wasted.
- ❑ For example, a blue photon produces same energy as red photon).
- ❑ Maximum efficiency ~30%.

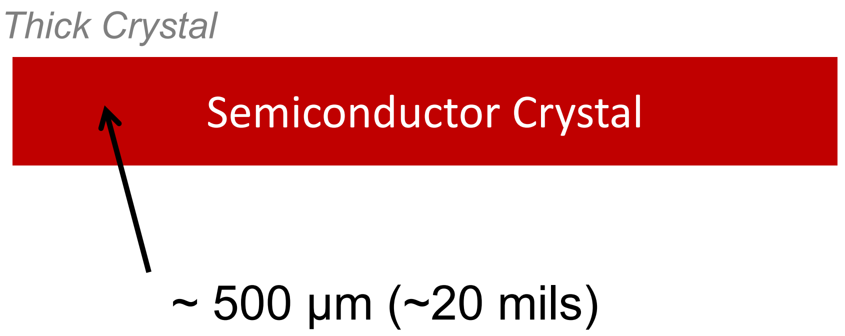
- ❑ In multi-junction cell, blue photon can produce more energy than red photon.
- ❑ Maximum efficiency ~50% (for 3 cells).
- ❑ More complex fabrication → More $$$.

Composition (Different Semiconductors)



Thick Crystal or Thin Film





- Very thin films possible if semiconductor absorbs light strongly (depends on composition).
- Uses less material.
- Requires supporting substrate.
- Typically polycrystalline.

- Self-supporting.
- Single crystalline.

Multi-Junction Solar Cells

Crystallinity

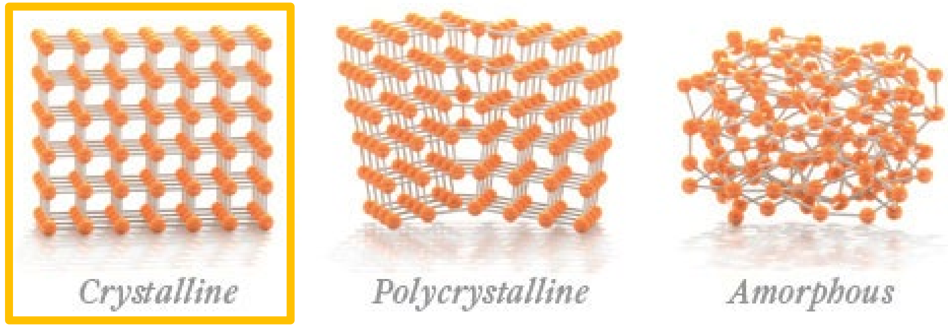


Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:

P
N

Multi-Junction:

P
N
P
N
P
N

Small Bandgap

Medium Bandgap

Large Bandgap

Thick Crystal or Thin Film

Thin-Film

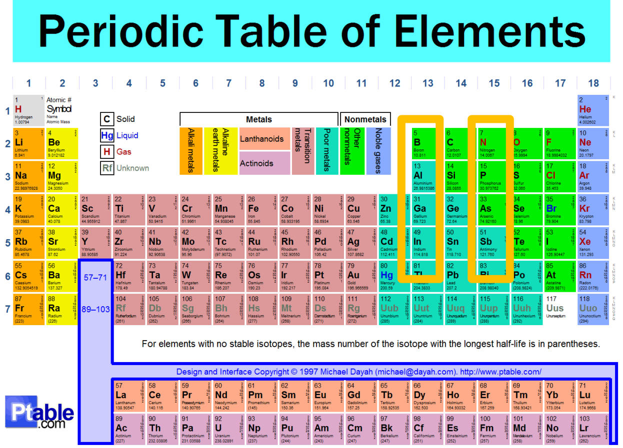
Semiconductor Thin Film

Substrate (Glass / Plastic)

Thick Crystal

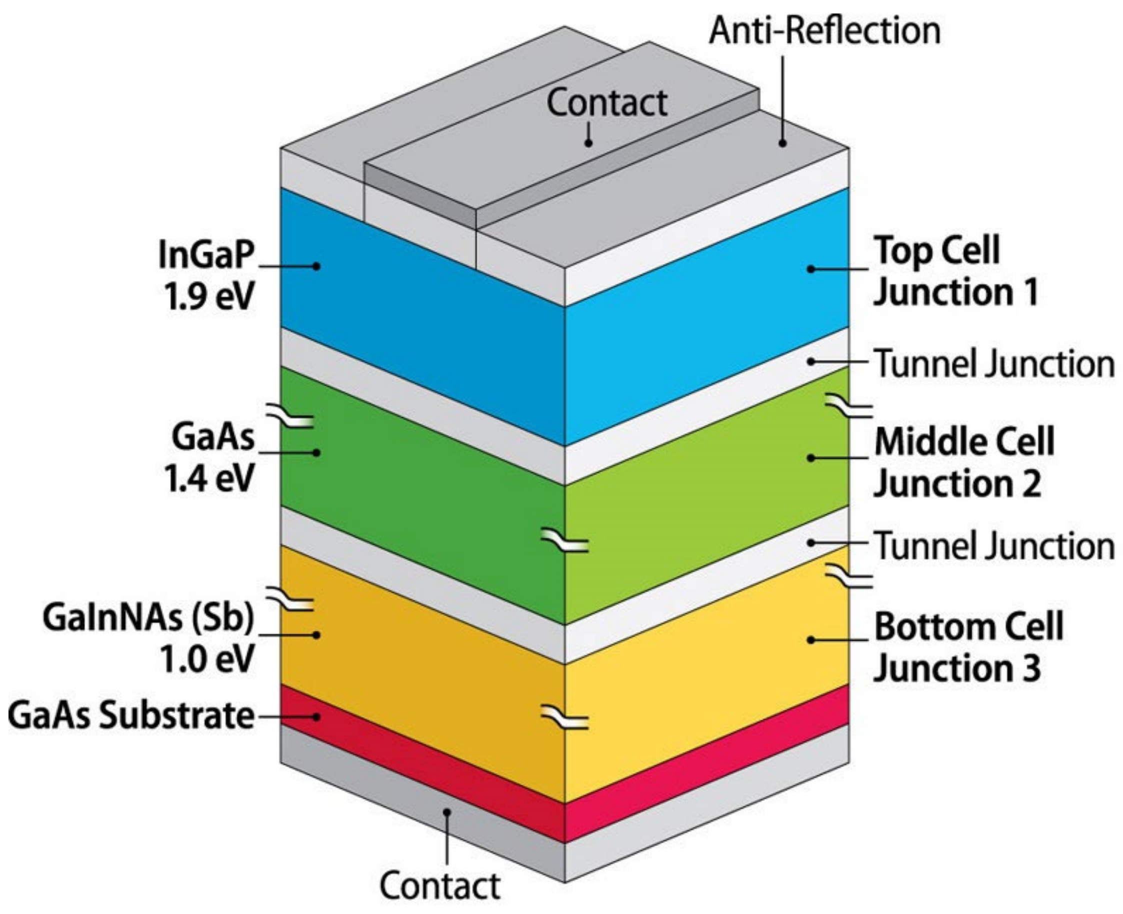
Semiconductor Crystal

Composition



Example: *Near-World Record Multi-Junction Cell*

- Solar Junctions
- 43.5% (2012)
- Recent advances in efficiency due to ability to grow new unique combinations of materials on top of one-another.



from: http://www.nrel.gov/continuum/spectrum/awards.cfm

Disadvantage: *Very Costly*

Many layers of P- and N- doped III,V semiconductors

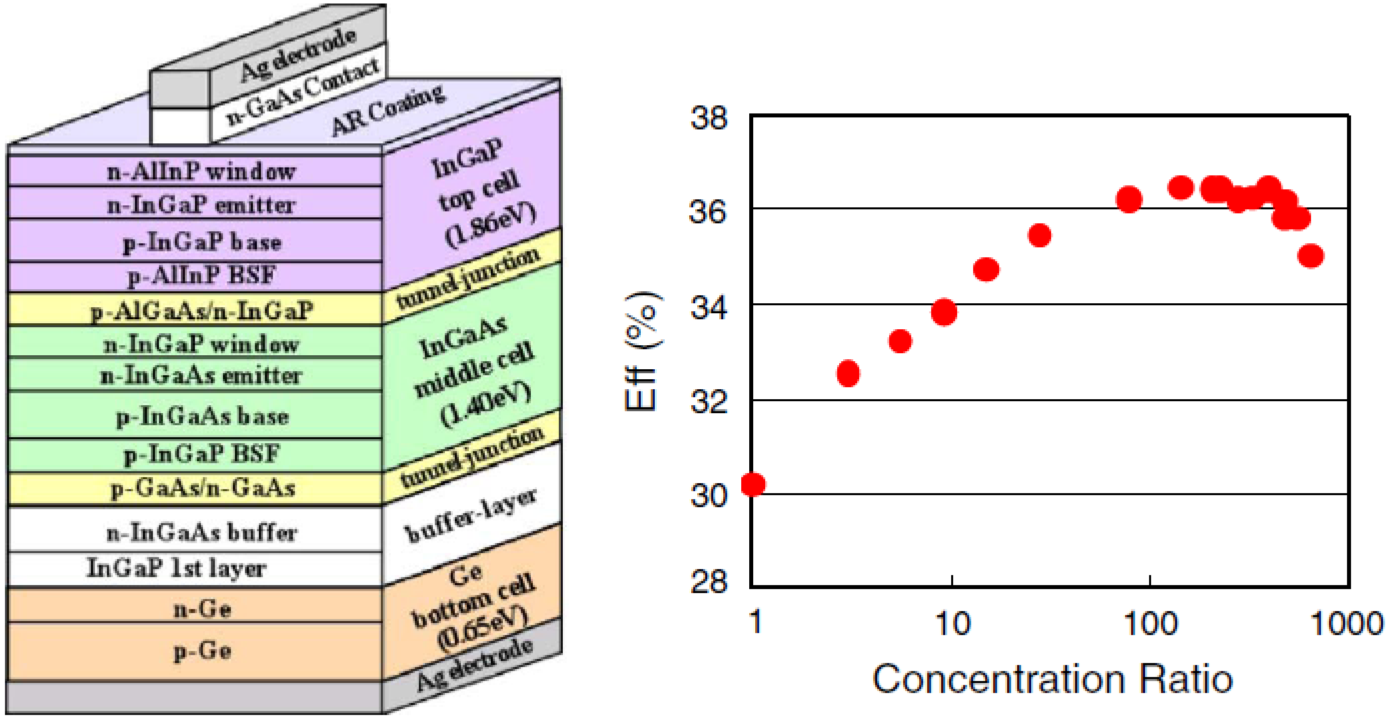
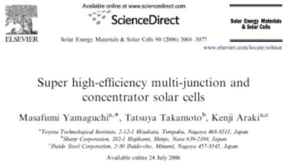


Fig. 5. A schematic cross section of a high-efficiency InGaP/InGaAs/Ge 3-junction soar cell and efficiency of a concentrator cell as a function of concentration ratio.

- Higher efficiency but much higher cost!


Available online at www.sciencedirect.com
ScienceDirect
Solar Energy Materials & Solar Cells 90 (2006) 3068–3077
Solar Energy Materials & Solar Cells
www.elsevier.com/locate/solmat

Super high-efficiency multi-junction and concentrator solar cells

Masafumi Yamaguchi[a,*], Tatsuya Takamoto[b], Kenji Araki[a,c]
[a]Toyota Technological Institute, 2-12-1 Hisakata, Tempaku, Nagoya 468-8511, Japan
[b]Sharp Corporation, 282-1 Hajikami, Shinjo, Nara 639-2198, Japan
[c]Daido Steel Corporation, 2-30 Daido-cho, Minami, Nagoya 457-8545, Japan

Available online 24 July 2006

Possible Solution: *Concentrators*

- Reduce cost by using lenses to focus light from large areas into smaller solar cells

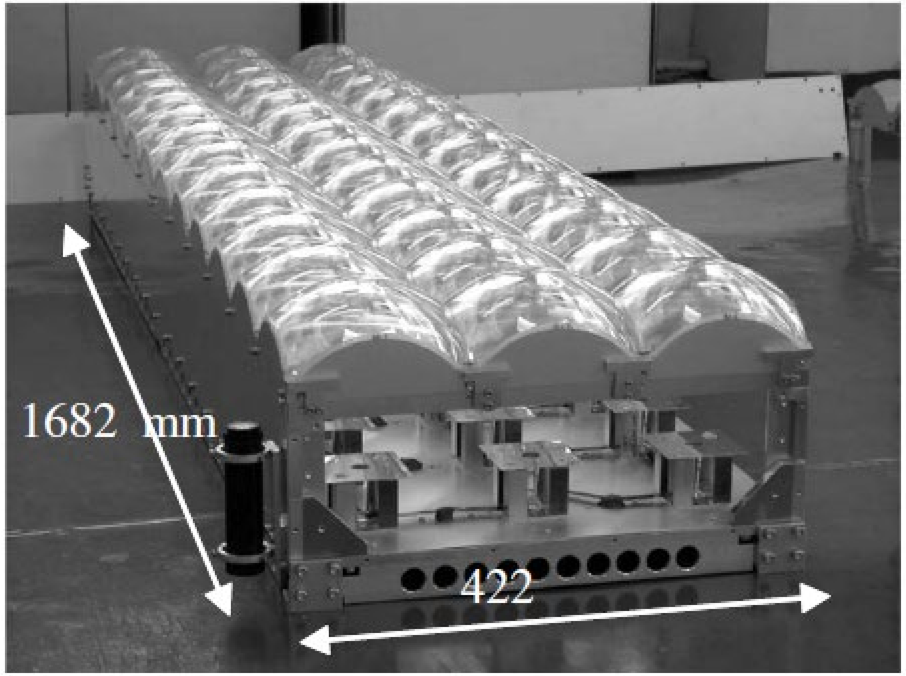
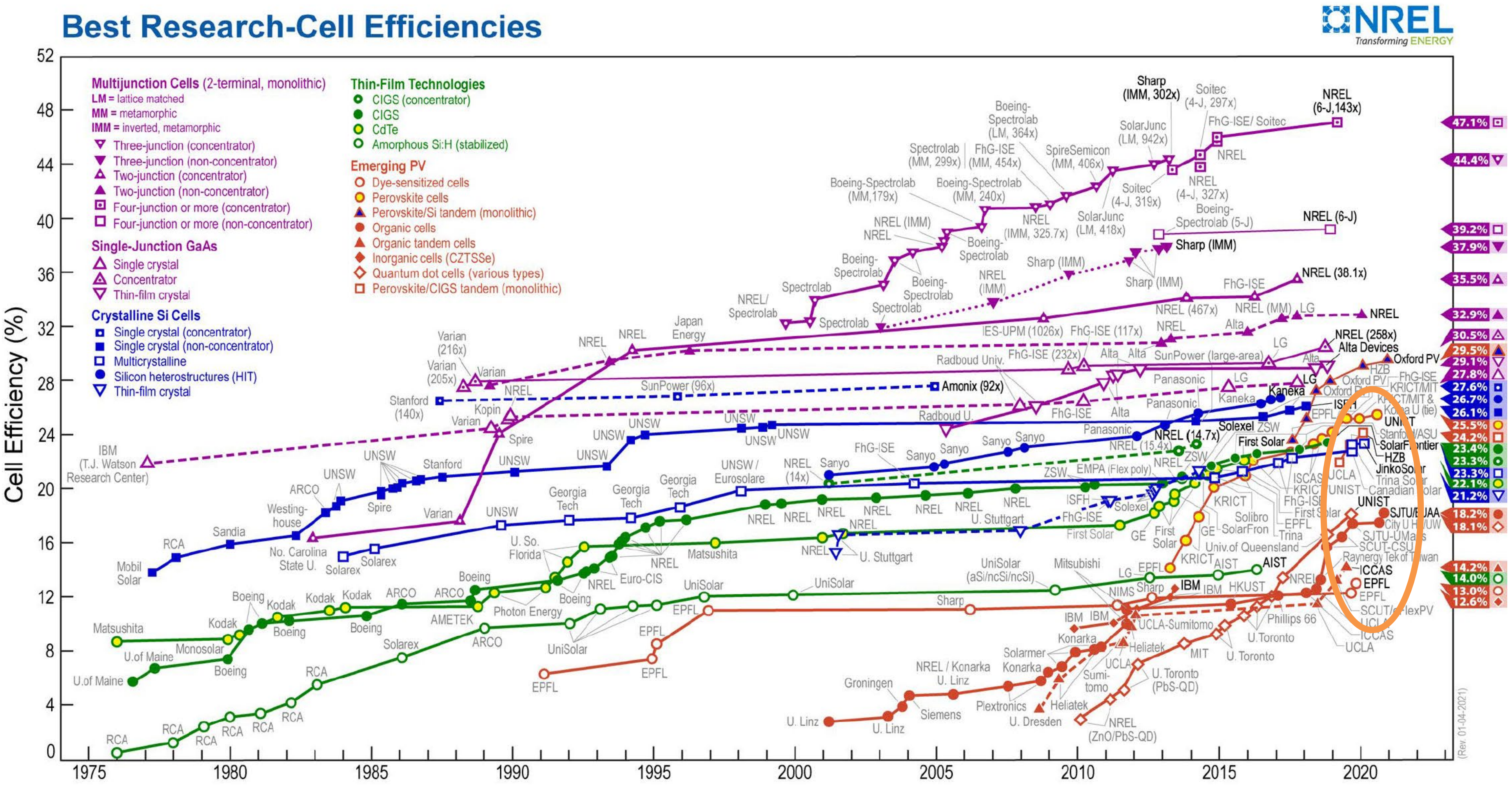


Fig. 6. 7000 cm^2 and 400X concentrator module with the 36 receivers connected in series and dome-shaped Fresnel lens made by injection mold.

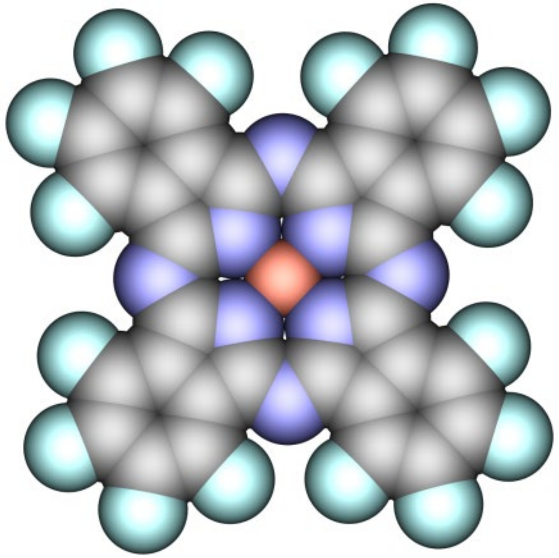
- Must track the sun to enable focusing ➔ expensive.

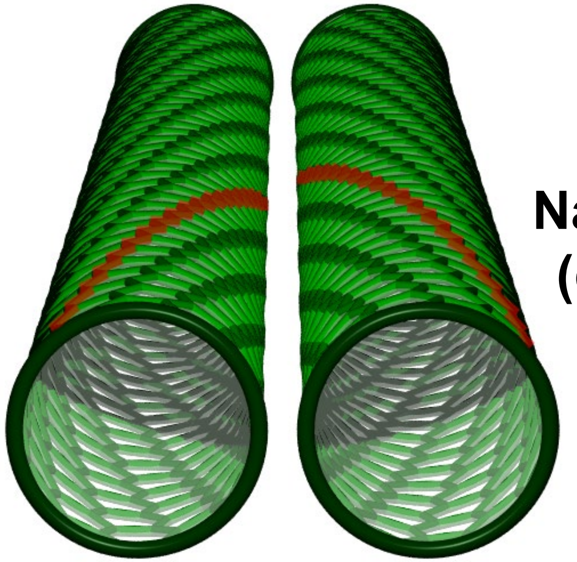
Highly Exploratory Cells



Highly Exploratory Cells: New Materials

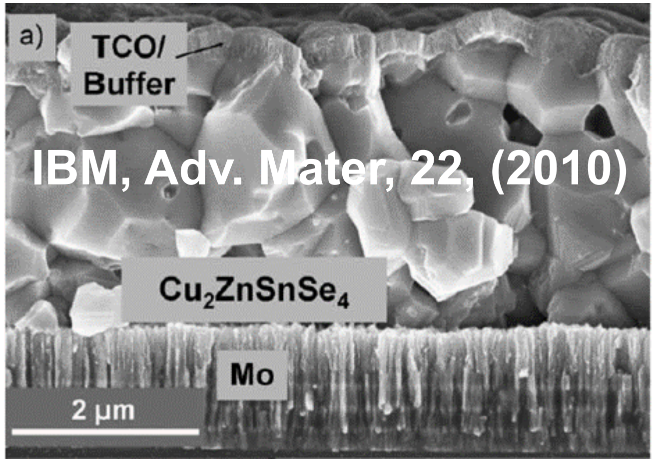
Organic molecules & polymers

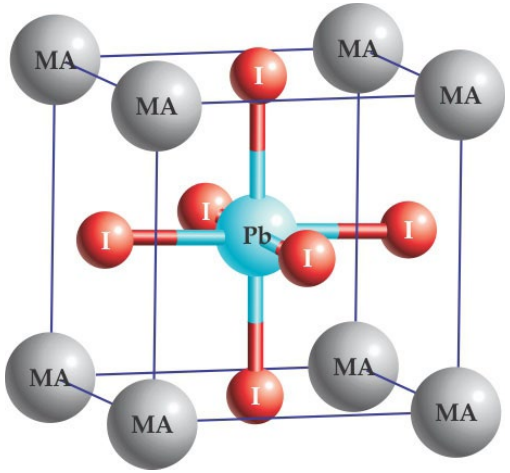




Nanotechnology (quantum dots and carbon nanotubes)

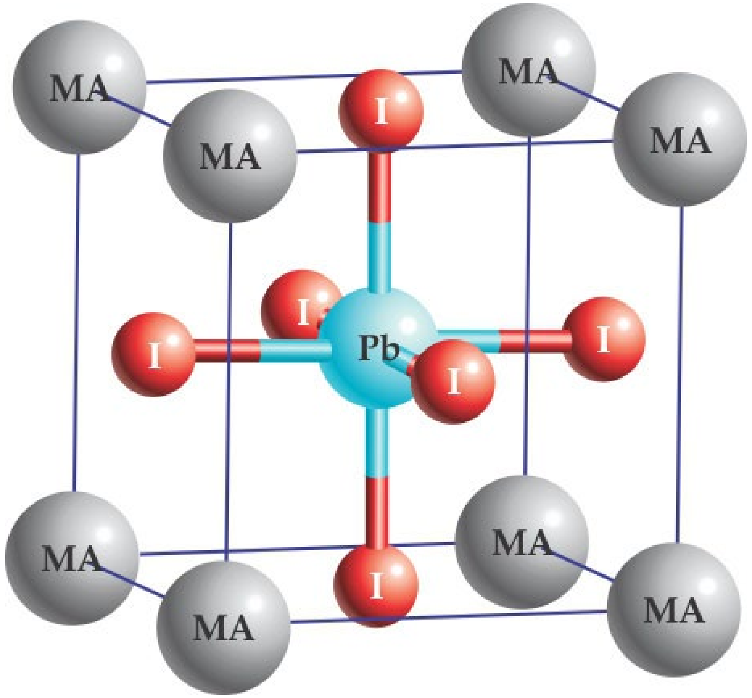
New inorganic semi-conductors





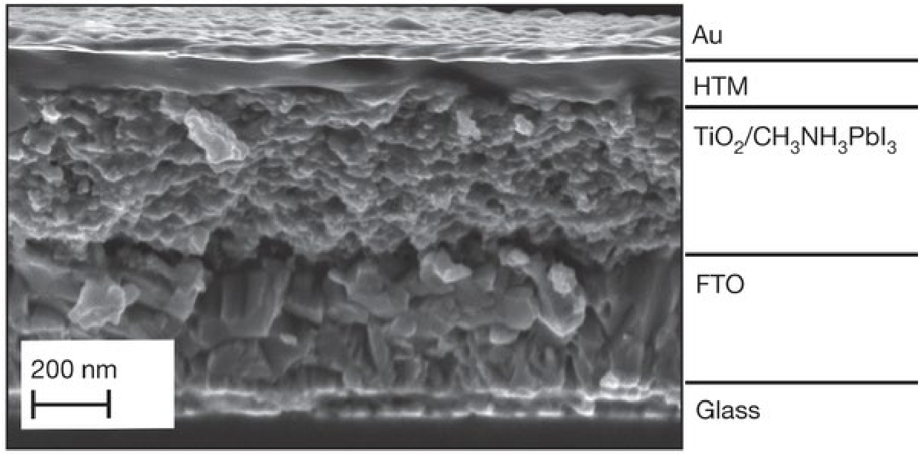
Inorganic/organic hybrid perovskites

Organic-Inorganic Hybrid Perovskites



MA = methylammonium

http://scitation.aip.org/docserver/fulltext/pt.5.7058figure1.jpg



http://www.nature.com/nature/journal/v499/n7458/images_article/nature12340-f2.jpg

- ❑ Discovered just a few years ago
- ❑ Solution-processable → Inexpensive
- ❑>20% already!!!
- ❑Stability and lifetime still an issue