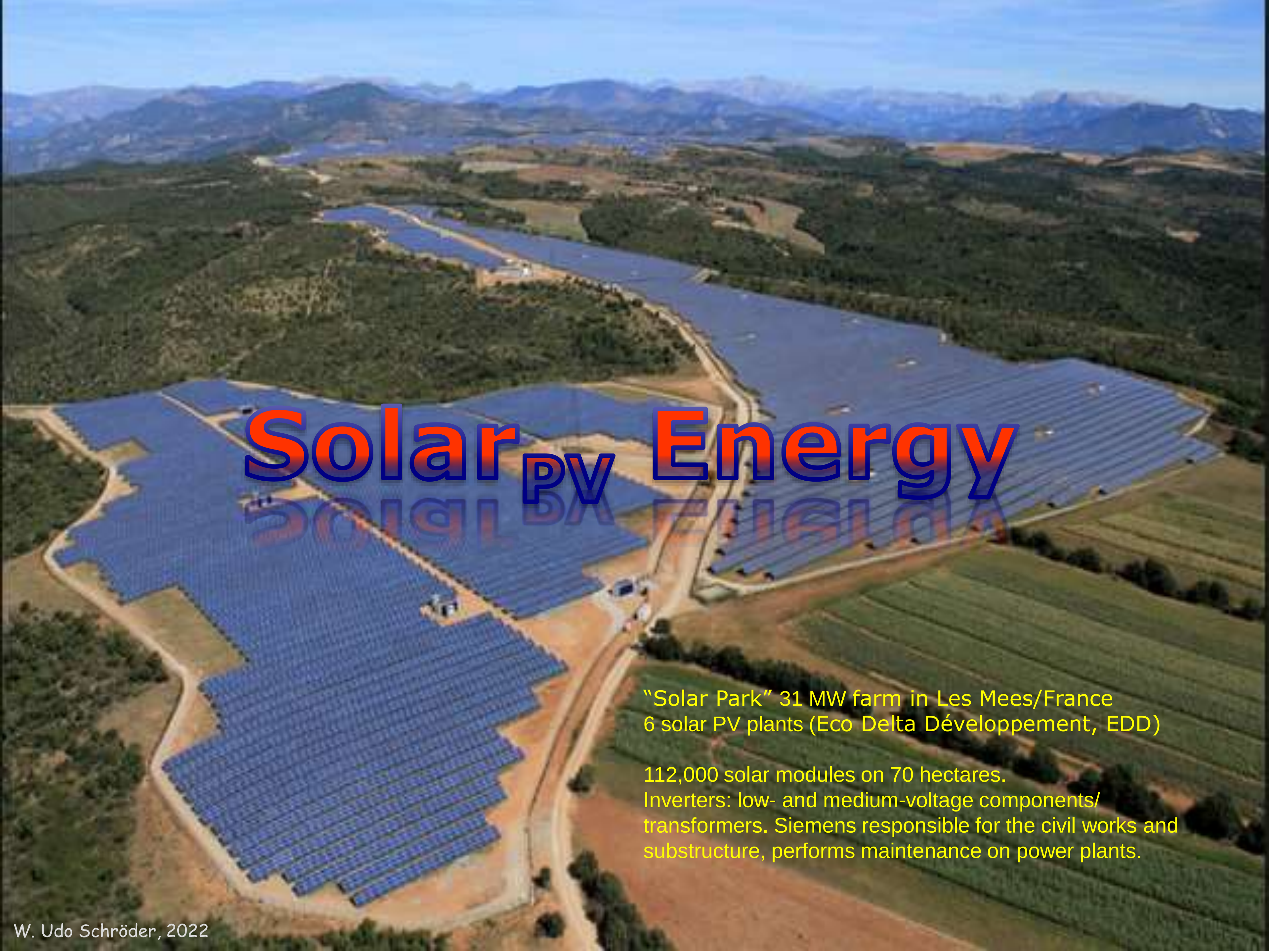


Solar$_{PV}$ Energy

"Solar Park" 31 MW farm in Les Mees/France
6 solar PV plants (Eco Delta Développement, EDD)

112,000 solar modules on 70 hectares.
Inverters: low- and medium-voltage components/ transformers. Siemens responsible for the civil works and substructure, performs maintenance on power plants.

Agenda

- Intro

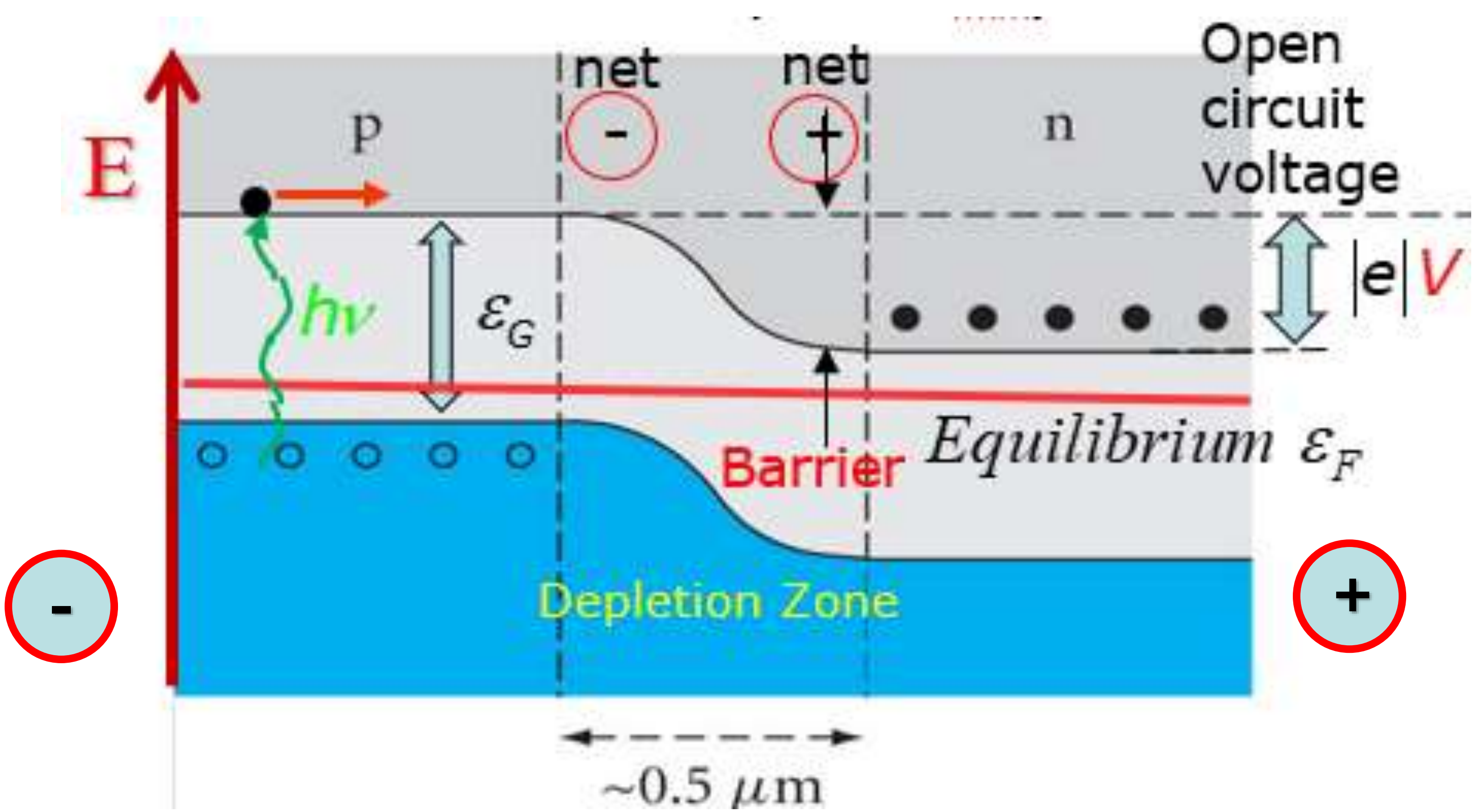
- Solar insolation, power density, solar emission spectrum
- Utility size(solar farms) & residential PV arrays

- Silicon solar photo-voltaic (PV) technology
  - Semiconductor band structure, gap, junctions
  - Charge carriers in n-type and p-type semiconductors
  - Photocell operation, efficiency
  - Silicon wafer, cell manufacture
  - Materials and emissions in construction

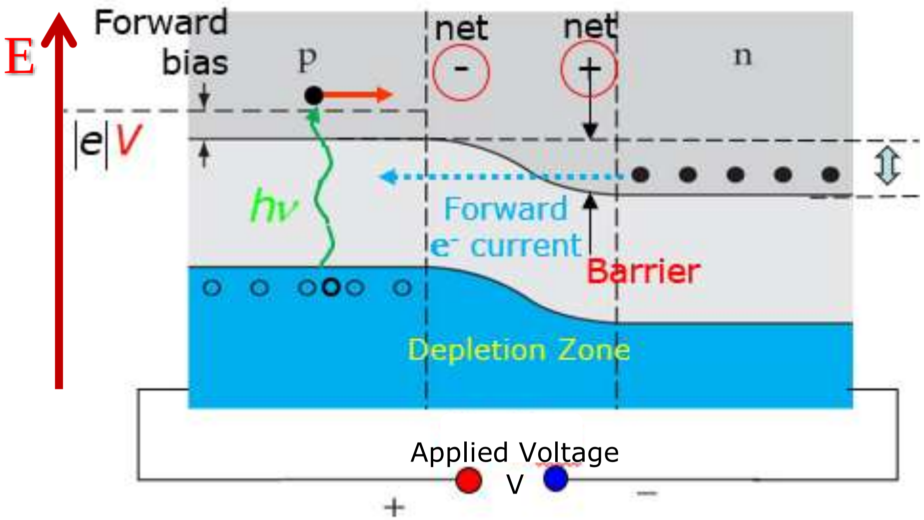
- US installations and performance, system cost and incentives
- Solar power strategic issues

Semiconductor Junction Diodes

In asymmetric junction zone, no free charge carriers (e^- or holes) → Depletion Zone. Extra + charges in n-region
→ e- have lower energy (more strongly bound).
Effective barrier prevents additional migration of charges→ charge-free zone (except thermal excitations & photo ***h*ν**)!



Semiconductor Junction Diodes



Forward bias lowers barrier

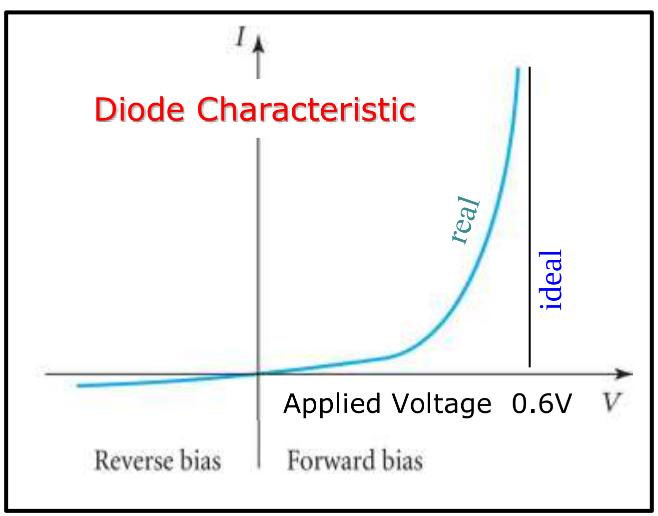
Forward: normal n → p across junction due to thermal

No Bias ***V*** applied → $I \approx 0$

Forward bias lowers barrier

→ $I \neq 0$, *increases.*

Reverse bias: smaller p → n reverse e⁻ current due to thermal transitions over higher barrier. → *Diode Characteristic*



Diff & *Field* *Currents*: $I(V) = I_{sat} \cdot \{e^{+e \cdot V/kT} - 1\}$ *Fermi – Dirac Statistics*

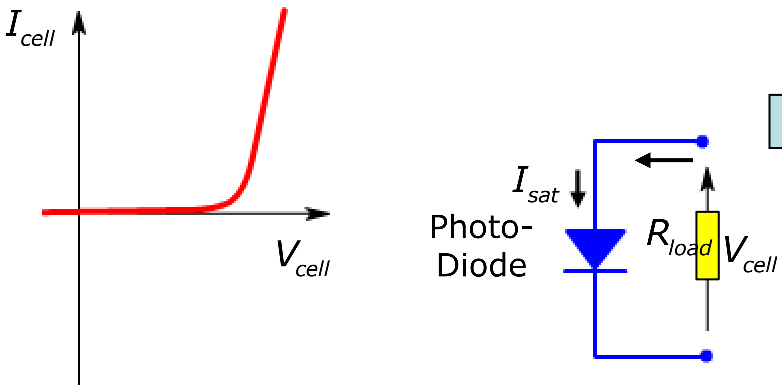
$Ambient\ T:\ kT = 25\ meV\ @\ T = 293K$

Elementary charge e,

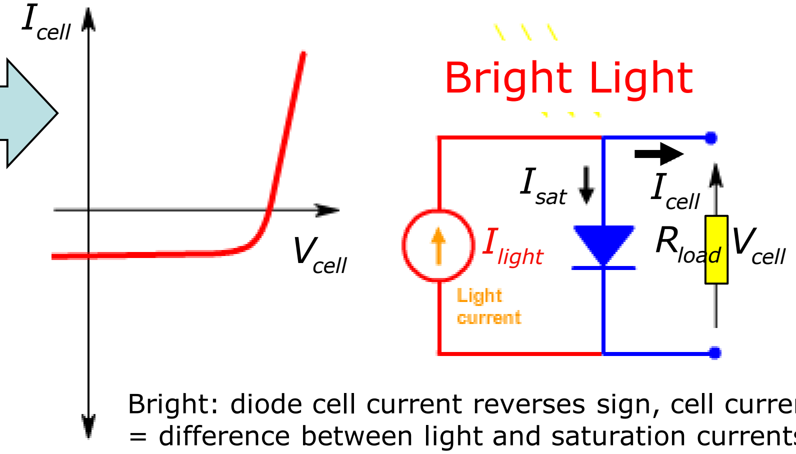
"Saturation" ("dark", "field") current I_{sat}

Cell Equivalent Electronic Circuits

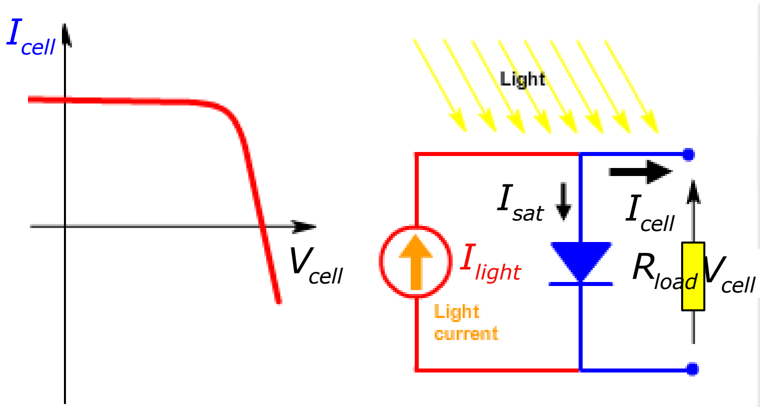
I_{cell} can be measured via R_{Load}



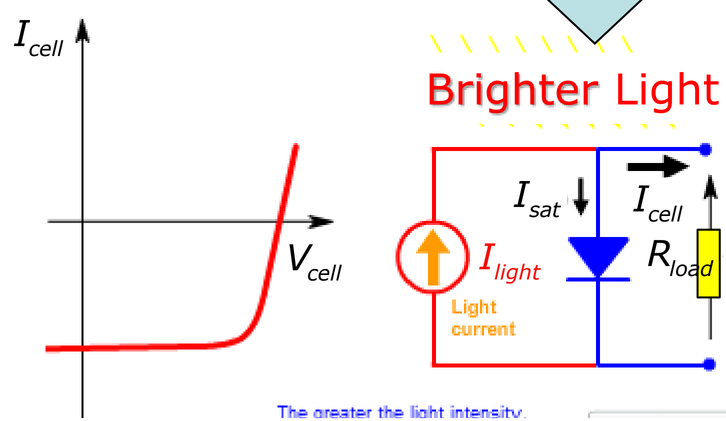
Dark: normal diode functions, saturation dark current



Bright: diode cell current reverses sign, cell current = difference between light and saturation currents



Convention: define cell current as positive.

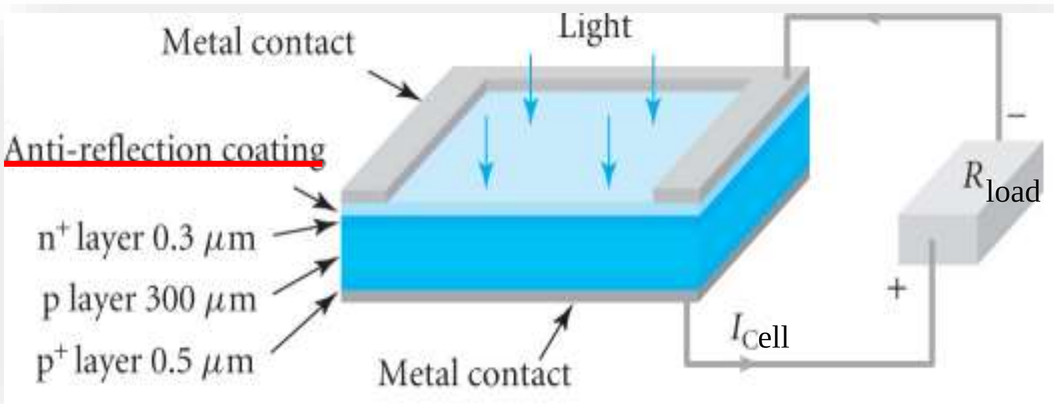


Brighter: diode current becomes more negative, cell current = difference between light and saturation currents increases.

By Convention

Observables in Photocell Operation

Observables: V_{cell}, I_{cell}



⁺ indicates extra doping, lower resistance.

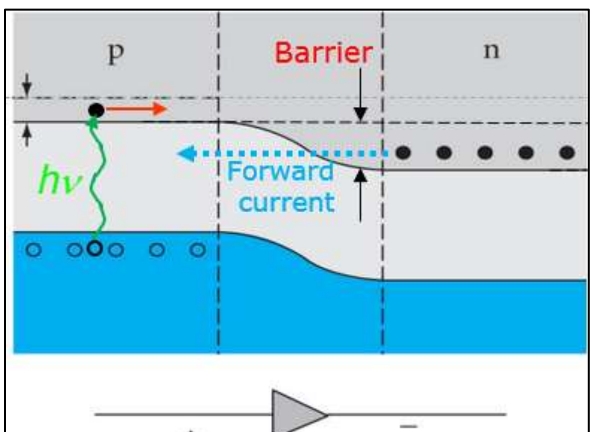
Light sensitive (solar) cell
Mode of operation

$$\varepsilon_G(Si) = 1.1\ eV$$
$$\lambda \le \lambda_G = \frac{hc}{\varepsilon_G} = \frac{1.24\,eV}{\varepsilon_G}\ \mu m$$

$\rightarrow e^- -$ *hole excitation if* $\lambda \le \lambda_G$

dissipates extra e^- *kin. energy*

I_{cell} dependence on R_{load} →



Forward bias lowers barrier

Photon $h\nu$ produces e⁻/hole pair in *depleted* domain → reverse current of electrons (and holes) $\vec{I}_{Light} \uparrow\downarrow \vec{I}_{sat}$

$$I_{cell} = I_{Light} - I_{sat} \cdot \left\{ e^{e \cdot V_{cell}/kT} - 1 \right\} =$$
$$= I_{Light} - I_{sat} \cdot \left\{ e^{R_{Load} \cdot I_{cell}/V_{th}} - 1 \right\}$$

"Thermal voltage"
$V_{th} := kT/e = 25mV$
Ohm's Law $V_{cell} = I_{cell} \cdot R_{Load}$

$R_{Load} \rightarrow \infty$ (*open circuit*): $I_{cell} \rightarrow 0,\ V_{cell} =: V_{OC}$

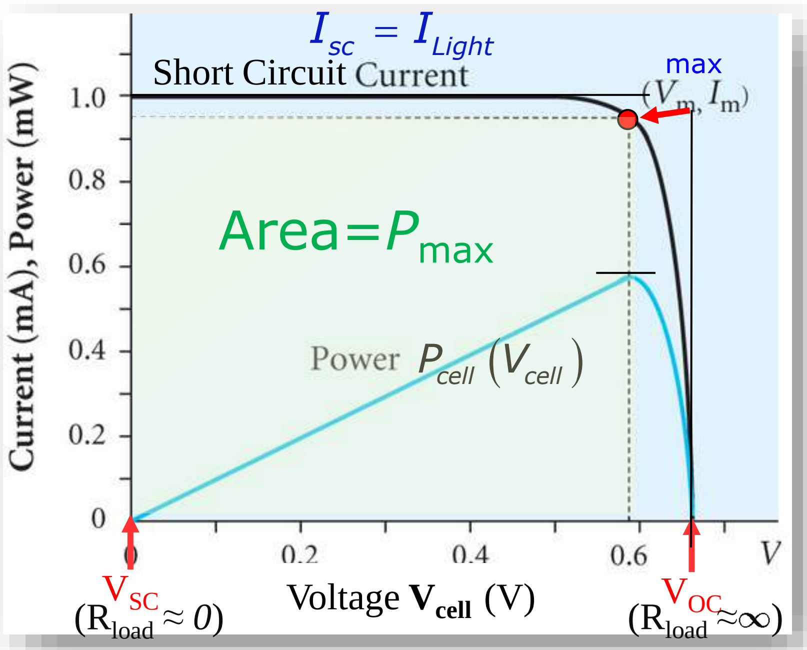
$$V_{OC} = V_{th} \cdot Ln\left[1 + \frac{I_{Light}}{I_{sat}}\right] \approx V_{th} \cdot Ln\left[\frac{I_{Light}}{I_{sat}}\right]$$

$V_{OC} = \left(V_{cell}\right)_{max}$
$I_{Light} \gg I_{sat}$

$R_{Load} = 0$ (*short circuit*): $I_{cell} = I_{sc} = I_{Light}$

Cell Power Characteristic

Cell Current-Voltage Characteristic



Power P_{cell} generated by illuminating cell, scan by varying light intens. or R_{load}

$(R_{Load} \ll R_{diode}) \rightarrow (R_{Load} > R_{diode})$

Rise and fall between short-circuit (SC) ($\boldsymbol{V_{cell}} \approx 0$) and open circuit ($\boldsymbol{I_{cell}} \approx 0$).

Between above limits, power evolution :

$$P_{cell} = I_{cell} \cdot V_{cell}$$

$$P_{cell} = I_{cell}^2 \cdot R_{load} \quad (Ohm's\ Law)$$

Current $\boldsymbol{I_{cell}}$ and power $\boldsymbol{P_{cell}}$ decrease with decreasing light intensity.

Typical nominal values: $\boldsymbol{I_{cell}}$ = 1mA, $\boldsymbol{I_{sat}}$ = 10^{-12} A, $\boldsymbol{V_{OC}}$ = 0.66 V,

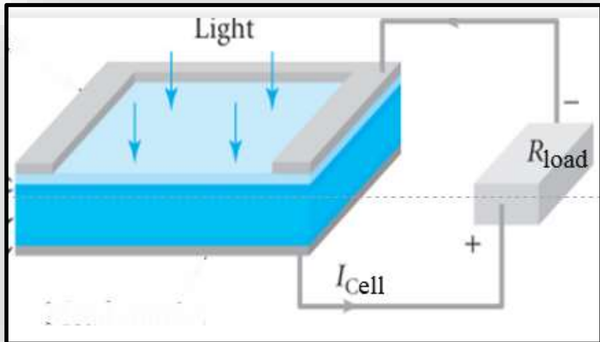
Actual $\boldsymbol{P_{cell}} \leq \boldsymbol{P_m}$=0.58 mW, $\boldsymbol{V_{cell}} \leq V_m$=0.58V →const $\boldsymbol{I_{cell}} \leq I_m = I_{sc}$=0.95 mA

$$"Fill\ Factor": FF = P_{max} / (I_{SC} \cdot V_{OC})$$

$$Deduce\ from\ \{I_{SC}, V_{OC}\} \rightarrow P_{max} = FF \cdot I_{SC} \cdot V_{OC}$$

FF=Ratio of area under power curve to limiting rectangle→ measure of steepness (ideal) of diode I-V characteristic.

Example



Given: *1-cm²* photocell with saturation current I_{sat}= *2·10⁻¹²A* and short-circuit current I_{sc}= *30mA.* *Calculate the expected maximum power output* P_{max} *and the load resistance* R_{Load} *required for max power.*

Thermal voltage

$V_{th} := kT/e = 25mV$

Ohm's Law

$V_{cell} = I_{cell} \cdot R_{Load}$

$$R = 0\ (short\ circuit):\quad I_{sc} = I_{Light} = 30mA$$
$$Thermal\ V_{th} = 0.025V,\ I_{sat} = 2 \cdot 10^{-12} A$$
$$V_{OC} \approx V_{th} \cdot Ln\left[\frac{I_{Light}}{I_{sat}}\right] = 0.025V \cdot Ln\left[\frac{30 \cdot 10^{-3} A}{2 \cdot 10^{-12} A}\right]$$
$$V_{OC} \approx 0.59V$$

$$I_{cell}(V_{cell}) = I_{Light} - I_{sat} \cdot \left\{e^{V_{cell}/V_{th}} - 1\right\}$$
$$= 30mA + 2 \cdot 10^{-12} A \cdot \left\{1 - e^{V_{cell}/0.025V}\right\}$$

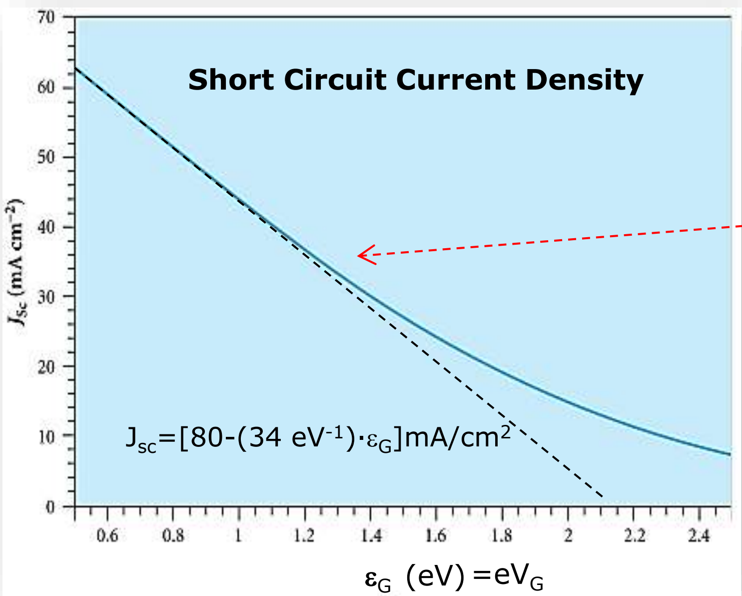
V_{cell} and I_{cell} can be chosen independently via light int. and R_{load}

$$\rightarrow P_{cell}(V_{cell}) = I_{cell} \cdot V_{cell} \quad \rightarrow search\ (numerically)\ for\ V_{cell} = V_{max},$$
$$for\ which\ P_{cell} = P_{max} \rightarrow R_{Load} = V_{cell}/I_{cell}$$

Choose this R_{Load} to maximize output power

$$Efficiency \rightarrow \varepsilon = \frac{P_{max}}{insolation\ power}$$

Cell Efficiency ε_G Dependence



Calculate $P_{\max}$ *with* ⇒ $P_{\max} = FF \cdot I_{SC} \cdot V_{OC}$

Approximate linear $\left(j_{SC} := I_{SC} / \text{Si cell area} \right)$

$$j_{sc} \approx j_\gamma \cdot \left(\frac{15e}{\varepsilon_G \pi^4} \right) \left(\frac{\varepsilon_G}{kT} \right)^3 \cdot e^{-\frac{\varepsilon_G}{kT}} \approx A - B \cdot V_G$$

$$V_{OC} \approx V_{th} \cdot Ln\left[I_{SC} / I_{sat} \right] = V_{th} \cdot Ln\left[j_{SC} / j_{sat} \right]$$

$e^- -$(Dark) current from $p-Si \rightarrow n-Si$

$j_{sat} \approx j_0 \cdot \exp\left(-\varepsilon_G / 2kT \right)$ Boltzmann Factor

$j_0 \sim 2 \cdot 10^{+9}\ mA/cm^2$ ~ typical

$\rightarrow j_{sat}(\varepsilon_G = 1.1eV) \sim 10^{-9}\ mA/cm^2$

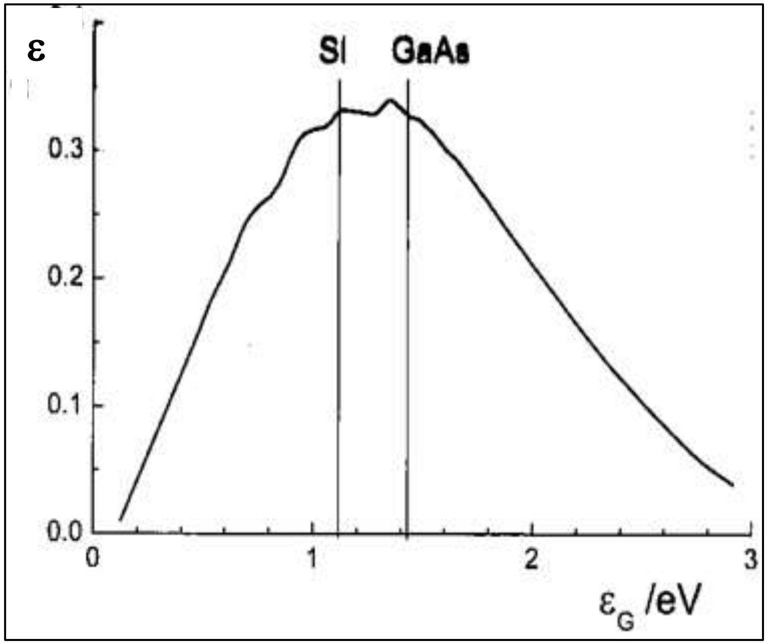
$$V_{OC} \approx V_{th} \cdot Ln\left[\frac{I_{SC}}{I_0} e^{+\varepsilon_G/kT} \right] = V_G - V_{th} \cdot Ln\left[\frac{I_0}{I_{SC}} \right] \rightarrow V_{OC} \approx V_G - 0.5V \text{ empirical}$$

$$\rightarrow P_{\max} \approx FF \cdot \left(A - B \cdot V_G \right) \cdot \left(V_G - 0.5V \right) \text{ Empirical formula}, \left(V_G = \varepsilon_G / e \right).$$

$$FF = 0.8 \rightarrow P_{\max} \approx 25 mA/cm^2, \rightarrow \text{Efficiency } \varepsilon\left(\varepsilon_G \right) = \frac{I_m \cdot V_m}{j_\gamma \cdot Area_{cell}} \leq 0.35 \text{ (Shockley – Queisser)}$$

more typical $\varepsilon = \left(17 - 20 \right)\%$

Shockley-Queisser Cell Efficiency



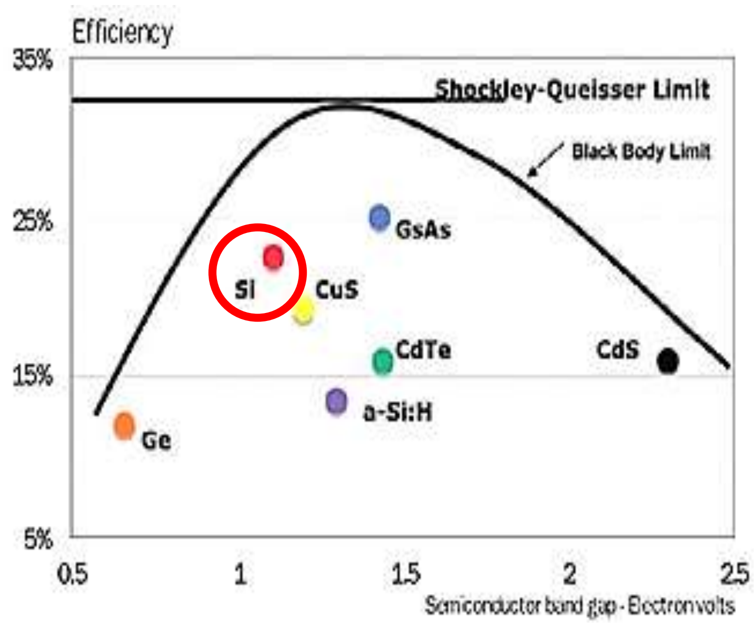
Solar cell maximum efficiency dependence on band gap energy,
Calculated with 1-Sun, A1.5 radiative recombination

Often used (economic) amorphous Si:
ε_G~(1.3-1.7 eV),
Lower efficiency ε = (12-13)%

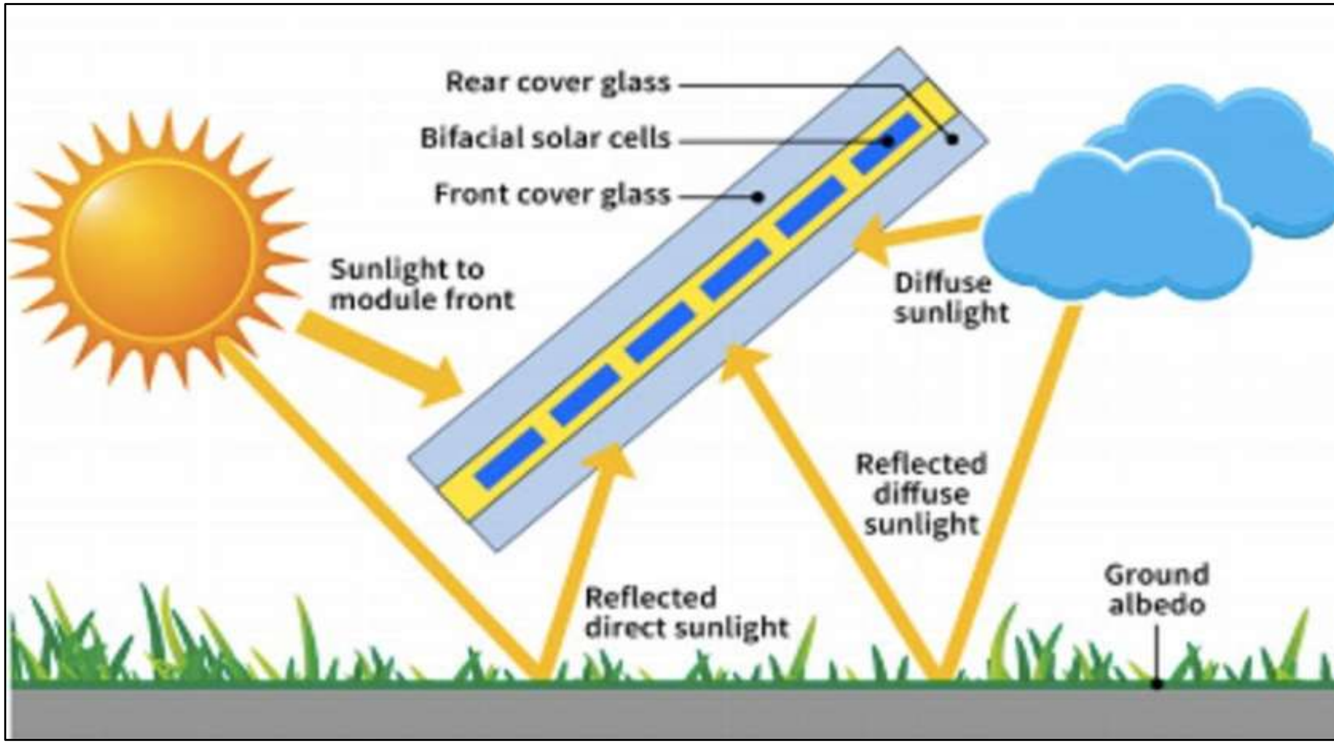
Solar cell conversion efficiency, different semiconductors.

Calculated with 1-Sun, A1.5 radiative recombination.

GaAs slightly better than Si but involves more fabrication steps.



New R&D: Bifacial PV Cells

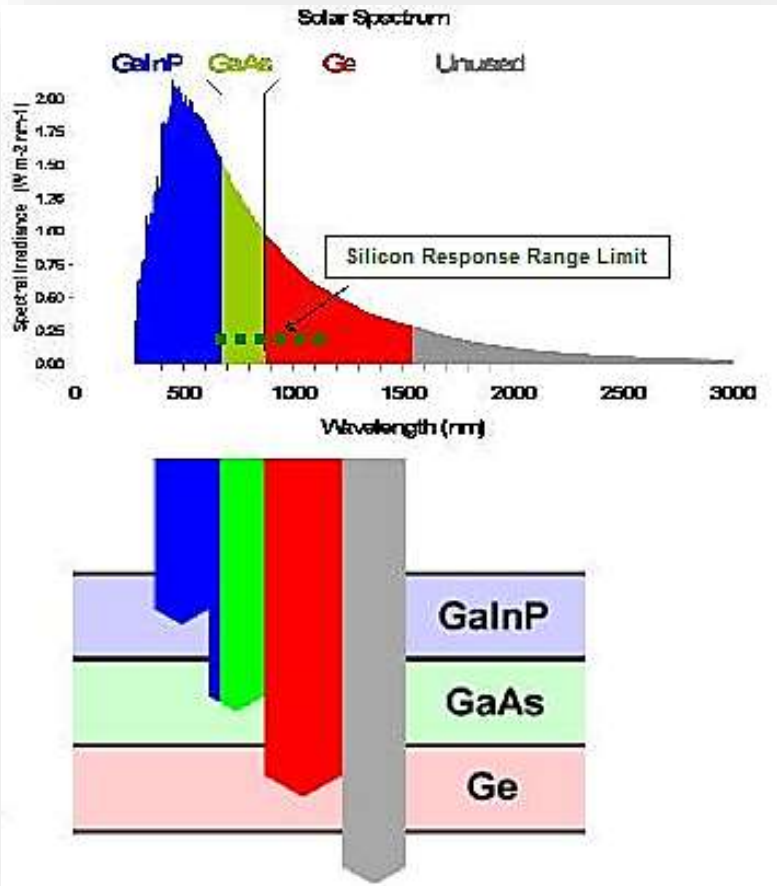


Reflected sunlight has same frequency as incoming light.

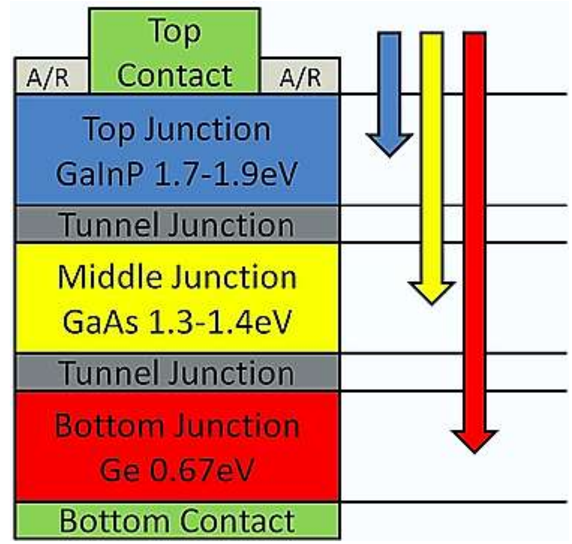
Study determined that two-sided, sun-tracking panels produce an average of 35% more energy than immobile single-panel systems and that they are 16% more cost-efficient.

That holds true even when accounting for changes in weather conditions.

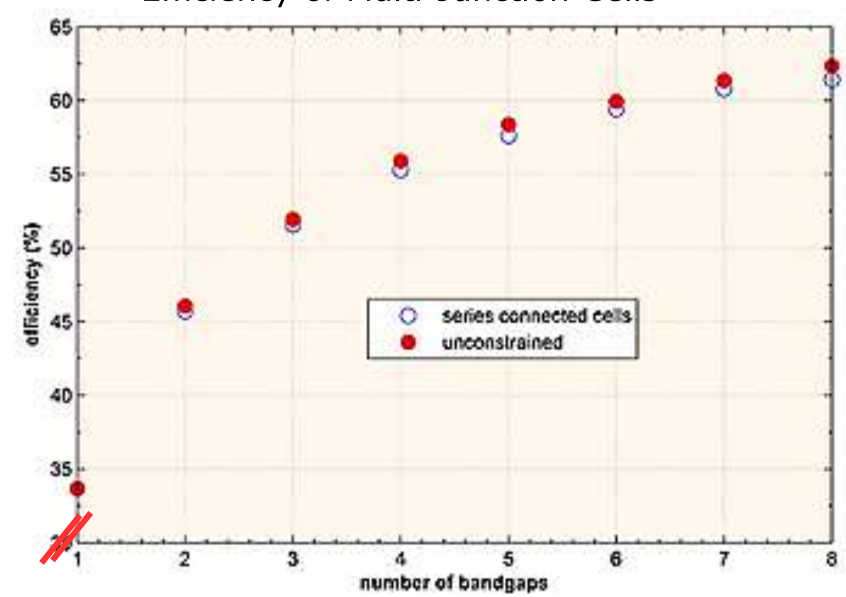
New R&D: Multi-Junction Cells



Multi-junction cells are stacks of different semiconductors, differential absorbers of sequential parts of the spectrum.

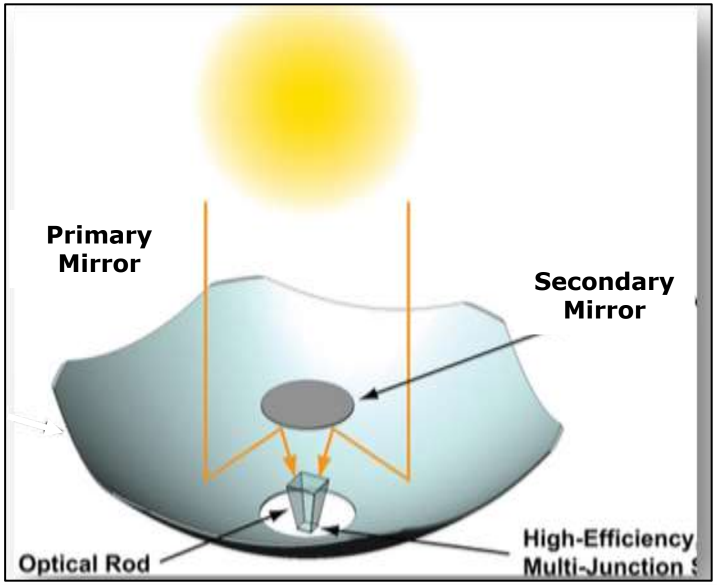


Efficiency of Multi-Junction Cells

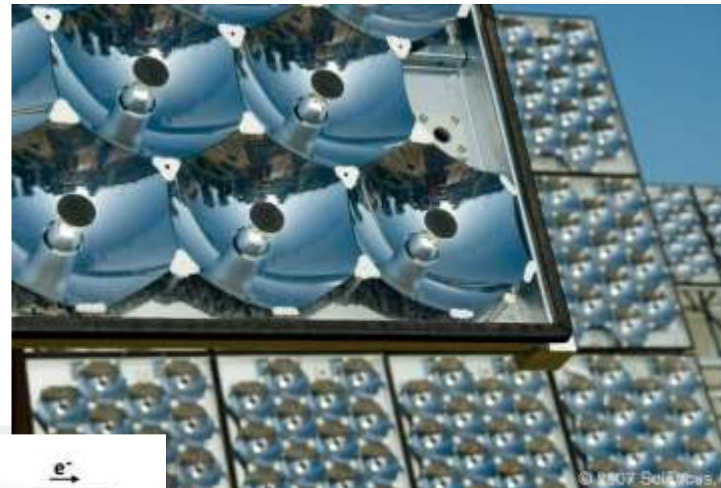


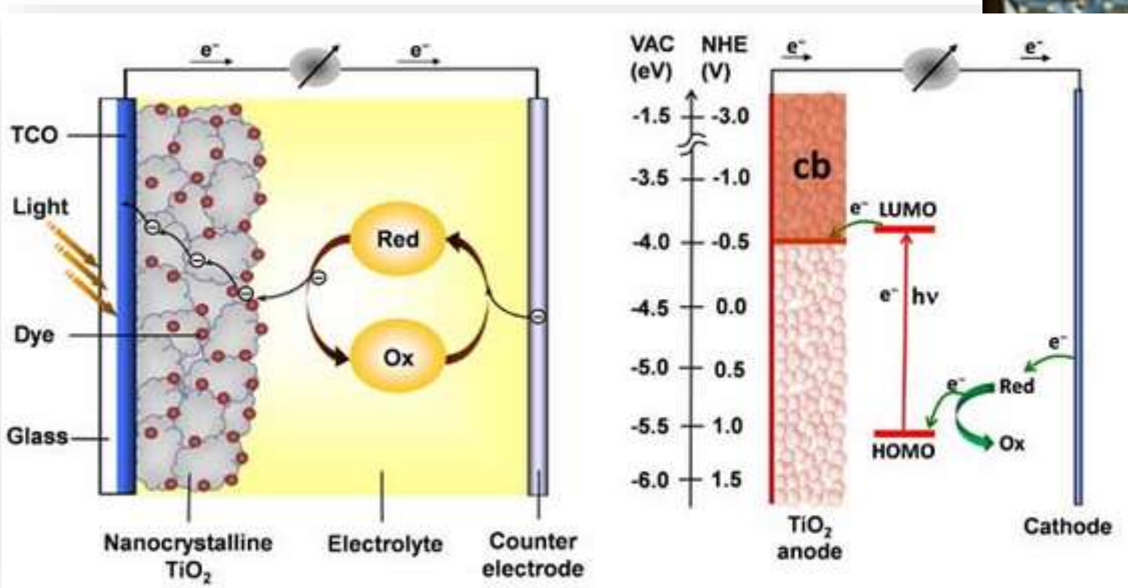
The maximum efficiency for a two junction tandem under the AM1.5G spectrum and without concentration is 47 %. At the peak efficiency the top cell has a band gap of 1.63 eV and the bottom cell has a band gap of 0.96 eV. Adding more layers makes less and less difference → saturation of efficiency 62.5%.

Cell Designs in R&D



Concentrated solar cells: focus radiation falling on large area onto small Si cells = save material, increase output of each cell.





Dye sensitized solar cells:
20-nm, dye-coated TiO_2 nanoparticles in electrolyte.

hν → dye- ***e⁻ h***, ***e⁻*** → TiO_2 CB

Electrolyte ion⁻ donates **e⁻** and fills dye-***h***

W. Udo Schröder, 2022

Thin-Film PV Solar Cells: CIGS

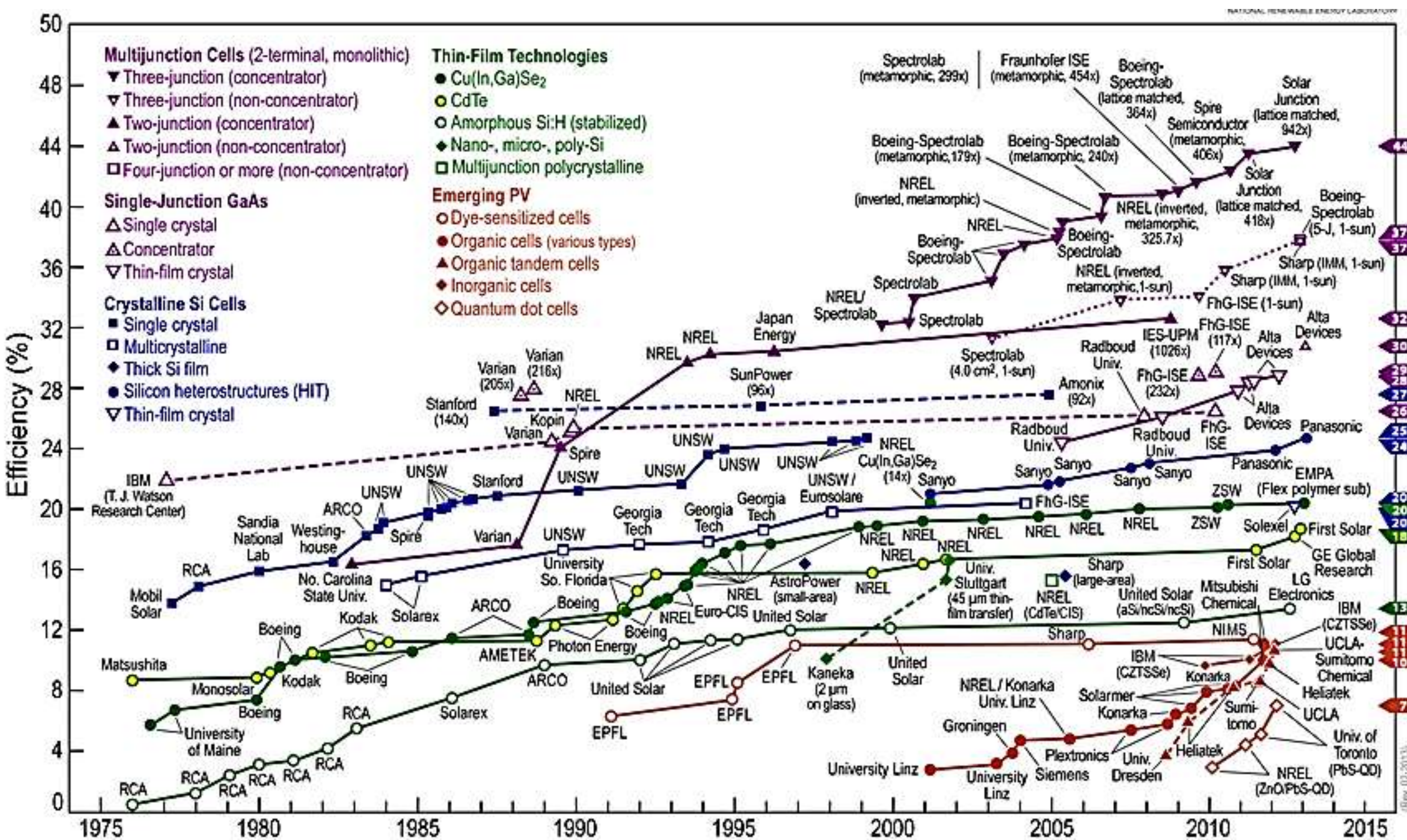
The ZSW institute's building in Stuttgart-Vaihingen has a façade with CIGS panels.

Nano-particles embedded in plastic.

2019: CIGS (Copper, Indium, Gallium and Selenium) cell efficiencies have surpassed all other thin film PV technologies, achieving 23.4% on the cell and 17.5% on the module level.
CIGS has also been deployed in ultra-high efficiency tandem cells, potential to achieve 30% efficiency.
Future efficiency development via band-gap tuning: Perovskite/CIGS tandem

Ongoing R&D: Efficiencies of Solar Cells

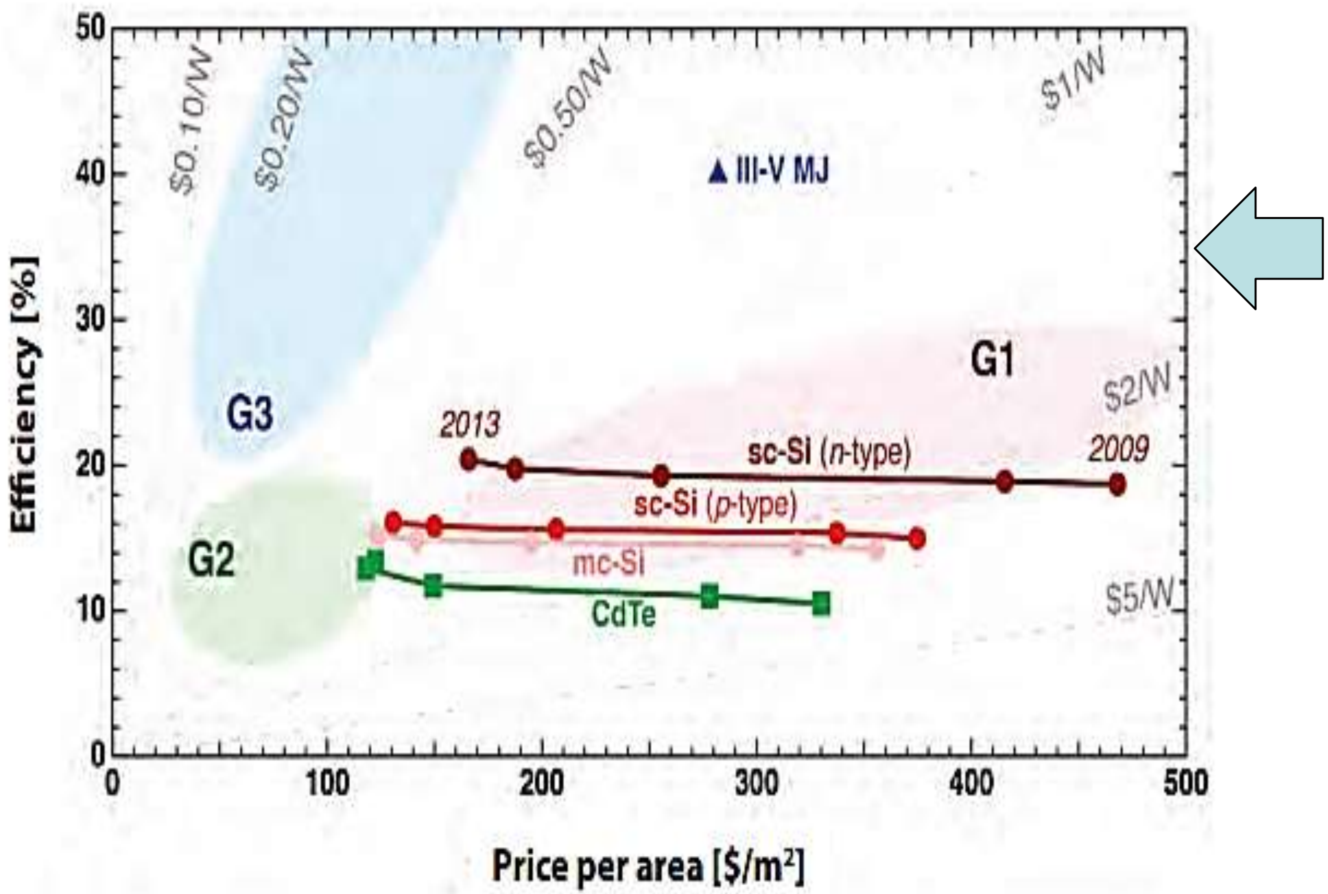
Standard with conventional processes: flat-panel multi-crystalline cells (240-250)W, e ≤ 20%.



http://theenergycollective.com/ericwesoff/208316/first-solar-crushes-solar-pv-efficiency-record, Acc. April 2013.

Mainstay Si cell production

Trends in Commercial PV Price/Performance



PV module efficiency and price per area (period 2009-2013).Conventional generations: G1 in red, G2 in green, and G3 in blue.

Current G1 and G2 modules cluster near the region originally defined as G2.

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Common Commercial Solar Cells

Silicon single-crystals:
Continuous, repetitive structure.
Rare in nature, needs to be grown in lab. → expensive for large crystals.

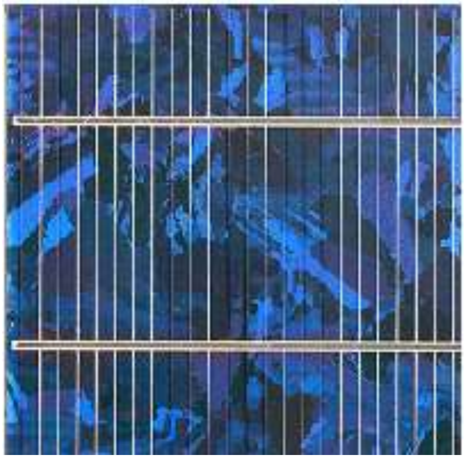
Solar cells made from single crystal, (200-300)μ wafers. Mono-crystalline cells, most efficient, most expensive.

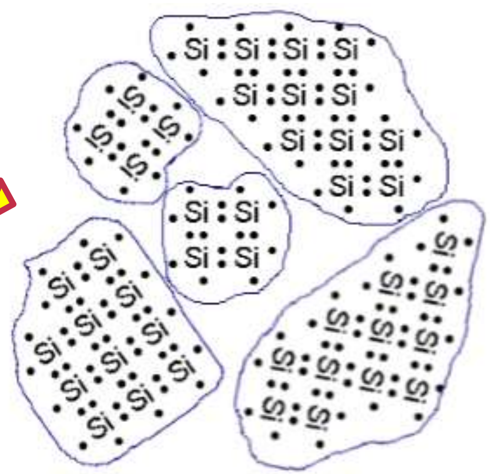
Multi-crystalline silicon:
Pieces made of more than one single-crystal, multiple domains.

Constituent crystals relatively small, easier to grow and cheaper.
Also less efficient, free charge carriers have to cross boundaries.

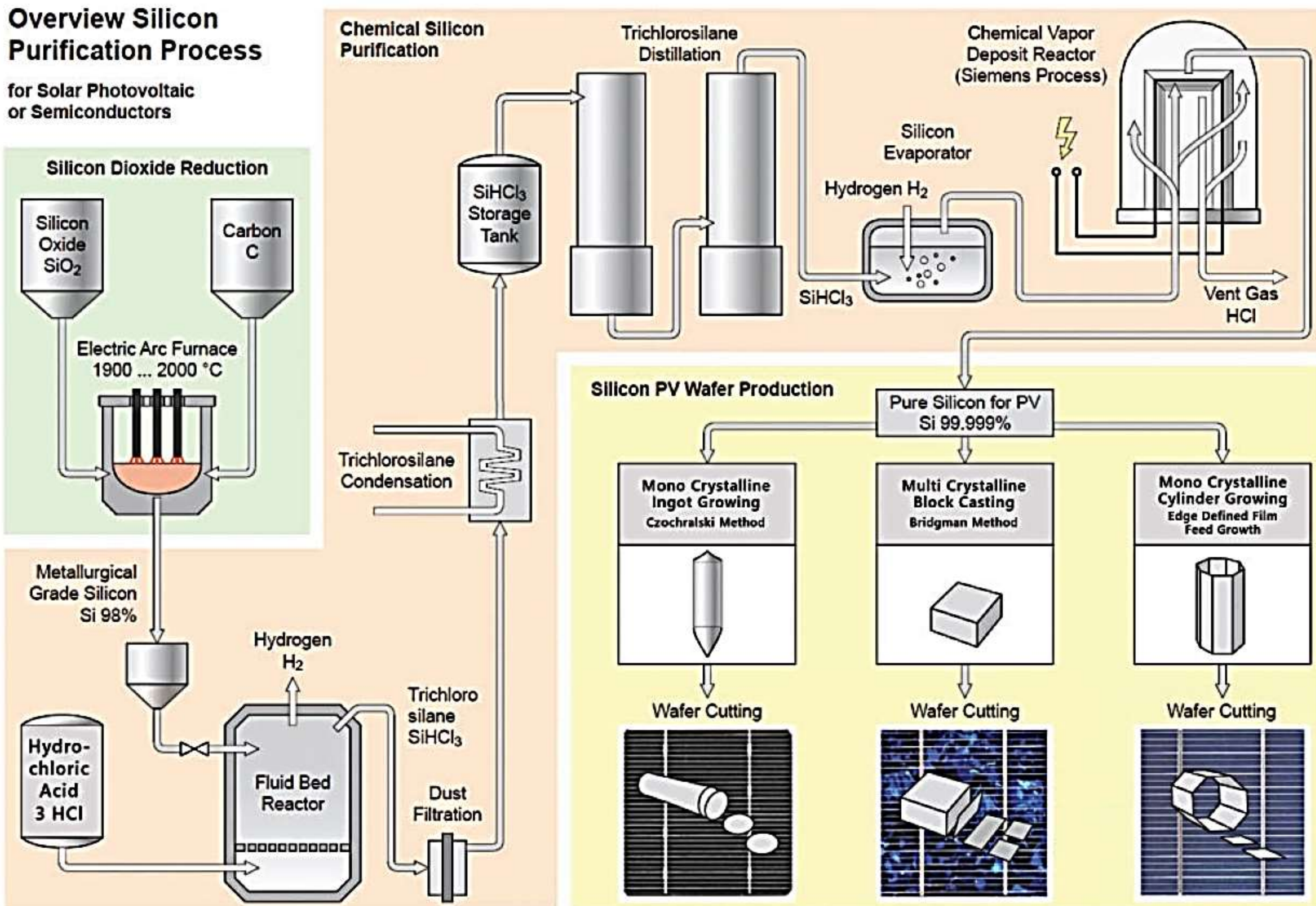
Amorphous ***a*-Si:H** <ε_G>=1.7eV, high absorbance.

New: Thin-film cells (1 μ thick), technique saves material.
Heterojunction cells: CdTe,..
Multi-layer cells
Organic semiconductors.

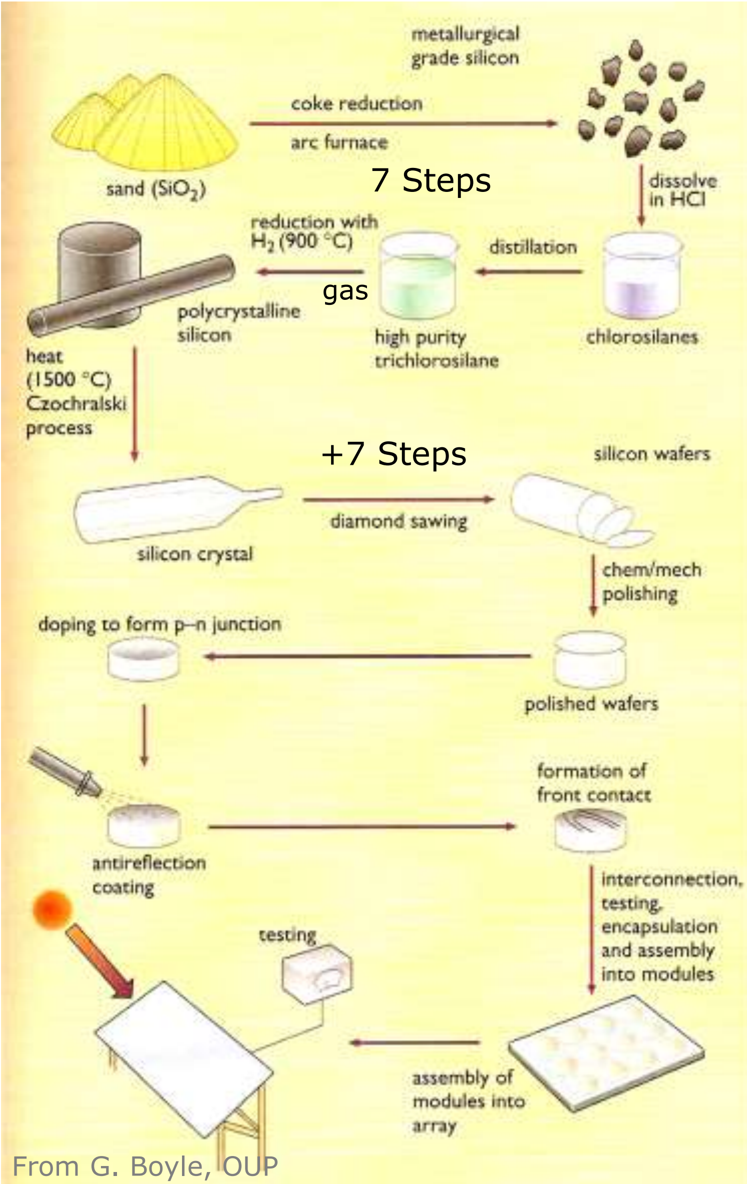




PV Cell Manufacture Chain



Cell Production Process

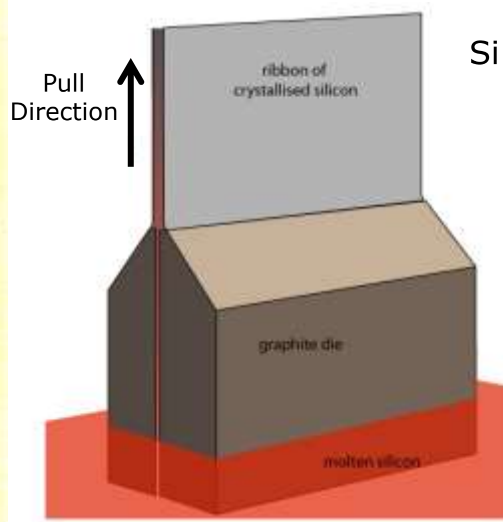


Single-crystal Si cell manufacture

Reduction of SiO_2 with coke. Chemical purification: Silicon tetrachloride ($SiCl_4$) and trichlorosilane ($HSiCl_3$) are intermediates in the industrial production of ultrapure silicon.

Chlorosilanes obtained from metallurgical Si
→ purified by fractional distillation
→ reduced with H_2 (900^0C) →
→ Si with 99.999999999 % (10^{-11}) purity.

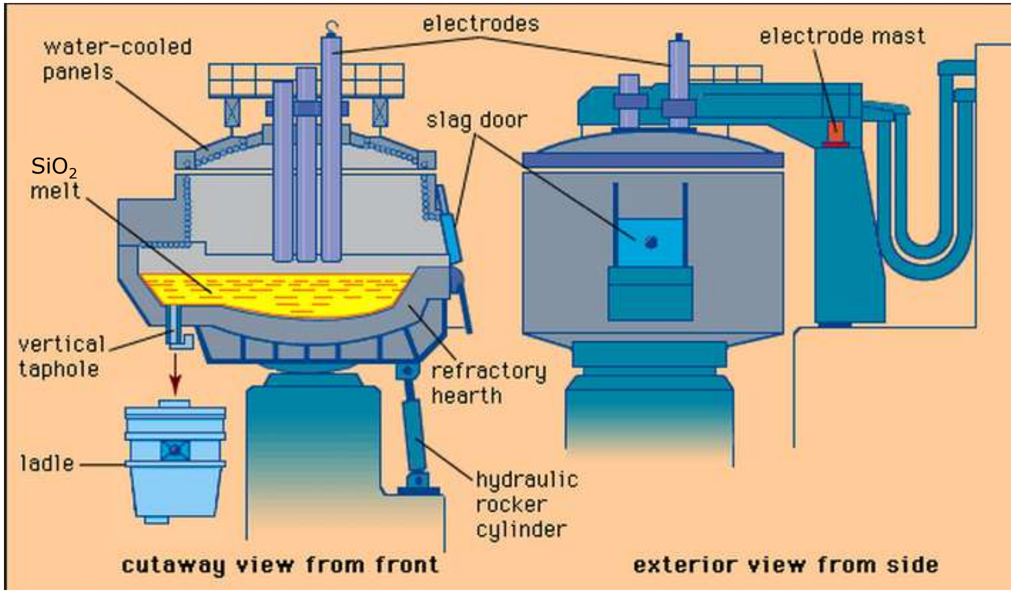
Czochralski process draws single-crystal ingot out of Si melt, originally developed for computer chip industry. Variations: edge defined, film fed single-crystal Si growth

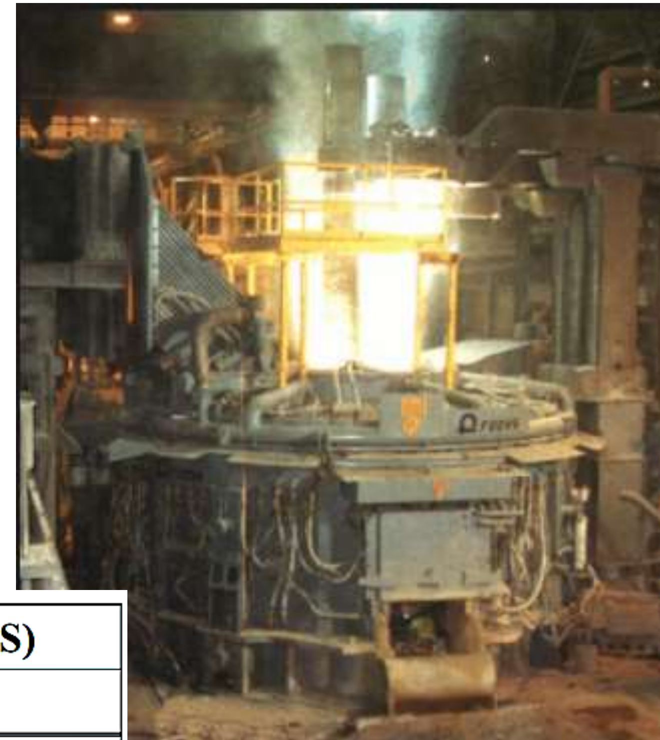


Si Ribbon

Si Cylinder

Semiconductor Grade Silicon Fabrication



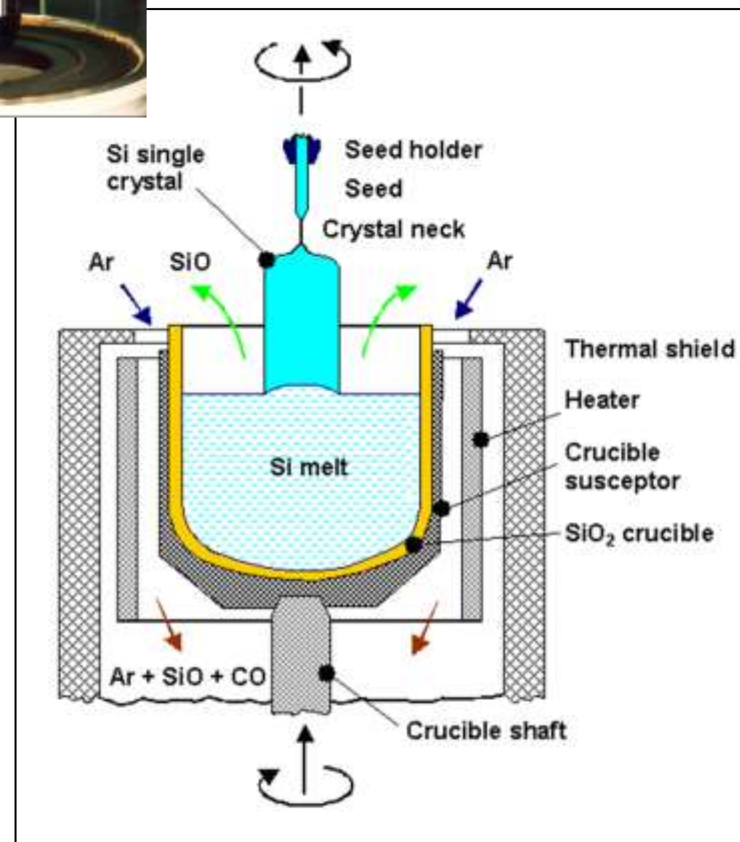


Steps to Obtaining Semiconductor Grade Silicon (SGS)		
Step	**Description of Process**	**Reaction**
1	Produce metallurgical grade silicon (MGS) by heating silica with carbon	$C (s) + SiO_2 (s) \rightarrow Si (l) + SiO (g) + CO (g)$
2	Purify MG silicon through a chemical reaction to produce a silicon-bearing gas of trichlorosilane ($SiHCl_3$)	$Si (s) + 3HCl (g) \rightarrow \underline{SiHCl_3 (g)} + H_2 (g) + heat$
3	$SiHCl_3$ and hydrogen react in a process called Siemens to obtain pure semiconductor-grade silicon (SGS)	$2SiHCl_3 (g) + 2H_2 (g) \rightarrow 2Si (s) + 6HCl (g)$

Arc furnace for processing materials with high melt temperatures, e.g., T_{fus} = SiO_2: 1,600^{0}C.

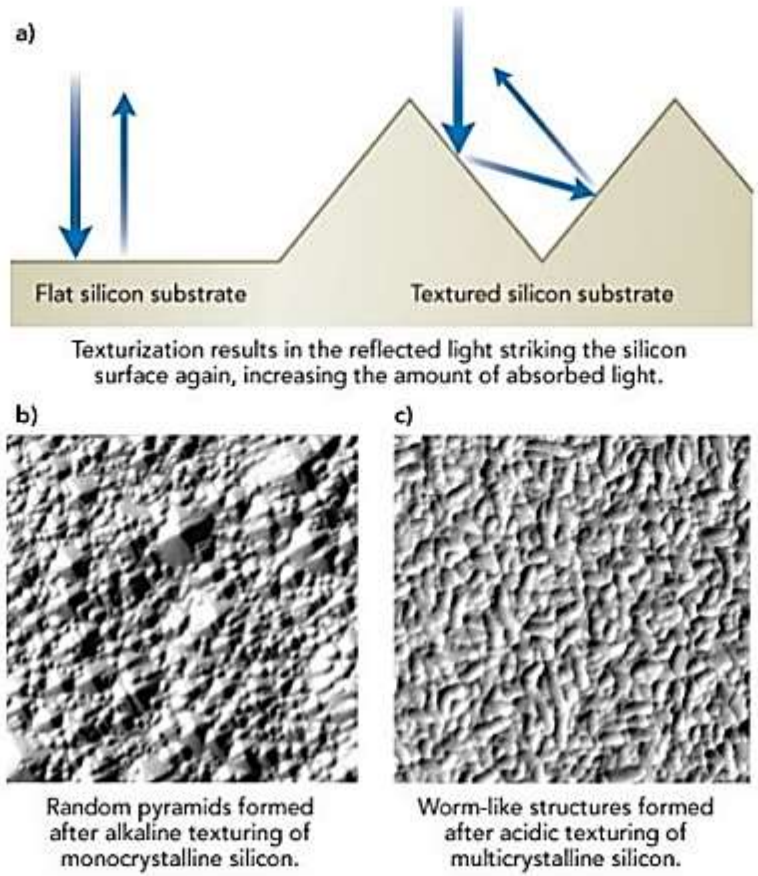
Czochralski Process

Metallurgical Si is melted in quartz crucible, seed Si crystal dipped into melt, slowly drawn while rotated. Impurities remain in melt, oxygen from crucible → Si crystal, stabilizes.



Large single-crystal suspended by thin **Si** seed crystal (inset, arrow). Seed crystal supports weight of the crystal and the torque needed to rotate crystal during its growth

Surface Treatment



a) schematic representation of increase in light absorption on a textured silicon surface; b) Silicon wafer after treatment with an alkaline texturing solution; c) Silicon wafer after treatment with an acidic texturing solution.

Surface treatment increases light trapping probability.

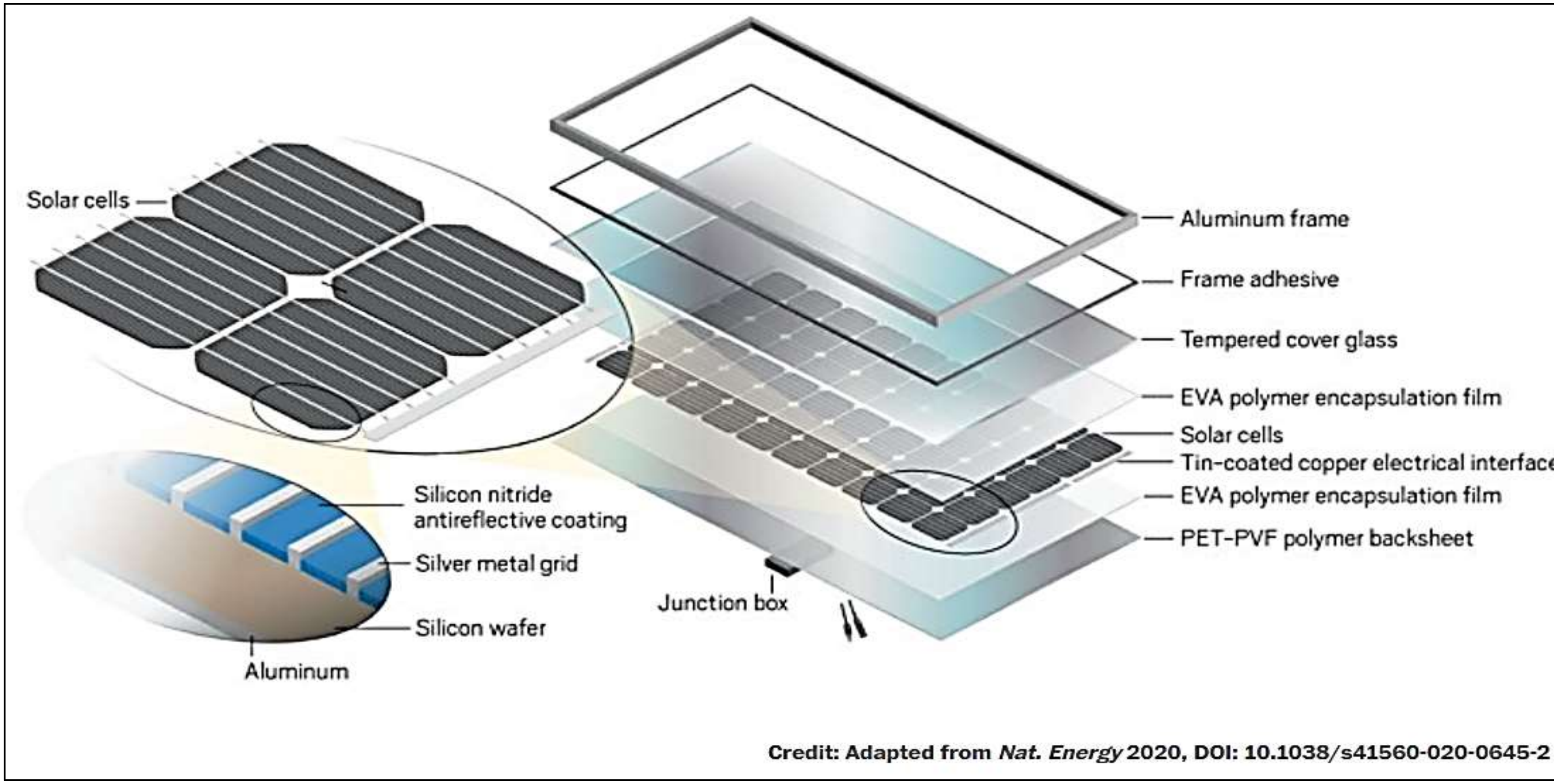
1) Anisotropic alkaline "texturing," mainly for mono-crystalline wafers: potassium hydroxide (KOH)/isopropanol (IPA) mixture → processing at (80°-90°C) for extended periods, 30 min → 8 hrs (newer methods).

2) Texturing multi-crystalline silicon wafers, isotropic acidic etch with (HF)/nitric acid (HNO_3) mixture, in which HNO_3 is added to oxidize the silicon surface and HF to strip the oxide.

Chemicals used in doping:
p-type silicon solar cell: phosphoric acid or $POCl_3$, dissolved by a simple HF dip.

After J. Hoogboom, S. Kuiper, P. Thomassen (Mallinckrodt Baker BV)
http://www.renewableenergyworld.com/rea/news/article/2010/02/performance-chemicals

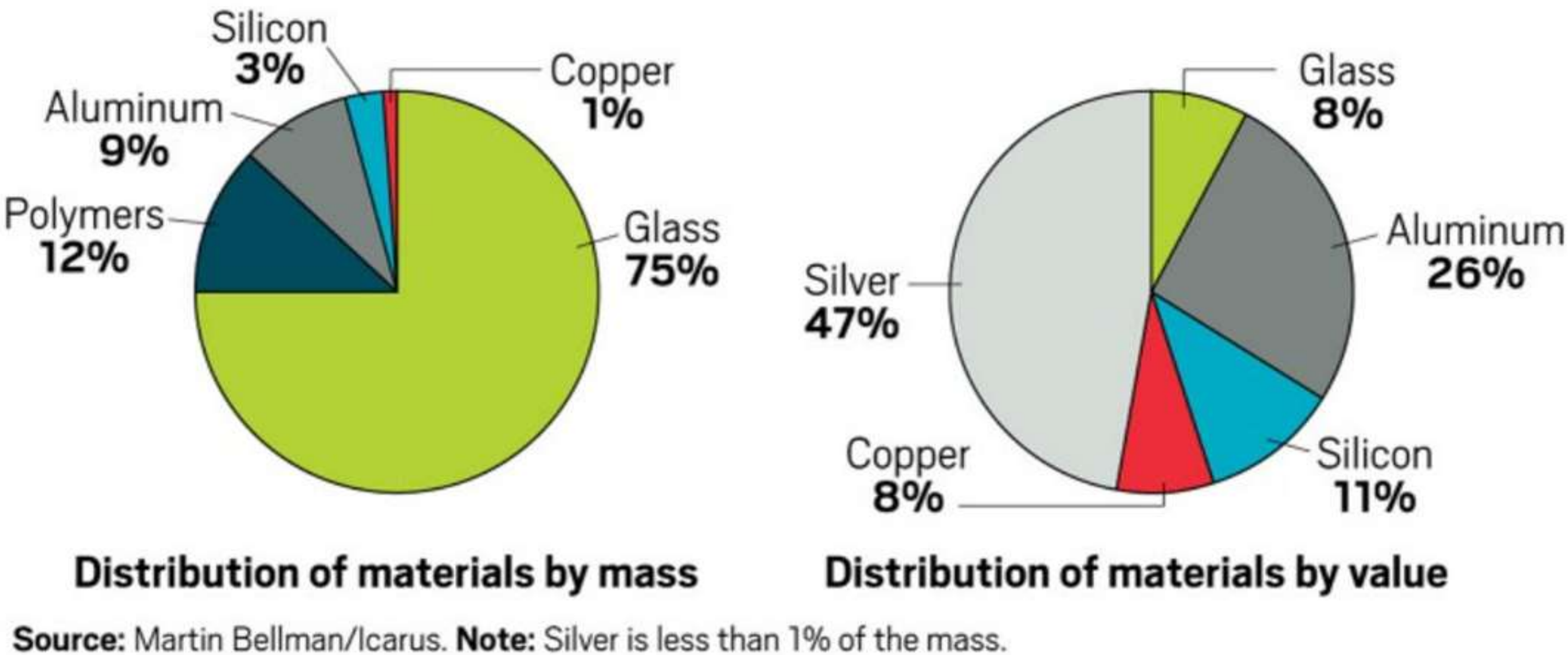
PV Solar Cell Assembly



Bulk materials like glass and aluminum make up more than 80% of the mass of a silicon photovoltaic cell.

But two-thirds of the monetary value of a cell's materials is from silver, silicon, and copper—more minor components.

Si-PV Cell Materials



Solar Performance in SW U.S.

Electricity generation Mesquite Solar 1-3 in 2017-2019. Location: Arlington, Maricopa County, Arizona → optimum capacity factors.

Generation (MW·h) of Mesquite Solar 1 (150MW)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2017	18,968	23,127	39,542	43,048	45,896	51,628	31,943	39,425	40,513	37,184	22,096	20,363	**413,734**
2018	23,598	25,234	32,580	38,786	48,925	47,774	42,202	42,713	41,106	29,406	25,482	17,198	**415,004**
2019	21,519	21,215	33,843	40,244	42,179	47,752	42,113	45,612	36,747	37,825	21,338	16,959	**407,345**

Generation (MW·h) of Mesquite Solar 2 (100MW with tracking)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016												13,255	**13,255**
2017	15,016	16,794	26,698	29,176	31,992	32,486	29,490	28,681	26,392	23,857	15,275	15,040	**290,897**
2018	17,201	18,569	24,484	28,562	32,739	31,729	29,461	29,075	26,015	16,891	15,900	14,396	**285,023**
2019	16,090	14,280	19,916	21,340	22,983	30,941	29,656	29,898	23,634	23,723	13,615	9,971	**256,047**

Generation (MW·h) of Mesquite Solar 3 (150MW with tracking)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2016												21,060	**21,060**
2017	22,673	25,705	40,558	43,985	48,952	49,978	44,174	43,447	39,846	35,670	23,425	22,187	**440,600**
2018	25,678	28,450	38,984	43,517	50,609	48,203	44,817	44,342	39,830	31,777	27,684	21,898	**445,789**
2019	25,460	26,613	38,070	43,410	47,869	48,938	45,483	45,652	39,165	39,109	25,772	20,096	**445,637**

Raw Materials Used in Energy Technologies

Materials (kg) needed for generating 1-GWh of electricity in various technologies, including basic resources. (1GWa = 8.7TWh)

Plant → Materials	Coal 45,5 %	Lignite 44 %	natGas 58 %	Nucl	Hydro 3 MW	Wind 1,5 MW, Off-sh	Solar thermal	Solar PV roof top
Iron	2.000	2.00	1.200	420	2.400	**5.200**	**3.470**	**5.200**
Bauxite	16	18	2	27	4	44	6	**2.000**
Copper	2	7	1	6	5	**65**	**252**	**230**
Limestone	7.000	20.000	6.400	800	6.000	2.490	2.100	10.000
Nickel	1,4	1,1	0,4	**15,5**	0,4	0,4	0,5	**14**
Coal	**501.300**	3.500	255	880	2.860	3.840	2.700	14.000
Lignite	5.180	**1.017.000**	300	500	2.750	5.100	745	32.900
natGas	1.160	800	**185.705**	1.070	730	1.560	440	5.690
Crude Oil	3.760	1.200	2.220	610	580	720	1.750	4.300
Uranium	0,34	0,2	0,003	**26,5**	0,007	0,02	0,03	0,92

GHG Emissions From PV Plants

Major Construction Inputs and GWE (after 20 yr) for a Photovoltaic Plant[a] 4.1 GW installed, $3.6B(1997)

MT = metric ton

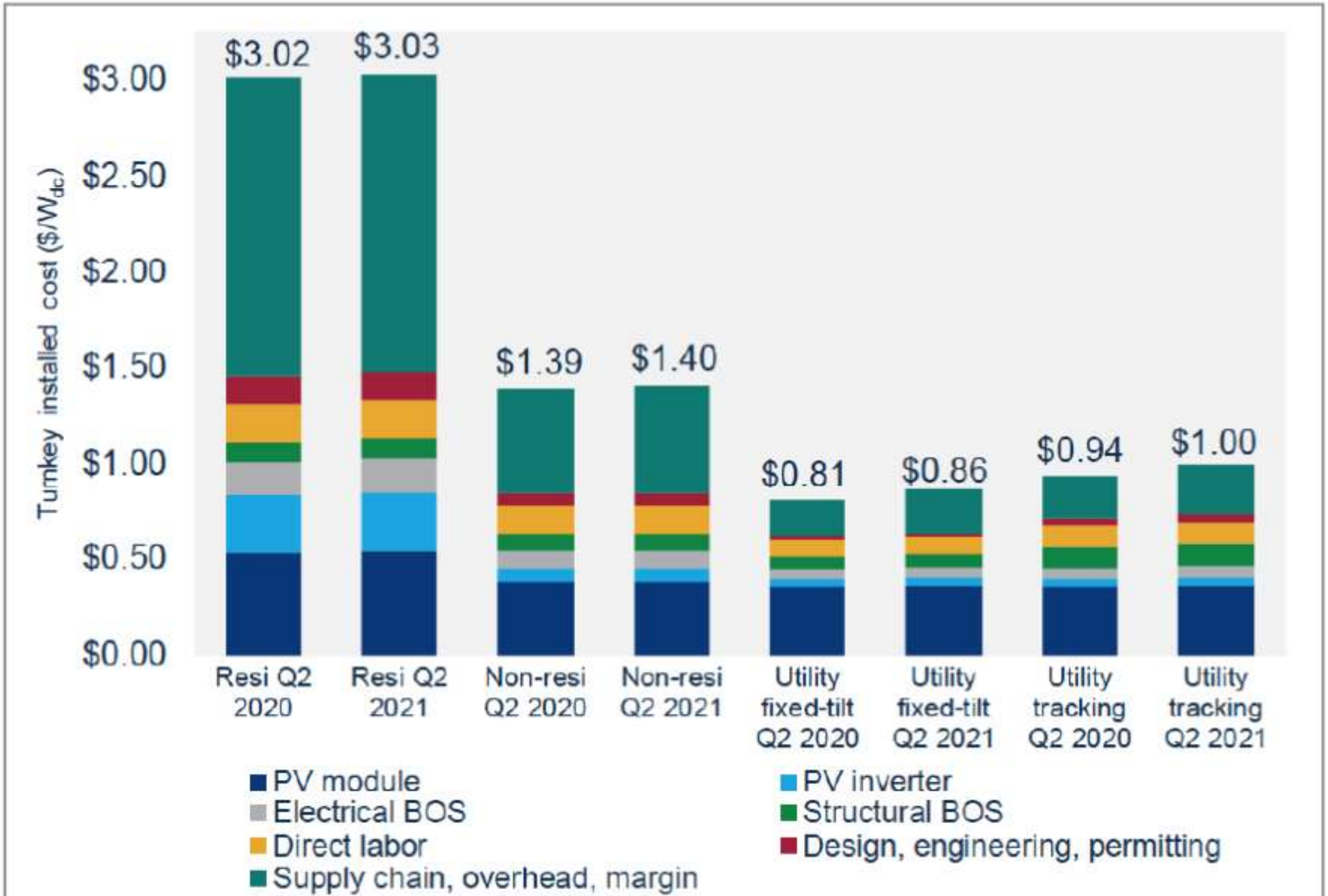
construction inputs	total MT	unit cost (1992 \$/MT)	total cost (1992 \$)	GHG emissions (MT of CO_2 equiv) CO_2	$+ CH_4$	$+ N_2O$	= GWE
steel	4 600 276	385[b]	1 772 797 382	6 957 724	4 216	35 924	6 997 865
copper	480 029	2 368[b]	1 136 805 659	984 580	1 617	10 504	996 701
electricity (MWh)	7 556 010	36[c]	268 780 863	2 152 447	1 077	20 407	2 173 931
aluminum	177 788	1 268[b]	225 374 699	428 610	405	6 558	435 573
cement	2 222 356	55[b]	121 362 849	410 263	394	15 497	426 153
glass	1 066 731	50[b]	53 336 538	56 951	67	759	57 777
total			3 578 457 990	10 000 000	8 000	90 000	10 000 000

[a] Total emissions are rounded to one significant digit. [b] Ref *40*. [c] Ref *41*.

S. Pacca& A. Horvath, Environ. Sci. Technol. 36, 3194 (2002))

Land purchase for construction (51 km^2) not included in cost
Chemicals used in doping and surface treatments: phosphoric acid H_3PO_4, phosphoryl chloride (phosphorus oxychloride, $POCl_3$), potassium hydroxide (KOH), isopropanol (IPA), hydro-fluoric acid (HF), nitric acid (HNO_3).

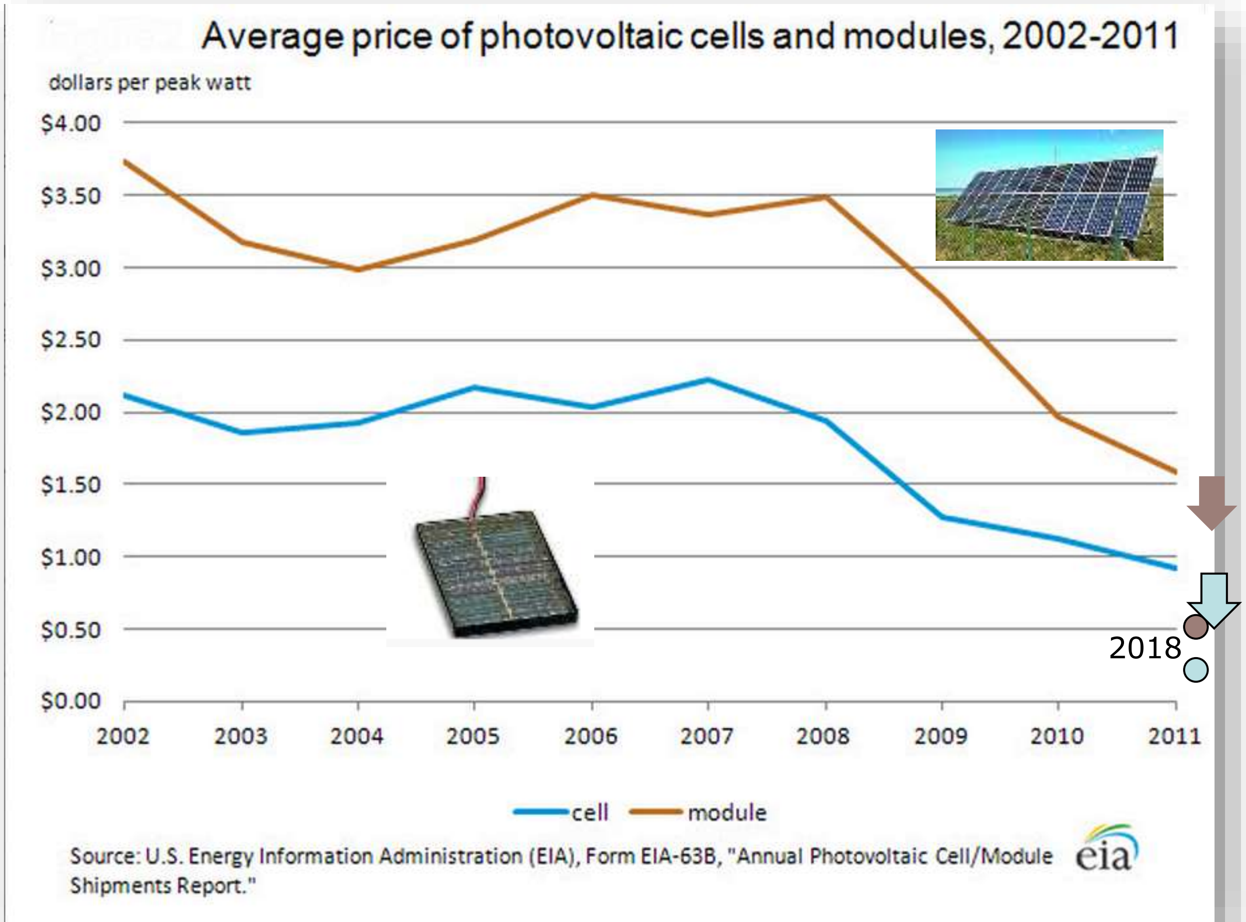
US National PV Solar System Prices



Source: Wood Mackenzie

Price increases Q2 (2020) → Q2 (2021), future changes supply change from China to ?? US manufacturing costs?

Price/Performance



Average $/$W_p$ of shipped PV cells & modules at $3-3.5 before Great Recession.

After 2008:

Price collapse Δ$>50%

Significant installation prices.

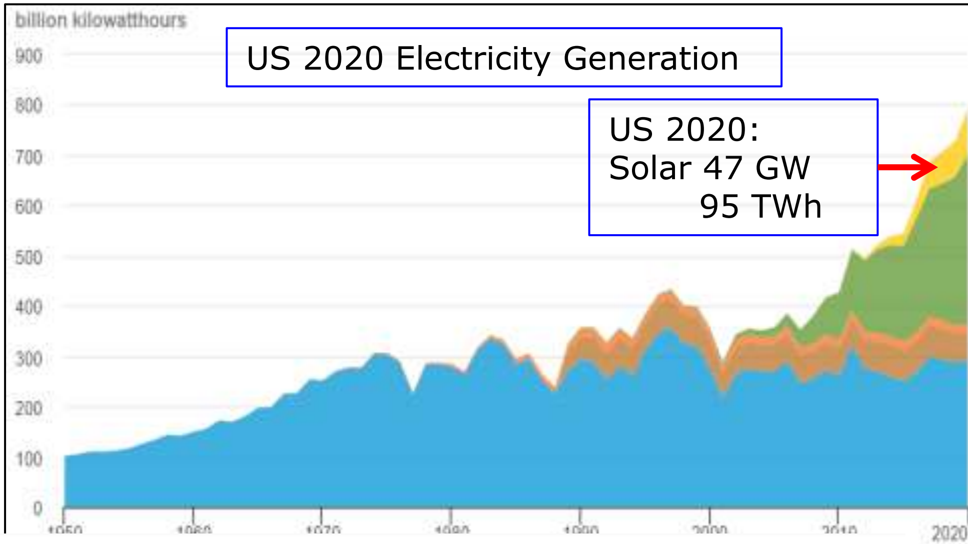
Module Efficiency 2011:
(W_e/incoming sol. Flux)

- **0.16 Crystalline Si.**
- **0.11 Thin-film Si.**
- **0.29 Concentrator.**

Power unit "peak-Watt" = maximum power P_{max} delivered by a cell exposed to insolation with wavelength spectrum characteristic of 45^0 incidence ("A1.5") with power density 1kW/m^2.

Efficiency = percentage of incident solar energy (input) converts to electricity (output) under standard rating conditions.

Performance: U.S. PV Installations



Net Electric Power (2020)	
Coal:	19%
Nat Gas:	40%
Nuclear:	20%
Hydro:	7.3%
Wind:	8.4%
Solar:	2.3%
Total:	**4,120 TWh**

Source: Wood Mackenzie; Note that pricing has increased in past quarters (in Q3 2017 thanks to module price increases from limited global tier 1 module capacity available to the US market, and in Q4 2019 and Q1 2020 as more developers began utilizing more expensive mono PERC modules), but total system pricing has never increased both QoQ and YoY across all market segments before Q2 2021.

Source: Wood Mackenzie; note that Wood Mackenzie's forecasts do not assume any extension of the ITC

Big US PV Projects: Mesquite Solar