Energy Policy

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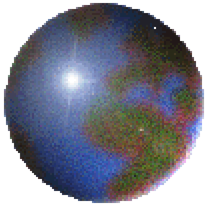

Showstoppers & Bottlenecks to Terawatt Solar Photovoltaics

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Outline

- Principle of solar cells
- Current & future global energy demands
  - Scales required for solar PV
- Requirements for a terawatt-capable PV technology
- Showstoppers & bottlenecks to terawatt PV
  - Availability of raw materials
  - Energy input for Si wafers & modules
  - Recycling of end-of-life PV modules
  - Terawatt-scale storage of solar electricity
  - Manufacturing and installation costs
- Suggested strategic R&D directions for PV

Acknowledgments

- This talk is based primarily on:
  - M. Tao, Terawatt Solar Photovoltaics: Roadblocks and Opportunities (Springer, 2014, ISBN 978-1-4471-5642-0)
  - C.S. Tao, J. Jiang, M. Tao, "Natural resource limitations to terawatt-scale photovoltaic solar cells," Solar Energy Materials and Solar Cells 95, 3176–80 (2011)

Background

U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM
PVMC

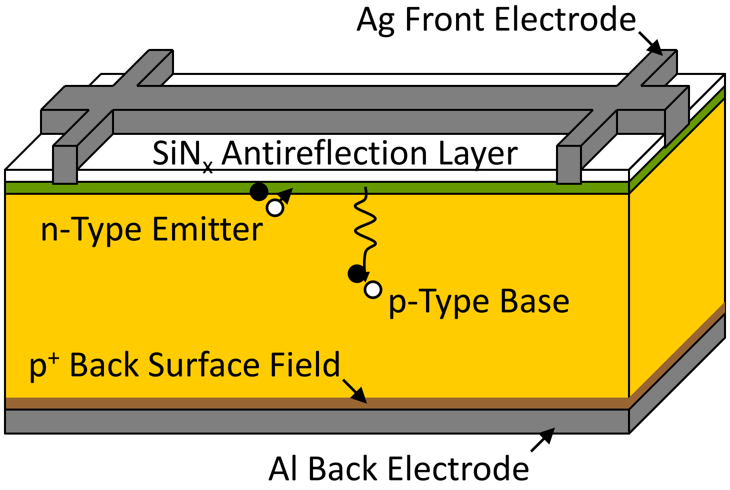
- This analysis started with the establishment of the U.S. Photovoltaic Manufacturing Consortium (Albany, NY, 2011)
  - Led by SEMATECH & funded by U.S. Department of Energy & States of New York & Florida
  - A 5-year joint effort initiated by SEMATECH (D. Holladay) & myself (2006–2011)
  - Forced me to look into longer-term, bigger-picture, national & global issues for PV technologies
  - First presentations at Electrochemical Society fall meeting (Vienna, 2009) & U.S. PV Consortium Workshop (Washington DC, 2010)

Arizona Landscape

Sunrise over Four Peaks from my home

Principle of Solar Cells

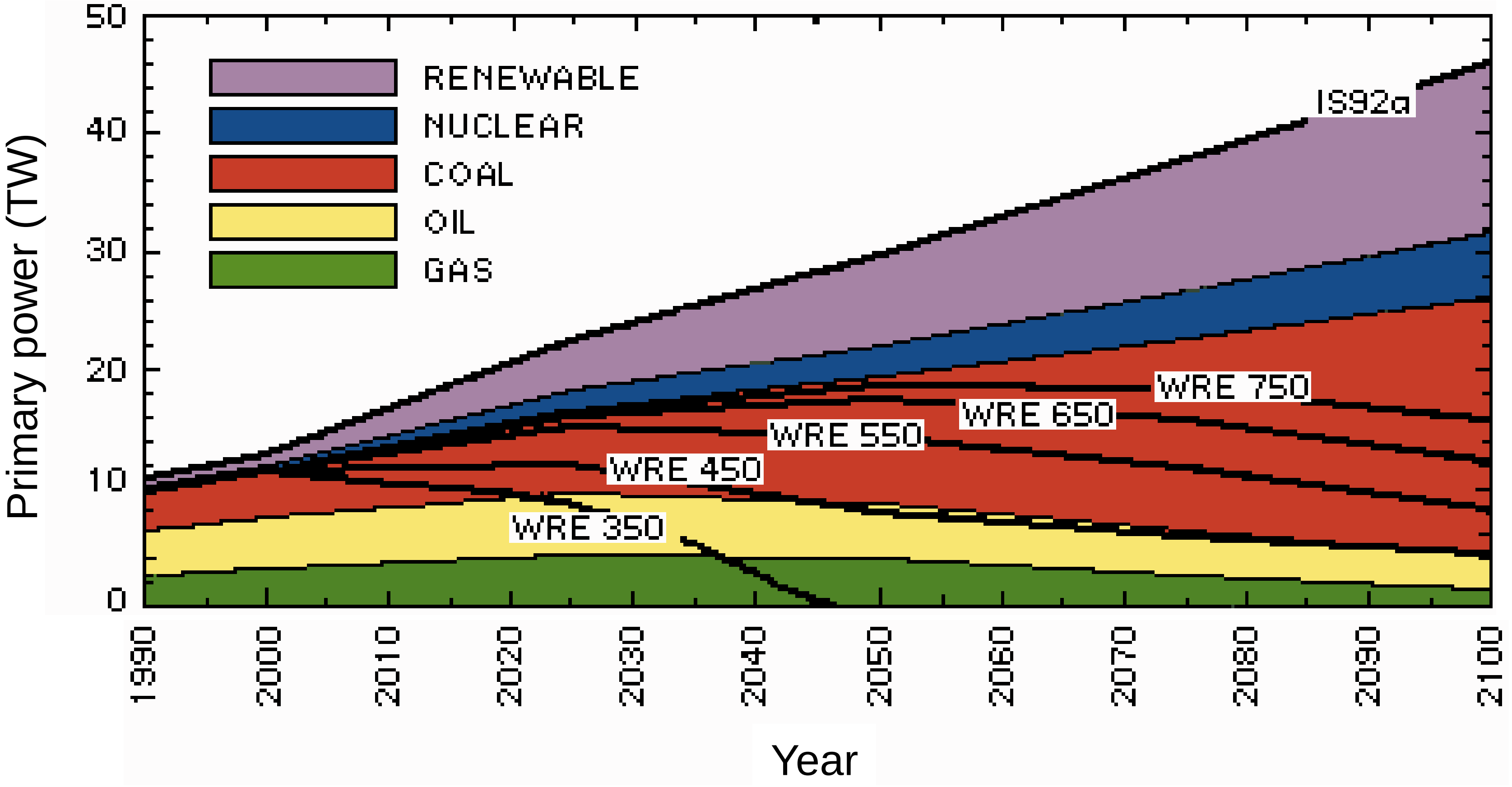
- Light-induced voltage
  - Employed for solar-to-electric conversion
- Two key processes
  - Light absorption
  - Charge separation
- Two requirements
  - Light absorber: molecule or semiconductor
  - Potential difference: p-n, Schottky, or hetero



Si Solar Cell Operation

Si wafer: 200 μm low 10^{16} B doping
Emitter: 0.5 μm 10^{19} P doping
BSF: 10 μm low 10^{19} Al doping
SiN_x: 75 nm

How Much Energy Do We Need?



Current global consumption 18 TW (18×10^{12} W)

Projected demand in 2100 46 TW

Hoffert et al, Nature 395 (1998) 881

Conclusion #1

- Any solar PV technology has to be deployed at a TW scale, or it will make little impact on our energy mix
  - By 2100, global energy demand will be 46 TW
  - If 30% from PV, that is 13.8 TW from PV
  - Time-averaged output ~15% of peak output, so ~92 TW_p PV installation needed
  - If the average lifetime of PV modules is 25 years, the annual production needs to reach ~3.7 TW_p/yr

We need ~100 TW_p of solar PV installed
& ~4 TW_p/yr annual production!

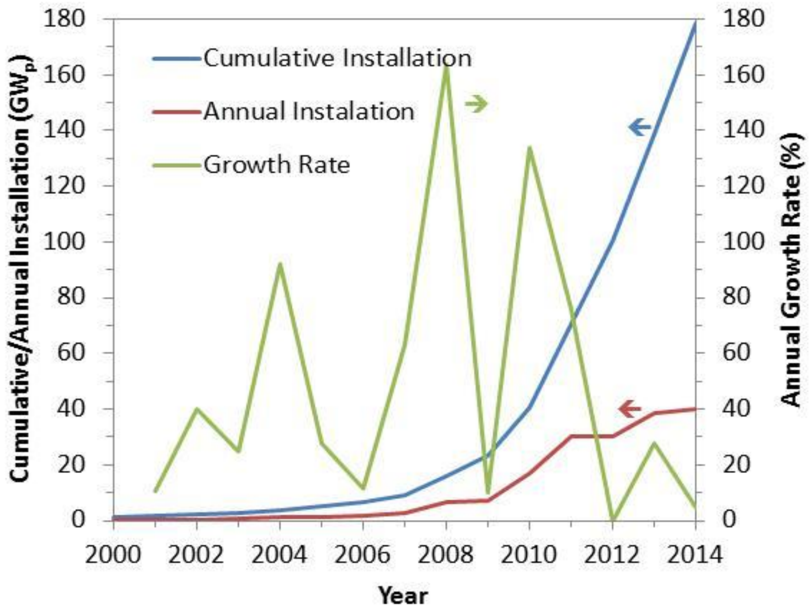
Implications of Terawatt PV

- Terawatt-scale deployment of any PV technology requires massive amounts of natural resources
  - Raw materials, chemicals, electricity, water, transportation…
  - Limited supplies of natural resources could prevent PV from reaching a terawatt scale
- There are huge amounts of wastes and end-of-life modules from any PV technology
  - Limited capabilities to handle/recycle them would prevent PV from reaching a terawatt scale

Status of PV Industry as 12/31/14

- ~180 GW_p global installed capacity
  - Annual revenues ~$250B
  - ~50 GW_p/yr production
  - ~45% annual growth since 2005
  - ~0.5% global electricity capacity
- If 30% by 2100, the industry has to expand >500-fold in 85 years

The potential for PV is enormous!



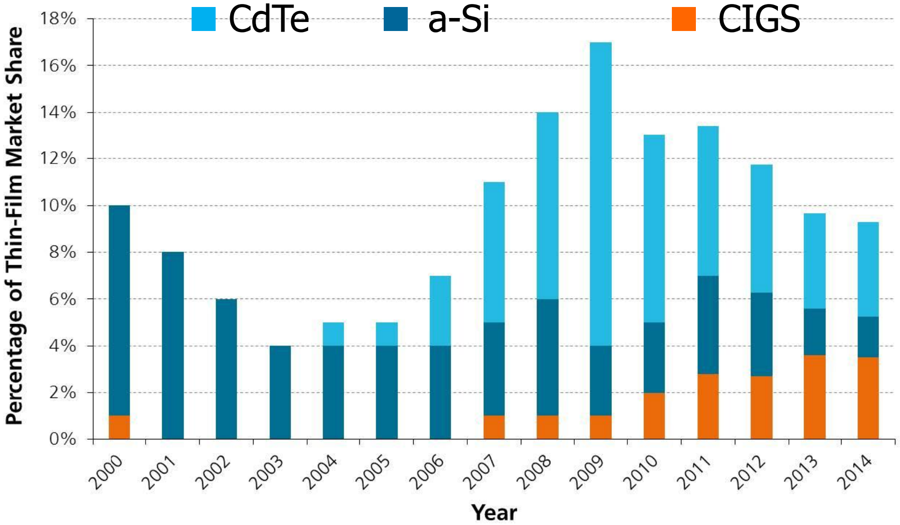
Growth of PV Industry

Huge ups & downs as an industry in its infancy

European Photovoltaic Industry Association 2015

PV Industry Breakdown 2014

- Four commercial technologies
  - Wafer-Si (~200 μm): ~91%
    - Multi-Si >55%
    - Mono-Si ~35%
  - Thin-film (<5 μm): ~9%
    - CdTe: ~4%
    - Si (amorphous or microcrystalline): ~2%
    - $CuIn_xGa_{1-x}Se_2$ (CIGS, x~0.7): ~3%

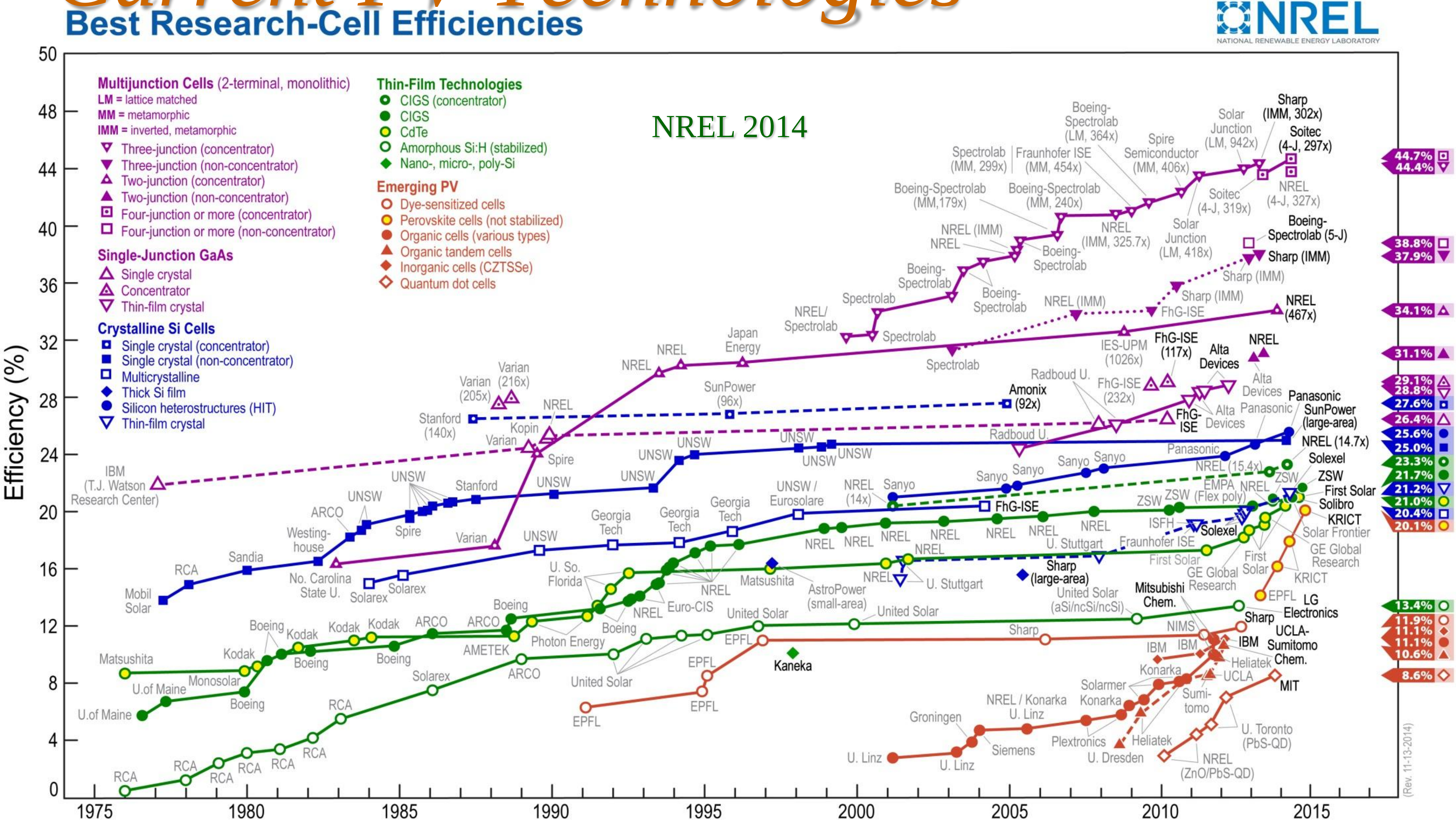


CdTe Market Share

- CdTe peaked in 2009 (13%) & has been losing market share since
- CdTe will continue to lose, & wafer-Si will continue to gain, market share

Fraunhofer ISE 2015

Current PV Technologies



Cost: A Well-Known Bottleneck

Technology	**Cost (¢/kWh)**
Wind	~7
PV	~13
CSP	~24
Geothermal	~5
Hydropower	~8
Natural Gas	7–11
Coal	9–12
Nuclear	~10

2020 Cost of Electricity*

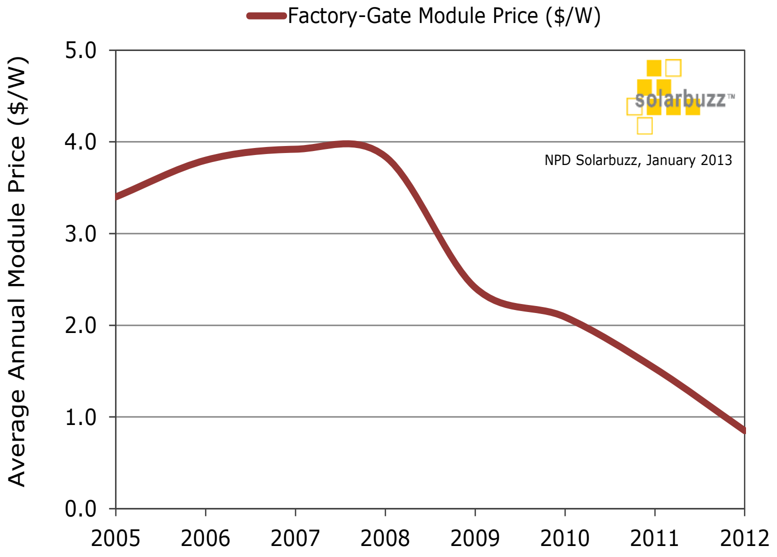
- Solar electricity 3× more expensive than other forms of electricity today
- By 2020 it is likely <1.5× more expansive according to DOE

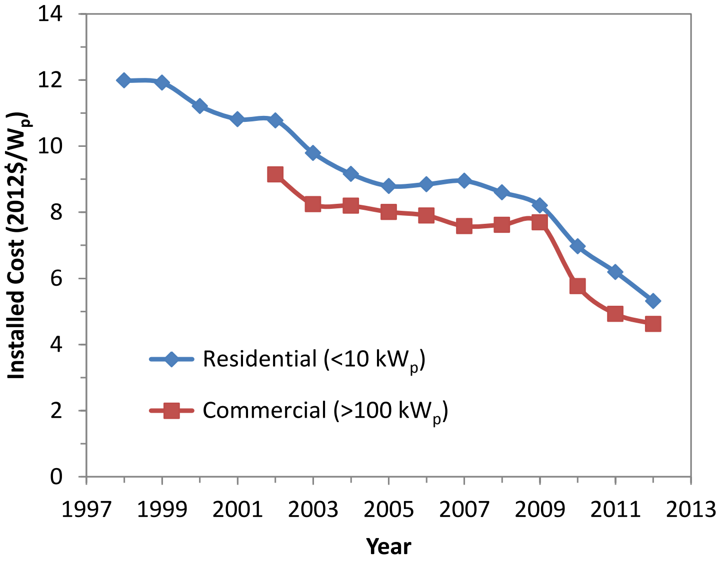
- Cost is a major bottleneck: ~3× today
- But
  - But solar cost is coming down quickly
  - Fossil fuel prices going up quickly
- Would the PV industry take off when fossil fuel prices exceed PV cost?

The answer is likely a NO!

* DOE EIA, Annual Energy Outlook 2015

Cost Trend





Historical Module Price

System Costs

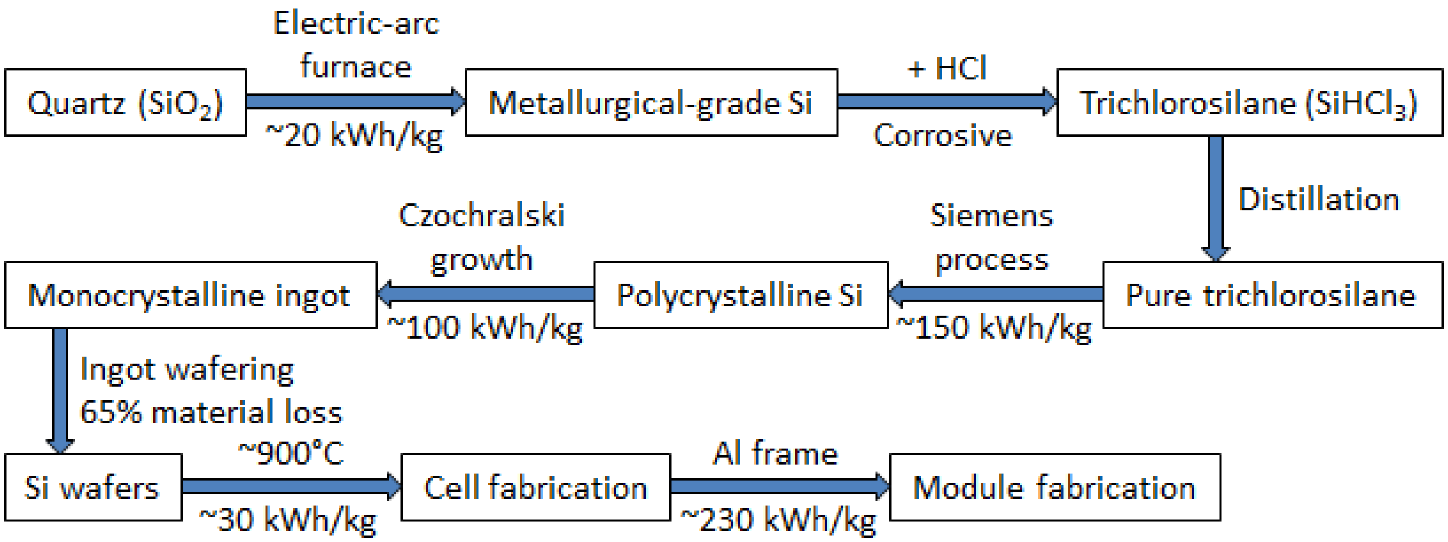
Module price down 4-fold since 2005
System cost down 1.7-fold since 2005

Residential & commercial
Utility-scale system $\$3.45/W_p$ in 2012

NPD Solarbuzz 2013

G. Barbose et al, Tracking the Sun VI (2013)

A Bottleneck for Wafer Silicon



Quartz (SiO_2)

Electric-arc furnace

~20 kWh/kg

Metallurgical-grade Si

+ HCl

Corrosive

Trichlorosilane ($SiHCl_3$)

Distillation

Pure trichlorosilane

Siemens process

~150 kWh/kg

Polycrystalline Si

Czochralski growth

~100 kWh/kg

Monocrystalline ingot

Ingot wafering

65% material loss

Si wafers

~900°C

~30 kWh/kg

Cell fabrication

Al frame

~230 kWh/kg

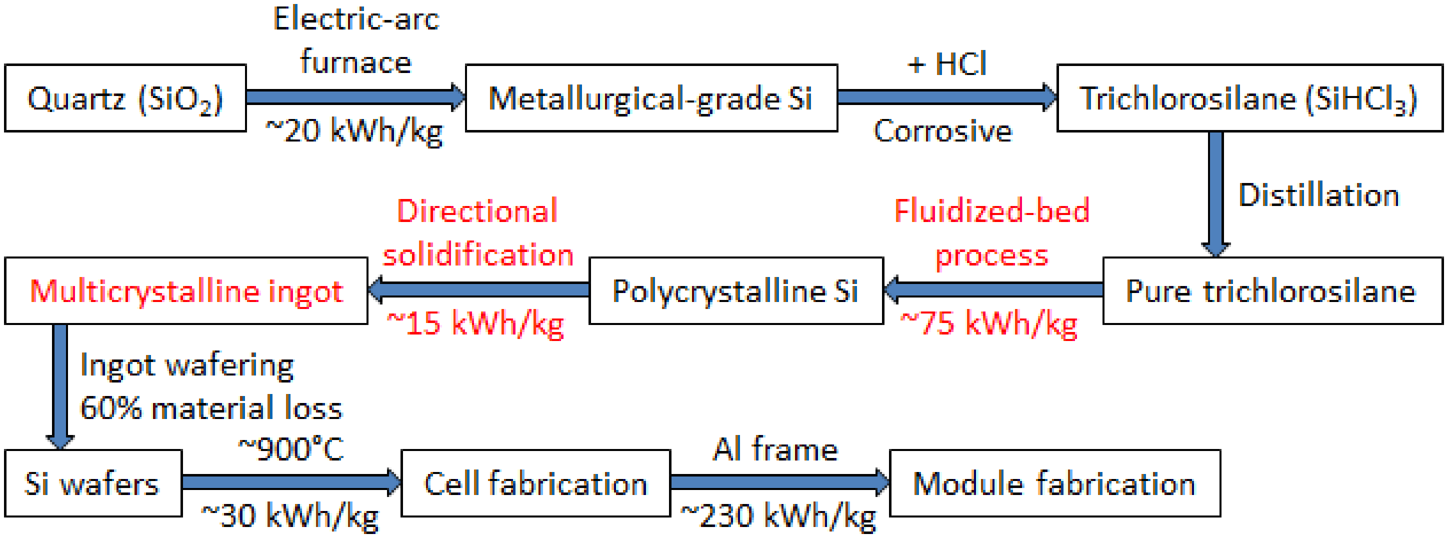
Module fabrication

- The process to make w-Si modules is costly, energy-intensive and polluting: ~4.2 kWh/W_p for monocrystalline Si modules
- Annual production of 3.7 TW_p of mono-Si modules would require ~79% of the 2012 global electricity consumption,* w/o considering transmission losses

C.S. Tao et al, SEMSC 95 (2011) 3176

* DOE EIA, International Energy Statistics 2014

An Alternative Process



Quartz (SiO_2)
Electric-arc furnace
~20 kWh/kg
Metallurgical-grade Si
+ HCl
Corrosive
Trichlorosilane ($SiHCl_3$)
Distillation
Pure trichlorosilane
Fluidized-bed process
~75 kWh/kg
Polycrystalline Si
Directional solidification
~15 kWh/kg
Multicrystalline ingot
Ingot wafering
60% material loss
Si wafers
~900°C
~30 kWh/kg
Cell fabrication
Al frame
~230 kWh/kg
Module fabrication

- Directional solidification replaces Czochralski growth: 100 kWh/kg down to 15 kWh/kg & less material loss during wafering, but multi-Si ingot

The industry trades performance for cost!

- Fluidized-bed process may replace Siemens process, but powder formation

Energy Payback Time

- 1 W_p PV produces ~1.35 kWh/yr in AZ
  - ~15% time-averaged output
- Energy payback time in Arizona
  - Location dependent
  - ~3 yrs for mono-Si
  - ~2 yrs for multi-Si cells
  - After that, installed PV produces net energy

Energy input for various scenarios*

	Siemens Process	**Fluidized-Bed Process**
Mono-Si Module	~4.2 kWh/W_p	~3.3 kWh/W_p
Multi-Si Module	~3.4 kWh/W_p	~2.5 kWh/W_p

* M. Tao, Terawatt Solar Photovoltaics: Roadblocks and Opportunities (Springer, 2014)

Energy Means Cost

- Electricity input for poly-Si is ~220 kWh/kg (Siemens)
  - In U.S., industrial electricity ~7¢/kWh
  - Electricity cost for poly-Si is ~$15/kg: How can the industry profit when the poly-Si price drops below $20/kg?
    - Use of cheap hydropower, but its capacity limited*
    - Self-generation ~5¢/kWh
    - Low energy input = low cost + short energy payback time
- Electricity consumption for mono-Si PV is ~4.2 kWh/W_p
  - Electricity cost for 1 W_p is 29¢/W_p
  - DOE target 50¢/W_p for modules: HOW?

* N.S. Lewis, MRS-B 32 (2007) 808

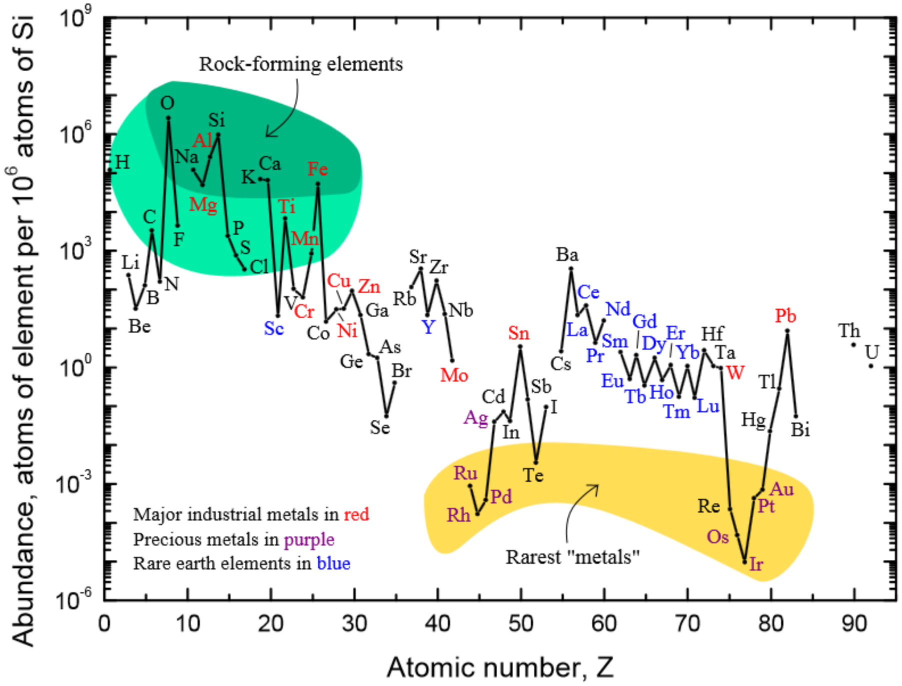
Requirements for Terawatt PV

- Material requirements
  - Abundant material
  - Low-cost material
  - Energy-efficient synthesis
  - Low-cost synthesis
  - Low-carbon synthesis
  - Minimum health & environmental impact
  - Stability & reliability in air & under UV
  - Recyclability of end-of-life modules
- Device requirements
  - High minority carrier lifetime
  - High absorption coefficient
    - Direct bandgap
  - Broad absorption spectrum
  - Suitable bandgap
    - ~1.4 eV
  - Both conduction types
  - Suitable resistivity

None of the current PV technologies meets all the requirements!

M. Tao, Interface 17(4) (2008) 30

CdTe



Abundance of Elements

- Phenomenal growth
  - First to reach $1/$W_p$
  - Grew 25-fold in 4 years
  - But having been losing market share since
- What will limit CdTe?
  - Known reserve of Te 24,000 tons*
  - Best scenario 492 GW_p
  - ~0.16% of the 2100 energy demand

USGS, Rare Earth Elements – Critical Resources for High Technology 2002

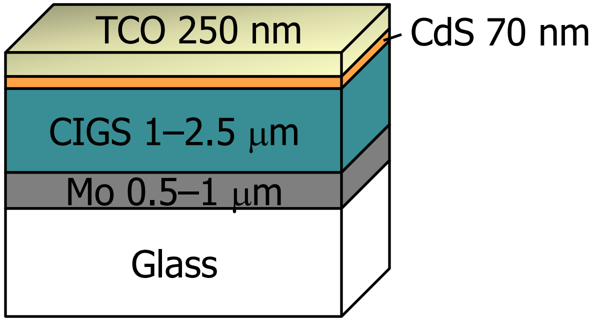
* USGS, Mineral Commodity Summary 2015

What Is Best Scenario?

- Estimation based on material consumption in PV modules and material reserve
  - If there is 10 g of material on the planet and the consumption is 1 g/W_p, only 10 W_p modules can be made
  - The assumption is 100% material utilization
    - All the reserve can be extracted: Some may be too expensive to extract
    - All the reserve exclusively for PV: Other industries may compete for the material
    - No material loss during module fabrication
  - The assumption also include indefinite module lifetime
    - Current modules are typically rated 25 years
  - None of these assumptions can be true – best scenarios

Other Scarce Materials: In

- Multiple issues with CIGS
  - Poor manufacturability: Poor uniformity of three cations
  - Limited availability of In
- Estimation of maximum power from CIGS
  - Known reserve of In 11,000 tons*
  - Composition $CuIn_{0.7}Ga_{0.3}Se_2$
  - Best scenario 1.1 TW_p
  - ~0.36% of the 2100 energy demand
- Competitions for In
  - FPD, LED, lasers, power devices, etc.
  - Hard for the PV industry to compete

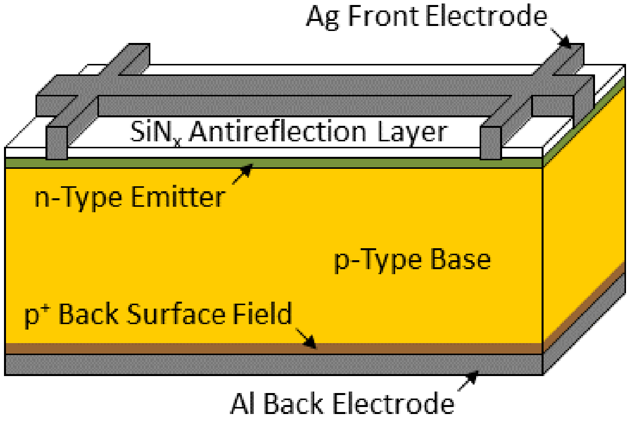


C.S. Tao et al, SEMSC 95 (2011) 3176

* USGS, Mineral Commodity Summary 2008

Other Scarce Materials: Ag

- Silver used in wafer-Si cells as front electrode
  - Known reserve 530,000 tons*
  - Best scenario 10.1 TW_p
    - 12 μm Ag assumed
    - 7% surface coverage
  - ~3.3% of the 2100 energy demand
    - Realistically maybe 2%
- Competitions for Ag
  - Solders, brazing alloys, batteries, catalyst, jewelry, silverware…



C.S. Tao et al, SEMSC 95 (2011) 3176

* USGS, Mineral Commodity Summary 2015

Conclusion #2

Without technical breakthroughs, current commercial PV technologies excluding thin-film Si would provide <4% of the 2100 energy demand under best scenarios

Cell Technology	Efficiency Used	Limiting Material	Reserve Base (ton)	Maximum Wattage	Averaged Output (TW)	% of 2100 Energy Demand
Wafer-Si	16.8%	Silver	530,000	10.1 TW_p	1.52	3.3%
CdTe	12.8%	Tellurium	24,000	492 GW_p	0.074	0.16%
CIGS	14.3%	Indium	11,000	1.1 TW_p	0.165	0.36%
Thin-film Si*	9.8%	TW capable	–	–	–	–

* Thin-film Si is the only technology capable of terawatt-scale deployment today, but it has lower efficiency and higher cost and is losing market share

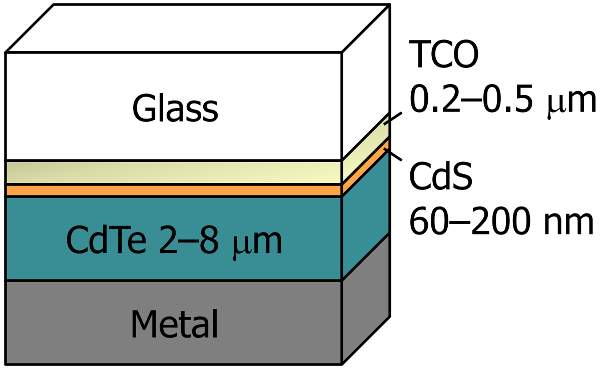
C.S. Tao et al, SEMSC 95 (2011) 3176

Annual Production of Materials

- Material production rate limits deployment rate of PV
- Required annual production ~3 TW_p/yr
    - With 92 TW_p total installation & 25-year module lifetime, ~3.7 TW_p modules will die each year
    - Annual production of 3.7 TW_p will maintain a steady-state 92 TW_p total installation

Annual Production of CdTe

- Annual production of Te ~550 tons*
  - Te to be depleted in 44 yrs
    - Reserve 24,000 tons
  - Best scenario 11 GW_p/yr
    - Realistically maybe 6 GW_p/yr
  - Current production ~2 GW_p/yr by First Solar
    - If First Solar has access to half of the Te produced, i.e. ~3 GW_p/yr
    - Room for growth limited for First Solar: It has to lose market share
    - First Solar has a good business model



But our energy/environmental crisis will not be solved by CdTe

* USGS, Minerals Yearbook 2012

** E. Fortunato et al, MRS-B 32 (2007) 242

Annual Production of Ag & In

- Wafer-Si employs Ag front electrode
  - Production of Ag 26,100 tons/yr*
    - Ag to be depleted in 20 yrs
  - Best scenario 498 GW_p/yr
    - Realistically maybe 300 GW_p/yr, currently ~50 GW_p/yr
- CIGS ($CuIn_{0.7}Ga_{0.3}Se_2$)
  - Production of In 820 tons/yr & that of Ga 440 tons/yr*
    - In to be depleted in 14 yrs
  - Best scenario 83 GW_p/yr
    - Limited by In

* USGS, Mineral Commodity Summary 2015

C.S. Tao et al, SEMSC 95 (2011) 3176

Conclusion #3

Without technical breakthroughs, current commercial PV technologies excluding thin-film Si would plateau at <600 GW_p/yr under best scenarios

Cell Technology	Efficiency Used	Limiting Material	Annual Production (ton)	Annual Production (GW_p/yr)	Years to Depletion
Wafer-Si	16.8%	Silver	26,100	498	20
CdTe	12.8%	Tellurium	550	11	44
CIGS	14.3%	Indium	820	83	14
Thin-film Si*	9.8%	TW capable	–	–	–

* Thin-film Si PV is the only technology capable of terawatt-scale deployment today, but it has lower efficiency and higher cost and is losing market share

C.S. Tao et al, SEMSC 95 (2011) 3176

Storage of Solar Electricity

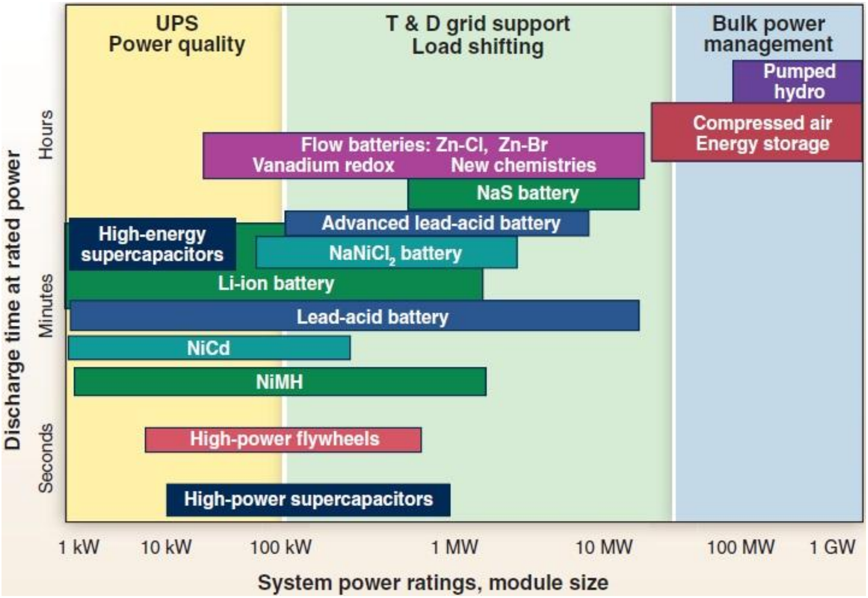
- First showstopper: ~3.7 TW$_p$ PV w/o storage
  - The grid can serve as a buffer, to some extent, w/o storage
    - But unlikely to take >10% from PV w/o storage
  - Current global electricity capacity 5.5 TW*
    - Limits PV capacity to ~550 GW or ~3.7 TW$_p$
- Second showstopper: ~30 TW$_p$ PV w/o conversion
  - In US, 32% of energy we use is non-renewable electricity**
    - Another 5% of energy is electricity from hydropower
  - Current global energy consumption ~18 TW
    - If 25% of energy is non-renewable electricity, i.e. 4.5 TW
    - Limits PV to ~30 TW$_p$ unless solar electricity is converted to a fuel

* DOE EIA, International Energy Statistics 2014

** DOE EIA, Annual Energy Review 2011

Storage Options

- GW capable
  - Limited by geology
    - Pumped hydropower
    - Compressed air
- kW to MW
  - Various batteries
  - Flywheel
  - Supercapacitor
  - Hear storage
  - Superconducting magnet



Storage Performance

TW scale storage requires GW scale capacity for hours or even days

* IRENA, Electricity Storage 2012

B. Dunn et al, Science 334 (2011) 928

Case Study for Batteries

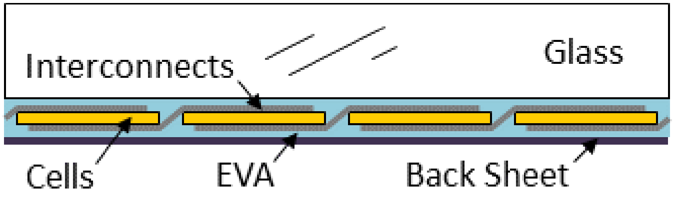
- If 30% from PV by 2100, i.e. 13.8 TW
  - If 50% of solar electricity requires storage, i.e. a minimum of ~1.7x10^{11} kWh to be stored on a daily basis
    - Actually more than 50% due to weather
  - Typical laptop batteries are 50 Wh each
    - At least 473 laptop batteries/person for the 7 billion people on Earth
    - Amounts of natural resources needed to make these batteries?
    - Amounts of wastes and dead batteries to handle?

Recycling of PV Modules

- Stead-state 92 TW_p total installation & 25-year module lifetime
  - 3.7 TW_p/yr modules through their lifetime
  - If these are wafer-Si modules with 16.8% efficiency, there are 2.2×10^4 km^2/yr dead modules
    - The size of New Jersey has to be recycled each year
- CdTe is recycled by First Solar
  - Cd is toxic & Te is rare
  - But many companies are overlooking recycling

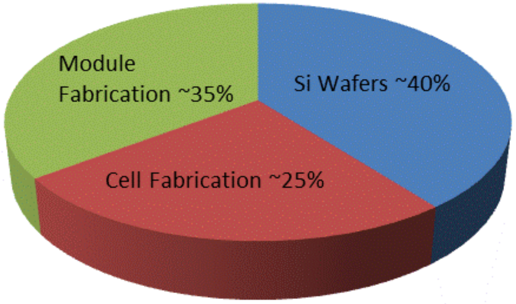
Recycling of Si Modules

- With >90% of the market, Si modules are not routinely recycled & technology not ready yet
  - Ag would be depleted in 20 years
  - Pb is toxic
- There are financial incentives to recycle Si modules
  - ~20 g/module of Ag worth \$10–30/module
    - 95% recovery and \$15–45/oz of Ag
  - ~650 g/module of solar-grade Si worth ~\$10/module
    - 90% recovery and \$18/kg of poly-Si
    - Savings in energy to purify Si



Cost Contributors

- Installation
  - >3/4 of the system cost, especially soft costs
    - Design, permitting, financing, labor, hardware…
- Energy
  - Poly-Si and Al frame
- Raw materials
  - Ag, Si, glass, Al frame, EVA, backsheet…
- Processing
  - Wafering, diffusion, AR coating, metallization, interconnect…
  - Non-vacuum continuous processing



Module Cost Breakdown*

* A. Goodrich et al, SEMSC 114 (2013) 110

Lower Cost by Standardization

- One factor: Each PV system is individually designed
  - Modules have different power & efficiency
    - Have to accommodate different modules w/ minimum mismatch
    - Require customized hardware
    - Replacing a bad module in a system is a headache
- The reason: Cell efficiency dispersion
  - Efficiency ranges 12–18% from “same” process, same ingot
    - Every cell/module has to be tested and sorted (binned)
    - Only cells with similar efficiencies are packaged into a module
    - Only modules with similar efficiencies are connected in an array
  - Commercial modules have 2% efficiency dispersion
    - Disqualified cells lead to a higher cost

How to narrow the efficiency spread down to, say, ±0.5%?

Summary

- Most PV technologies incapable of making an impact
- Strategic R&D directions for a sustainable PV industry
  - Wafer-Si based
    - Energy-efficient purification for solar-grade Si
    - Substitution of Ag with an Earth-abundant metal (Cu & Al)
    - Module standardization by cell efficiency uniformization
    - Non-vacuum continuous processing
    - Low-kerf wafering of ingot
    - Recycling of end-of-life cells/modules
  - Thin-film Si: lower cost & higher efficiency
  - Next-generation PV: Earth-abundant materials
  - Terawatt-scale storage of solar electricity

Innovation! Innovation!! Innovation!!!