Renewable Solar Energy:
Has the Sun Finally Risen on Photovoltaics?

Mark R. Pinto
Senior Vice President & Corporate CTO
General Manager, Energy and Environmental Solutions

Purdue University
February 20, 2009

think it. apply it.™

APPLIED MATERIALS®

Applied Materials Overview

- The global leader in Nanomanufacturing Technology™ solutions for the electronics industry
  - Ranked #1 in each of: semiconductor, flat panel display and solar equipment
- Fiscal year 2008 annual revenue ~ US$8B
- Strong commitment to R&D: last 5 years ~ US$1B per year
- Worldwide employees ~ 14,000
  - Global development in US, Europe, Israel, India, China, Russia
  - Manufacturing locations in US, Europe, Israel, Taiwan

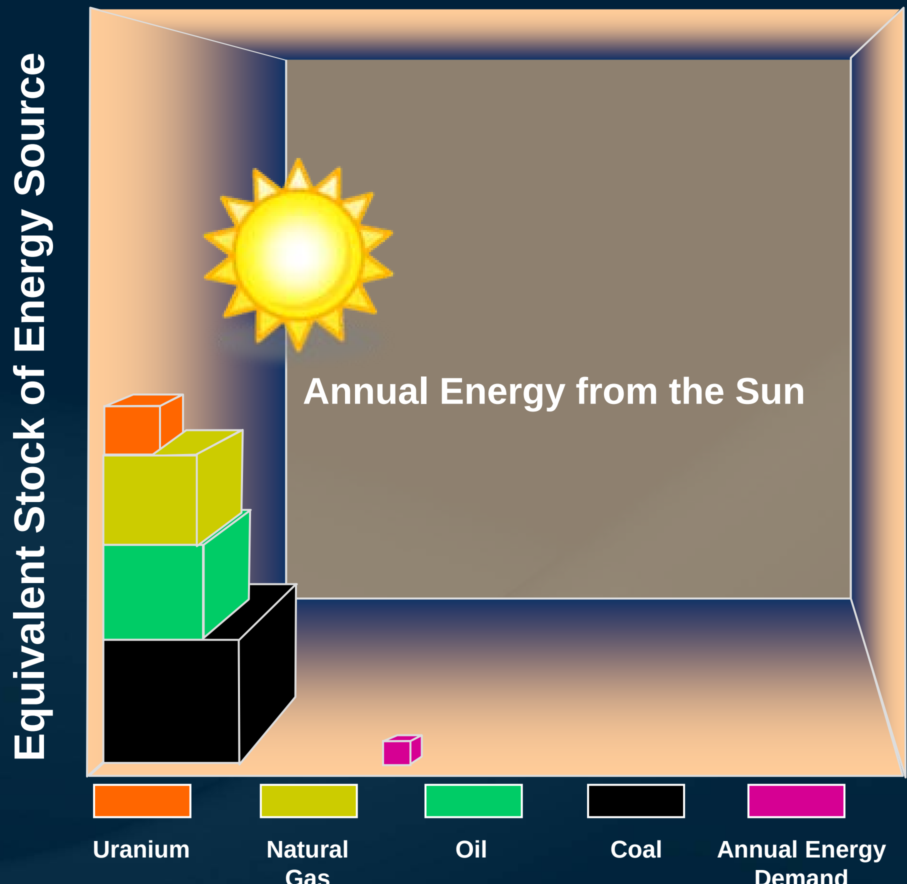



External Use

SOLAR/PV BACKGROUND

SOLAR/PV BACKGROUND

Solar Energy: Abundant, Clean and Secure

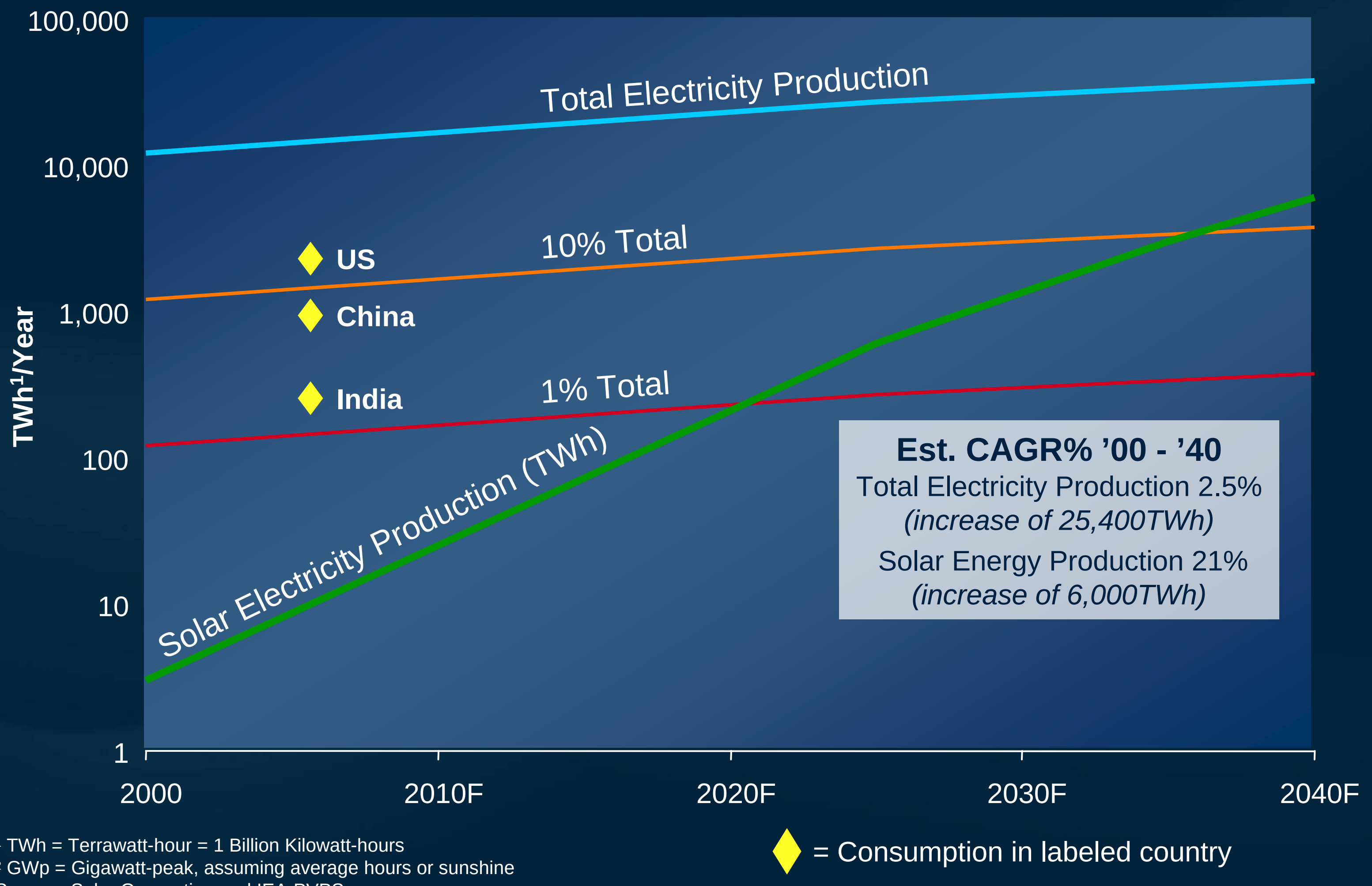


The Sun provides every day 10.000 times the energy needed on the planet

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that." – Thomas Edison, 1931.

External Use

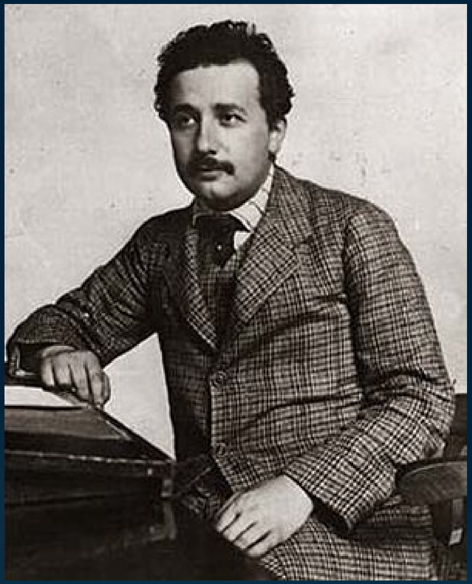
World Electricity Production Forecast
(2000 – 2040)

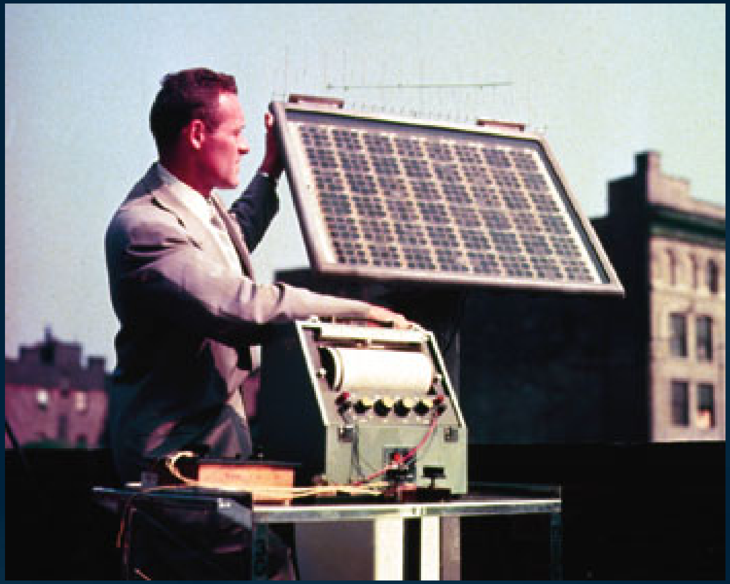


¹ TWh = Terrawatt-hour = 1 Billion Kilowatt-hours
² GWp = Gigawatt-peak, assuming average hours or sunshine
Source: Solar Generation and IEA-PVPS

External Use

Photoelectric Effect to First Si PV Panels



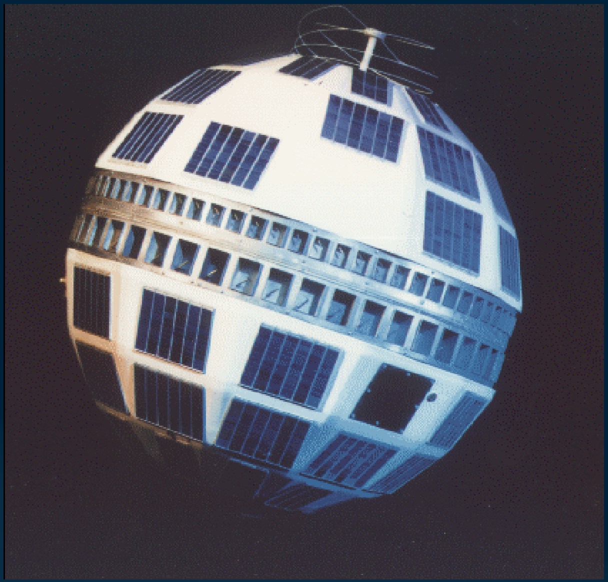


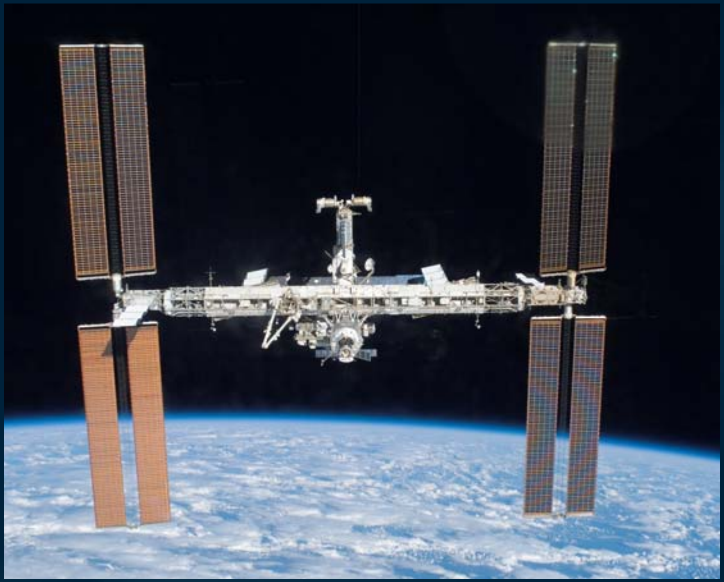
"Great benefits for telephone users and for all mankind will come from this forward step in harnessing the limitless power of the sun."

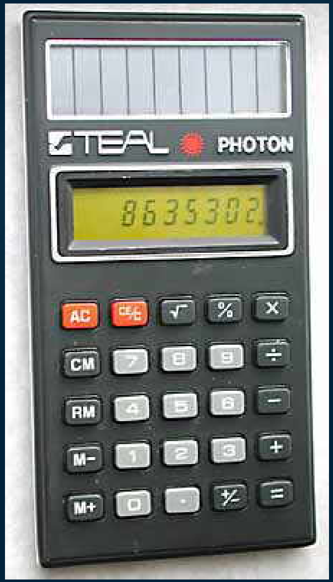
– Bell Telephone Laboratories, 1954.

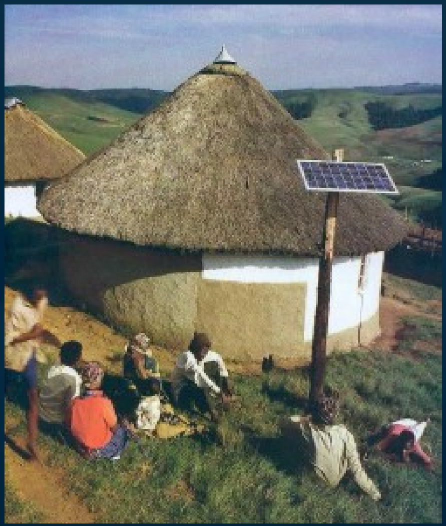
External Use

First PV Driver: Off Grid Applications





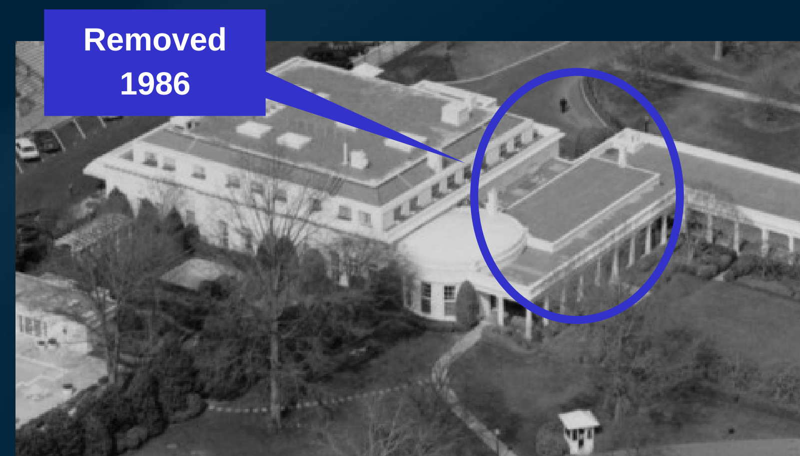




The Second Energy Crisis and Next 20 Years

- "I will soon submit legislation to Congress calling for the creation of this Nation's first solar bank, which will help us achieve the crucial goal of 20 percent of our energy coming from solar power by the year 2000." – Jimmy Carter, 1979

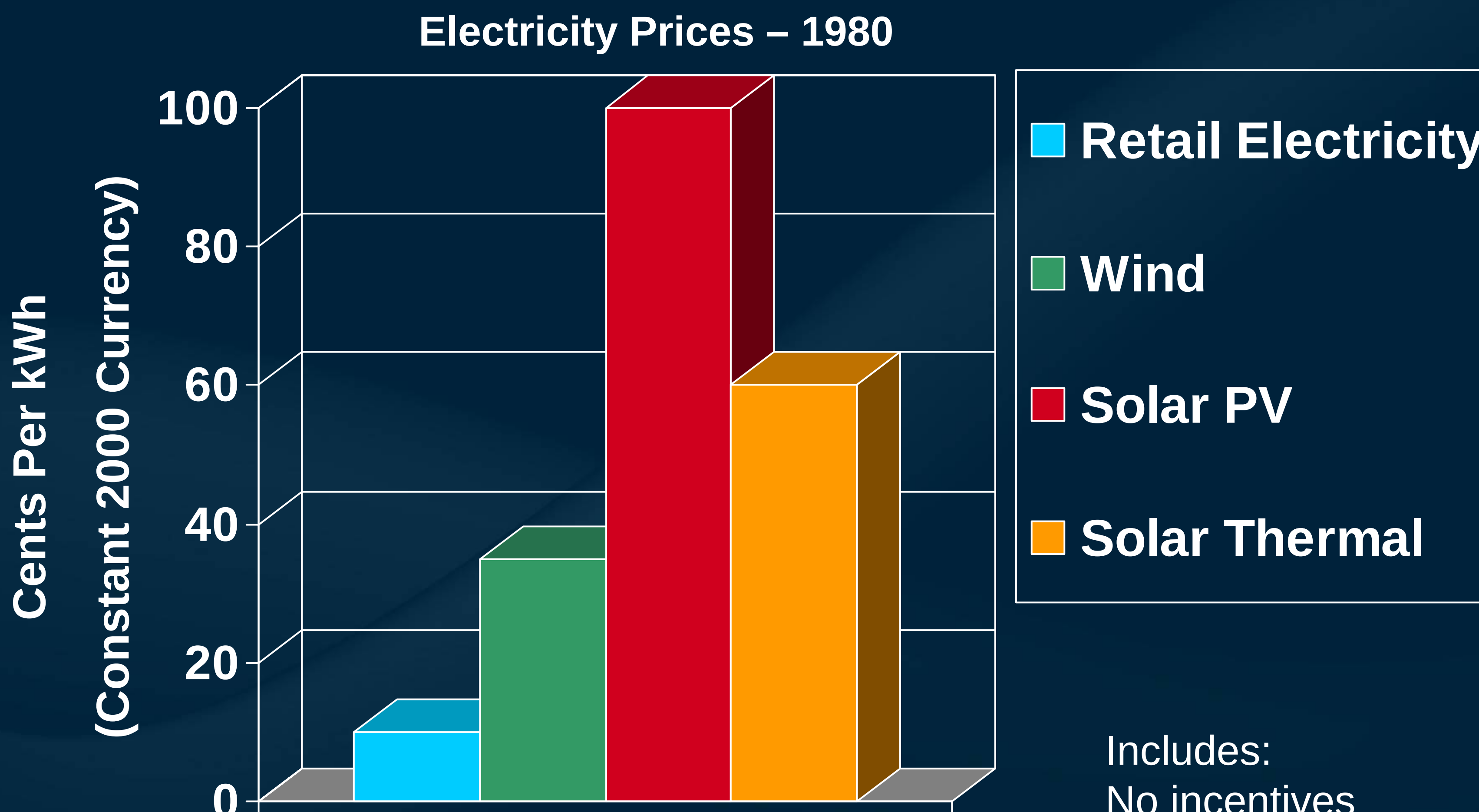
White House West Wing - 1984



White House West Wing - 1992

- "The administration has significantly reoriented the country's approach to energy matters in the past 2 years." – Ronald Reagan, 1983

The Problem was the Economics…



Includes:
No incentives
No Carbon impact

Sources: NREL, DOE

PV ECONOMICS

Key PV Growth Market Segments



Residential	Commercial Rooftop	Utility Scale
Today's Installed Base 5.4 GW	**Today's Installed Base** 4.2 GW	**Today's Installed Base** 5.4 GW
Market Drivers ▪High utility bills ▪Availability of incentives ▪Green choice	**Market Drivers** ▪High utility bills ▪Unpredictable cost ▪Under-utilized urban space	**Market Drivers** ▪Solar economics ▪Favorable tax policy ▪Unpredictable fuel and carbon costs

Total new PV installations in 2008 ~4.1 GW

Source: Navigant 2007, 2008, Marketbuzz 2008

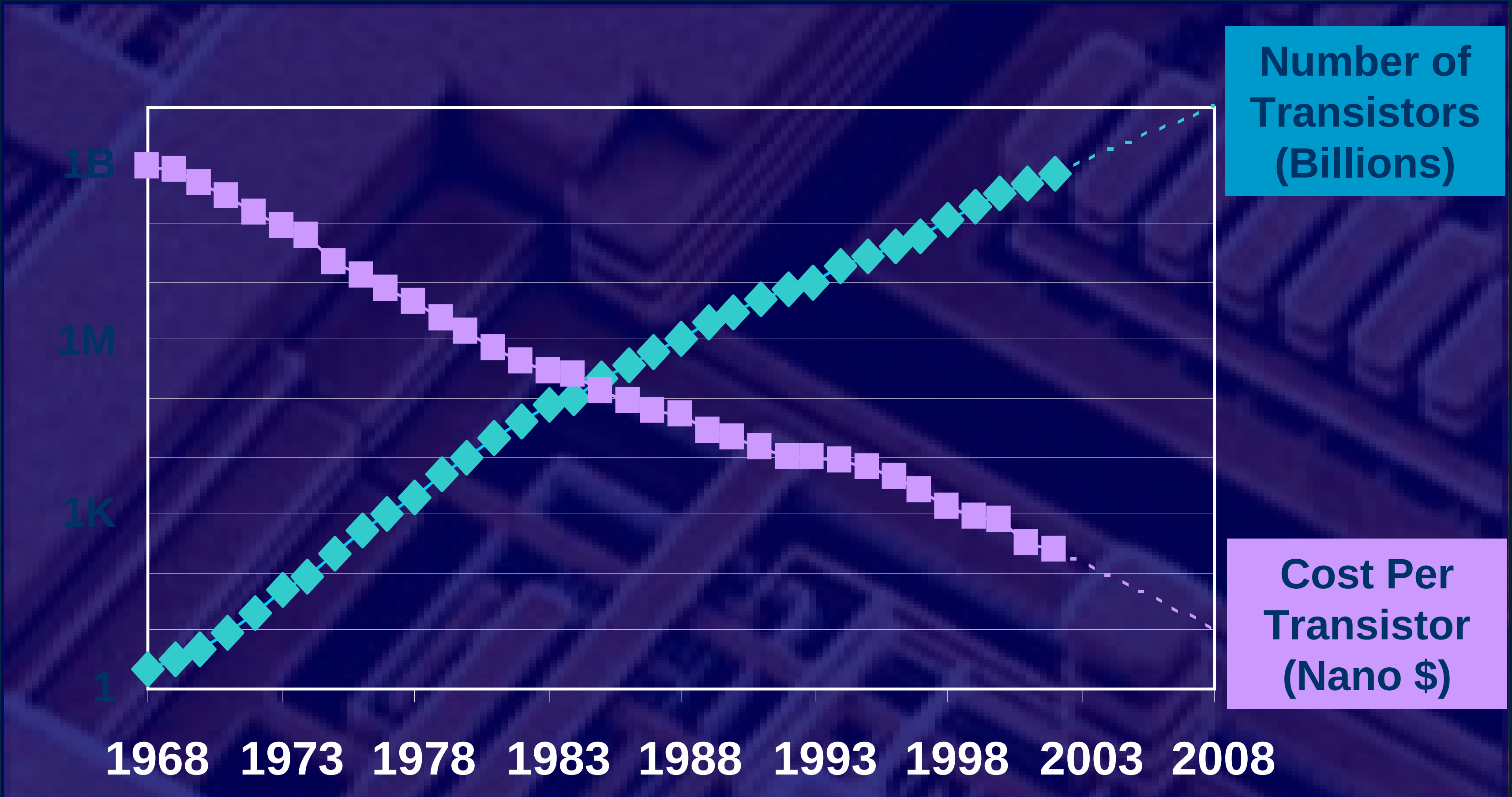
Components of PV Cost

+

- Materials cost
- Process cost
- Module efficiency

- Module efficiency
- Module size
- Module weight
- Labor cost
- Site costs

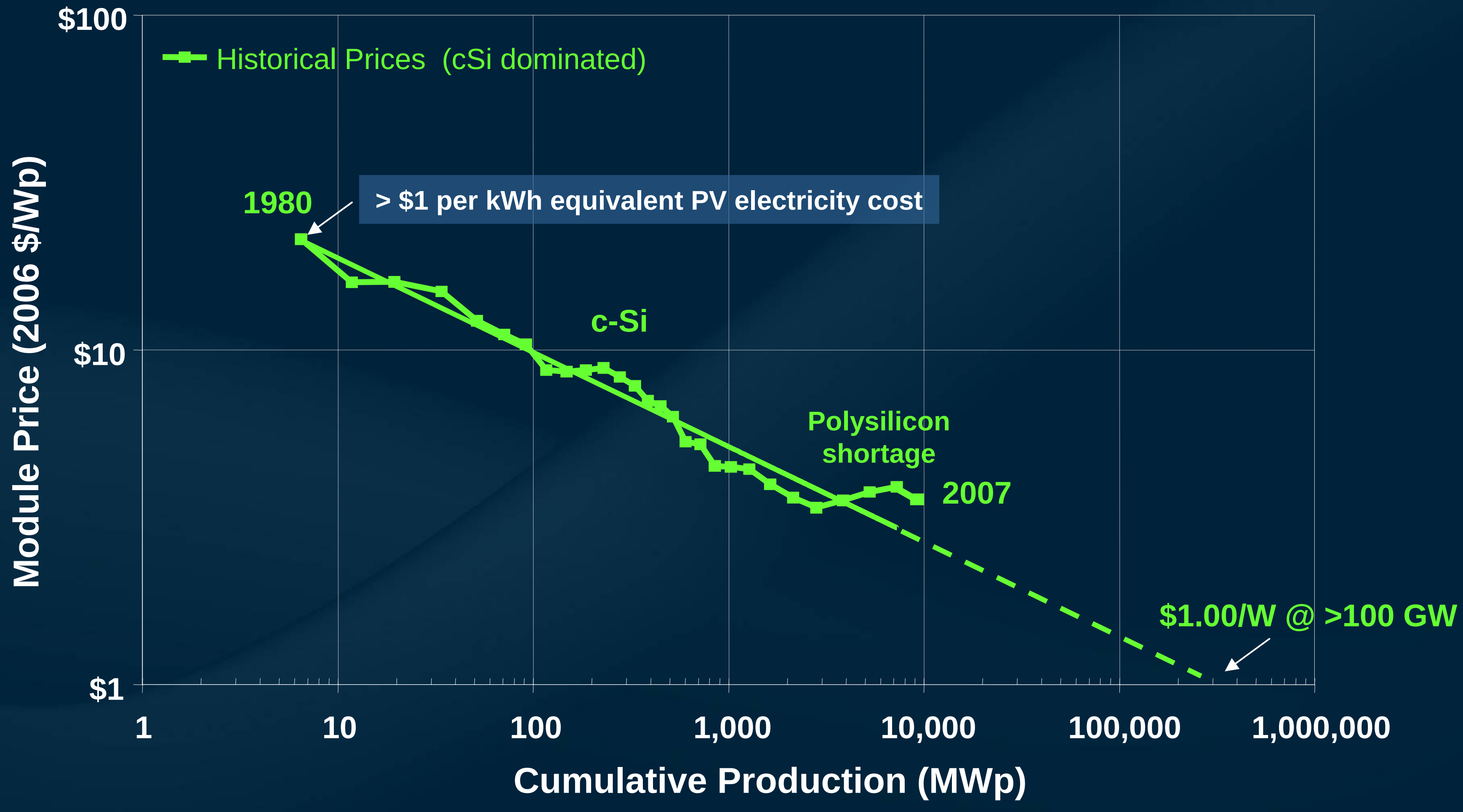
Learning Curves: VLSI and Moore's Law



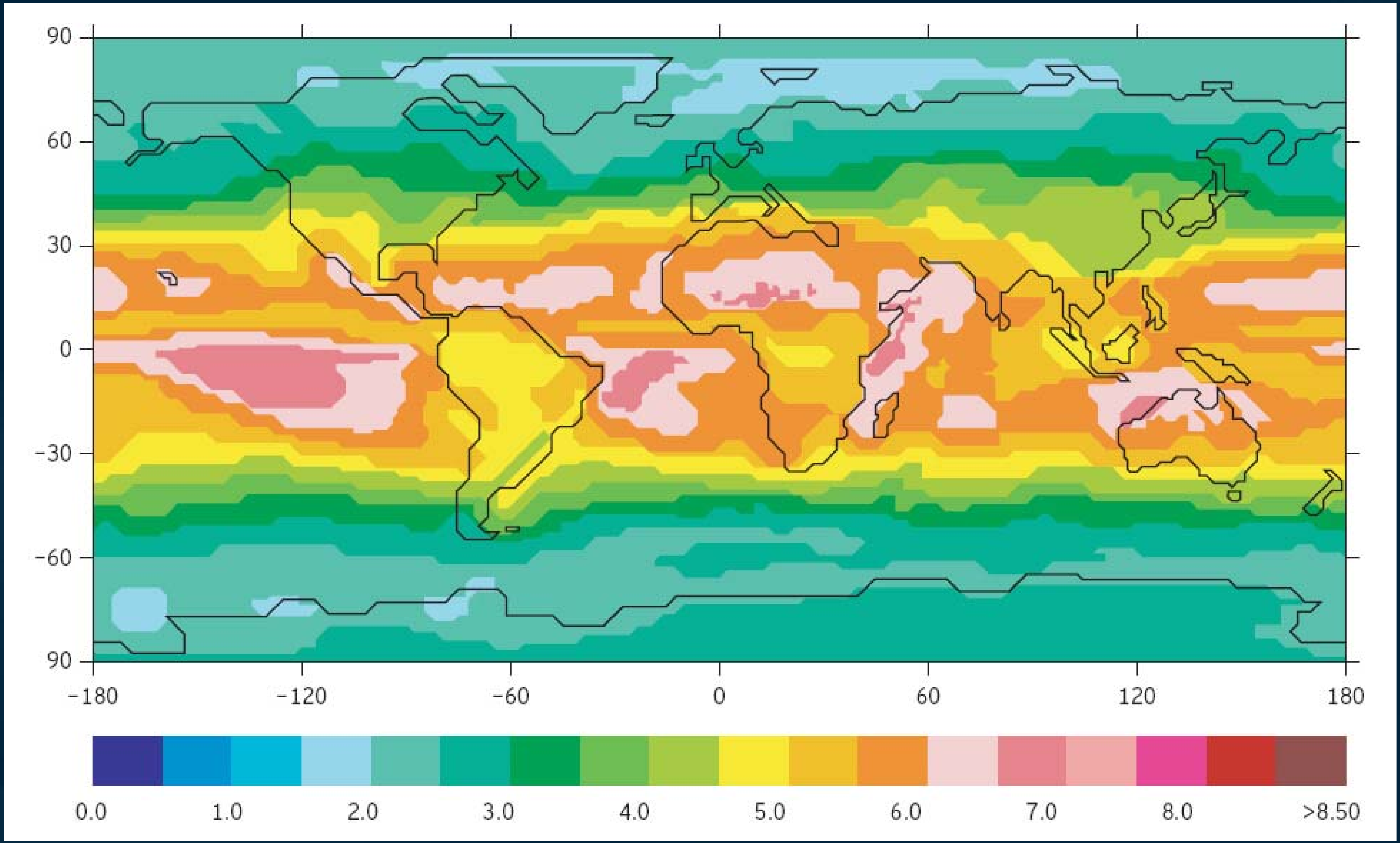
(Source: G. Moore, ISSCC 2003)

External Use

Solar Learning Curve: Module Cost/Watt



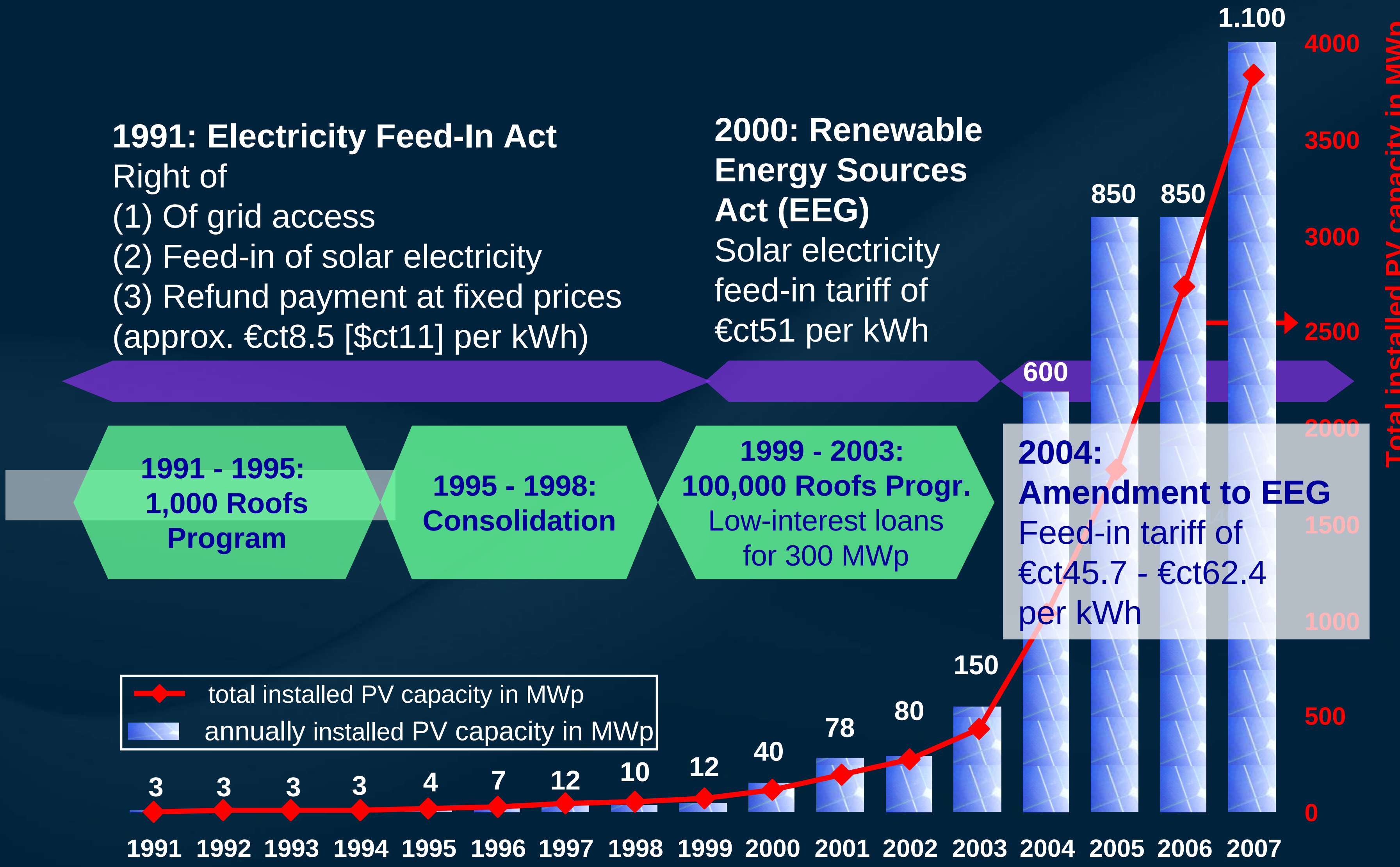
Annual Exposure to Solar Radiation



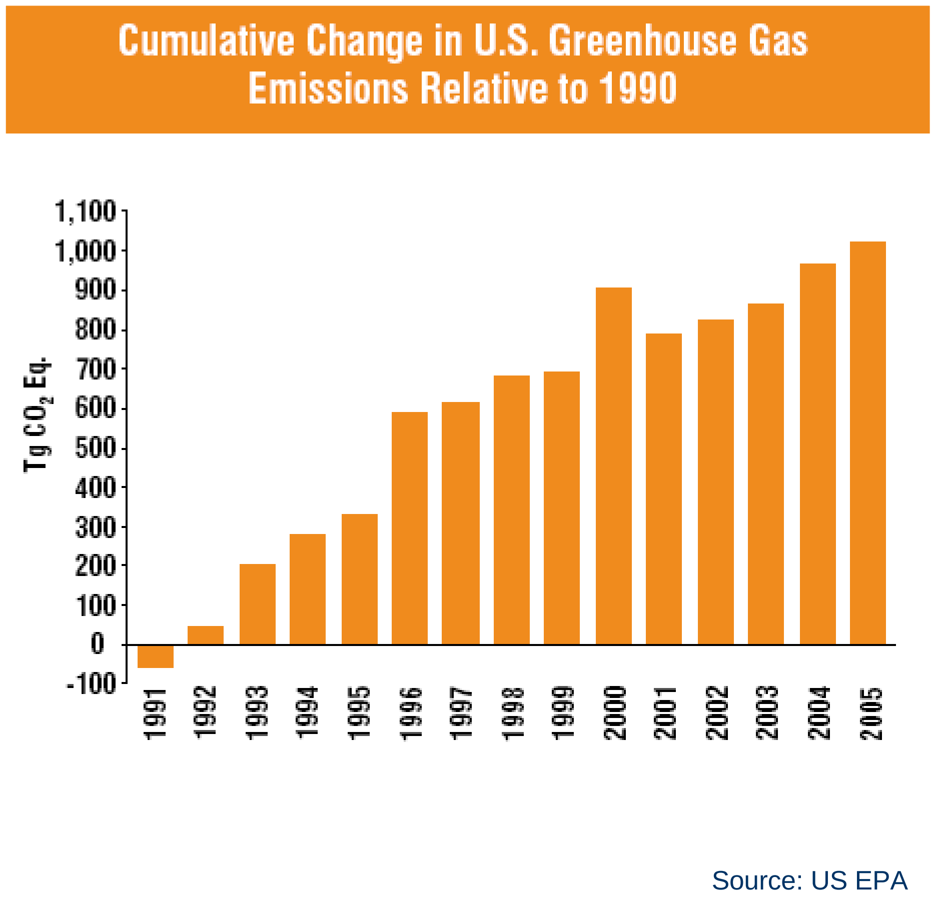
- An insolation of 6kWh/m^2/day (dark orange) translates to 2,190 hours of peak electricity generation from a PV module

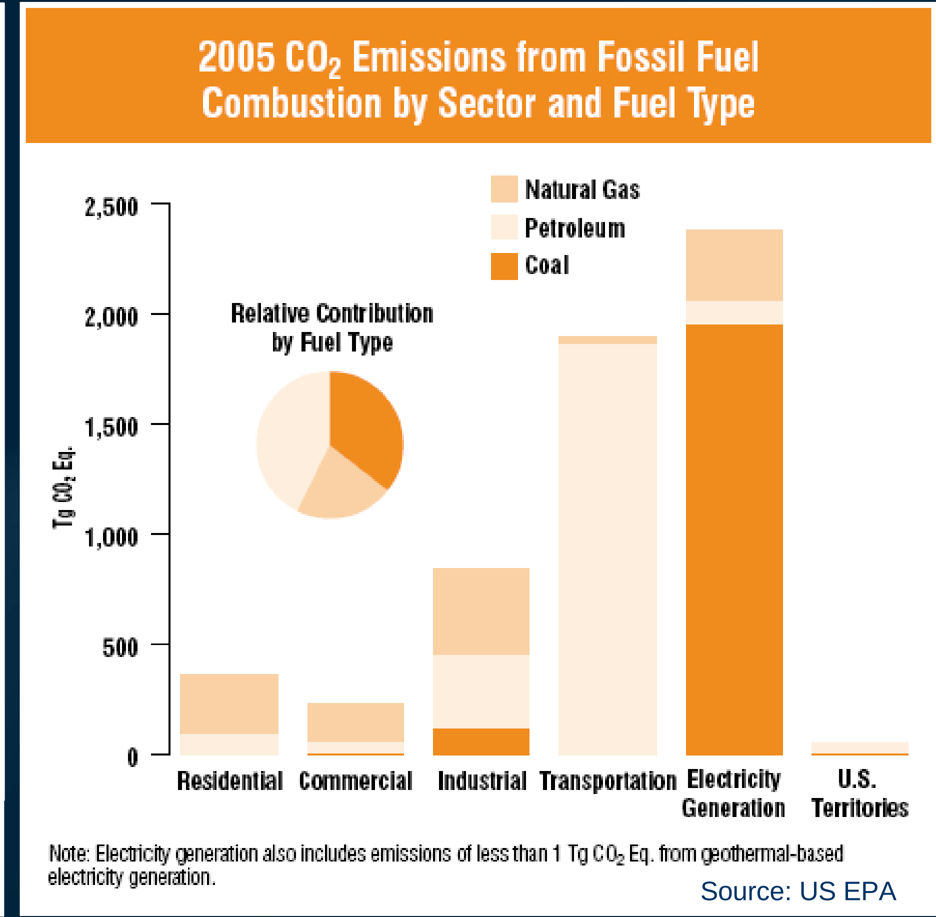
(NASA/SSE 2005)

Feed-In Tariff and the German PV Market



"Carbon Tax"?

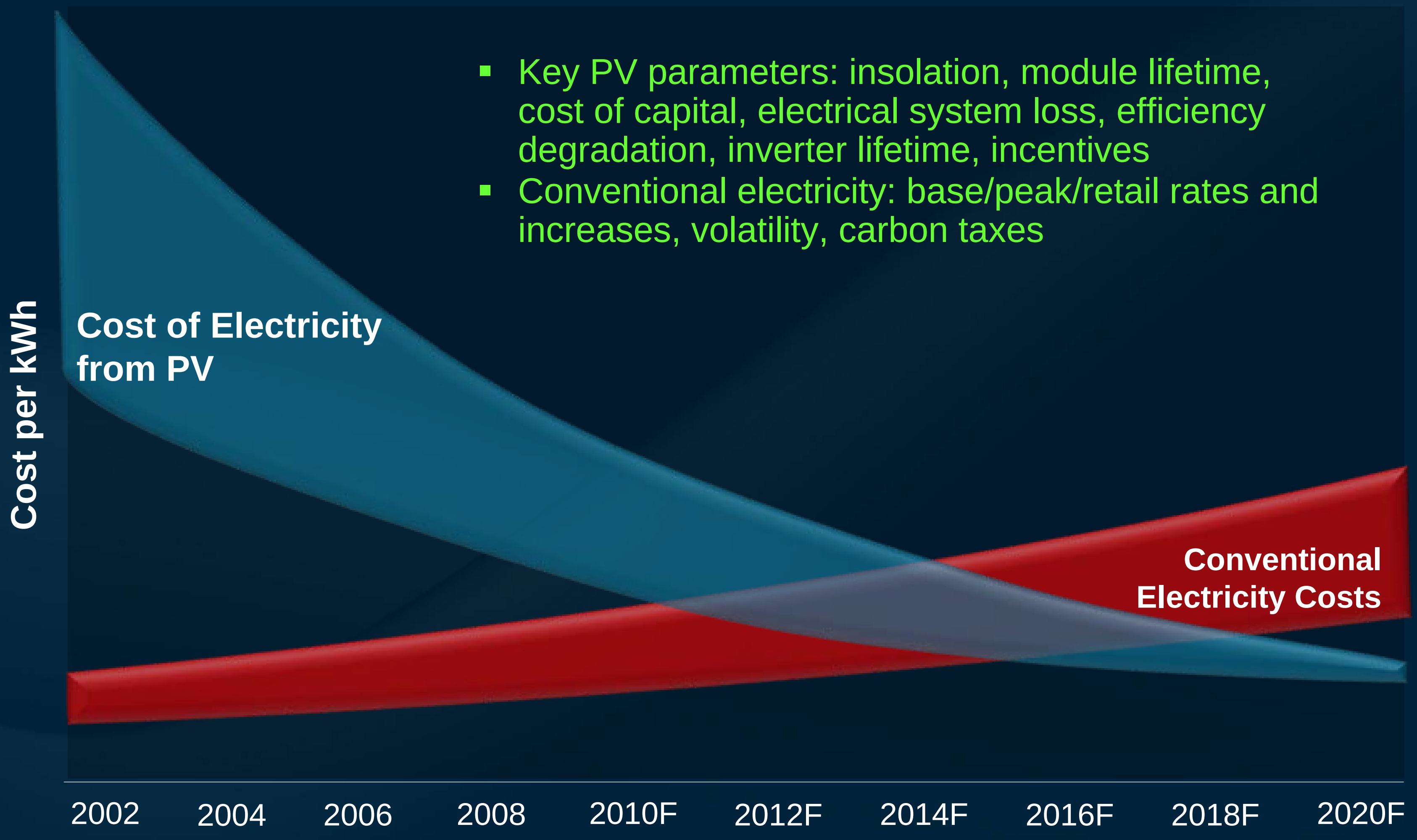




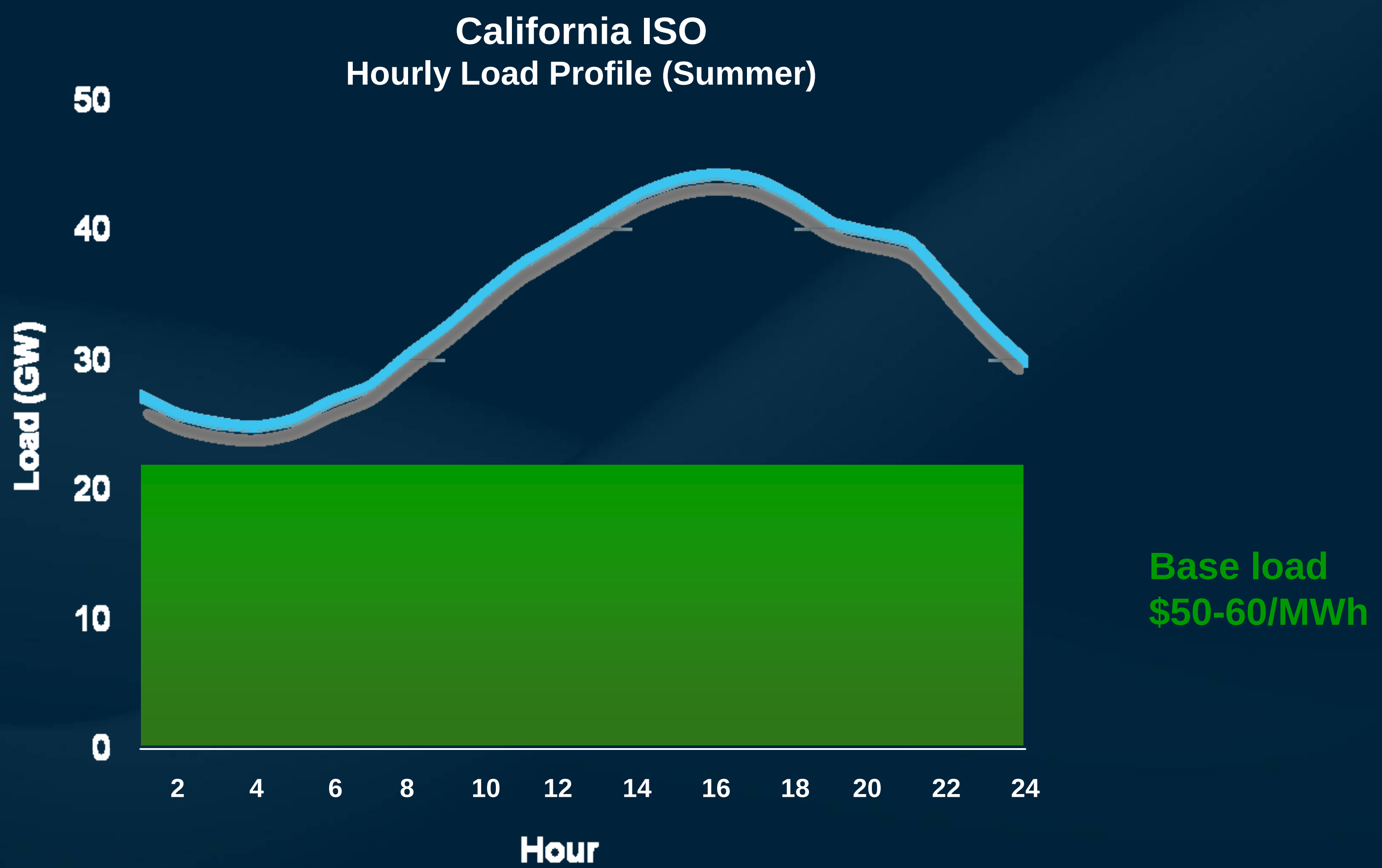
Tax of $100/ton increases coal based electricity rate by $0.07-0.09

External Use

Grid Parity: Entering a Zone of Inflection



Typical Summer Load Profile

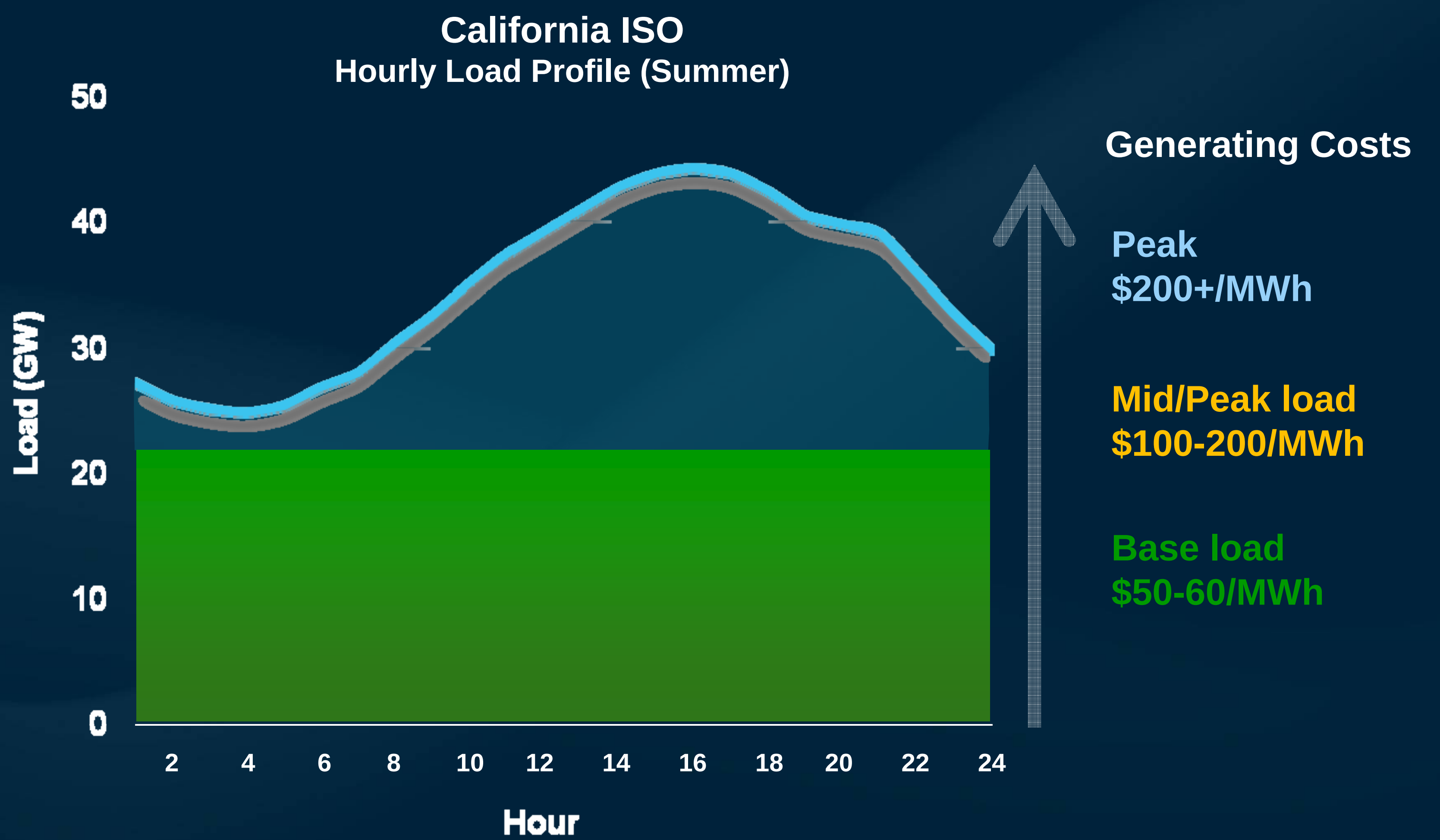


Source: Load - CAISO, System load Aug 14, 2008
Assumption: Solar - Solar generation: 15GWp (DC), 18% utilization

External Use

Typical Summer Load Profile

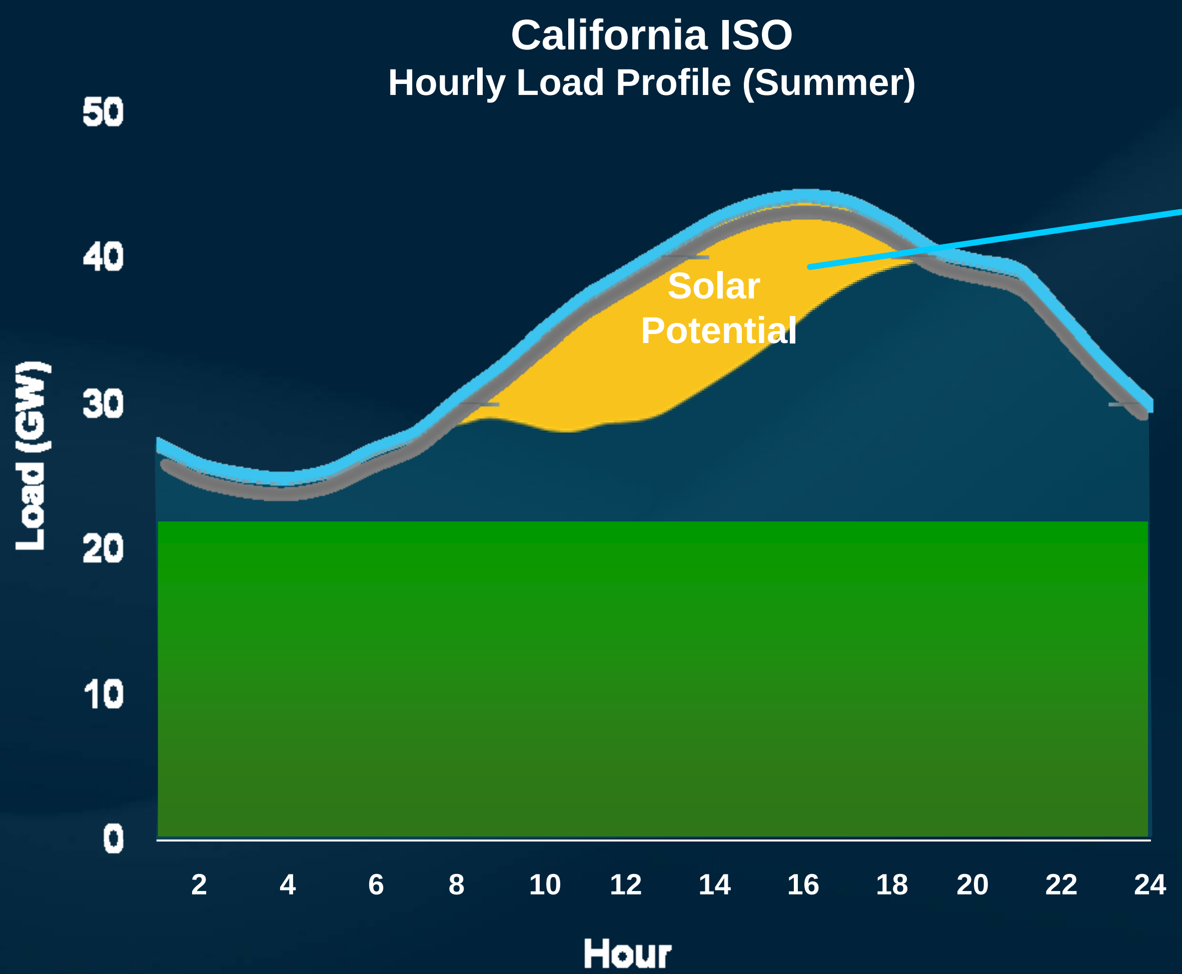
Generation costs increase with overall system load



Source: Load - CAISO, System load Aug 14, 2008
Assumption: Solar - Solar generation: 15GWp (DC), 18% utilization

Typical Summer Load Profile

Solar can serve >30% of peak generation needs

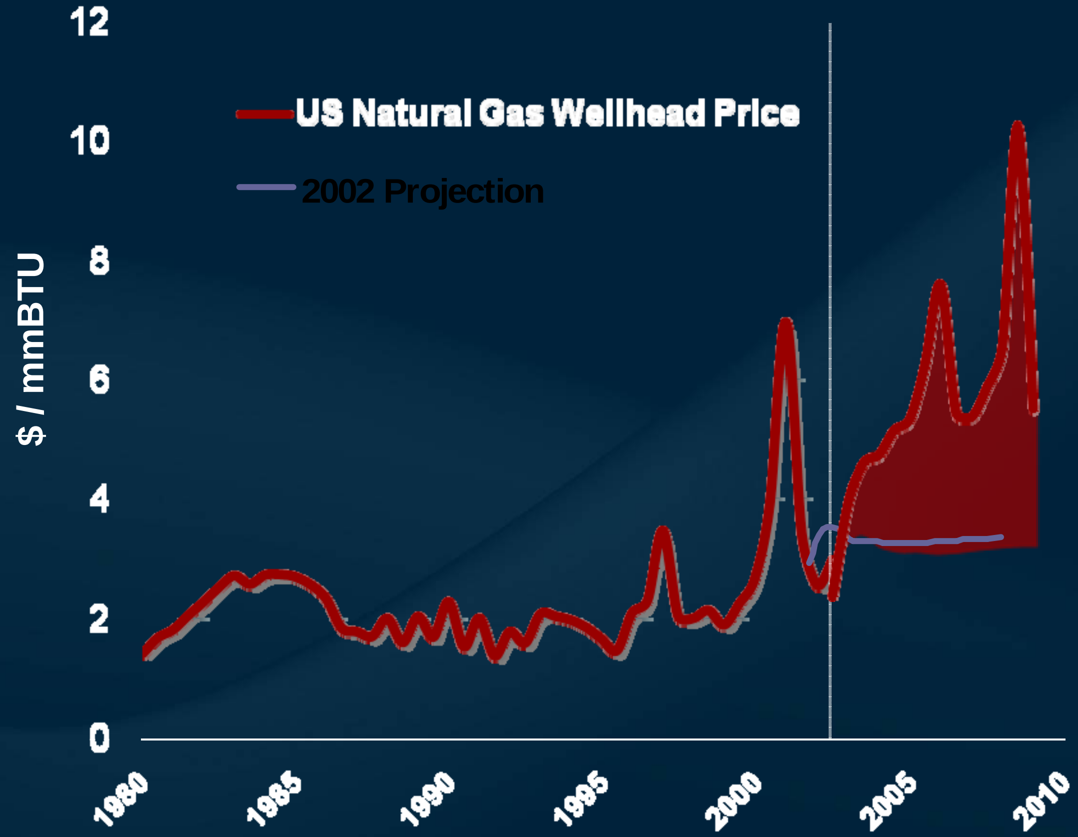


Benefits

- Fuel and capital savings
- Predictable & less volatile
- Emission savings
- Carbon hedge
- Transmission cost mitigation

Source: Load - CAISO, System load Aug 14, 2008
Assumption: Solar - Solar generation: 15GWp (DC), 18% utilization

Natural Gas Cost Projections Not Reliable
Unplanned Costs Passed to Rate Payers



$250M

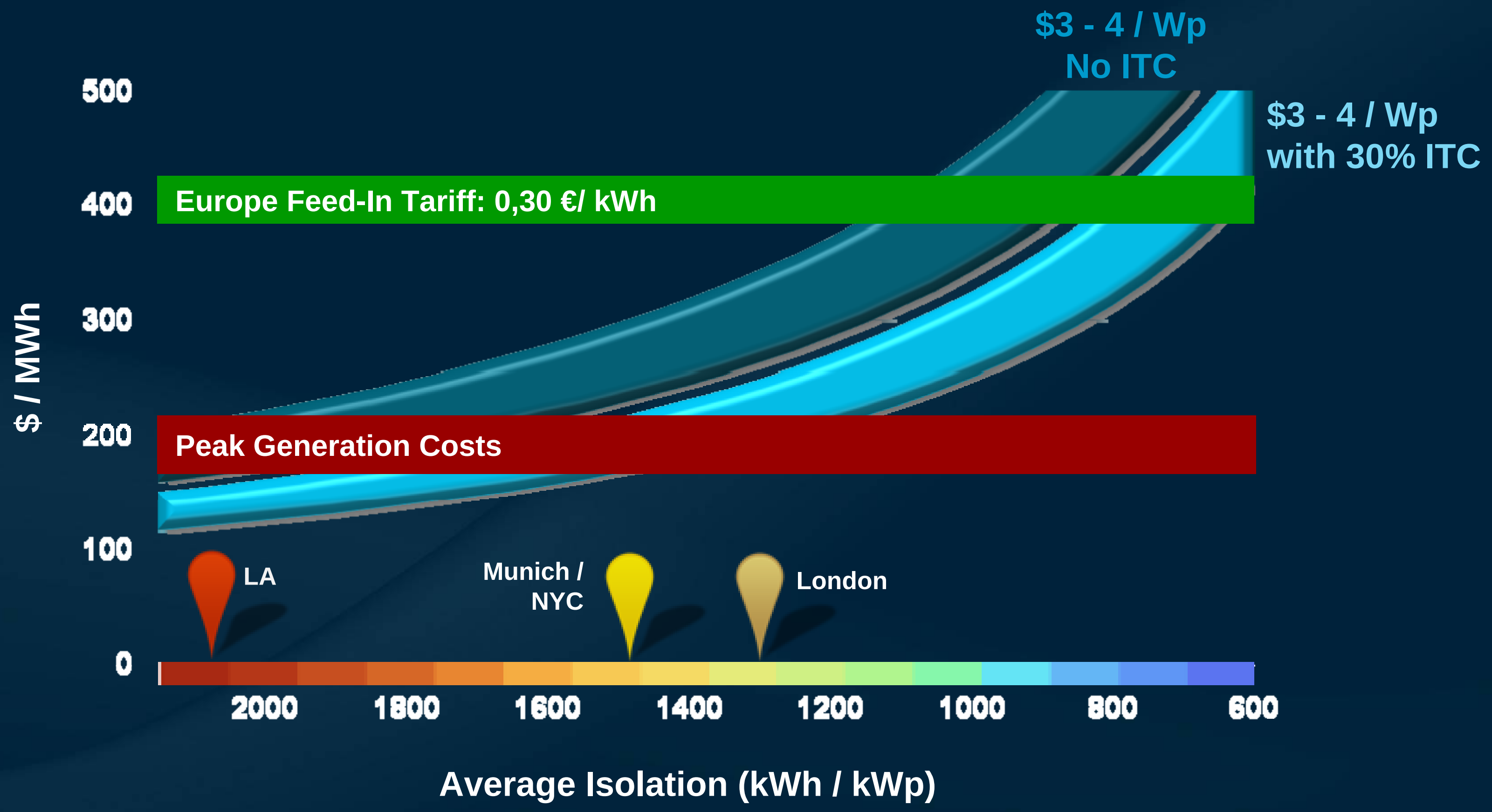
unanticipated fuel costs over 6 years per 500MW plant

Source: Actual, Forecast, 2001 Northwest Power and Conservation Council
Assumption: Per 500MW peaker plant , running 5hrs/day

External Use

Large PV Peaking Opportunity

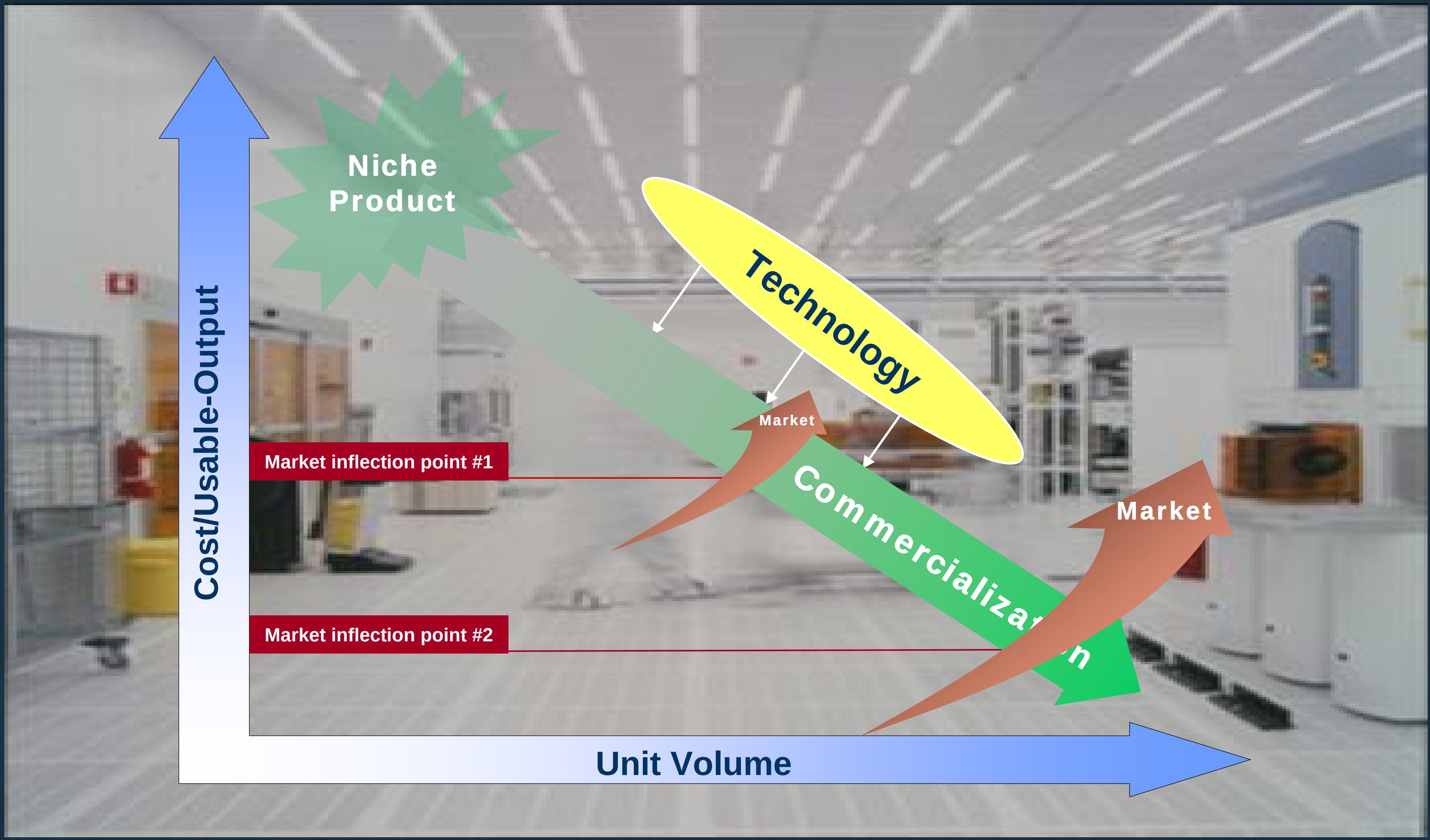
Today across all major OECD markets between $3-4/Wp



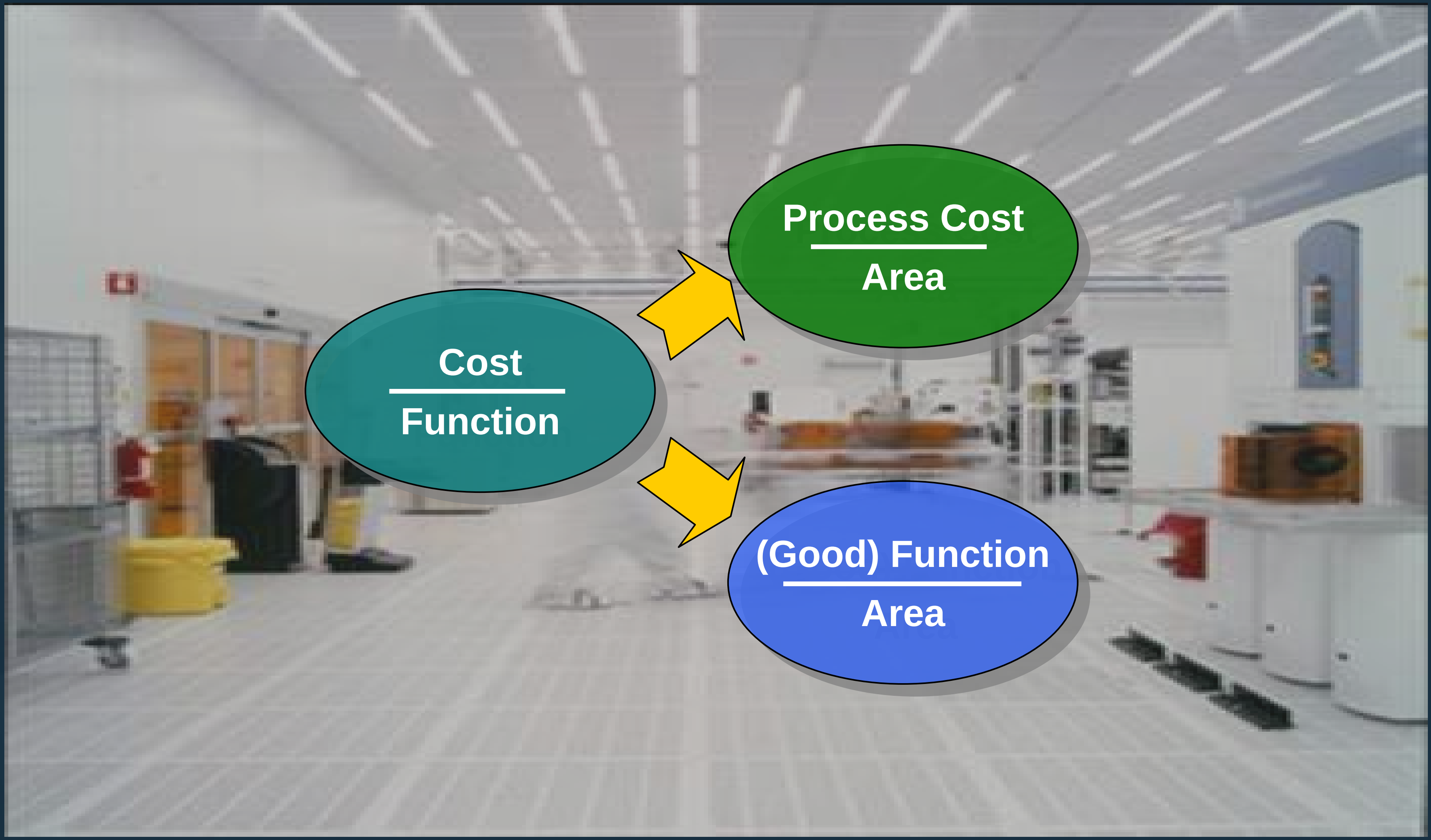
Peak Generation Costs: Heat Rate 14; Running between 2-6hrs/day. Sizing reflects 30% of peak load generation. Solar excludes Mfg Tax Credit. Feed-in Tariff avg across Europe

PV TECHNOLOGY

Reducing Cost Per Function Through Technology



Reducing Cost Per Function Through Technology



Nanomanufacturing Technology
Small features on a large production scale

Placing a nanotube?

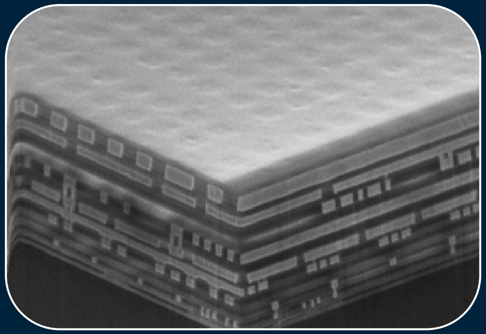
Scale Up?

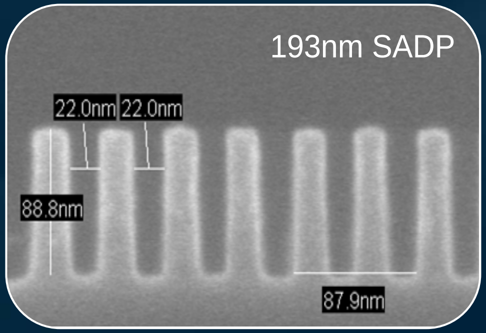
Additional Innovation

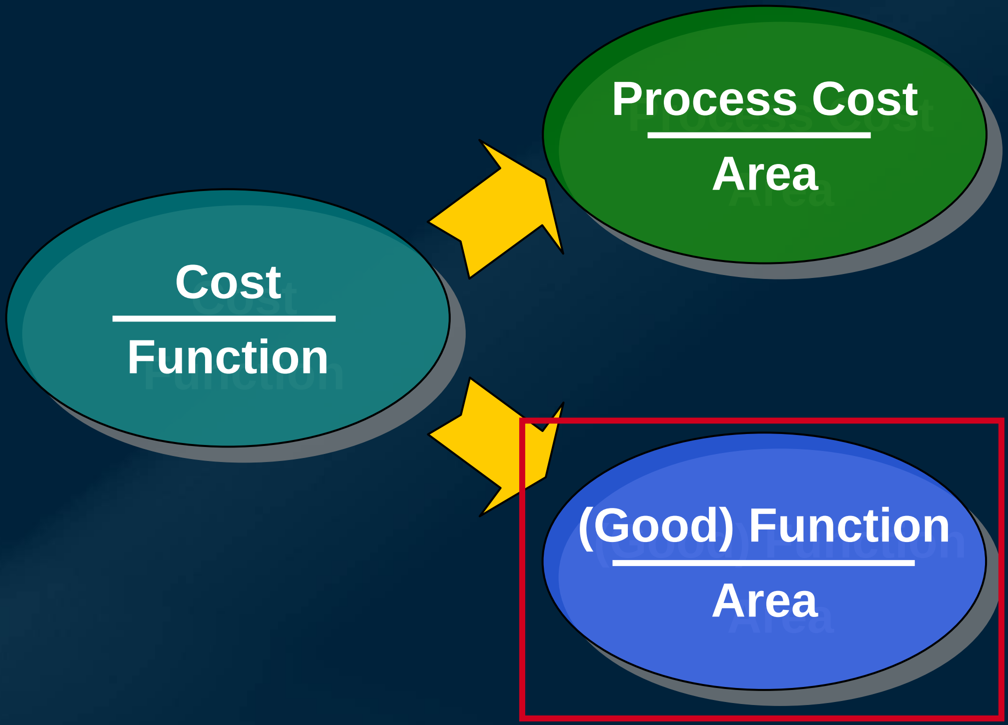
More Than Nanofabrication – Repeatable, Robust, Reliable, Controllable, Safe and Cost Effective

External Use

Cost Per Function: Nanoelectronics





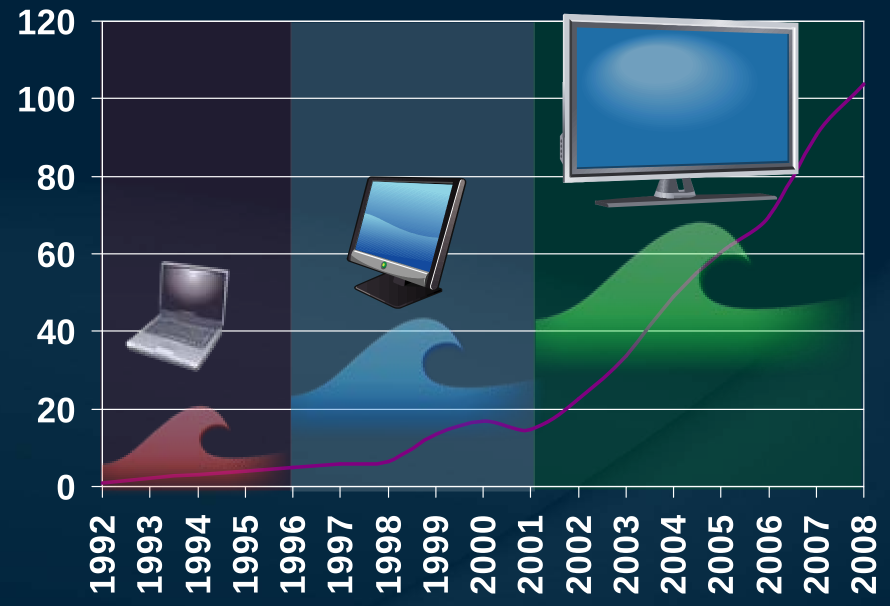


Scaling has been the primary cost driver for ICs – but not at an overcompensating increase in process cost/area

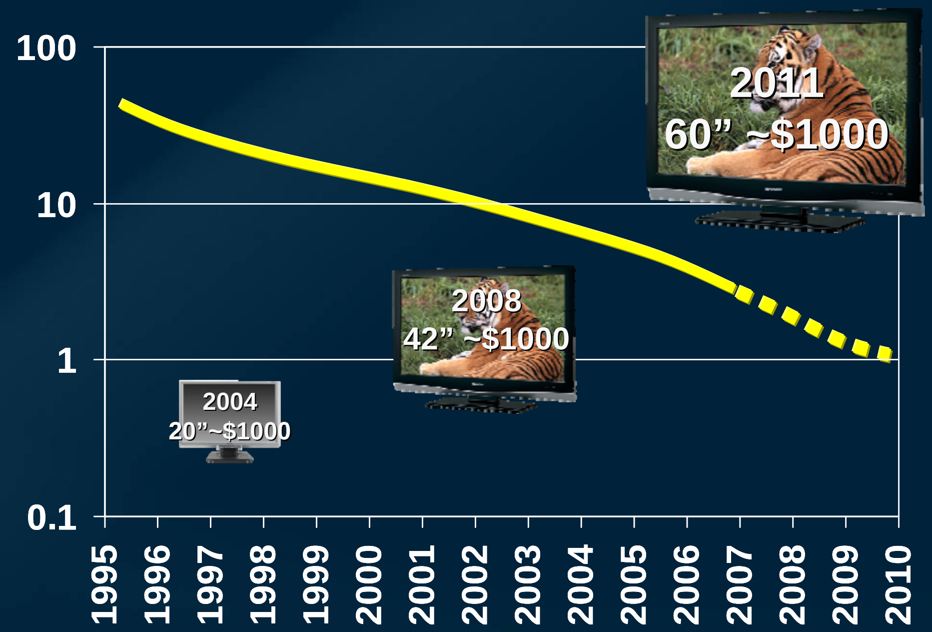
External Use

Flat Panel Display (LCD) Manufacturing

LCD Industry Revenue ($B)



Production Cost per Area (k$/m²)



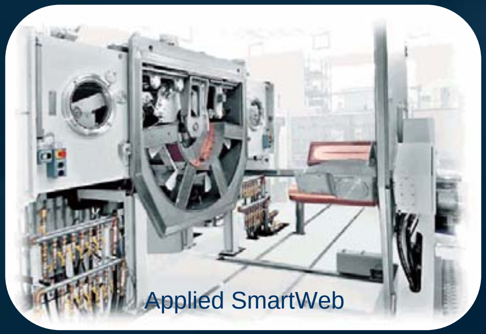
> 20% Bigger (HD)TV Every Year for the Same Price

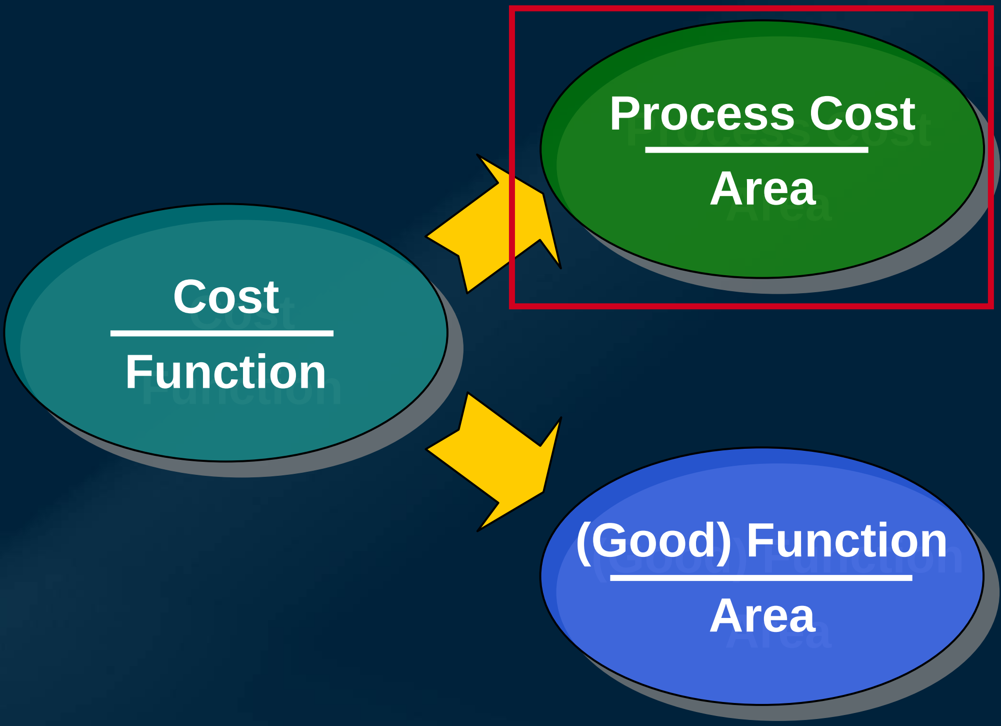
External Use

Cost Per Function: Displays & Arch Glass


Applied PECVD 5.7


Courtesy Sharp


Applied SmartWeb



Cost per area tends to be an equivalent or predominant factor in applications other than VLSI

External Use

Components of PV Cost

- Materials cost
- Pro
- ~~Module efficiency~~

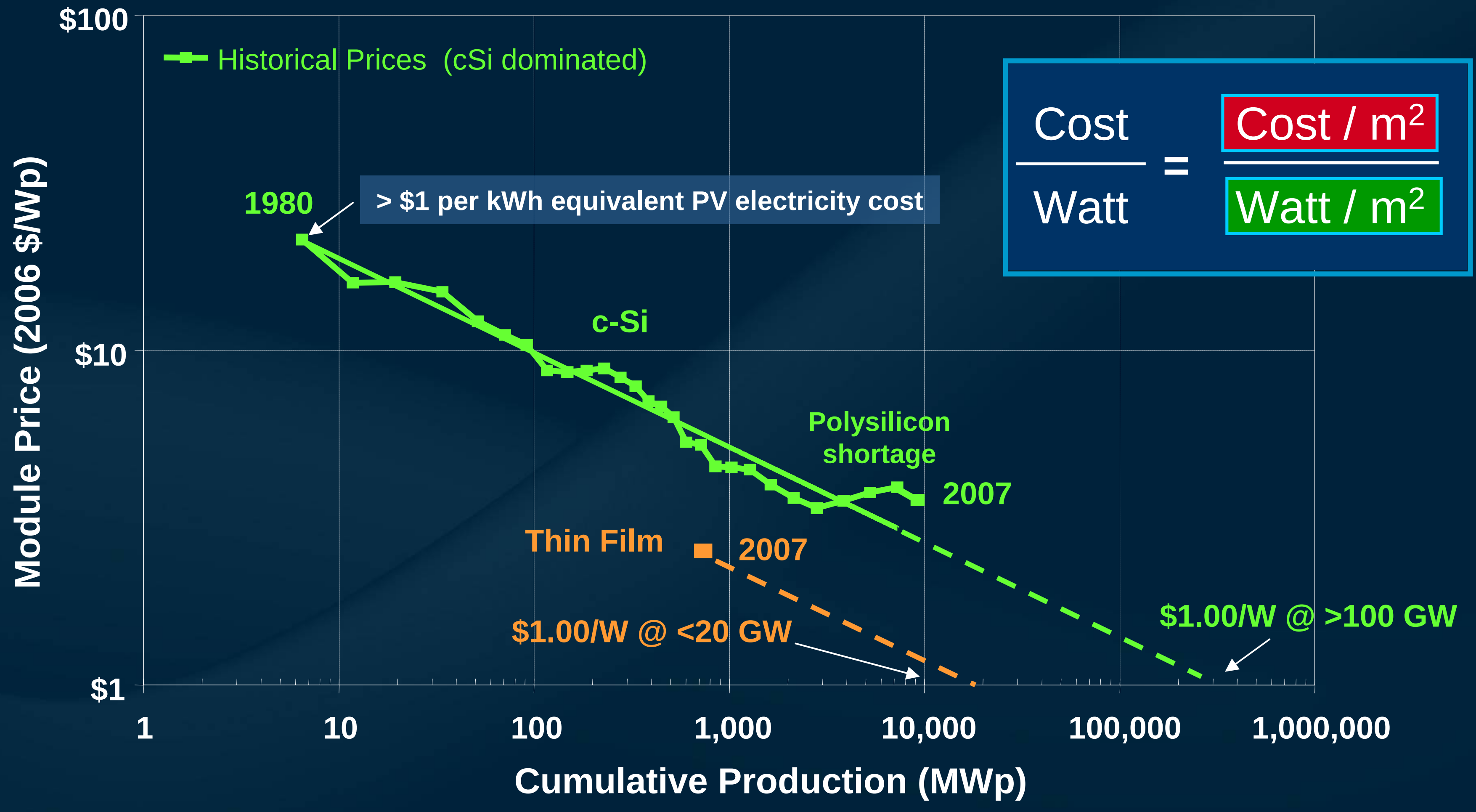
Cost / m^2

Watt / m^2

+

- Module efficiency
- Module size
- Module weight
- Labor cost
- Site costs

Solar Learning Curve: Module Cost/Watt



Source: Adapted from NREL

External Use

Key PV Technologies and Markets

Crystalline Silicon
Preferred for residential applications

Thin Film
Preferred for large scale applications

Common focus to drive down cost per watt

External Use

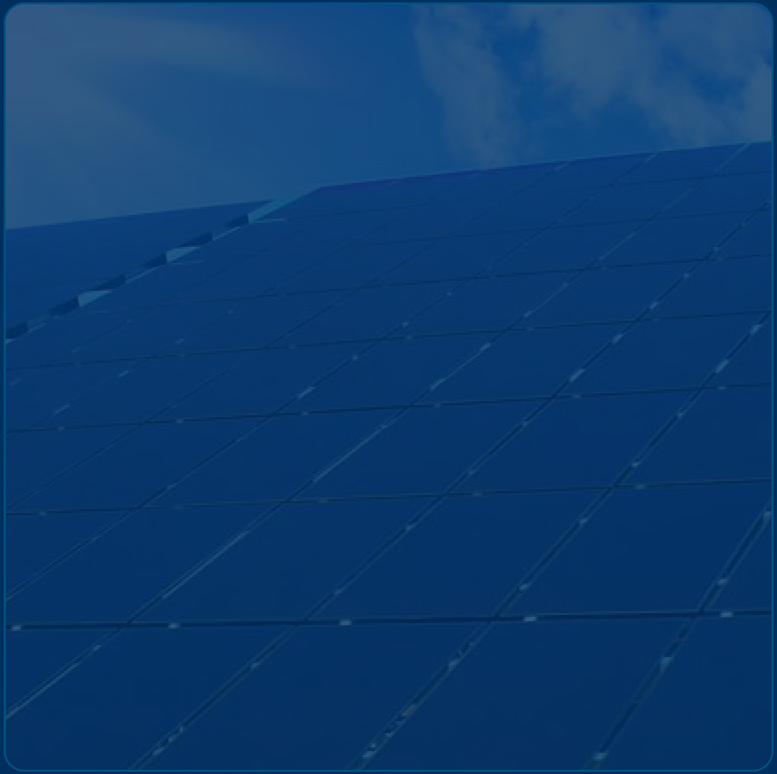
Key PV Technologies and Markets

Crystalline Silicon

Preferred for residential applications

Thin Film

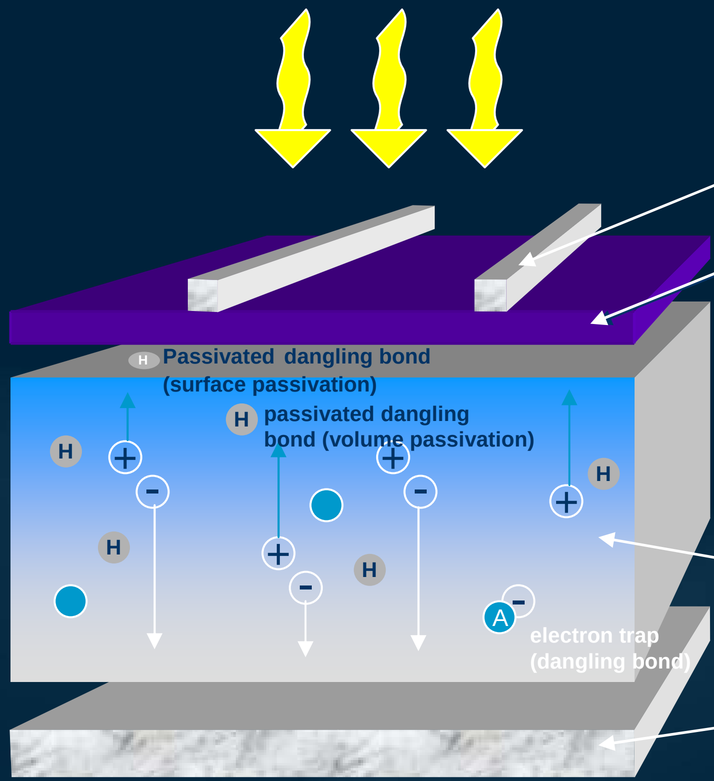
Preferred for large scale applications



Common focus to drive down cost per watt

External Use

Crystalline Solar Cells: Working Principle



Front contact

Ar and passivation coating (Silicon Nitride)

- Increase efficiency by optimized light coupling
- Increase efficiency by passivating dangling bonds
- Homogeneous optical appearance

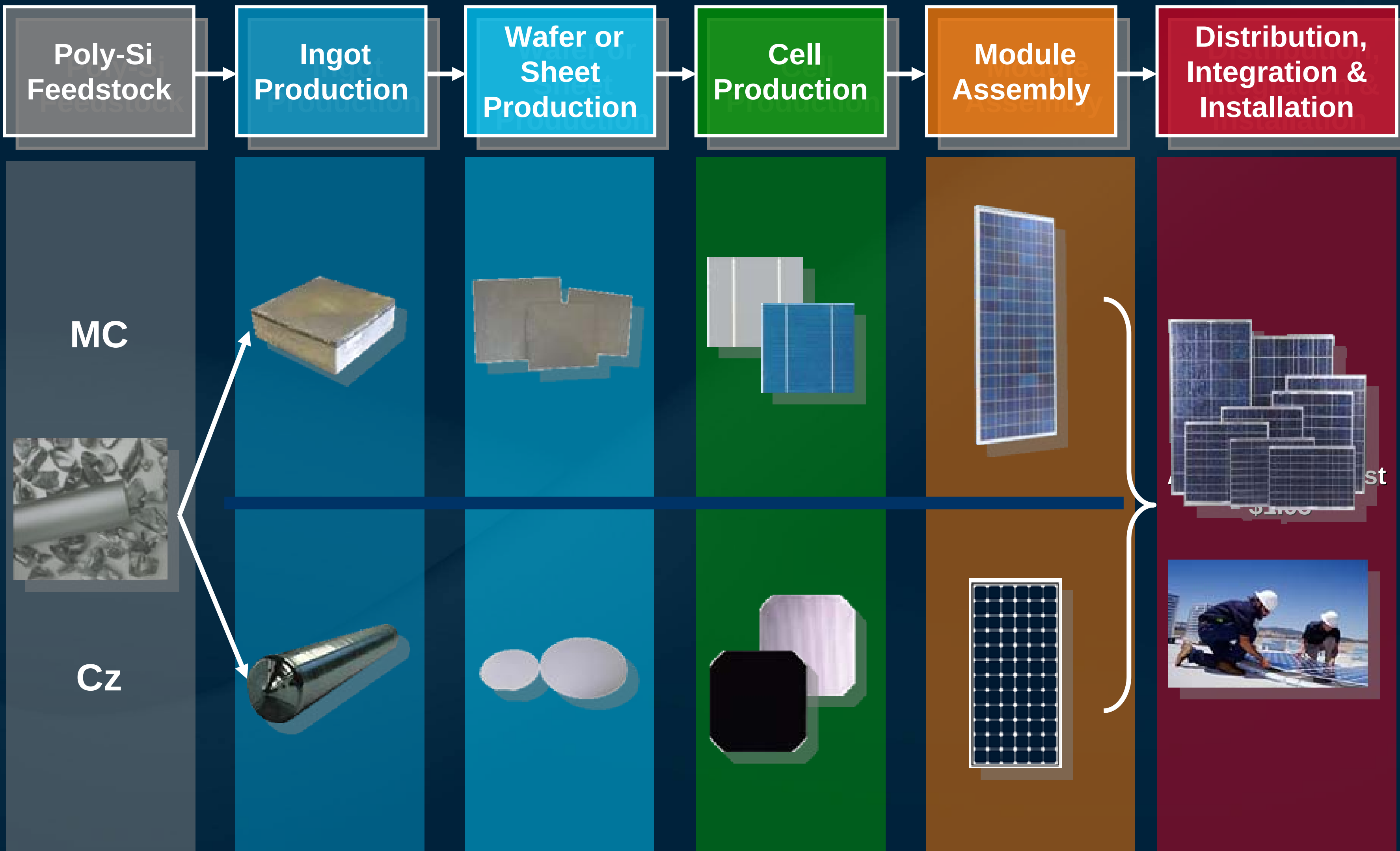
P-type crystalline silicon wafer with diffused N-type emitter and back surface field (BSF)

Metal back contact

Keys: Thin wafers + low process cost + conversion efficiency

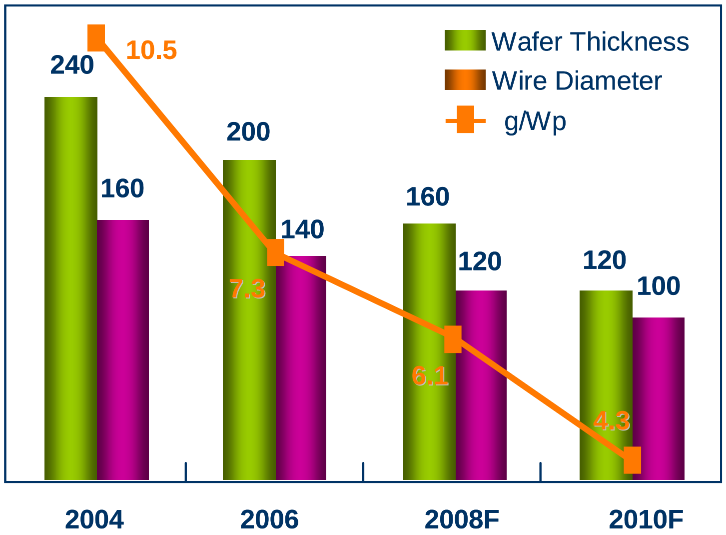
External Use

Wafer Based PV Value Chain

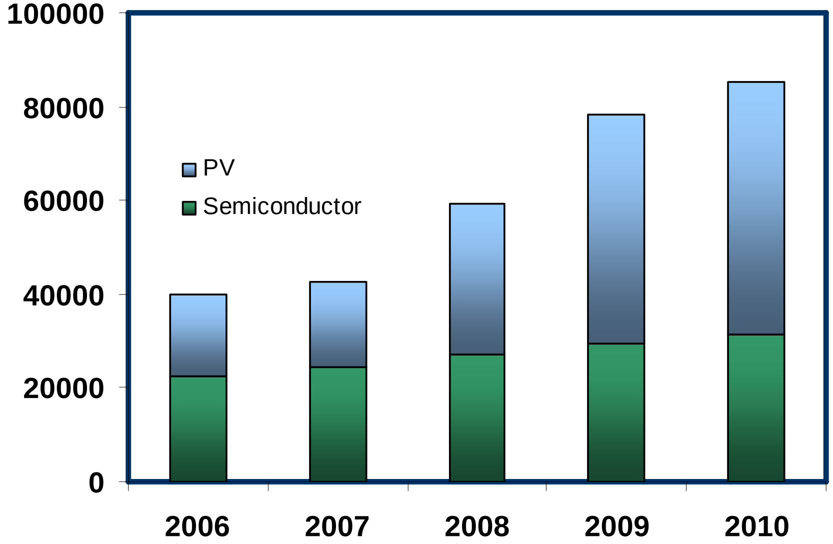


Improve Material Efficiency: Thin Wafers

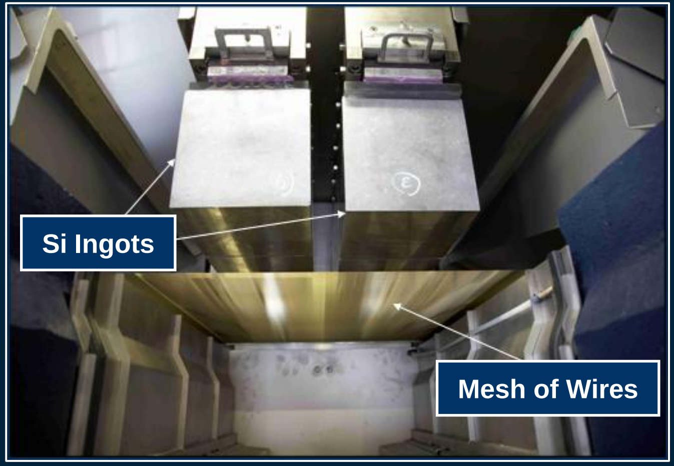
PV Wafering Roadmap



Polysilicon Production (Mton)



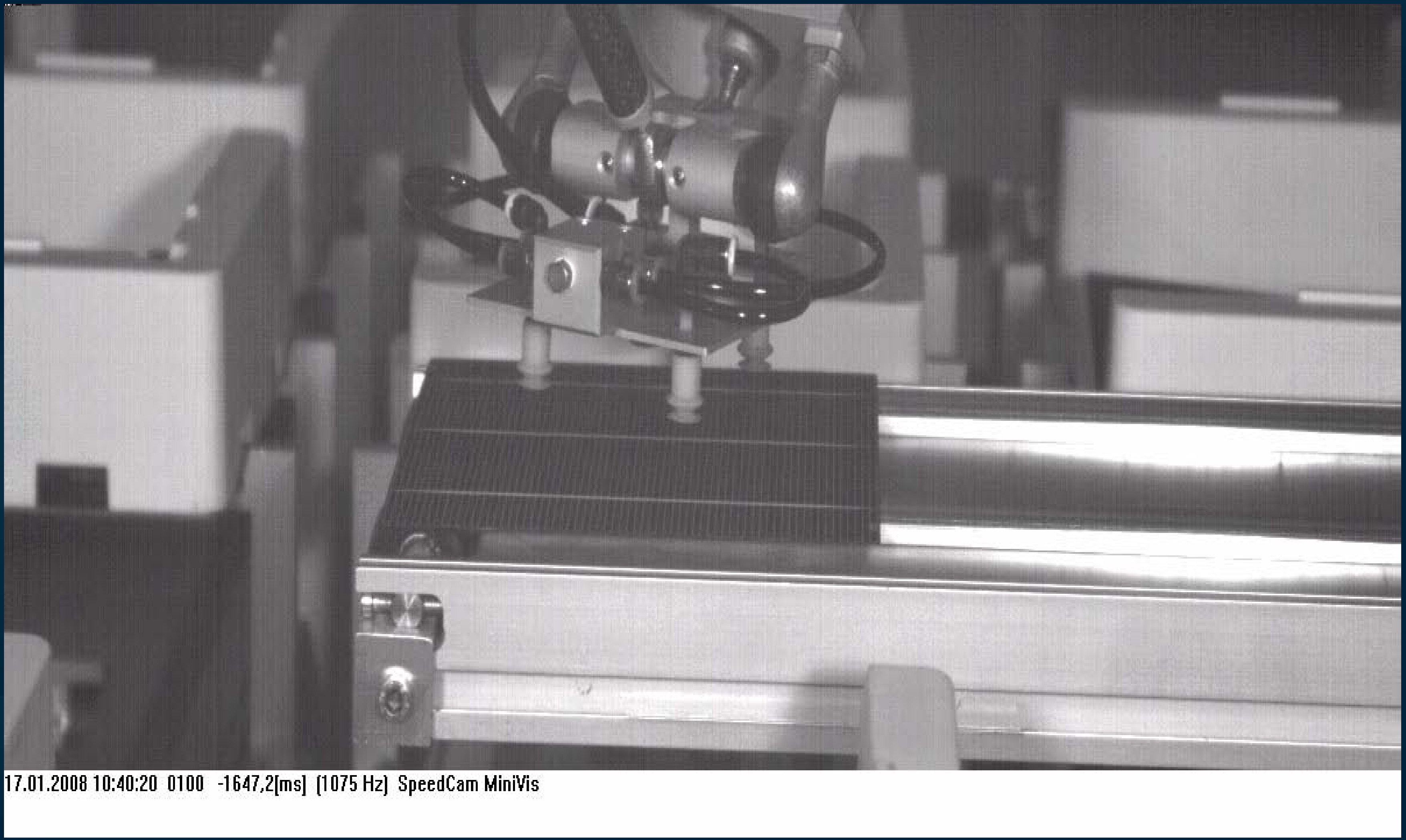
$$\frac{\text{Cost} / m^2}{\text{Watt} / m^2}$$



Data sources:
Wafering: S. Schneeberger, April 2007
Polysilicon: A. Bjørseth, June 2007

External Use

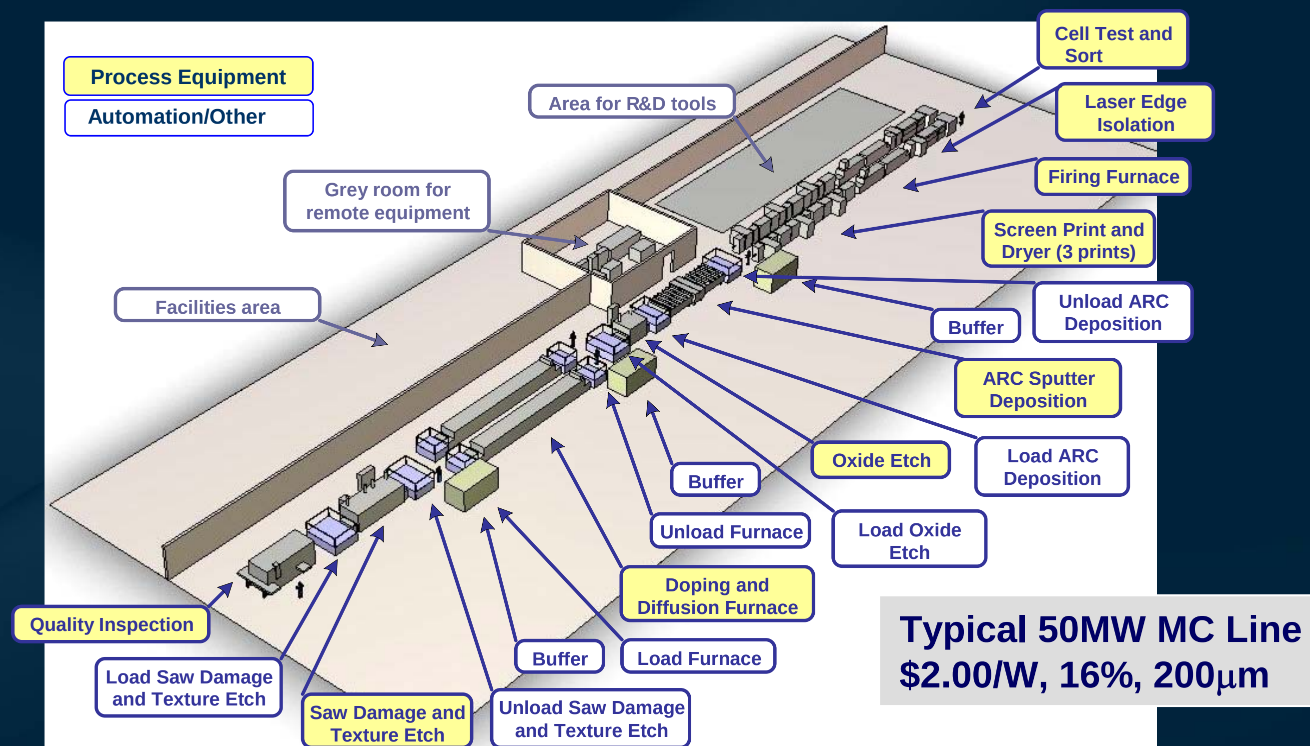
Ultra-Thin Wafer Automation



PV Fabrication Line Scale

	1980	2000	2005	2010
Production Line Size (MWp)	0.5	5	50	100
Lines Per Factory	2	3	4	10
Total Factory Size (MWp)	1	15	200	1000

$$\frac{\text{Cost} / m^2}{\text{Watt} / m^2}$$



Typical 50MW MC Line
$2.00/W, 16%, 200µm

1 GWp/year ~ 200X Si Area of Largest 300mm IC Fab

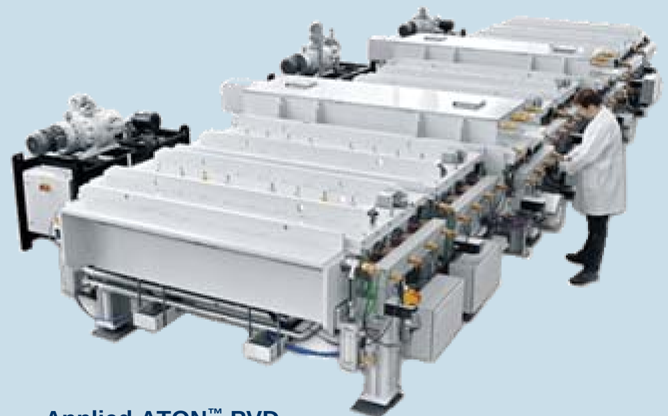
External Use

Processes Offering Scale + PV Efficiency

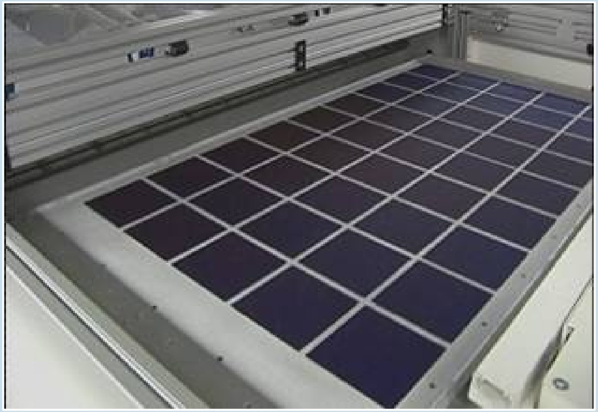
Cost / m²
Watt / m²

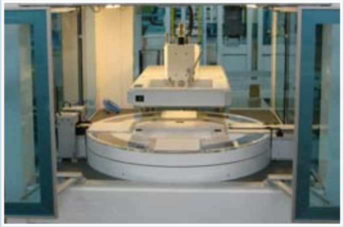
- Yield
- Thruput
- Uptime
- Thin wafers
- COC

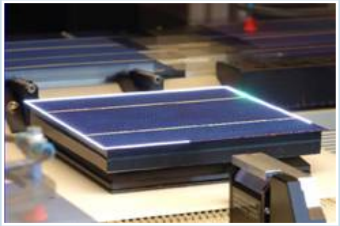
- Efficiency
- Uniformity



Applied ATON™ PVD





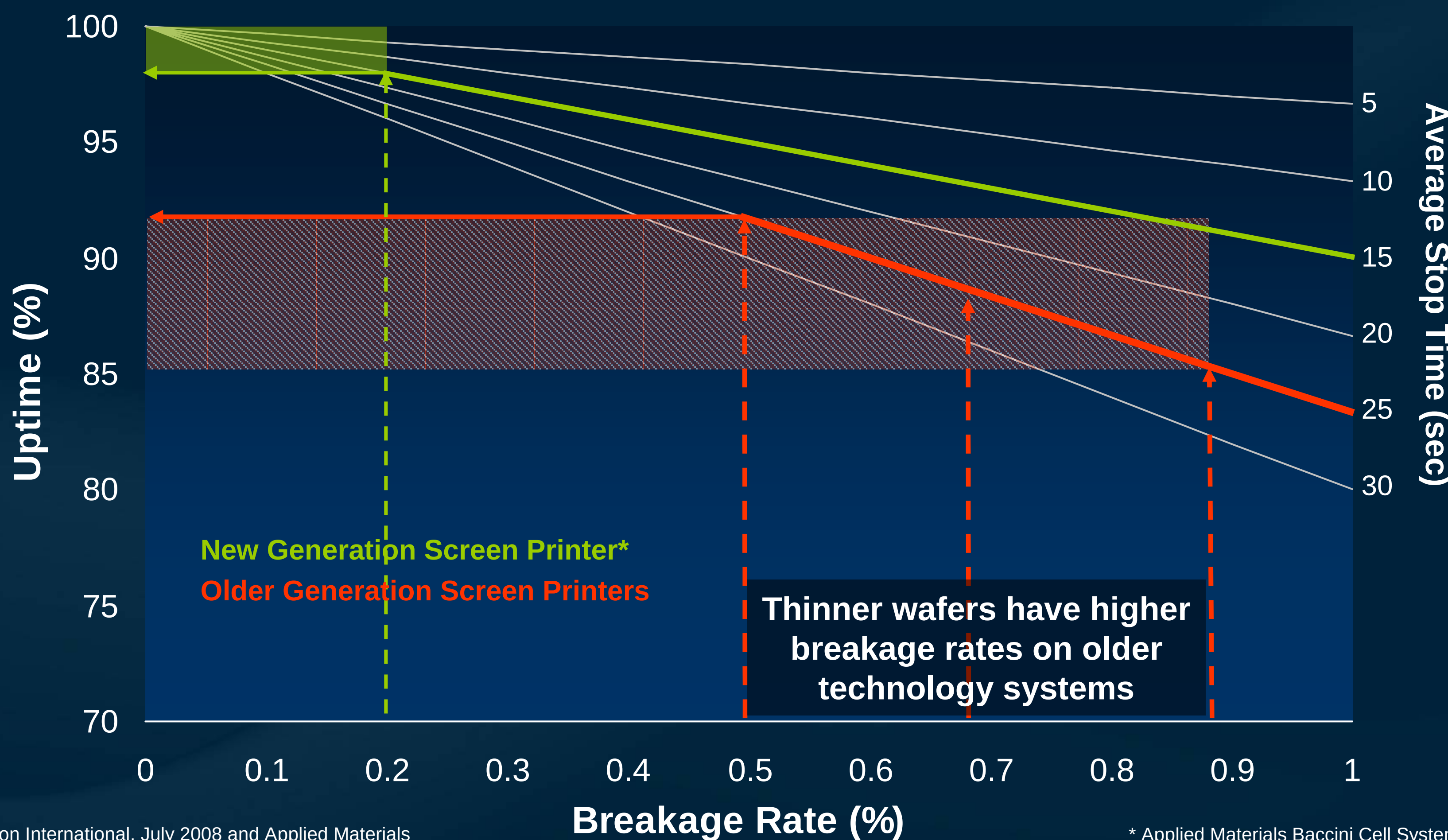


Applied Baccini Cell Systems Metallization Line

Requires throughputs of >1,000 wafers per hour

External Use

Example of Thin Wafer Processing



Source: Photon International, July 2008 and Applied Materials

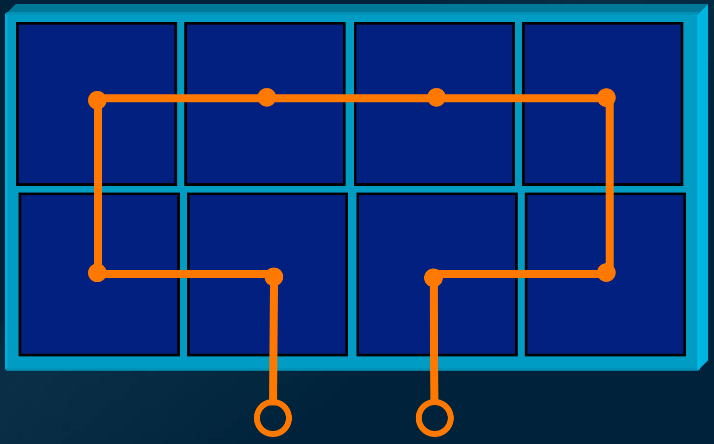
* Applied Materials Baccini Cell Systems

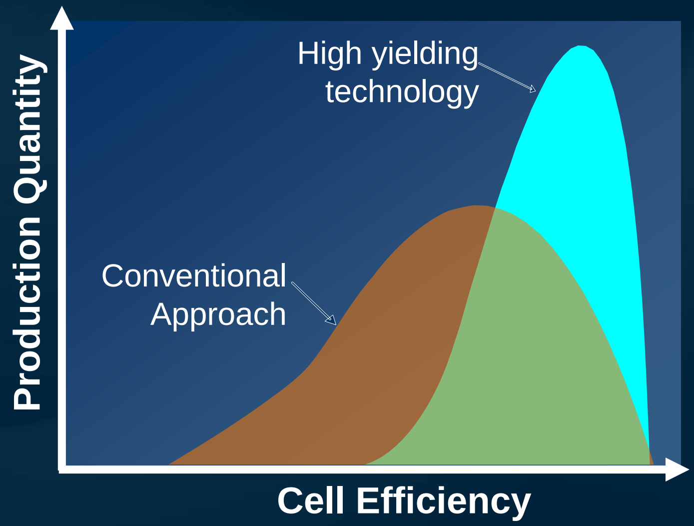
Low Cost = Thin Silicon + High Uptime

External Use

Production Uniformity and Wafer Binning

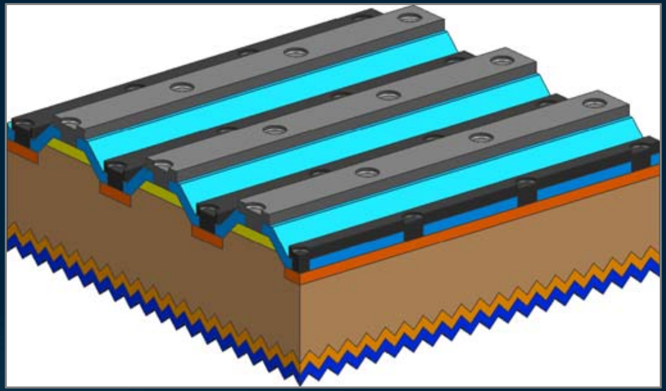
$$\frac{\text{Cost / m}^2}{\text{Watt / m}^2}$$





High Efficiency Commercial Silicon PV Cells

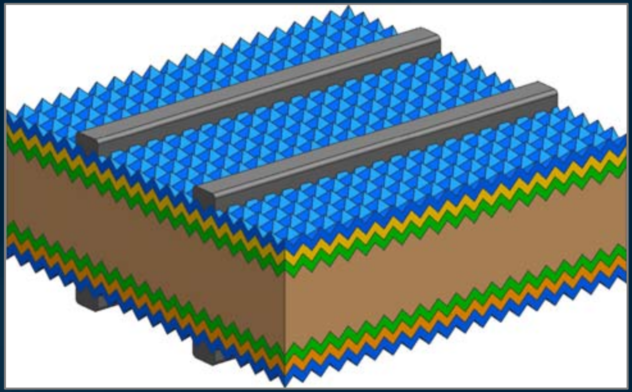
All Back Contact (Sunpower)



- Back contact structure minimizes series resistance and recombination loss
- 22.4% cell efficiency achieved

Source: D. DeCeuster et.al., Eur. PVSEC-22, 2007

HIT Cell (Sanyo)



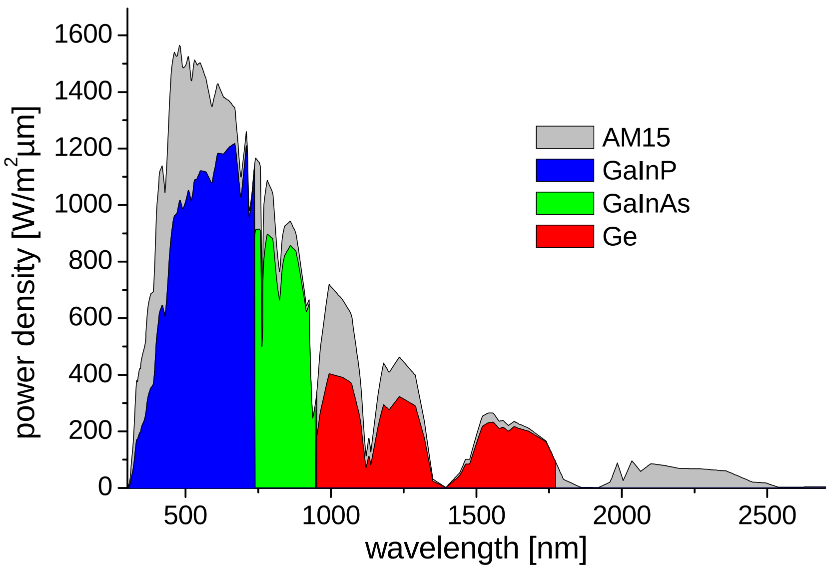
- Heterointerface creates a minority carrier mirror and improves thermal dependence
- 22.3% cell efficiency achieved

Source: Y. Tsunomura et.al., Intl. PVSEC-17, 2007

Comes at Additional Process Complexity

$$\frac{\text{Cost / m}^2}{\text{Watt / m}^2}$$

Beyond the ~31% Shockley-Queisser Limit



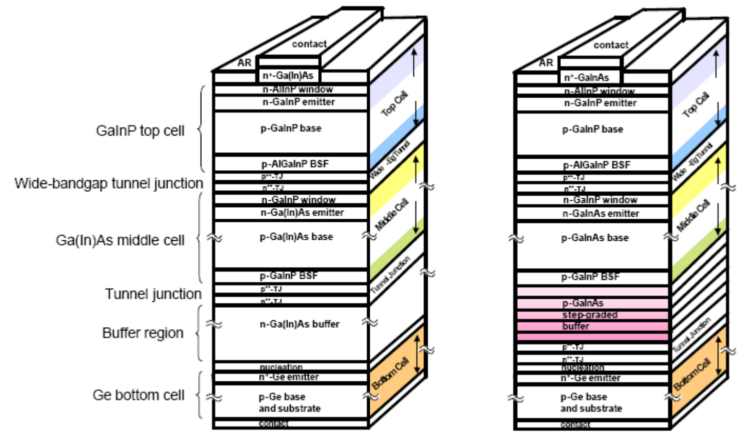
Maximum theoretical efficiencies:

2-jct. cells: 45.3%

3-jct. cells: 51.2%

4-jct. cells: 54.9%

Source: E. Weber



Lattice-Matched (LM)

Lattice-Mismatched or Metamorphic (MM)

Record cell efficiency achieved: 40.1%

Typical cell contains > 20 layers

Best W/gm – ideal for space applications

Source: R. King et.al., APL, 2007

Production Cost Limits Mainstream Use

$$\frac{\text{Cost} / m^2}{\text{Watt} / m^2}$$

External Use

Key PV Technologies and Markets

Crystalline Silicon

Preferred for residential applications

Thin Film

Preferred for large scale applications

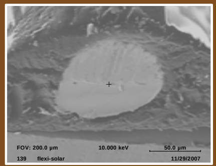
Common focus to drive down cost per watt

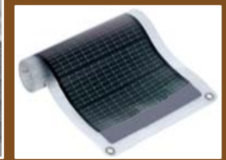
Thin Film PV Value Chain

Wafer or Sheet Production → **Cell Production (Si, CdTe, CIS)** → **Module Assembly** → **Distribution, Integration & Installation**

Cut Slabs & Coupons → Short Passivation & Cell Definition → Laminate & Autoclave → Finishing & Framing → Bond Electrodes → Cut Cells → Hi-Pot Test → Module Test & Ship

Source: Unisolar

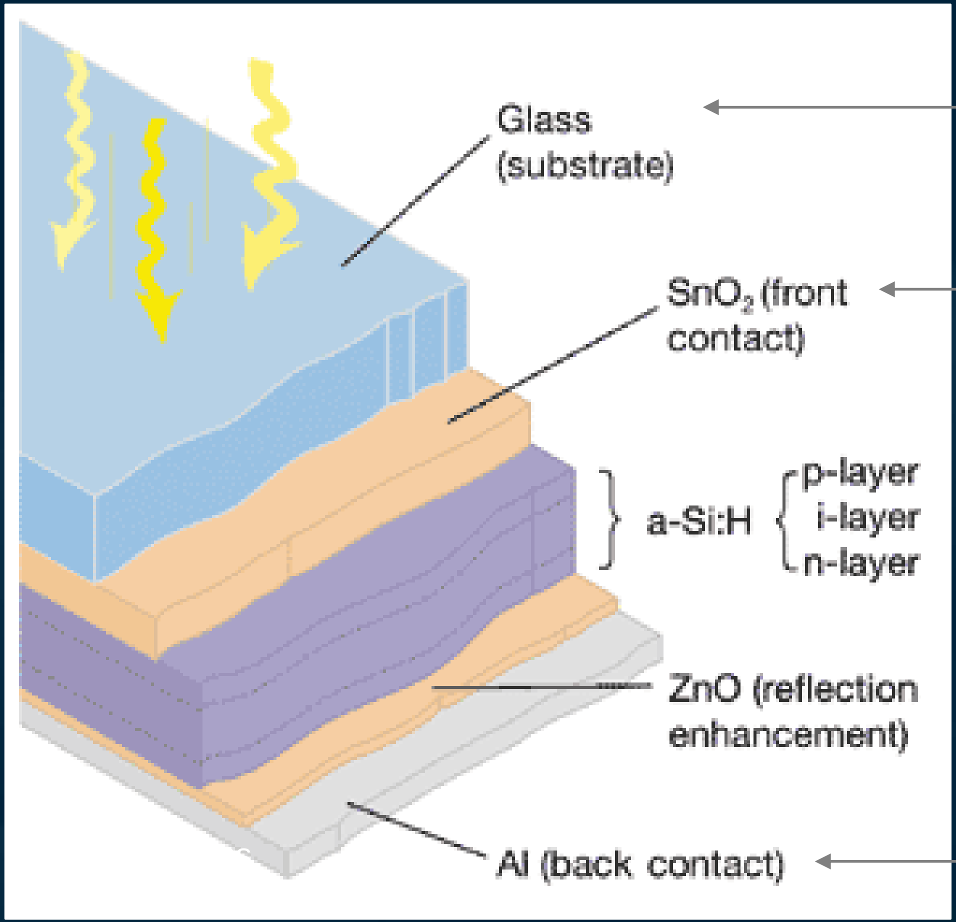




External Use

Basic Single Junction a-Si Solar Cell

6-6.5% Efficient with Production Costs ~$1.00-1.25/Wp



Standard soda-lime glass for single junction; possible low iron glass for tandem junction

"TCO" -- Typically provided by glass company; tandem structures may use ZnO

PECVD deposition – most important for efficiency, capital and operating costs

PVD deposition (RF sputter)

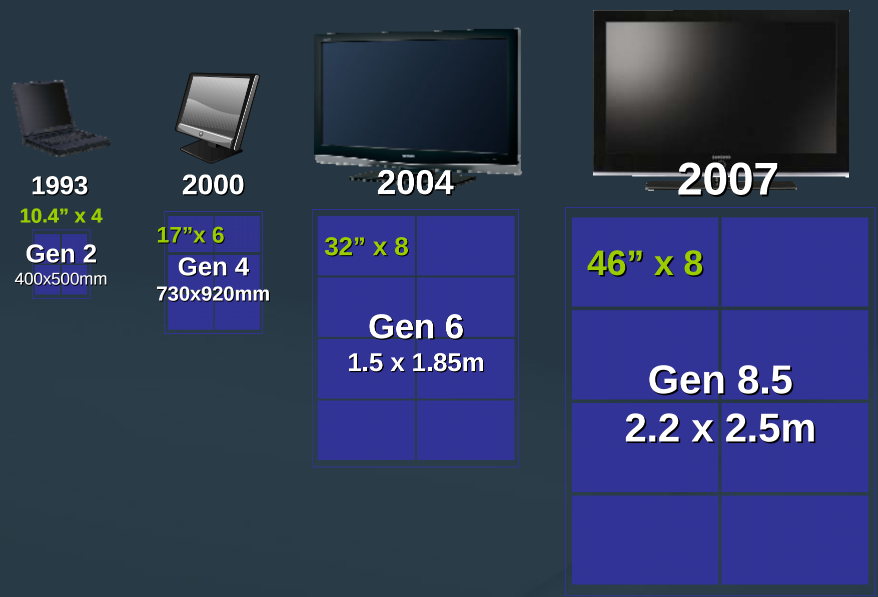
PVD deposition

Keys: Large substrates + low process cost + conversion efficiency

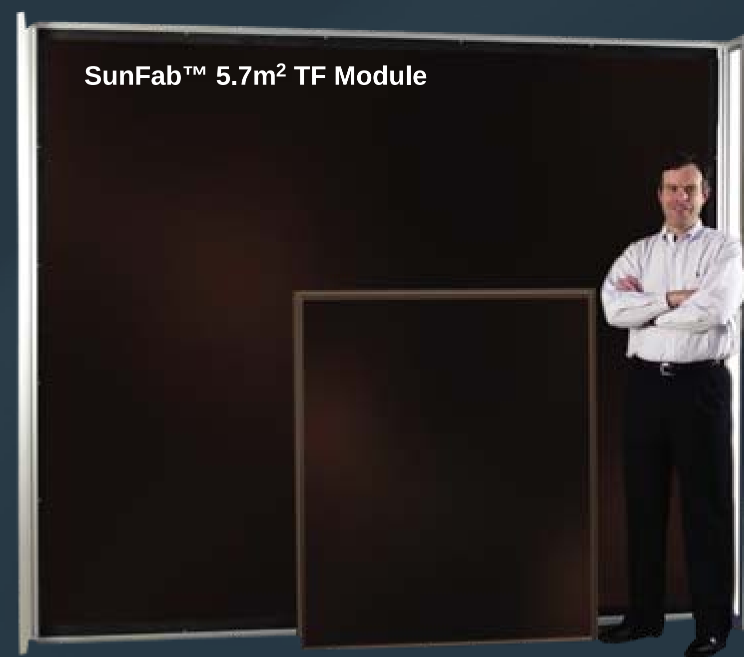
External Use

Large Area Processing = Lower Cost Per Area

Demonstrated in 15+ years of flat panel displays



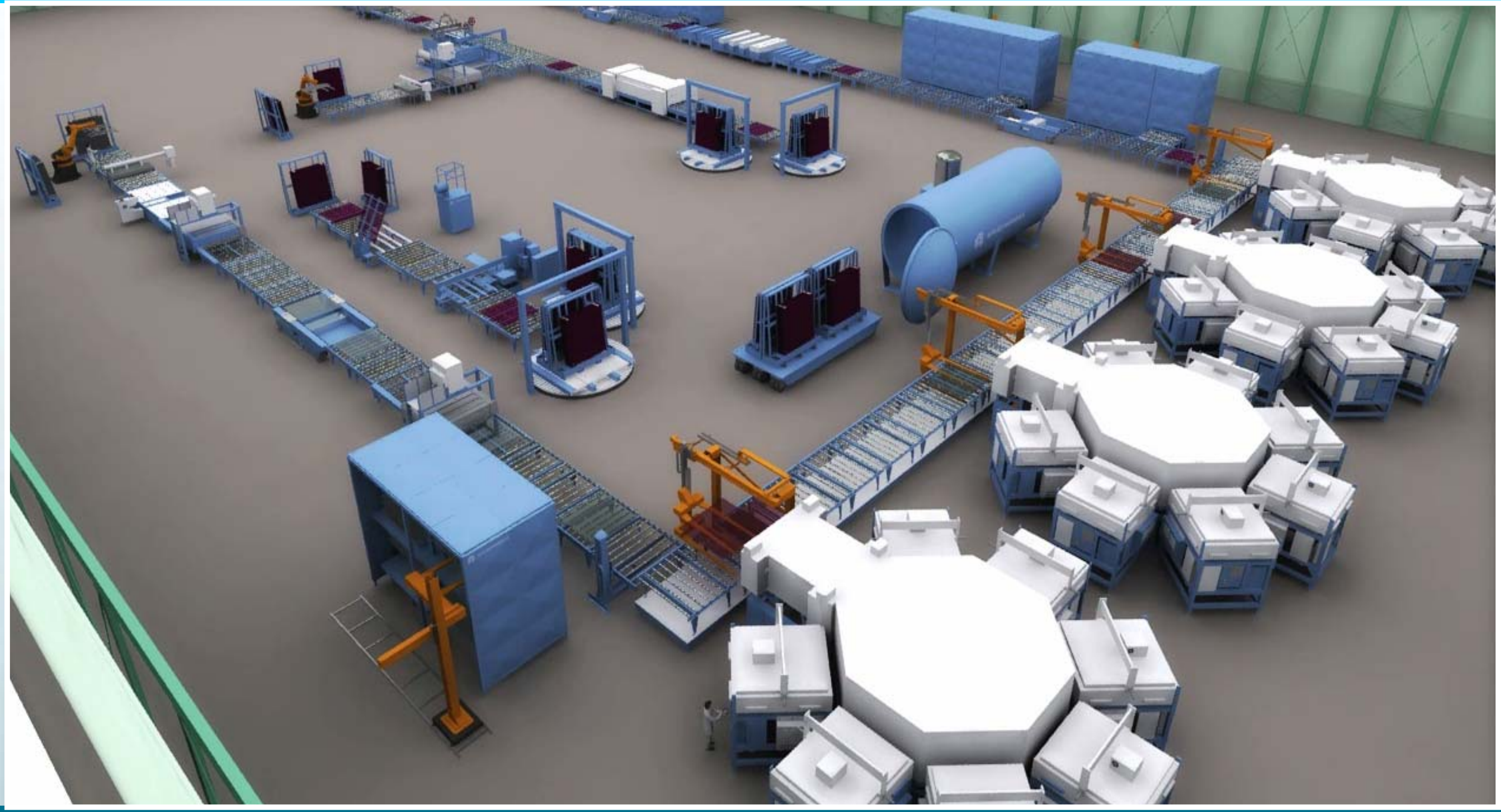
~20X Reduction in Display Cost/Area Due to Large Area Processing



Large Thin Film PV Modules Leverage Low Cost per Area Processing *and* Reduce Installation Costs

$$\frac{\text{Cost} / m^2}{\text{Watt} / m^2}$$

SunFab™ 5.7m² Thin Film PV Factory



SunFab™ 5.7m² Thin Film PV Factory

SunFab™ 5.7m^2 Thin Film PV Factory

APPLIED MATERIALS®

Leveraging Scale: GW TF PV Module Factory

- Consumes 500 tons of glass per day

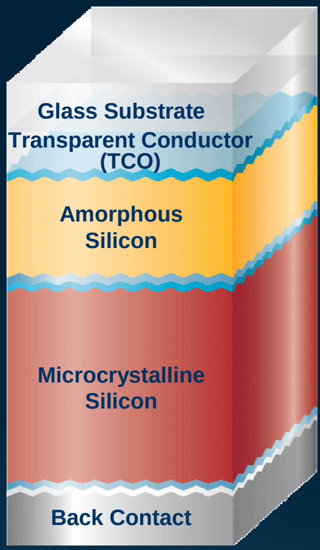
- PV factory (111 acres) is larger than the Magic Kingdom at Disney World (107acres)

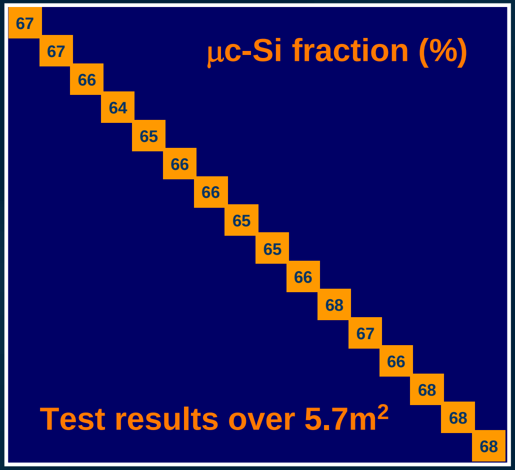
- Produces 6,000 modules per day or enough to cover 7 ½ football fields **per day**
  - Equivalent area of 450,000 300mm wafers per day

$$\frac{\text{Cost} / m^2}{\text{Watt} / m^2}$$

20% Cost/Wp reduction translates to 1+ year earlier parity

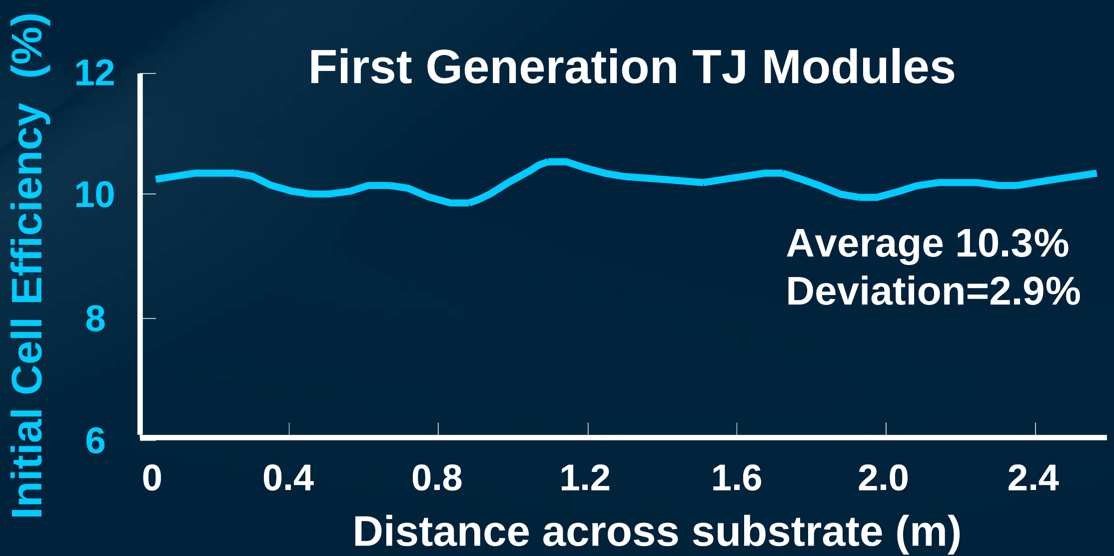
SunFab™ 5.7m2 Thin Film Si Technology





High efficiency elements

- aSi/uSi tandem junction
- Optimized TCO contact
- Laser pattern size/alignment
- Reflective back contact
- Advanced ARCs
- Light steering layers
- Triple junction structures

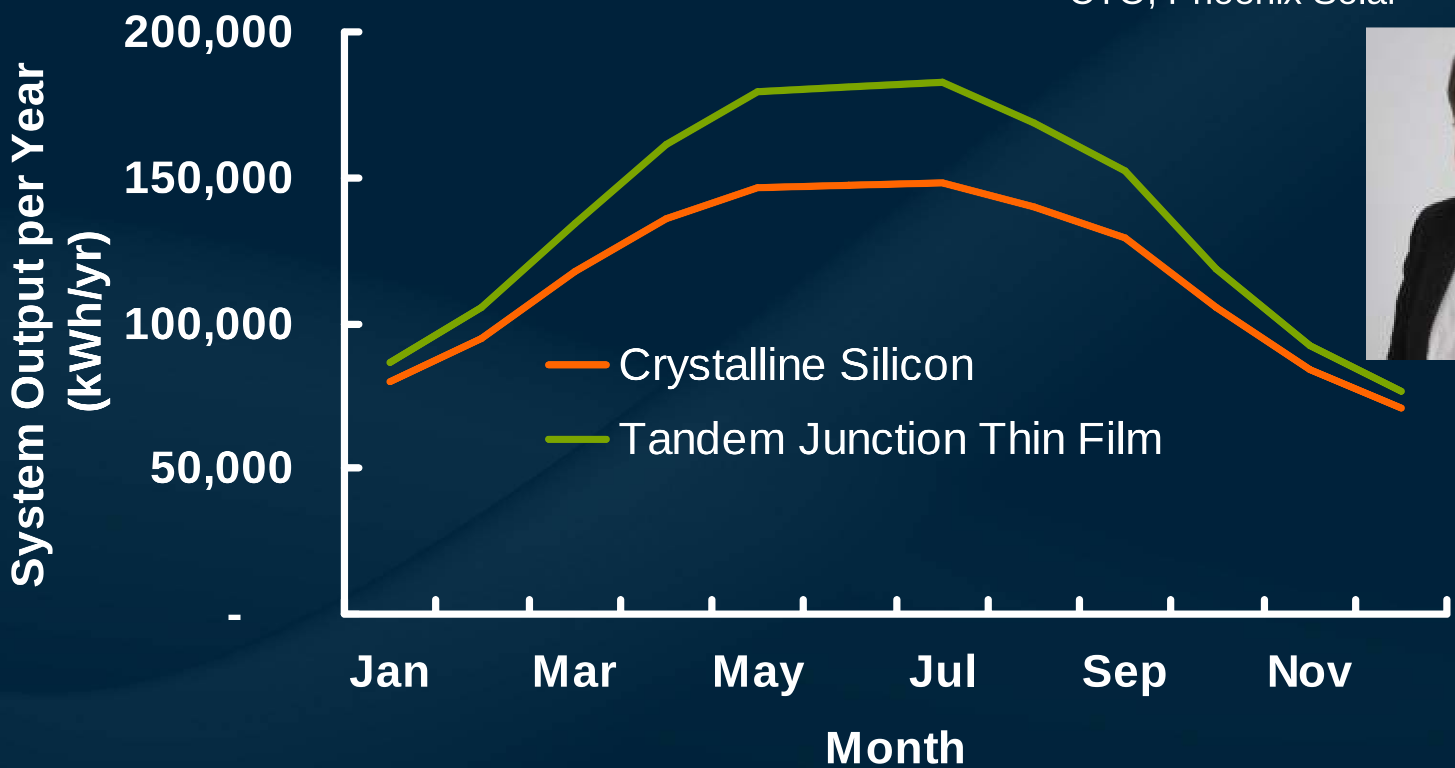


External Use

Thermal Coefficient Favors Thin Film

1MWp c-Si and Thin Film Comparison

"Because of the superior performance, we already sell some TF projects at a higher price to some investors than c-Si projects" – Manfred Bächler CTO, Phoenix Solar

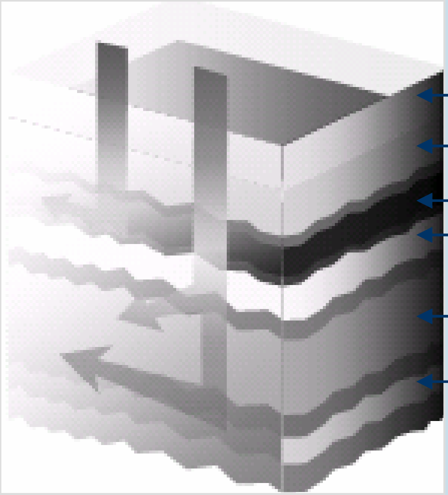


Thin Film Compares Favorably at Higher Operating Temperature

External Use

High Efficiency Thin Film Silicon PV Cells

Tandem Junction with Interlayer

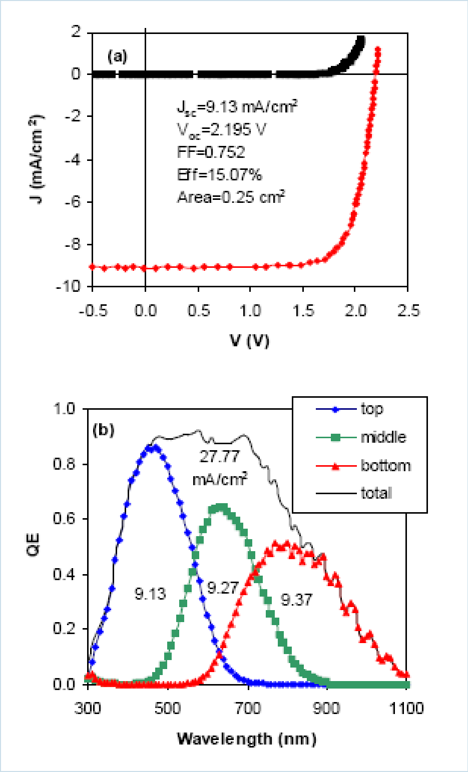


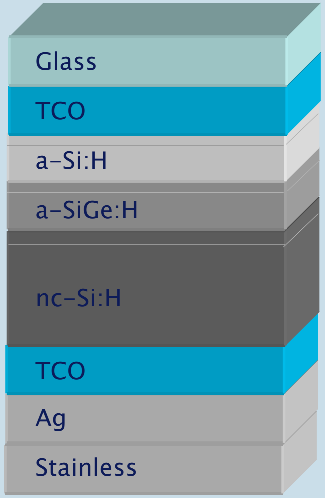
Interlayer optimizes light capture

Initial cell efficiency of 15.0% achieved

Source: S. Fukuda et.al., Eur. PVSEC-21, 2006

Triple Junction on Foil





15.1% initial efficiency

13.3% stable efficiency

Source: B. Yan et. al., 2006 IEEE WCPEC, pp. 1477-1480

TF Silicon Has Paths to Higher Efficiency

$$\frac{\text{Cost / m}^2}{\text{Watt / m}^2}$$

Components of PV Cost

- Materials cost
- Process cost
- Module efficiency

+

- Module efficiency
- Module size
- Module weight
- Labor cost
- Site costs

Downstream Advantages of Large Scale Modules

Utility Scale Solar Farms

- Larger 5.7m2 size:
  - Enables efficient mounting
  - Requires less cabling, rails, clips
- Results in >17% BOS savings
  - Equivalent to effect of > 2% efficiency improvement

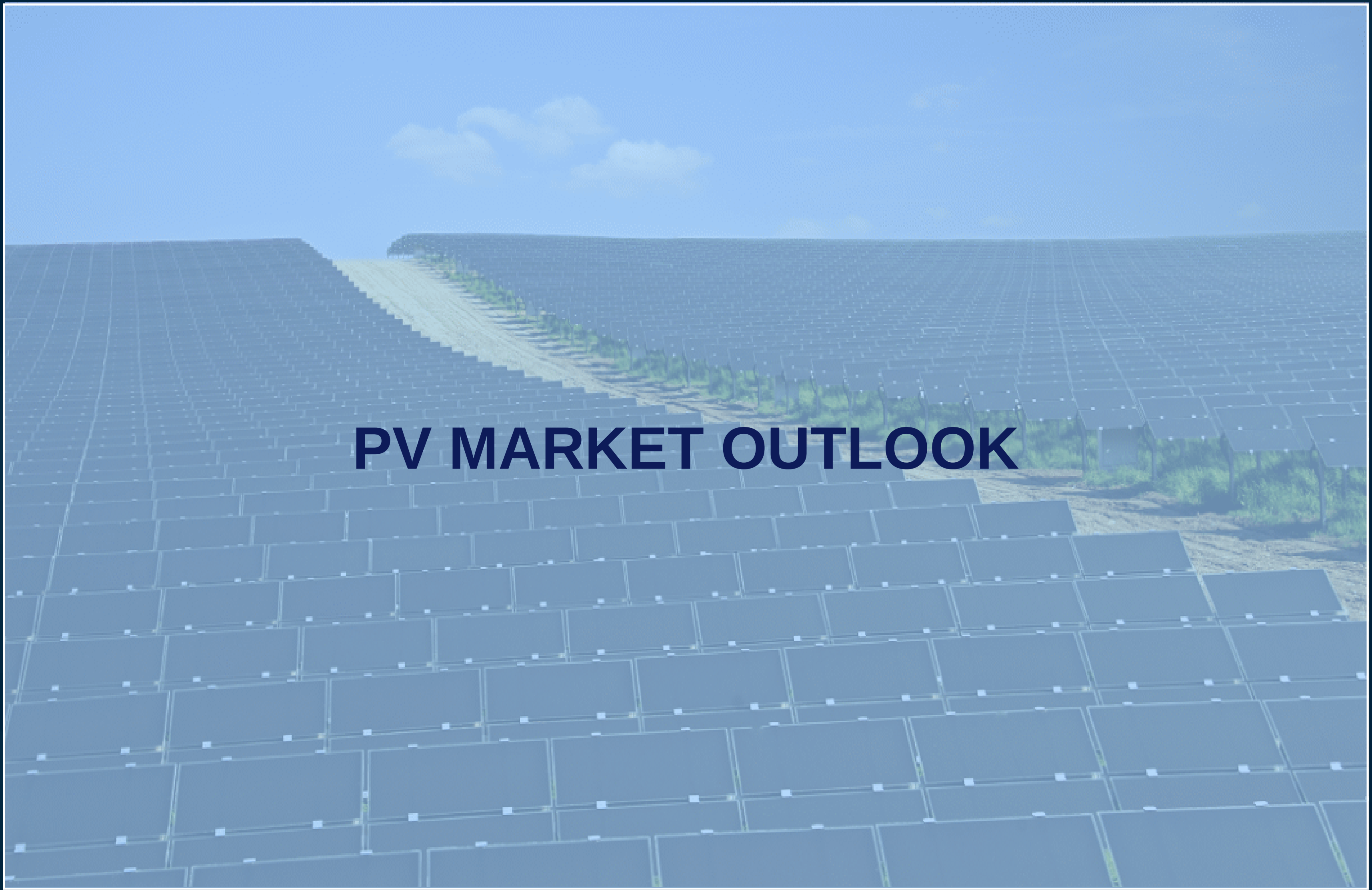
BIPV

Excelon Building, Spire Solar

- Larger 5.7m2 size:
  - Enables large panes without gluing
  - Avoids mismatch
  - Significantly reduces cost
- Becomes compelling to architects

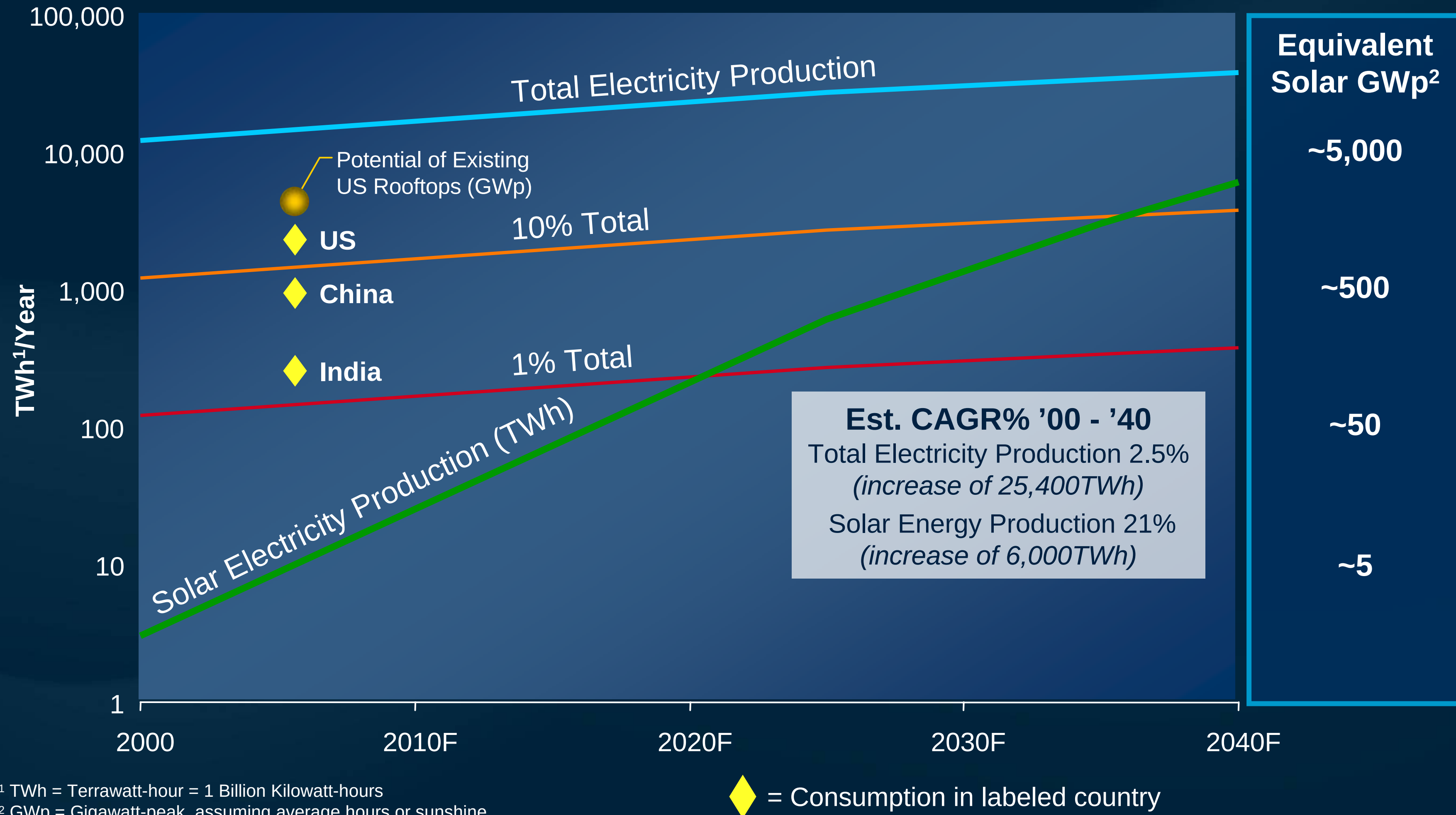
Source: One of the Top 3 German Installers

PV MARKET OUTLOOK



PV MARKET OUTLOOK

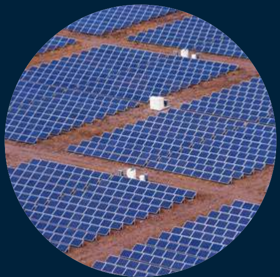
World Electricity Production Forecast
(2000 – 2040)



¹ TWh = Terrawatt-hour = 1 Billion Kilowatt-hours
² GWp = Gigawatt-peak, assuming average hours or sunshine
Source: Solar Generation and IEA-PVPS

External Use

Large-Scale PV Opportunities in U.S.



Groundmounts
100 GWp ~ 15% of Nevada Nuclear Test Site

Commercial Rooftops
10 GWp ~ 15% of Walmart-size rooftops

Residential Rooftops
10 GWp ~ 3% of rooftops

25% U.S. RPS* Standard implies:

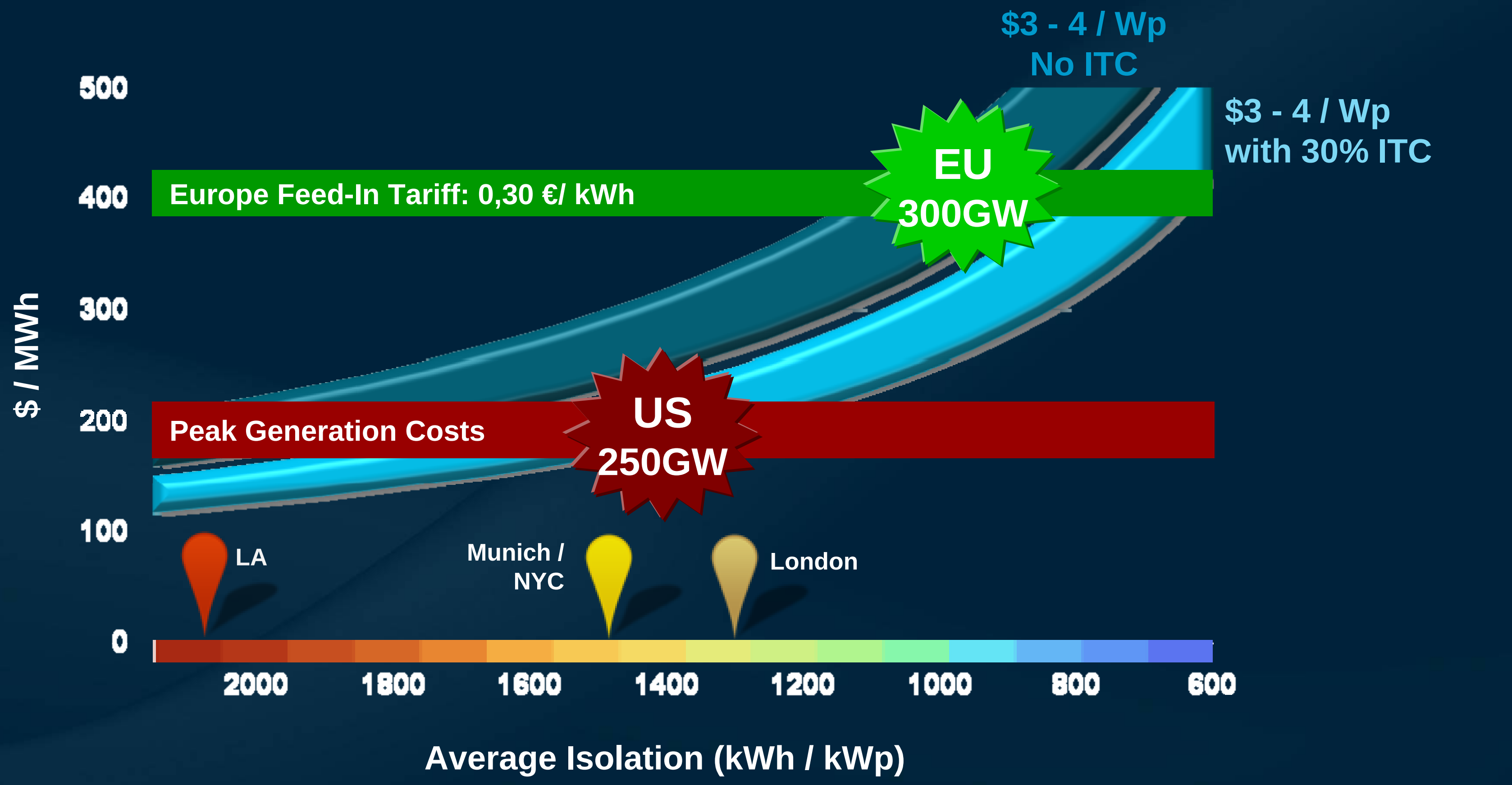
- ~250 GWp modules installed (based on 50% PV)
- ~40 GWp/year produced and installed ~ 1M jobs
- Requires ~33% CAGR in installations to achieve by 2025

*RPS = Renewable Portfolio Standard

Applied Materials Sunnyvale Campus

Large PV Peaking Opportunity

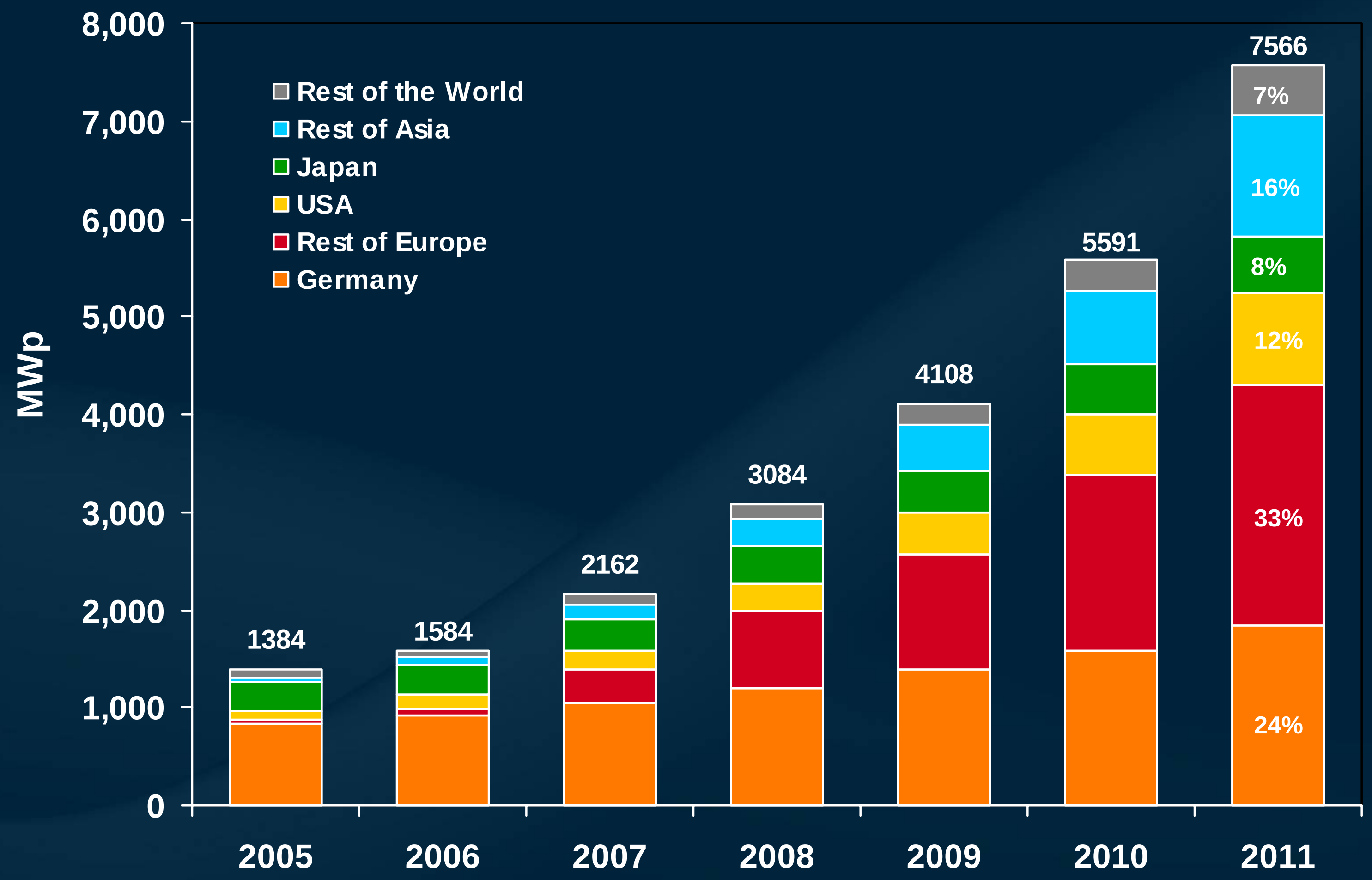
Today across all major OECD markets between $3-4/Wp



Peak Generation Costs: Heat Rate 14; Running between 2-6hrs/day. Sizing reflects 30% of peak load generation. Solar excludes Mfg Tax Credit. Feed-in Tariff avg across Europe

External Use

Annual PV Installations by Location

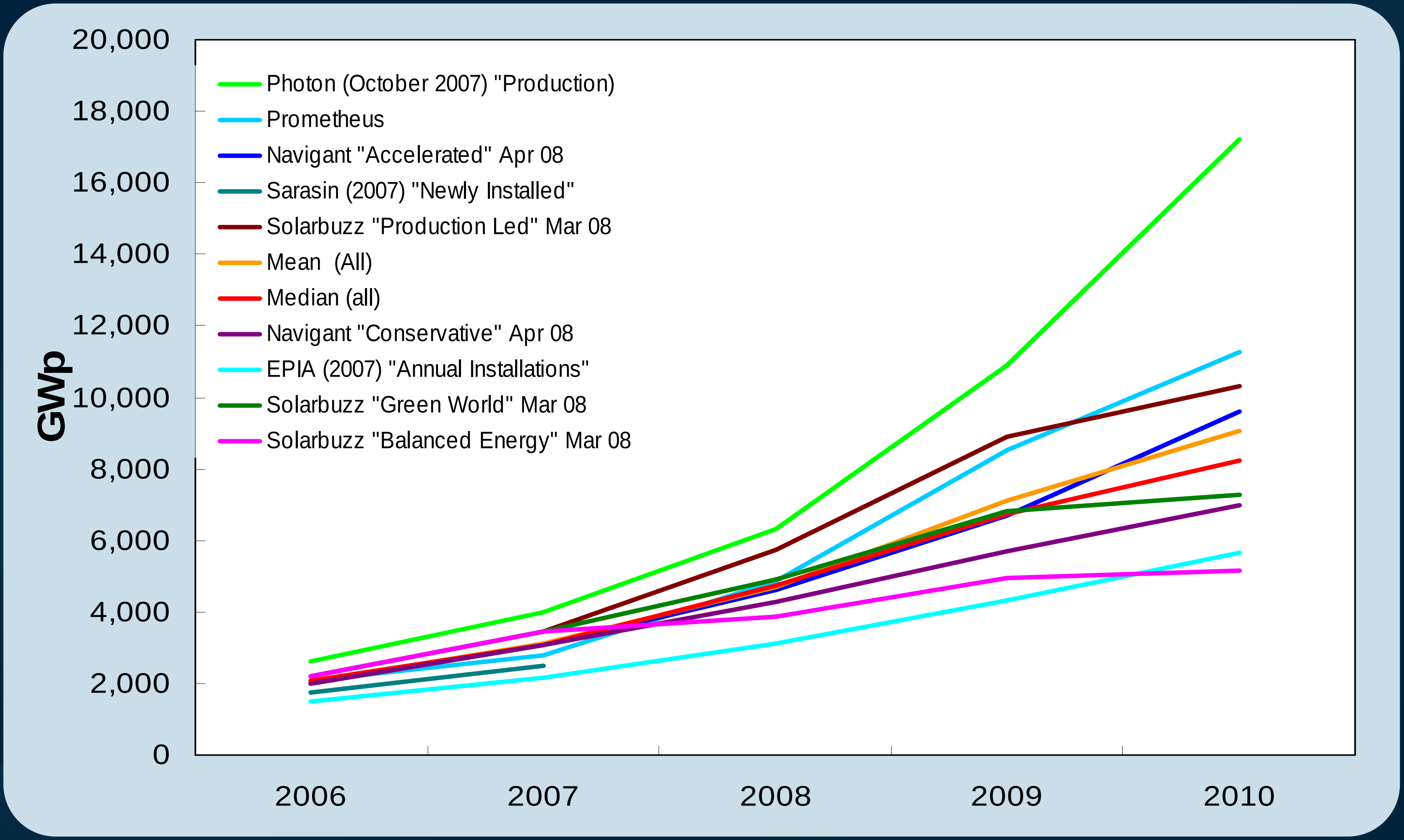


Total 2007 PV Installations in China + India ~ 45MW

Sources: EPIA, China Renewable Energy Development Project, Deutsche Bank, Lehman Brothers, Solarbuzz

External Use

Wide Range of Market Growth Forecasts†



2010 Median Corresponds to ~ $7B PV Equipment Market

† Forecasts before Sept/Oct 2008 global financial crisis

External Use

Summary and Conclusions

- This time PV is real
  - Incentives, carbon taxes, climate concerns are catalysts and not fundamental drivers
- Economic inflection points are within range
  - Passed parity for peak loading at many locations
- Nanomanufacturing technologies can be enabling
  - Process cost/area is key
  - Eventually could use a good battery

Time to Catch Some Rays…

External Use

Question 1

Question 2

Question 3

External Use