National Renewable Energy Laboratory
Innovation for Our Energy Future

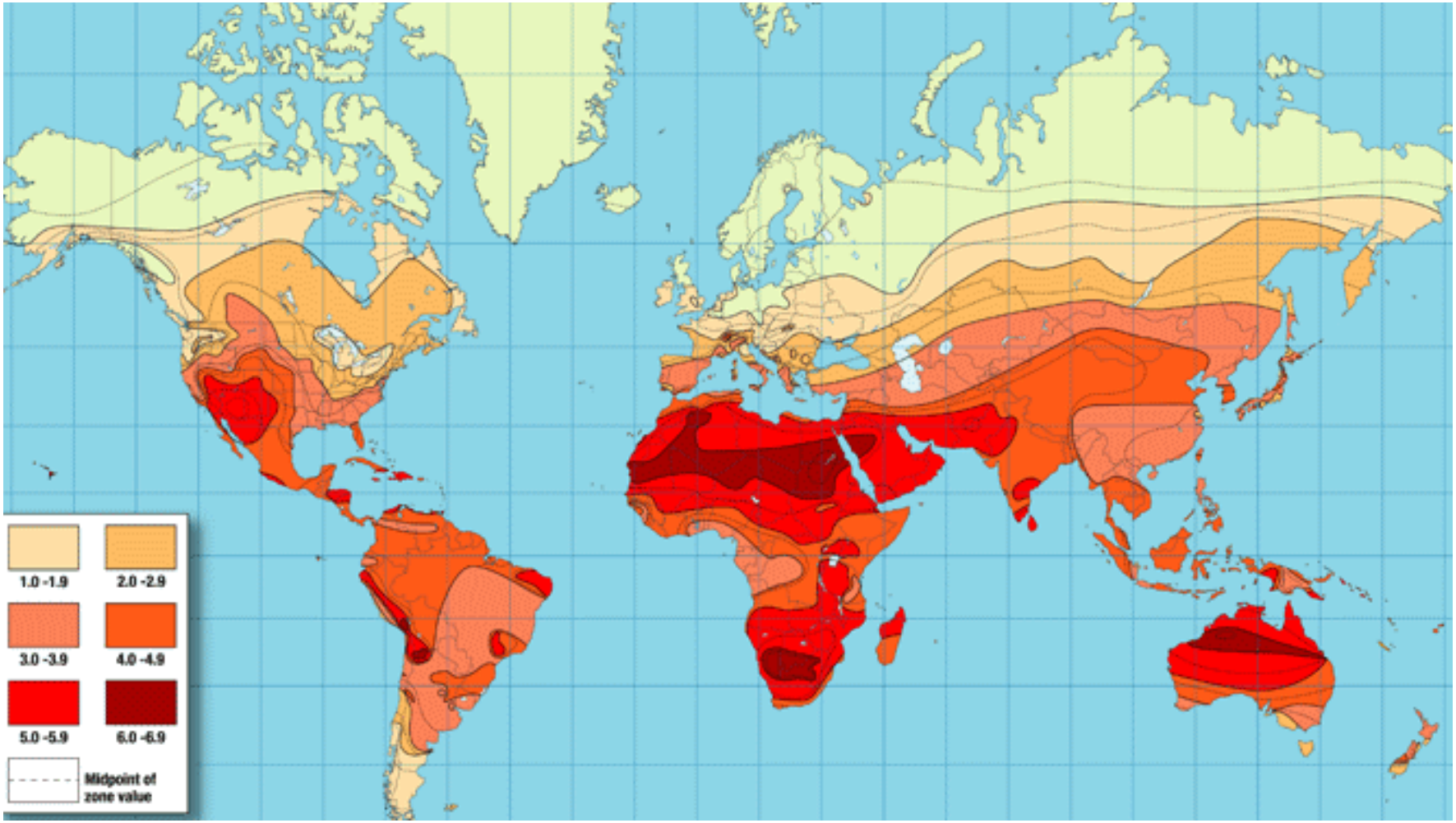
The Promise of Solar Electricity

Dr. Dan E. Arvizu
Laboratory Director

October 22, 2008

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Robust Global Solar Resource



http://howto.altenergystore.com/Reference-Materials/Solar-Insolation-Map-World/a43/

Applications of Solar Heat and Electricity

Solar Thermal

Photovoltaics (PV)

Concentrating Solar Power (CSP)

Distributed Generation, on-site or near point of use

Centralized Generation, large users or utilities

Transportation

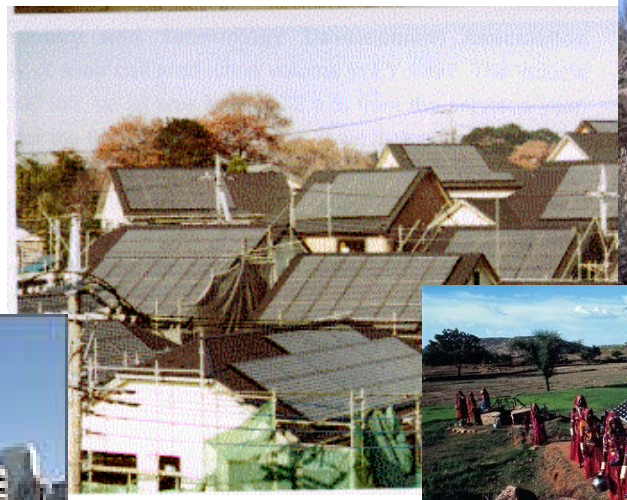
Residential & Commercial Buildings

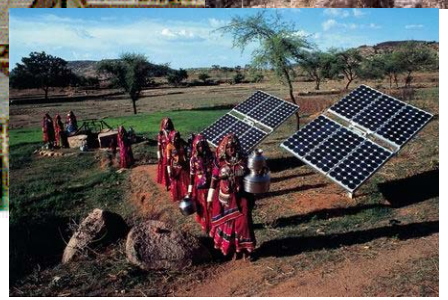
Industrial

Photovoltaics – Solar Electricity

Photovoltaics (PV)

- Direct conversion of sunlight to electricity

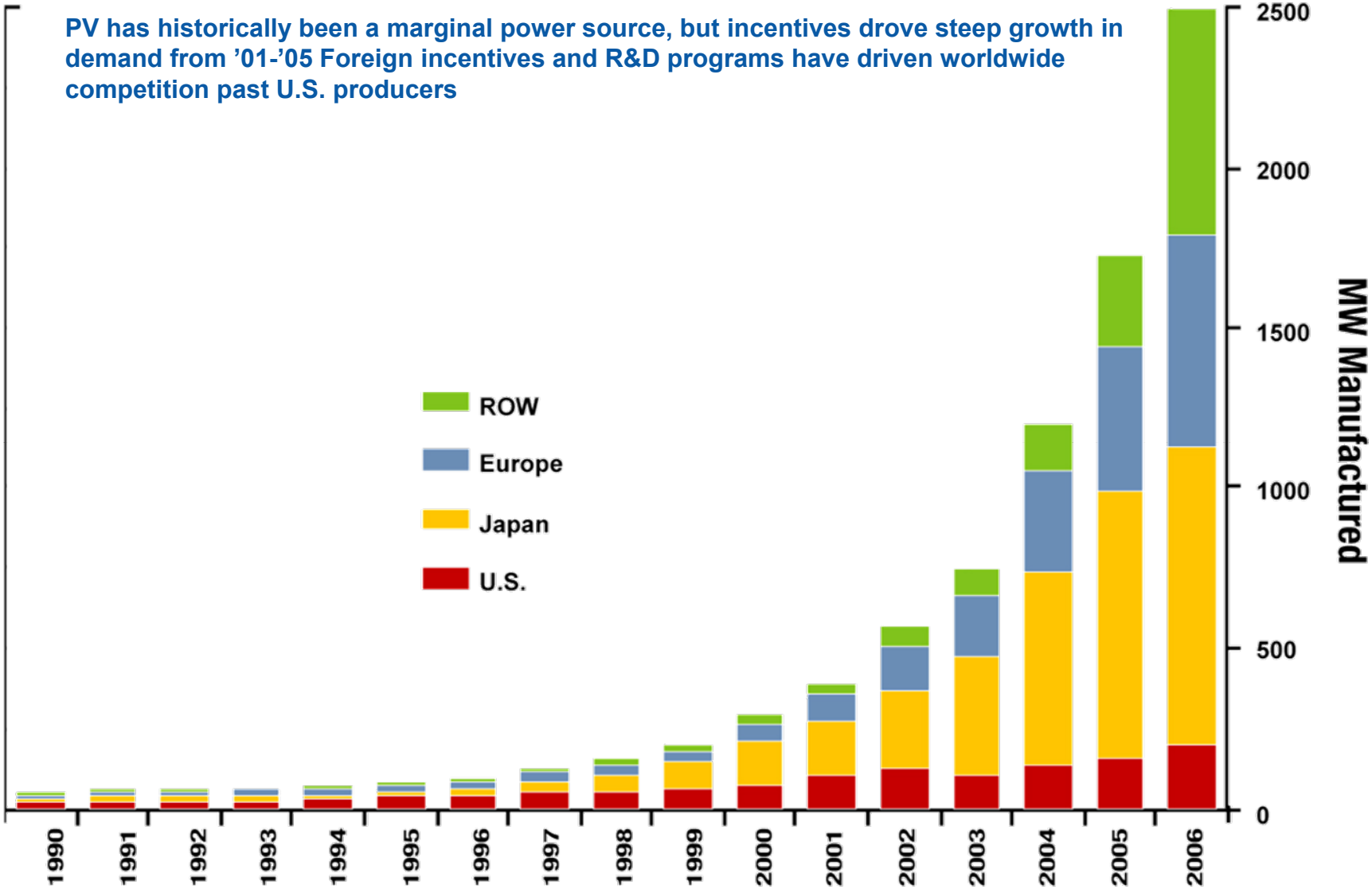




Advantages

- Modular (mW to many MW)
- No (or few) moving parts
- Noise and pollution free
- Reliable; low operating costs
- Abundant, indigenous resource (30,000 km^2 PV for 800 GW)

Worldwide PV Shipments



Photovoltaics R&D

4% Organic PV

Customizing organic molecules for optimal cell efficiency in materials that can be processed without expensive vacuum chambers

1% Dye Sensitized Cells

Advancing the efficiency and stability of inexpensive dye-based solar cells with novel nanostructures

22% Wafer Silicon

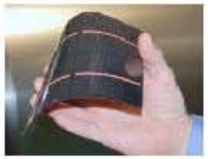
Combining thin amorphous and wafer silicon to make high efficiency cells with smaller total amounts of silicon

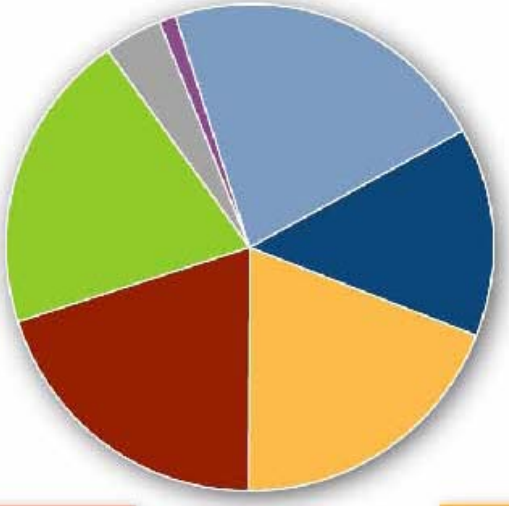
Developing new ink-jet printing methods for silicon electrical contacts

20% Thin Films (CIGS)

Supporting the novel manufacture of CIGS cells from ink-based precursors

Transferring discovery that highest performance material has nanostructured patterns into a fast and uniform manufacturing process





14% Concentrator PV

Devising strategies for making quicker, easier, less precise cells but maintaining record performance

Achieving record efficiencies (33.8%) even without concentration

20% Thin Films (CdTe)

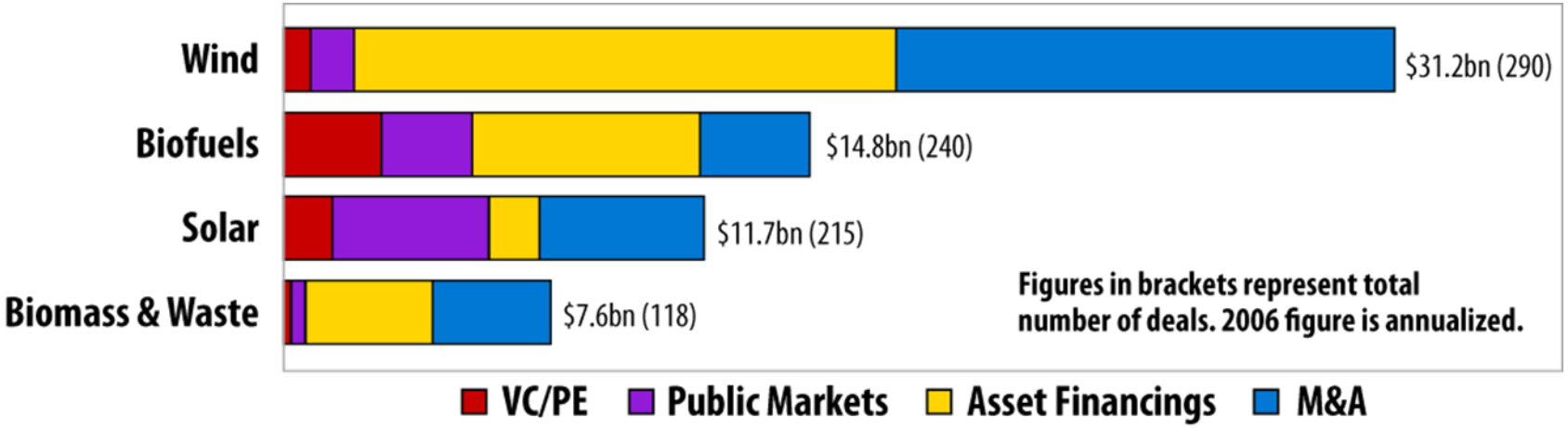
Produced thinner films with same cell performance

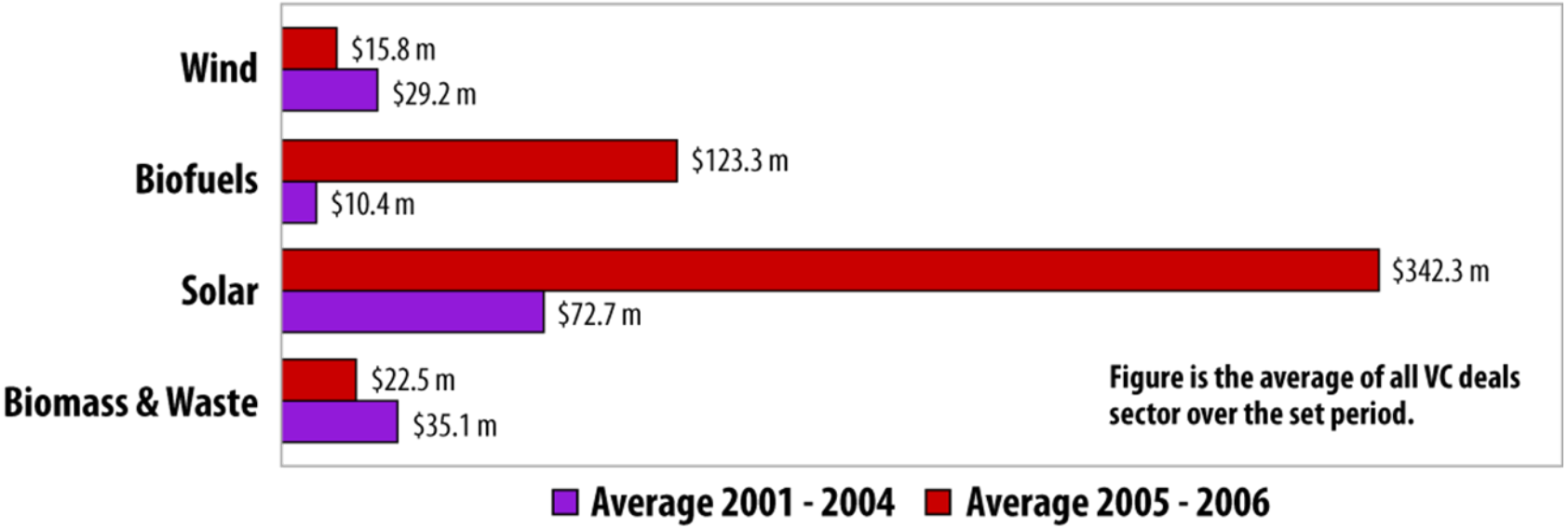
Discovered a more durable way to make electrical contacts

19% Thin Films (Silicon)

Developing methods of making thin silicon film solar cells on inexpensive glass and at low processing temperatures

Money is Flowing into the Sector

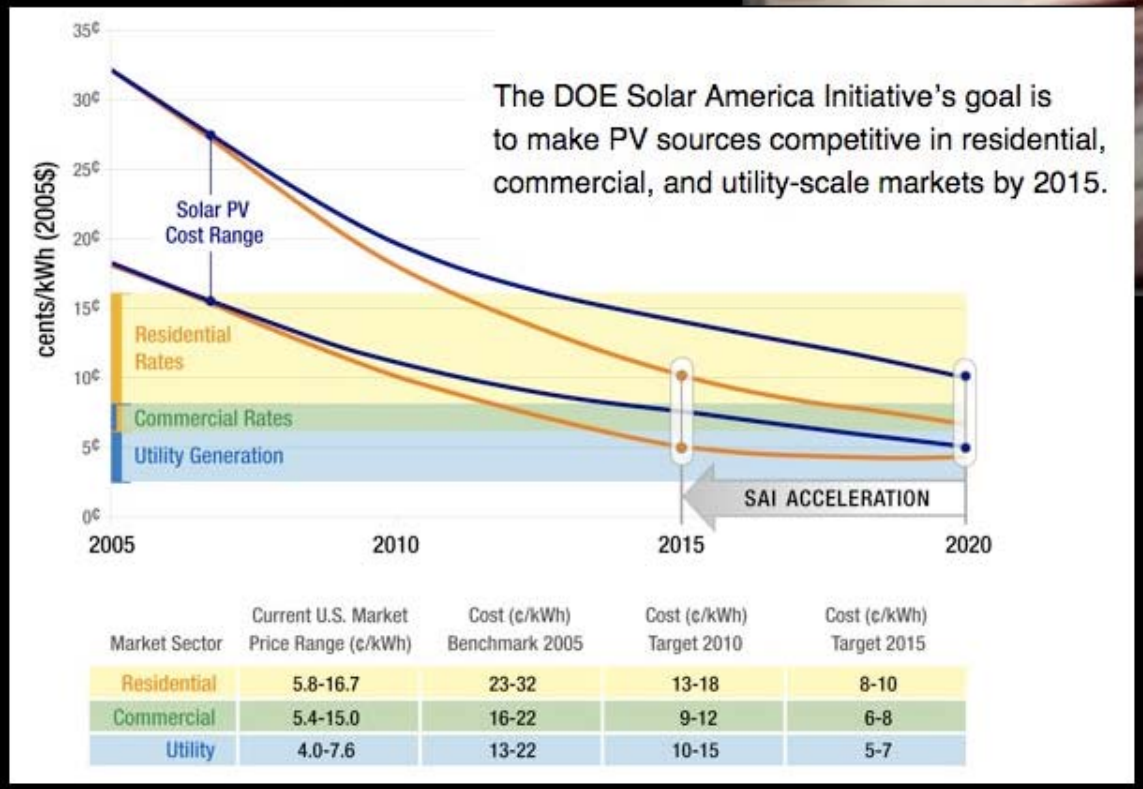




Four Messages:

- Solar is real *now*
- Investment in *policy* and *R&D* equal priorities
- Need to drastically cut the time from lab-bench discovery to manufacturing
- Overall investment in science and technology has to be increased (balance, workforce . . .)

Solar America Initiative



Market Sector	Current U.S. Market Price Range (¢/kWh)	Cost (¢/kWh) Benchmark 2005	Cost (¢/kWh) Target 2010	Cost (¢/kWh) Target 2015
Residential	5.8-16.7	23-32	13-18	8-10
Commercial	5.4-15.0	16-22	9-12	6-8
Utility	4.0-7.6	13-22	10-15	5-7

SAI 2015 Targets

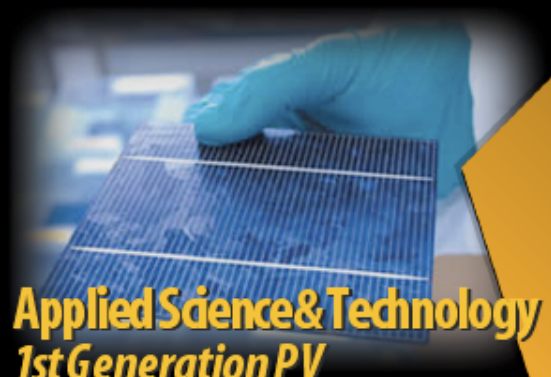
Electricity Price

Residential: $0.08-$0.10/kWh
Commercial: $0.06 to $0.08/kWh
Utility Scale: $0.05-$0.07/kWh

Cumulative Installations

5-10 GW

Technololgy Investment Pathways



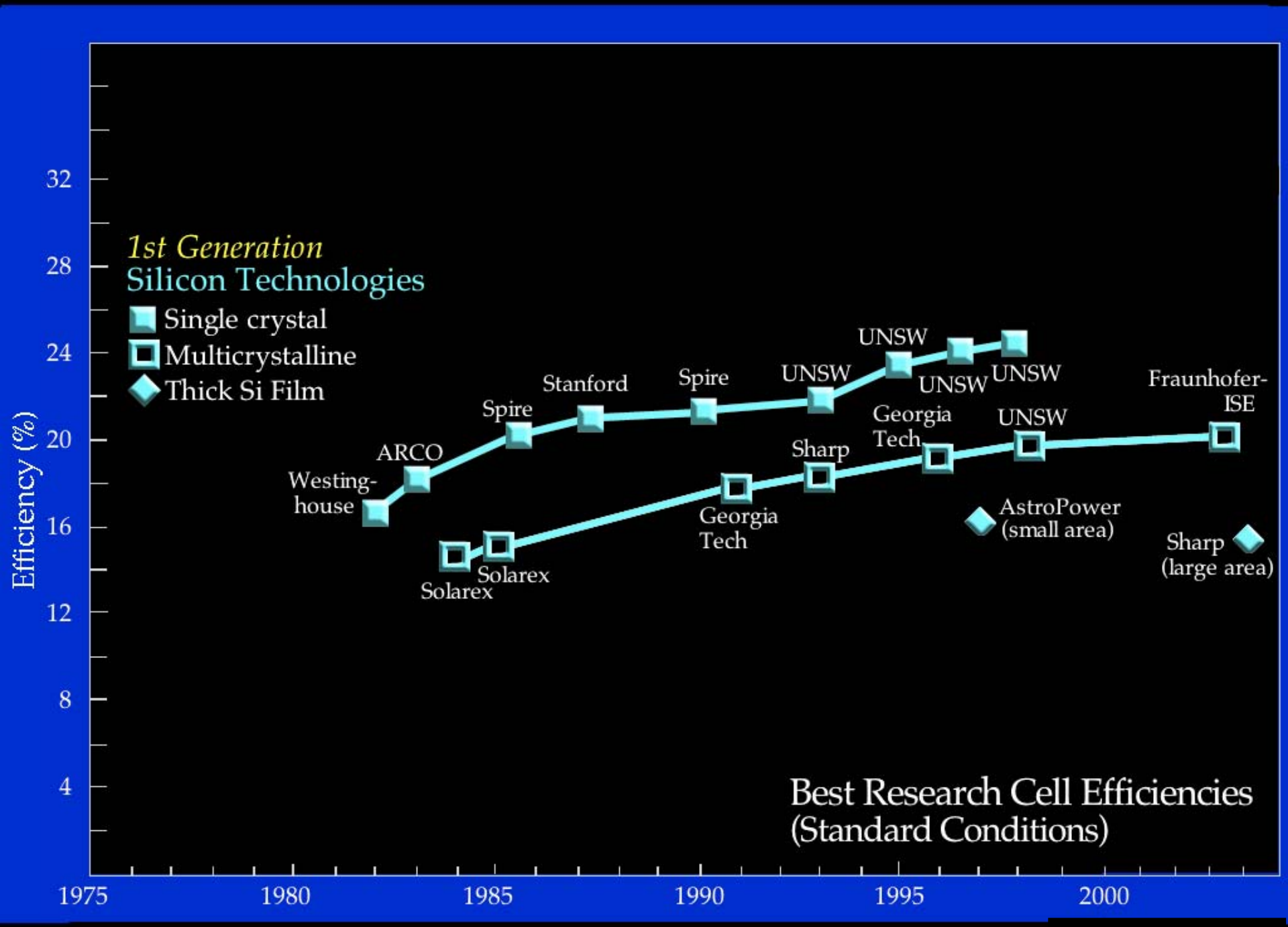
Applied Science & Technology

1st Generation PV

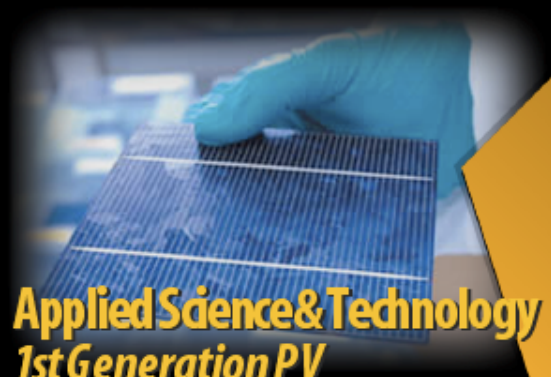
- Silicon

Evolutionary

(3-5 years)


1st Generation
Silicon Technologies
Single crystal
Multicrystalline
Thick Si Film
Efficiency (%)
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
Westing-
house
ARCO
Spire
Stanford
Spire
UNSW
UNSW
UNSW
UNSW
Fraunhofer-
ISE
Solarex
Solarex
Georgia
Tech
Sharp
Georgia
Tech
UNSW
AstroPower
(small area)
Sharp
(large area)
Best Research Cell Efficiencies
(Standard Conditions)

Technololgy Investment Pathways



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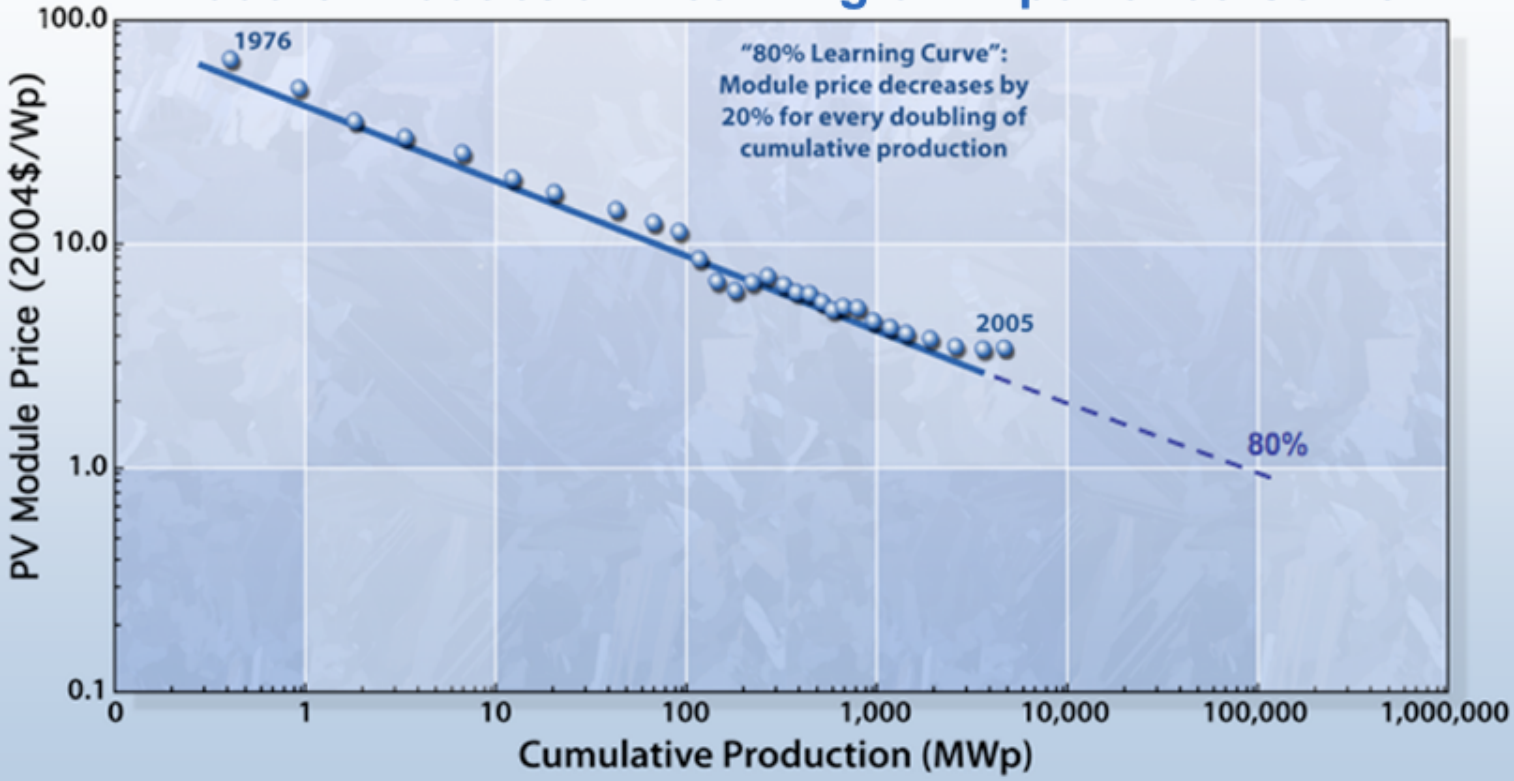
Technolology Investment Pathways

Module Production Learning or Experience Curve



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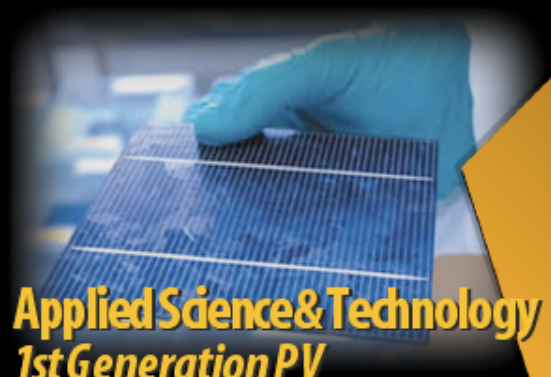

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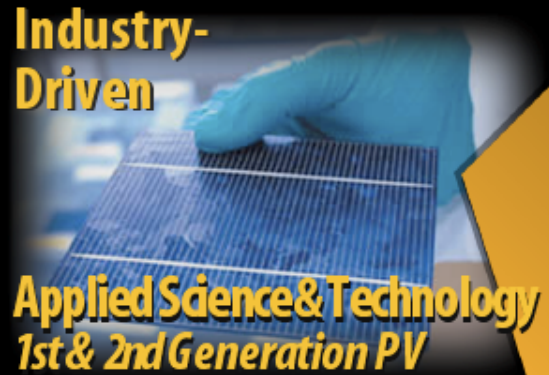


Industry-Driven

Applied Science & Technology

1st & 2nd Generation PV

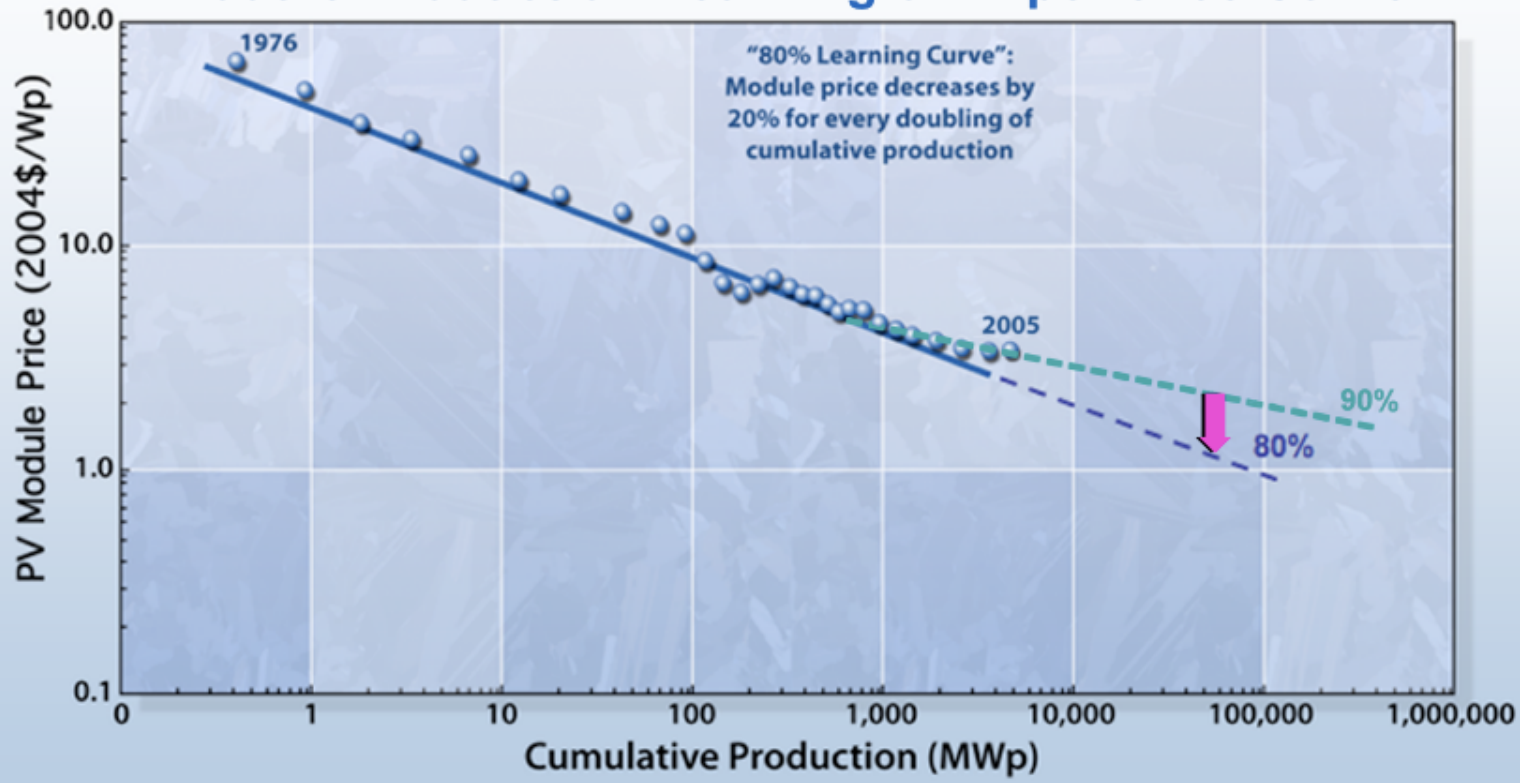
- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

Accelerated Evolutionary

(3-5 years)

Technololgy Investment Pathways

Module Production Learning or Experience Curve



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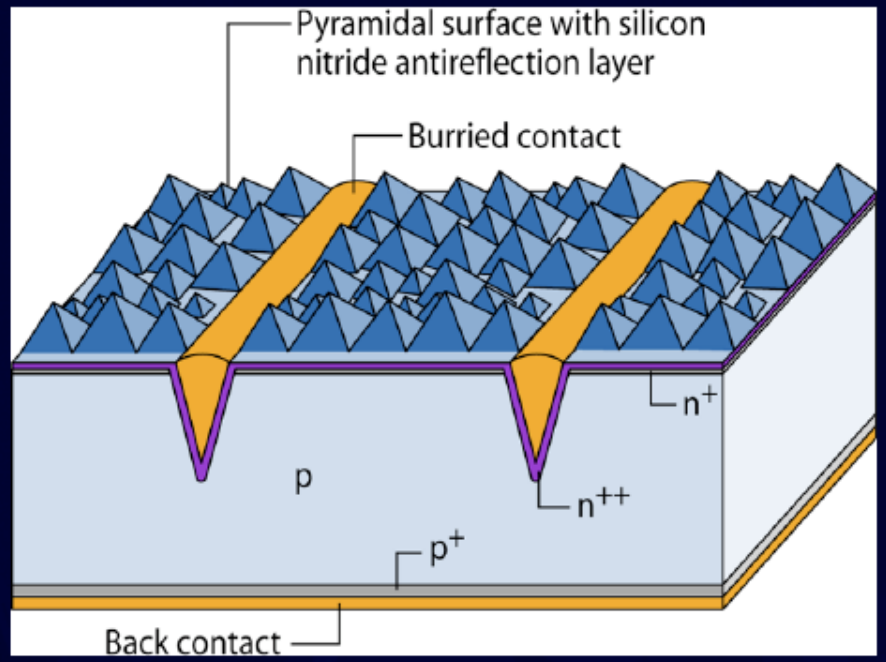
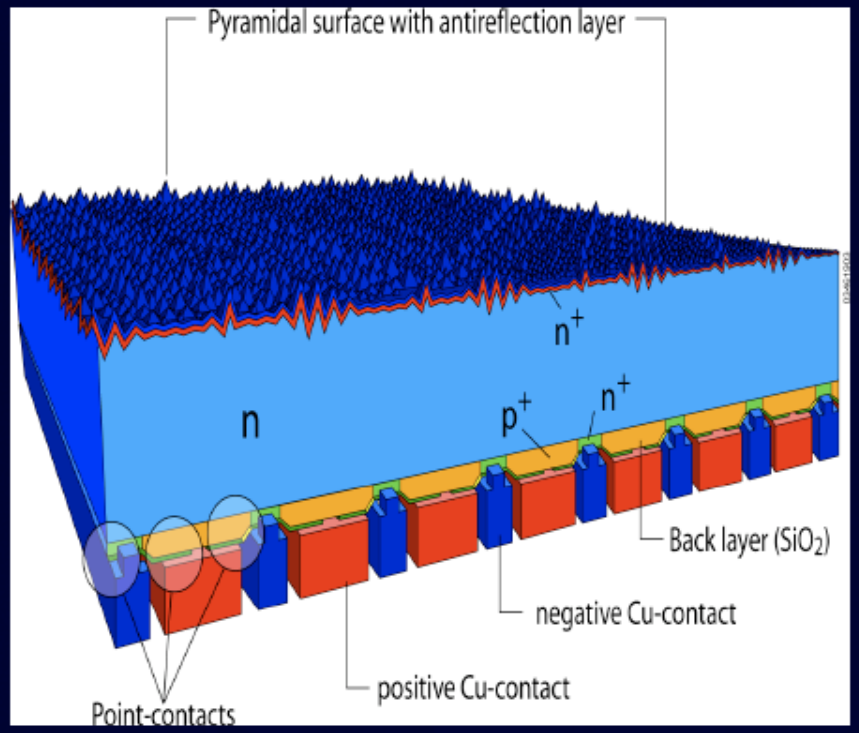
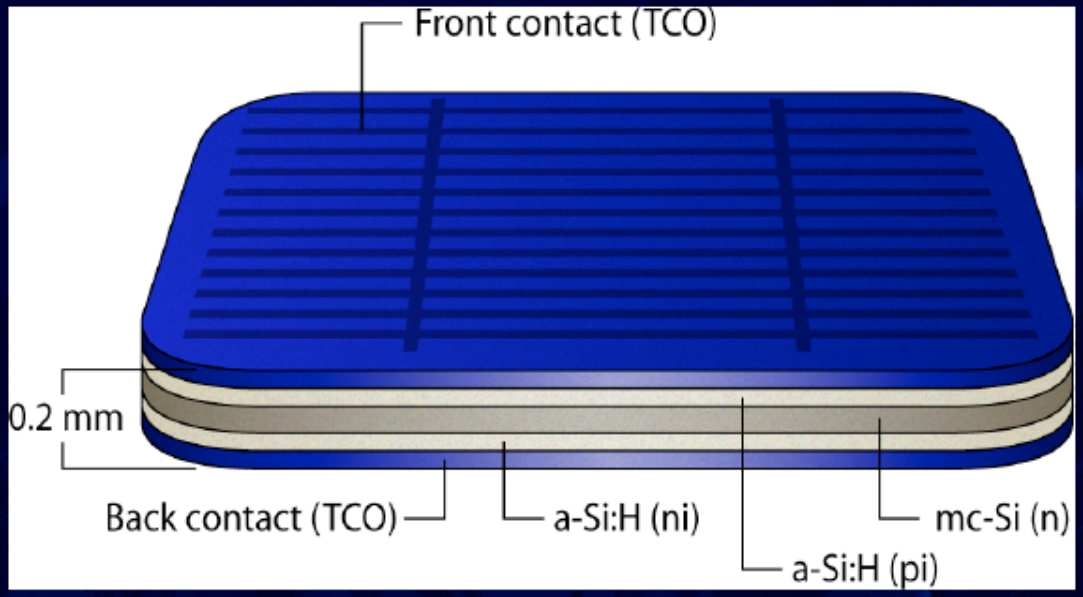
PV Si 20% Club



BP Saturn

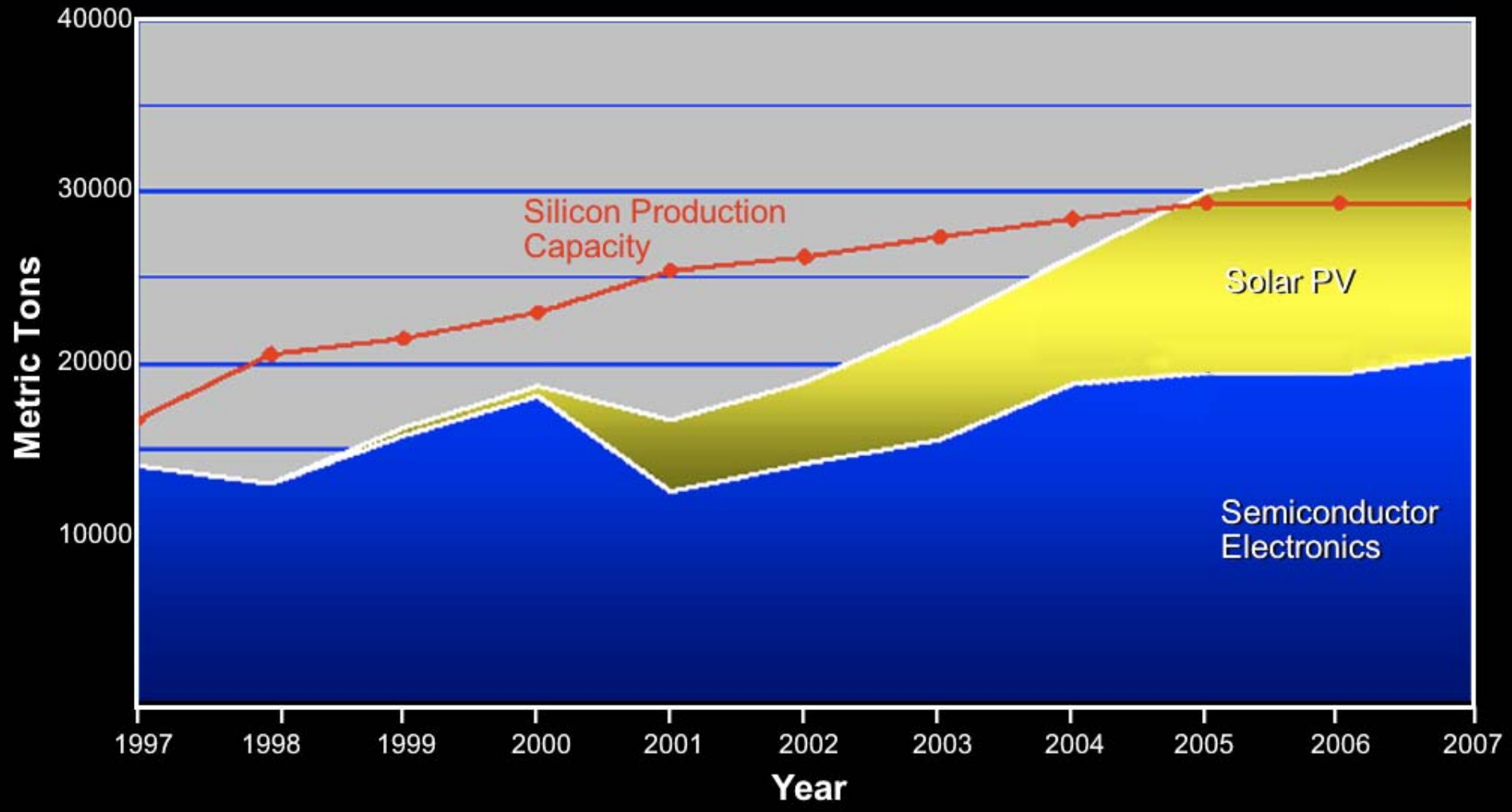


SunPower Cell



Sanyo HIT Cell

The Silicon Issue



Benefits . . .

Made the Si industry examine itself.

- Better Si material utilization
- Process improvements
- Performance improvements

Problem: Si Shortage

Benefits . . .

Made the Si industry examine itself.

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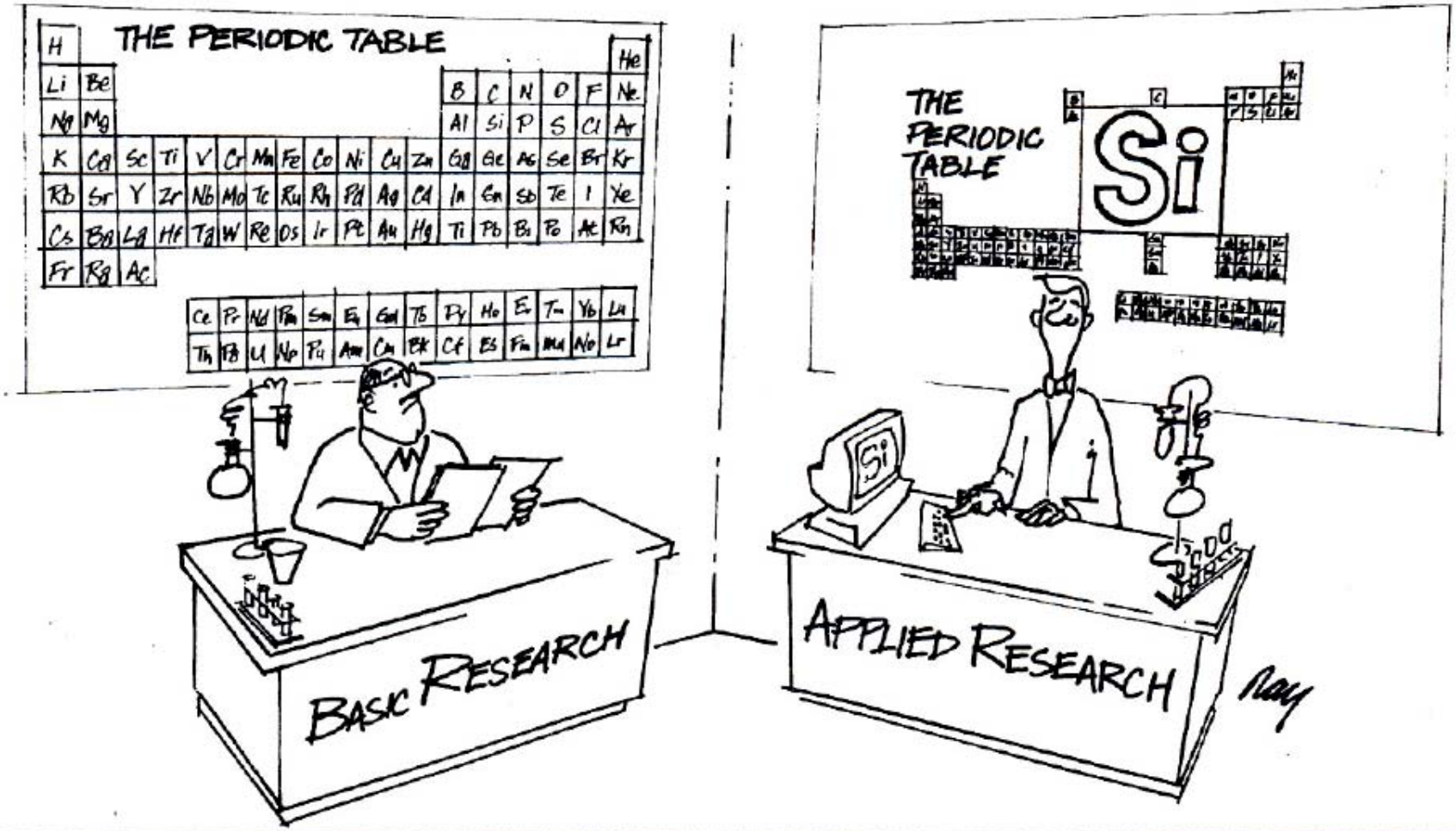
- Process improvements
- Performance improvements

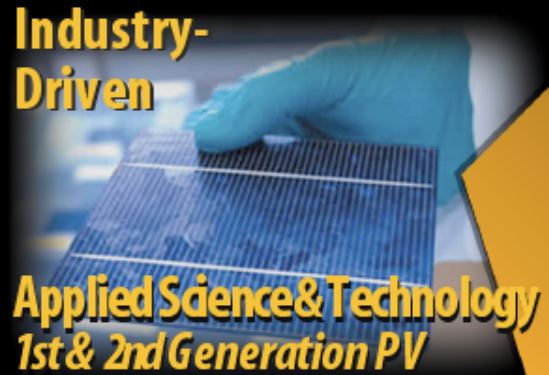
Accelerated other technologies.

- Thin films into the marketplace
- Established companies look at alternatives

Problem: Si Shortage


THE PERIODIC TABLE
BASIC RESEARCH
THE PERIODIC TABLE
Si
APPLIED RESEARCH

Technololgy Investment Pathways



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Accelerated Evolutionary
(3-5 years)

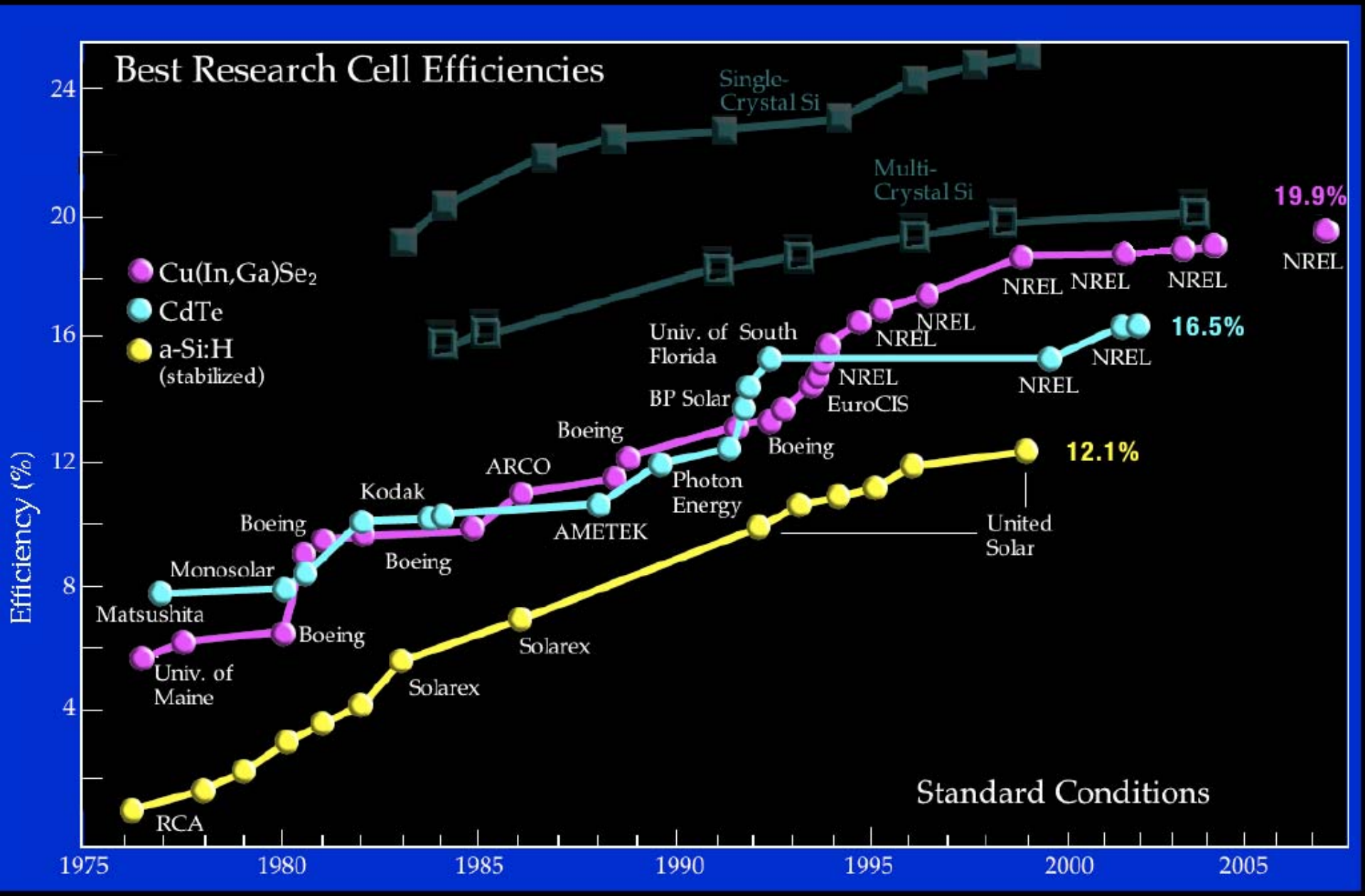
Disruptive
(3-15 years)

Technology-Driven

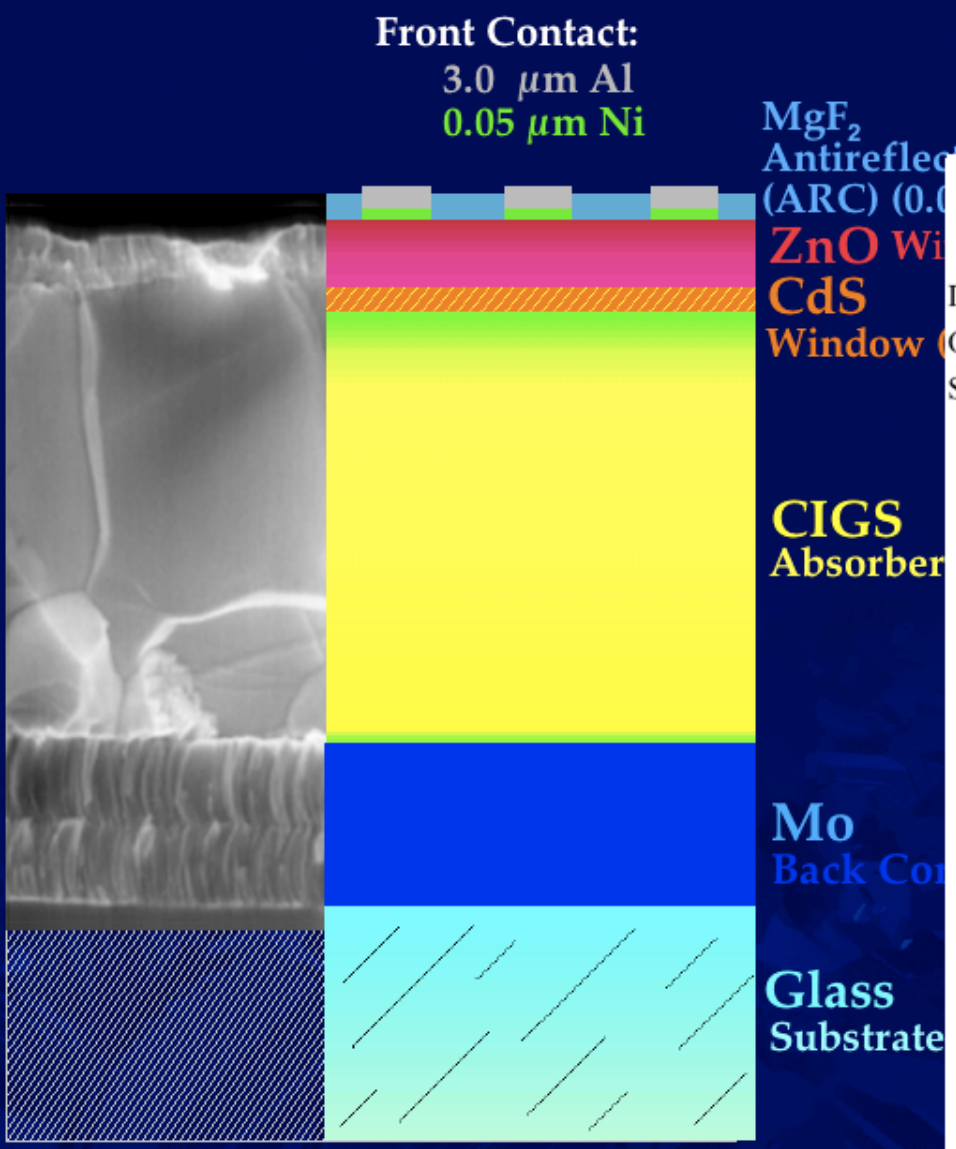
Transformational Science & Technology

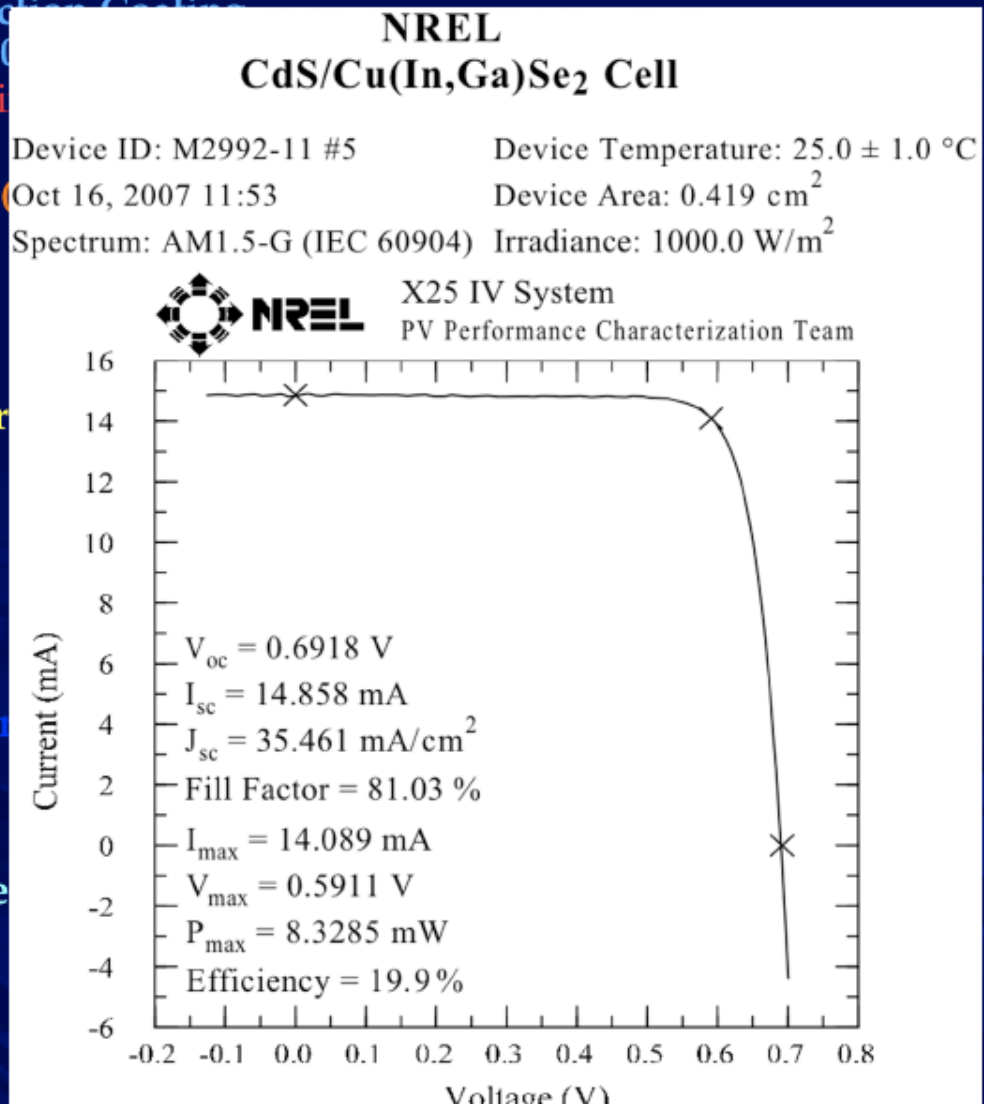
2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%


Best Research Cell Efficiencies
Single-Crystal Si
Multi-Crystal Si
Cu(In,Ga)Se2
CdTe
a-Si:H (stabilized)
19.9%
16.5%
12.1%
NREL
Univ. of South Florida
BP Solar
EuroCIS
Boeing
ARCO
Kodak
Photon Energy
AMETEK
United Solar
Monosolar
Matsushita
Univ. of Maine
Solarex
RCA
Standard Conditions
Efficiency (%)
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005

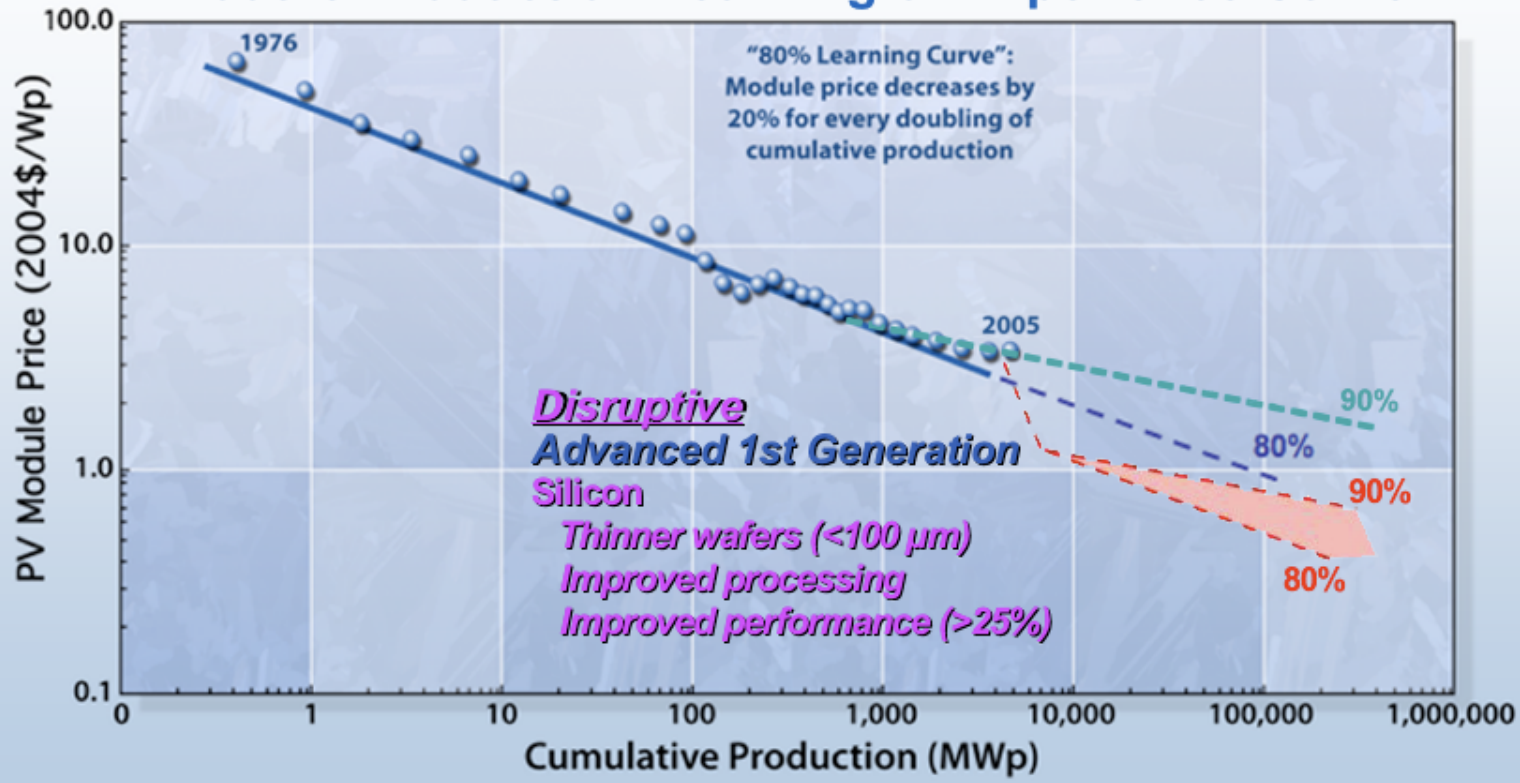
Thin-Film $Cu(In,Ga)(S,Se)_2$ - CIGSSe





Technololgy Investment Pathways

Module Production Learning or Experience Curve



Industry-Driven

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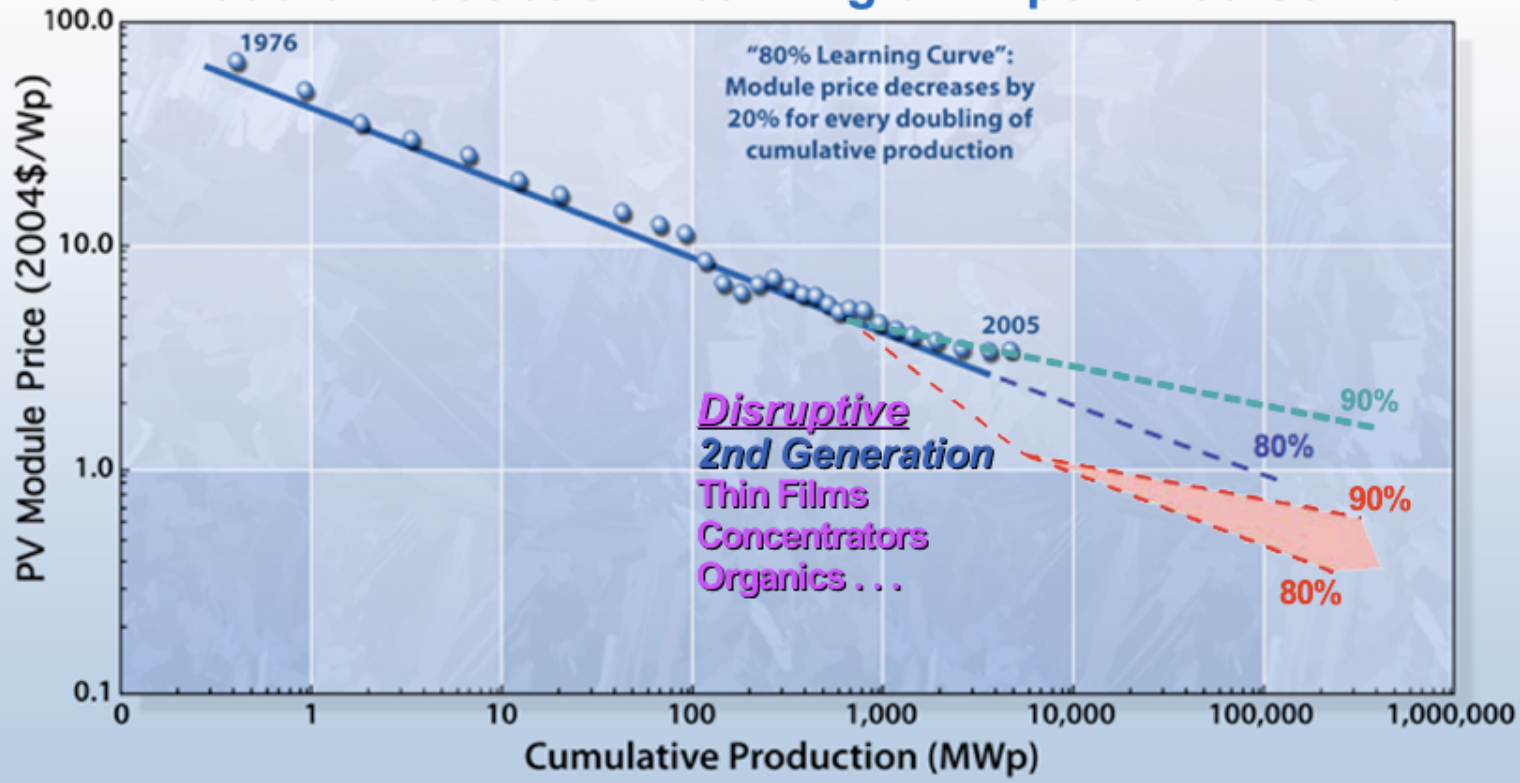

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Applied Materials announces $1.9 billion deal for solar panels

By Matt Nauman
Mercury News
Article Launched: 03/04/2008 10:15:17 AM PST

Applied Materials, the Santa Clara chip equipment maker, announced a deal this morning to supply $1.9 billion worth of machinery for making thin-film solar panels.

Green Energy
More updates and information

The tools will be used in factories that will manufacture enough solar panels to produce 1 gigawatt of electricity a year. Last year, the world's solar industry produced enough panels to make 12 gigawatts of electricity.

"It is the largest sales agreement in Applied history and quite possibly in the history of the solar industry," said Patricia Zepeda-Vera, a company spokeswoman.

Applied Materials won't name its customer for this transaction, she said, but it needed to file something with the U.S. Securities and Exchange Commission due to the size of the contract.

The company was only identified in SEC filings as "a privately held corporation based outside the United States."

Applied said in its most recent earnings report for its first fiscal quarter that it took $260 million worth of orders in its division that sells solar-panel-production equipment, up from $31 million in its first fiscal quarter of 2007.

Most of those orders came from companies outside the United States, it said - 24 percent from Taiwan, 19 percent from Korea, 13 percent from Japan, 12 percent from Europe and 10 percent from China and Southeast Asia. North American companies placed 22 percent of the orders.

The company's operating loss for that product line rose from $15 million to $48 million due to increased R&D spending on lower-cost solar equipment, amortization of recent acquisitions and marketing cost for its expanding solar business.

Contact Matt Nauman at mnauman@mercurynews.com or (408) 920-5701.

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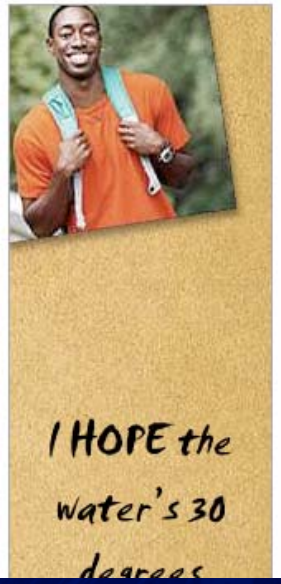


Thin-Film PV Companies (USA)

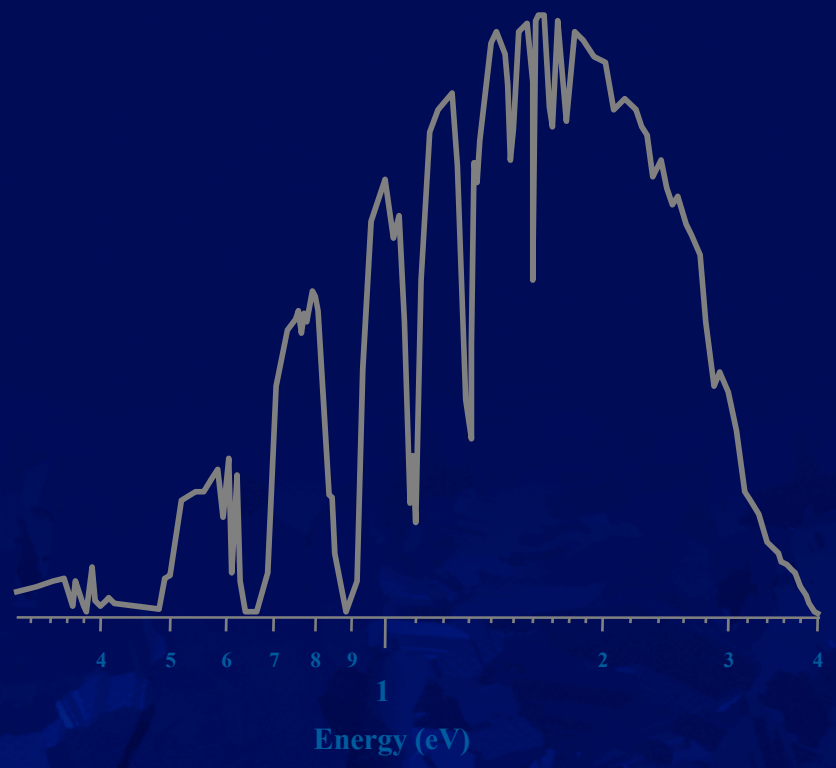
a-Si/Thin-Si
Uni-Solar – MI
Applied Materials – CA
Power Films – IA
Energy PV – NJ
MV Systems – CO
XsunX – CA
OptiSolar – CA
Signet Solar – CA
Nano PV – NJ
MWOE Solar – OH
Proto Flex – CO
New Solar Ventures – NM
Innovalight – CA
Nanogram – CA
Soltaix – CA
Xunlight Corp. - OH

CdTe
First Solar – OH
PrimeStar Solar – CO
AVA Solar – CO
Solar Fields – OH
Canrom – NY
Ascentool – CA
Nuvo Solar Energy – CO
Zia Watt Solar – TX
Solexant – CA
Bloo Solar – CA

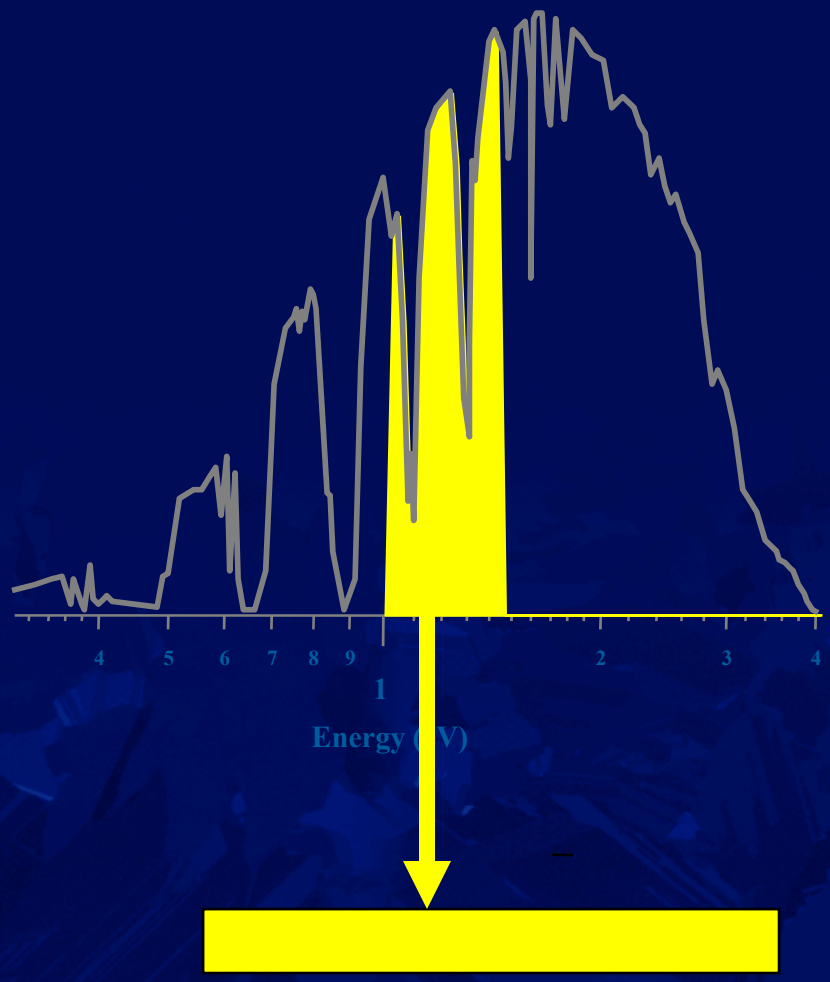
CIS
Global Solar – AZ
Miasole – CA
Energy PV – NJ
Ascent Solar – CO
ISET – CA
ITN/ES – CO
Daystar – NY
Nanosolar – CA
Heliovolt – TX
Solo Power – CA
Solyndra – CA
RESI – NJ
Light Solar – NV
Ampulse – TN
Stion – CA

Organic
Konarka – MA
Plextronix – PA
GPEC – NJ
LumoFlex – GA
MicroFab – TX
Luna Innovations – VA

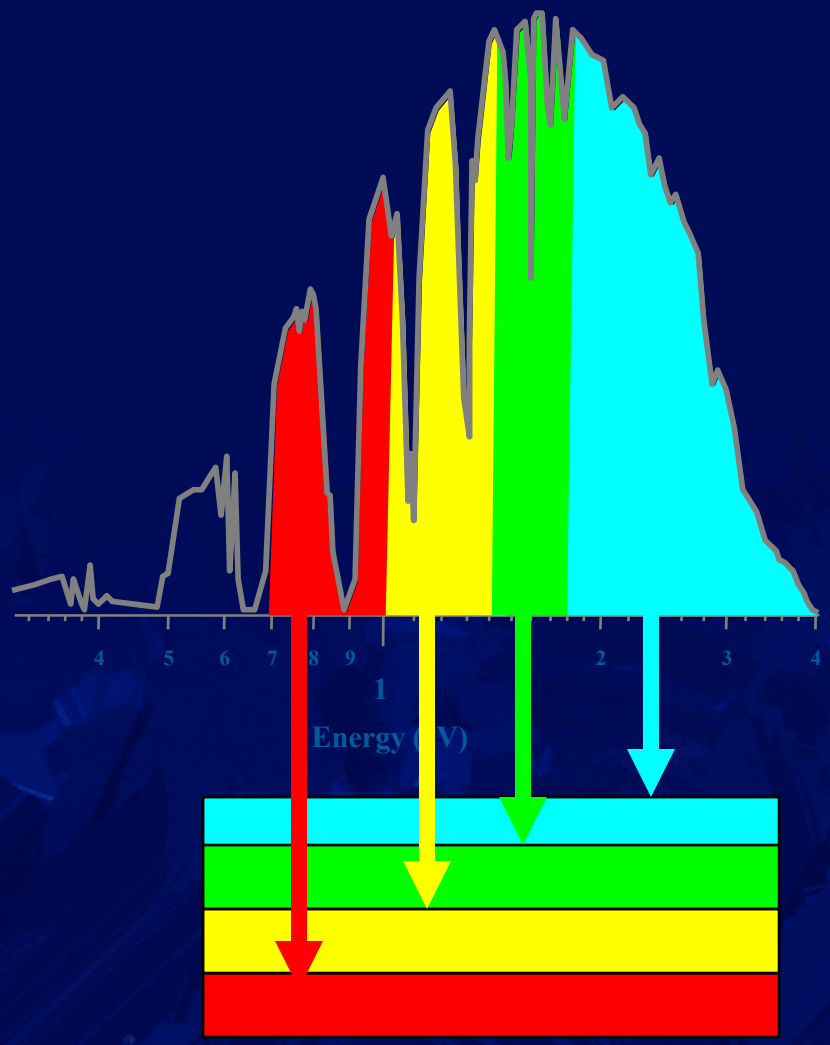
Terrestrial solar spectrum



Single-junction cells respond to a specific portion of the solar spectrum

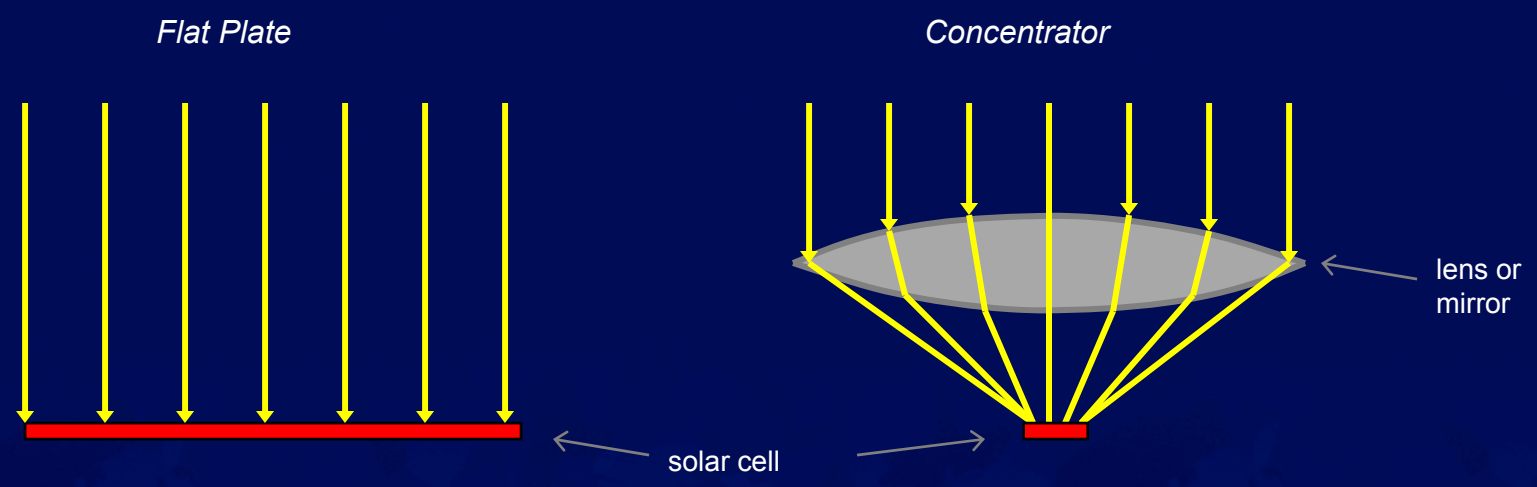


Multijunction cells use multiple materials to more fully match the solar spectrum

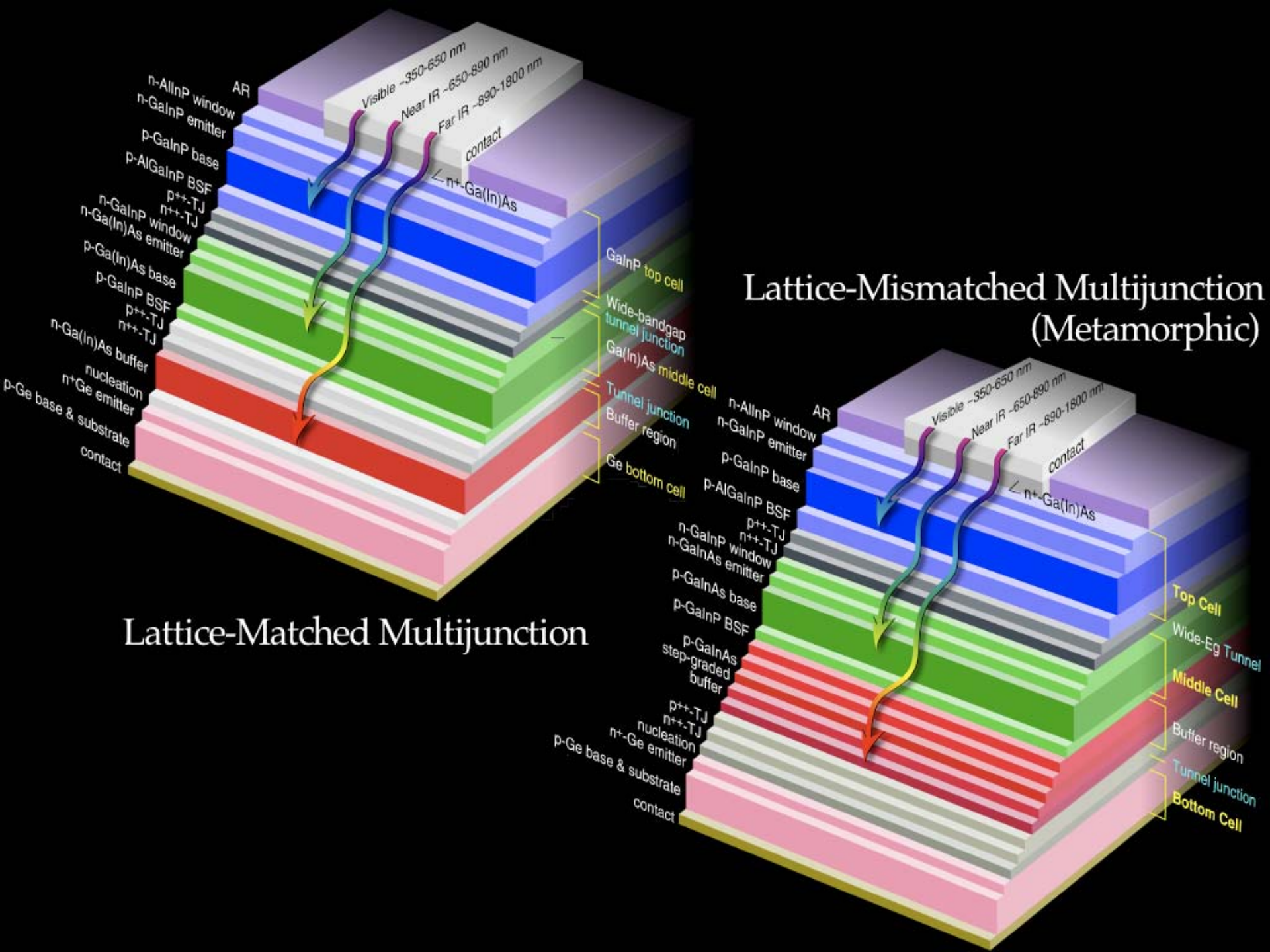


Concentrator Photovoltaics

Use optics to reduce the cell area *(from 2 to more than 1000 times)*



Shifts the major system cost from the cell to the optics
Can afford more efficient, expensive cells


Lattice-Matched Multijunction
AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-Ga(In)As emitter
p-Ga(In)As base
p-GaInP BSF
p++-TJ
n++-TJ
n-Ga(In)As buffer
nucleation
n+Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
GaInP top cell
Wide-bandgap tunnel junction
Ga(In)As middle cell
Tunnel junction
Buffer region
Ge bottom cell
Lattice-Mismatched Multijunction (Metamorphic)
AR
n-AlInP window
n-GaInP emitter
p-GaInP base
p-AlGaInP BSF
p++-TJ
n++-TJ
n-GaInP window
n-GaInAs emitter
p-GaInAs base
p-GaInP BSF
p-GaInAs step-graded buffer
p++-TJ
n++-TJ
nucleation
n+-Ge emitter
p-Ge base & substrate
contact
Visible ~350-650 nm
Near IR ~650-890 nm
Far IR ~890-1800 nm
contact
n+-Ga(In)As
Top Cell
Wide-Eg Tunnel
Middle Cell
Buffer region
Tunnel junction
Bottom Cell

Spectrolab **GaInP/GaInAs/Ge Cell**

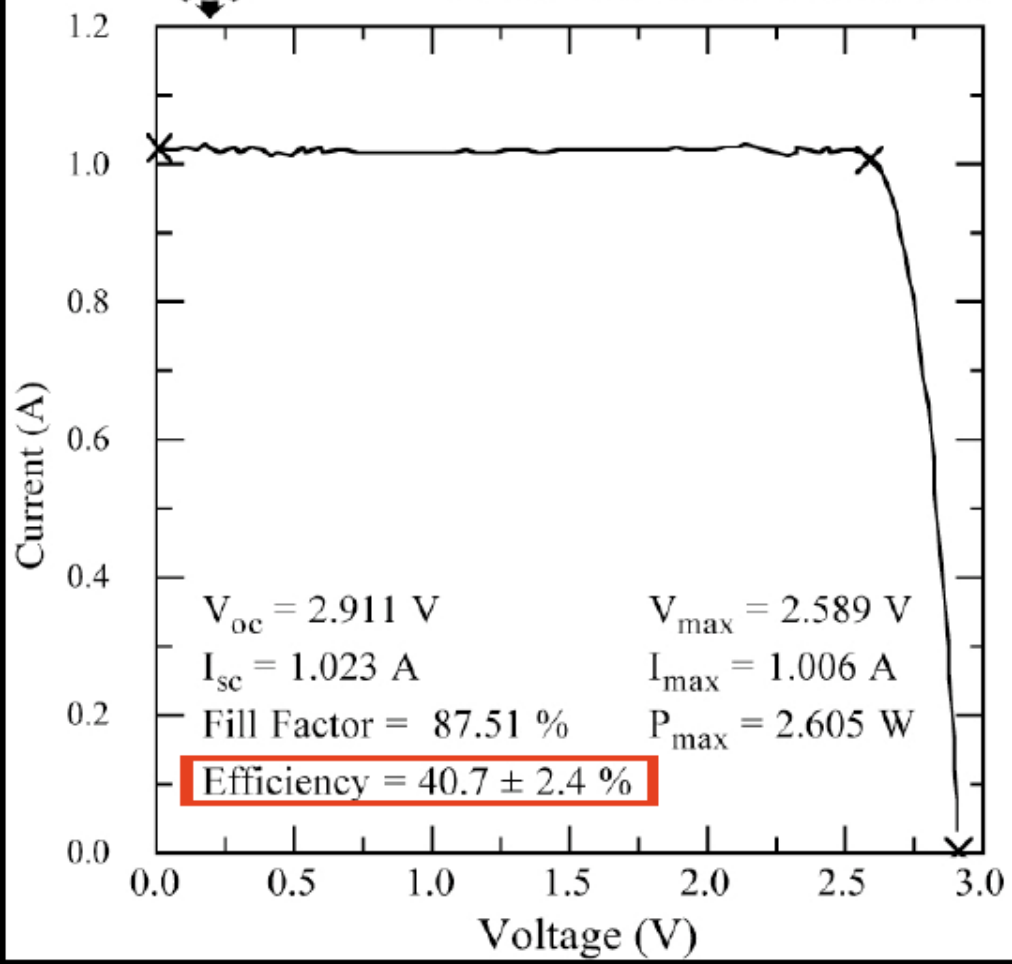
Sample: 6997-C407 Device Temperature = 25.0°C

Wed, Sep 6, 2006 7:46 PM area used = 0.26685 cm^2

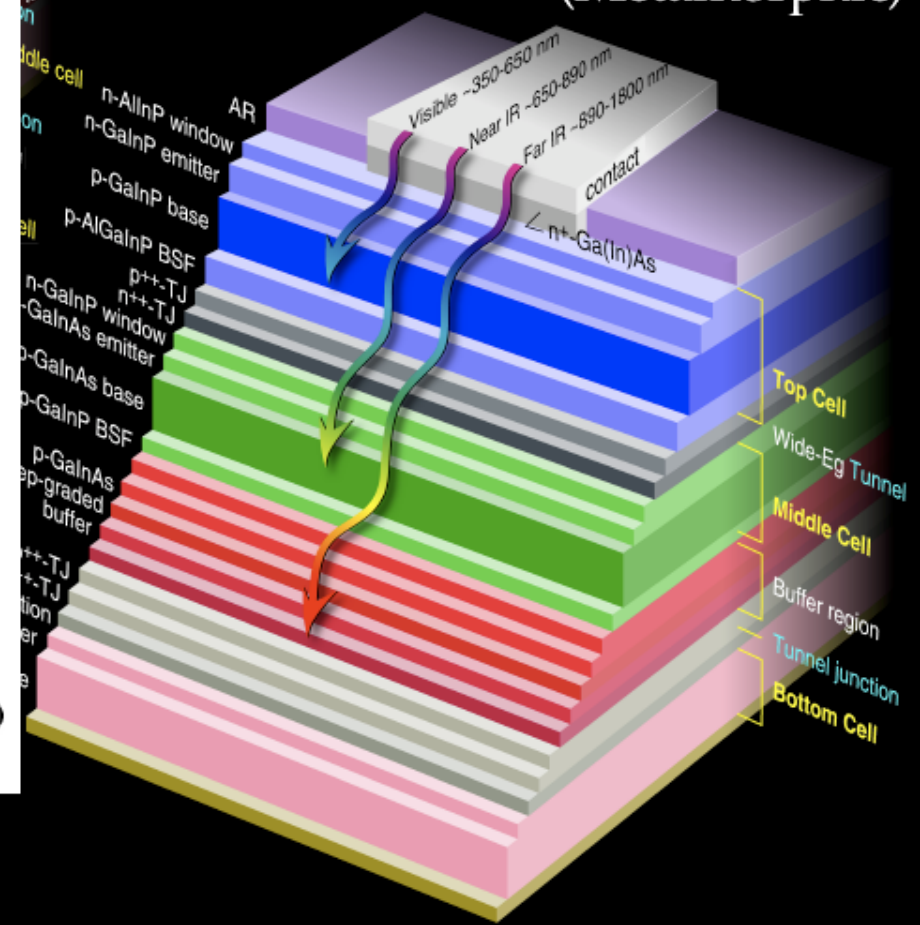
HiPer Direct Reference Irradiance: 240037.1 W/m^2

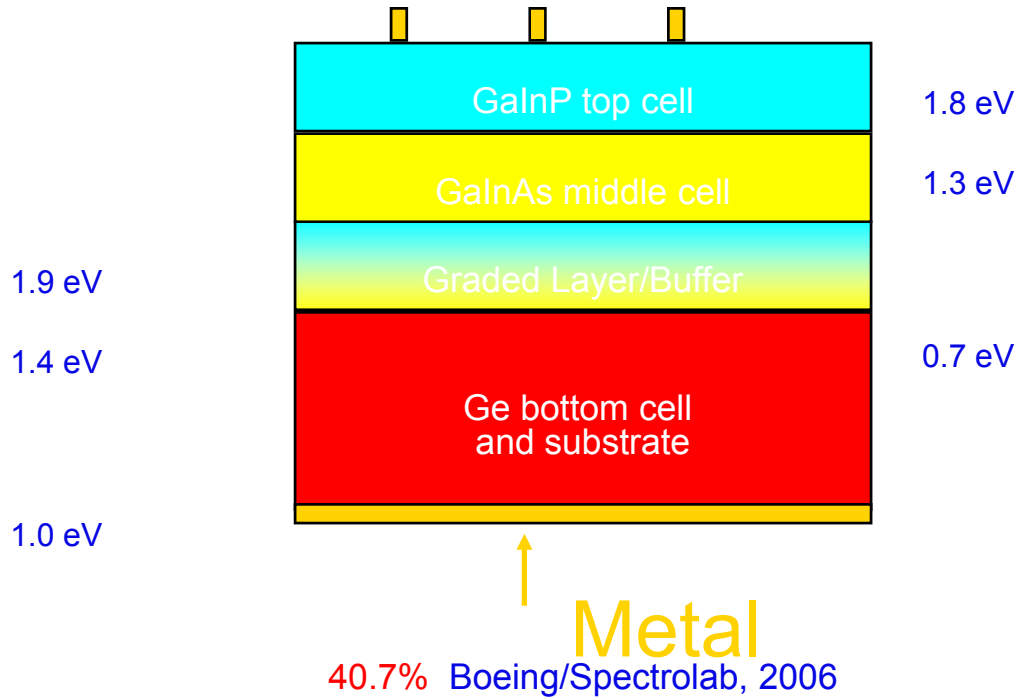
NREL HIPSS

PV Performance Characterization Team

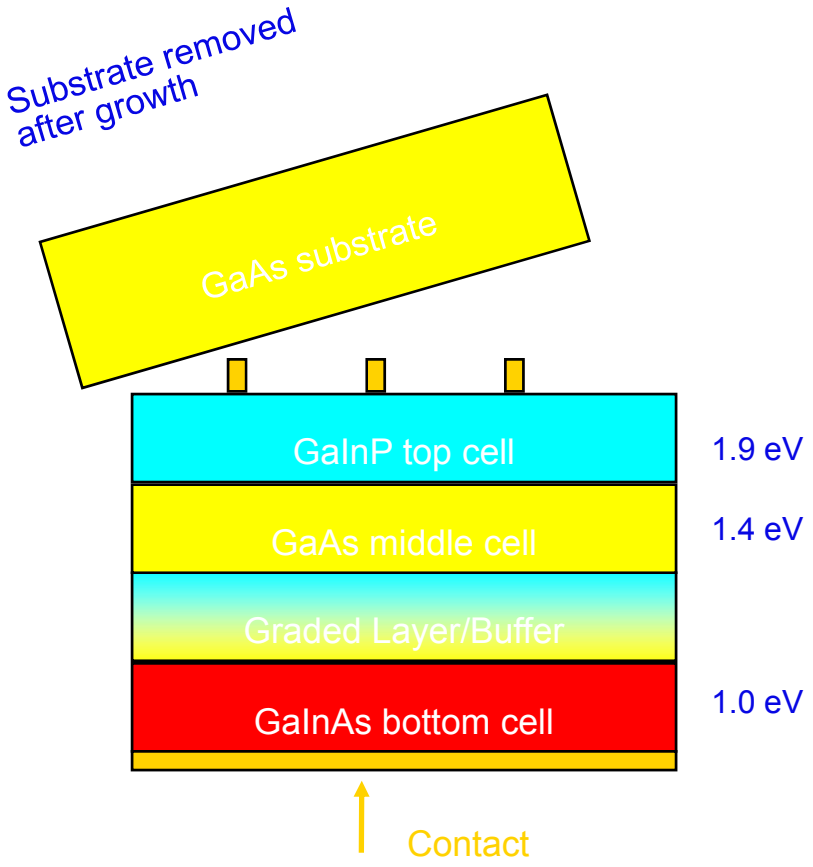


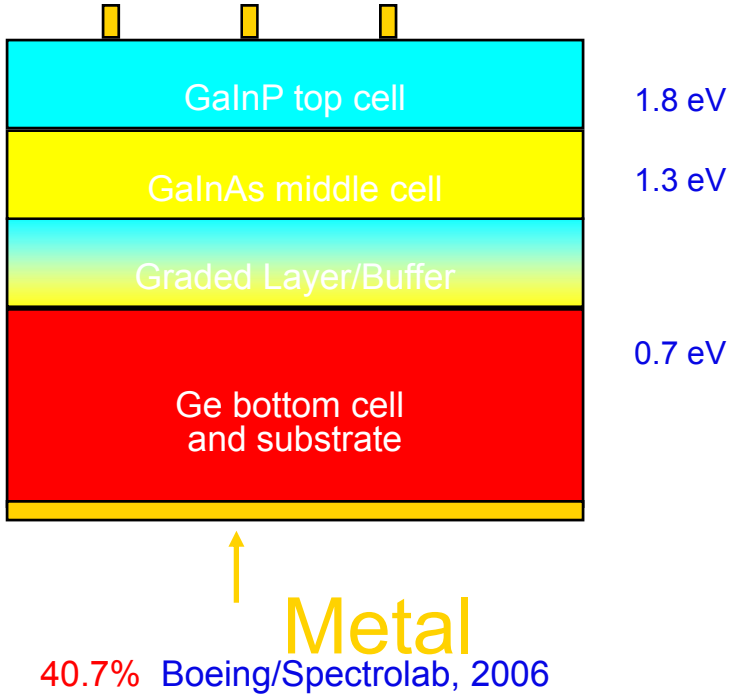
Lattice-Mismatched Multijunction (Metamorphic)





New research: from 40% to 50%





40.7% Boeing/Spectrolab, 2006

38.9% @ 80 suns
NREL, 2007

New research: from 40% to 50%

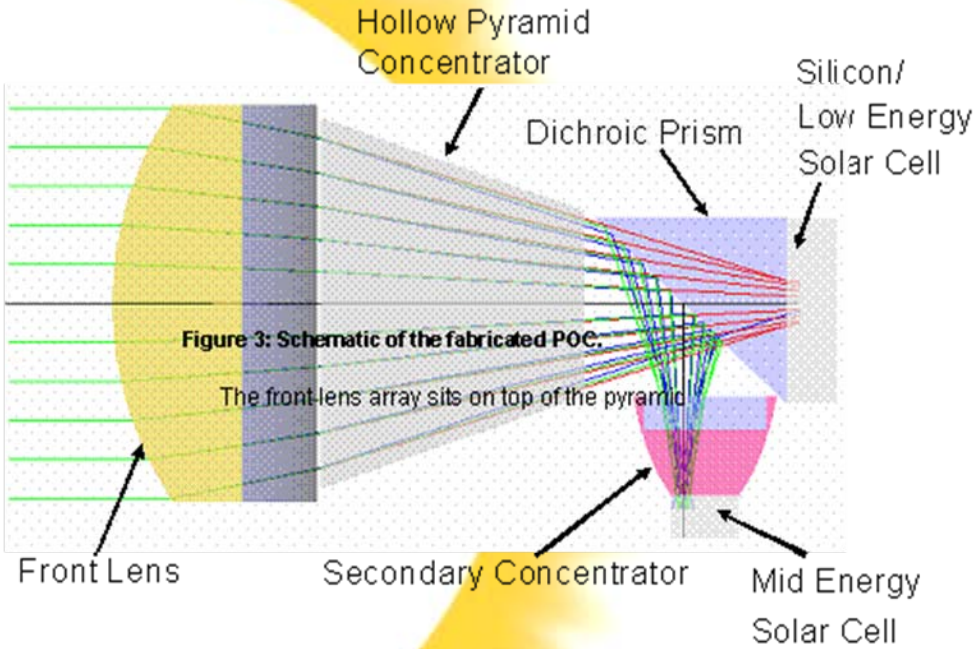


Figure 3: Schematic of the fabricated POC.

The front-lens array sits on top of the pyramid

Technololgy Investment Pathways

Industry-Driven

Applied Science & Technology

1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

Accelerated Evolutionary
(3-5 years)

Disruptive
(5-15 years)

Technology-Driven

Transformational Science & Technology

2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%

CPV Companies (USA)

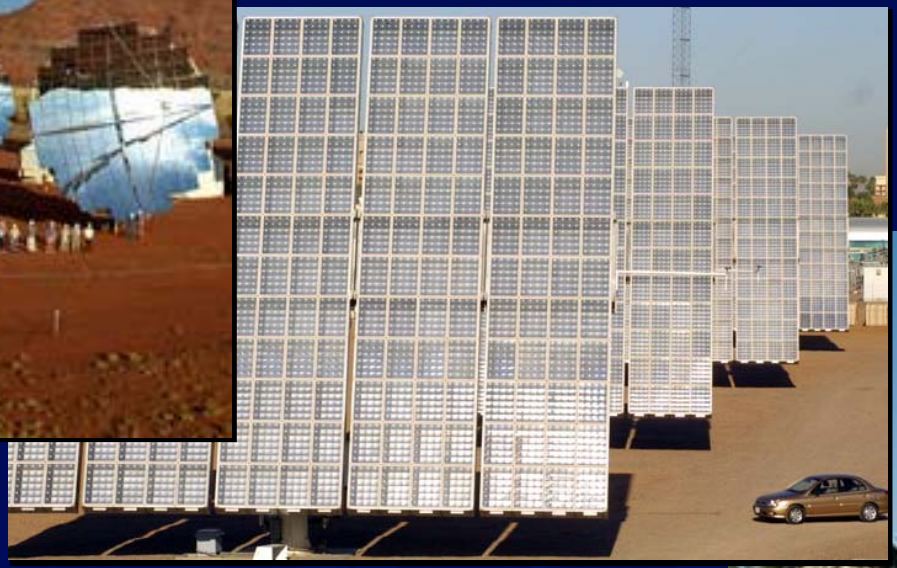
Triple-Junction
High Efficiency
(cells/modules/systems)
Spectrolab - CA
Emcore - NM
MicroLink Devices - IL
Opel International - CT

Modules/Systems
Amonix - CA
JX Crystals - WA
SolFocus - CA
Practical Instruments - CA
Stellaris - MA
Soliant - CA
Energy Innovations - CA
Midway Labs - IL
Prism Solar Technologies - NY
Enfocus Engineering - CA
Solaria - CA
Cool Earth Solar - CA
Greenvolts Inc. - CA

CPV Systems

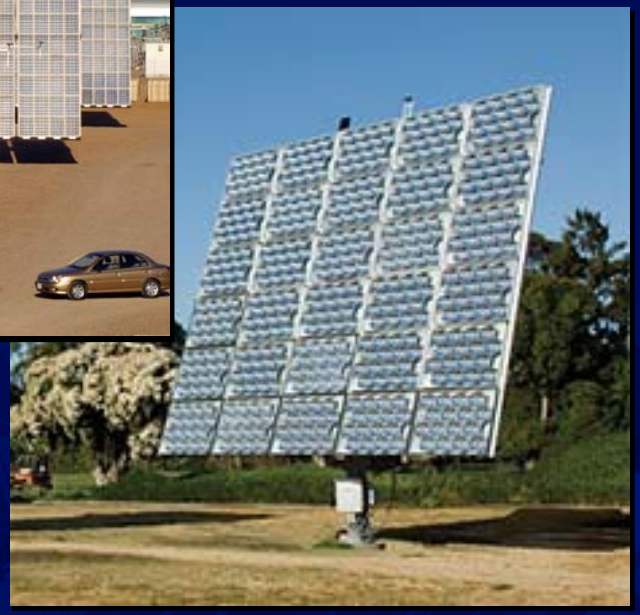
www.amonix.com

Solar Systems
(reflective)



www.solarsystems.com.au

Amonix *(refractive)*



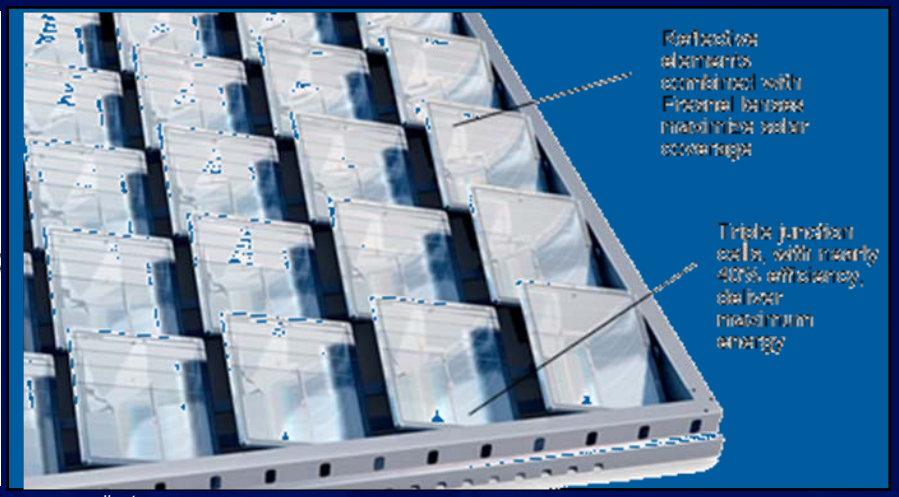
www.Solfocus.com

Solfocus
(reflective & optical rod)

Low-Profile CPV Systems

www.energyinnovations.com

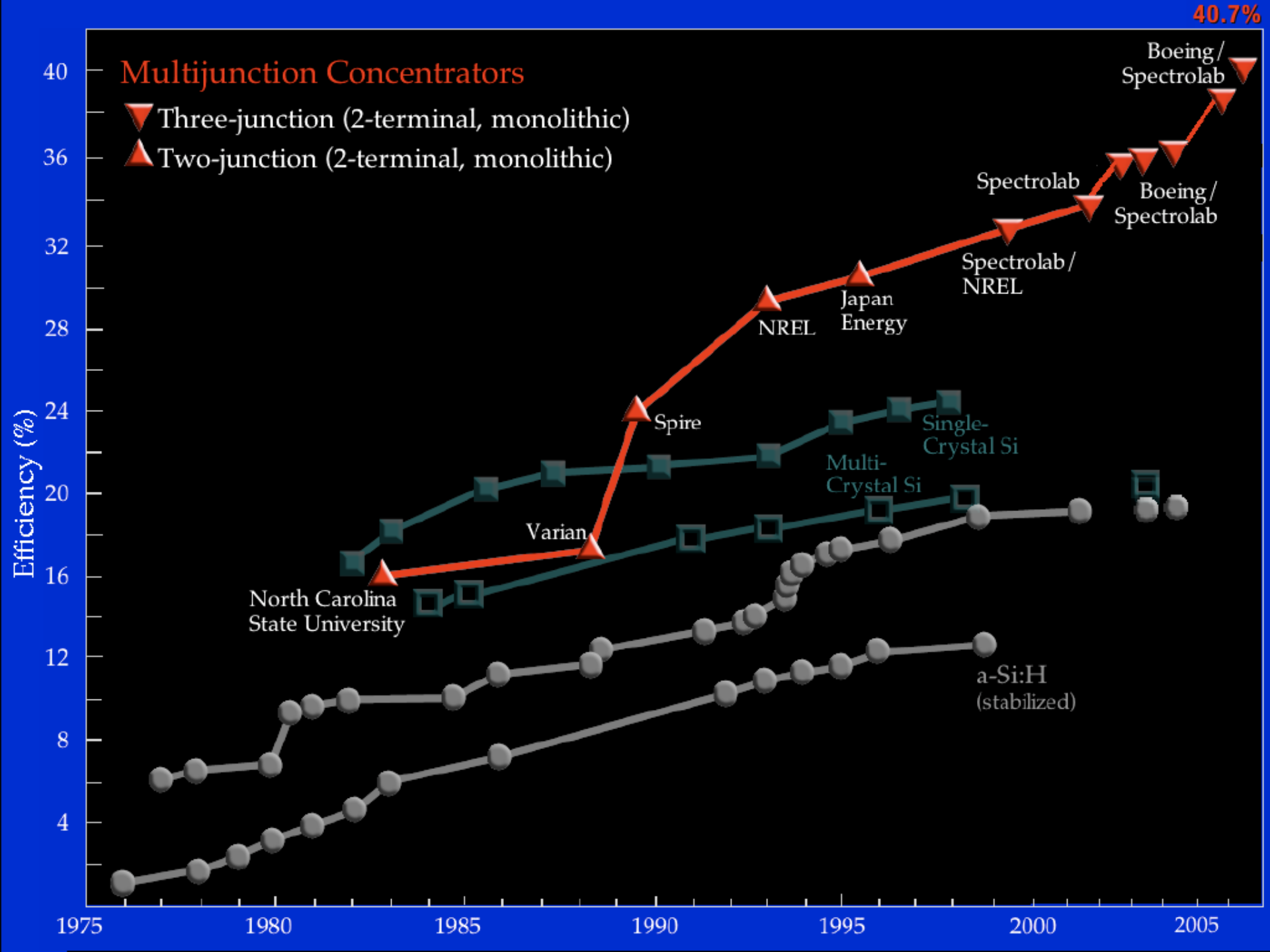
Energy Innovations *(800-suns)*

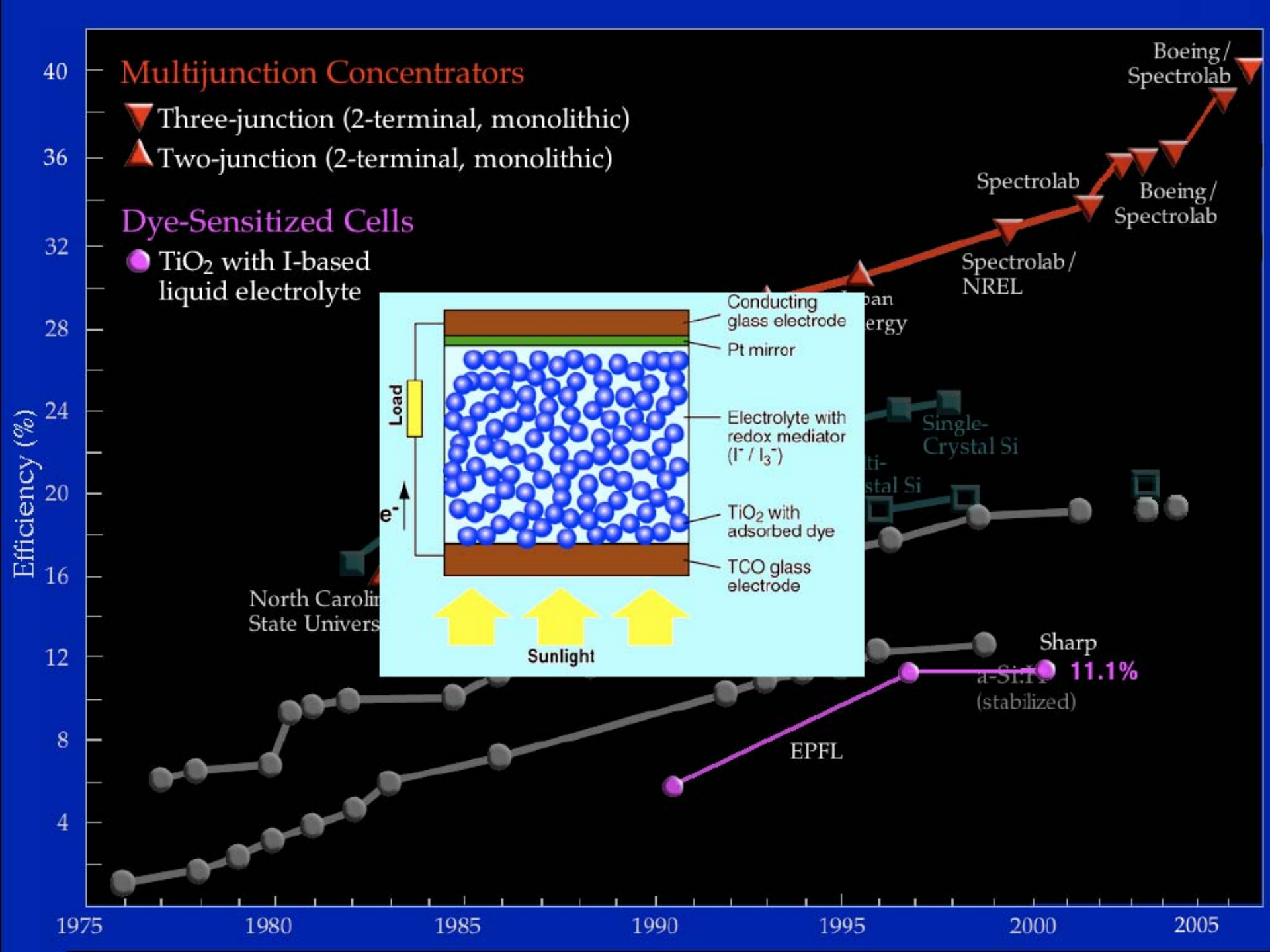


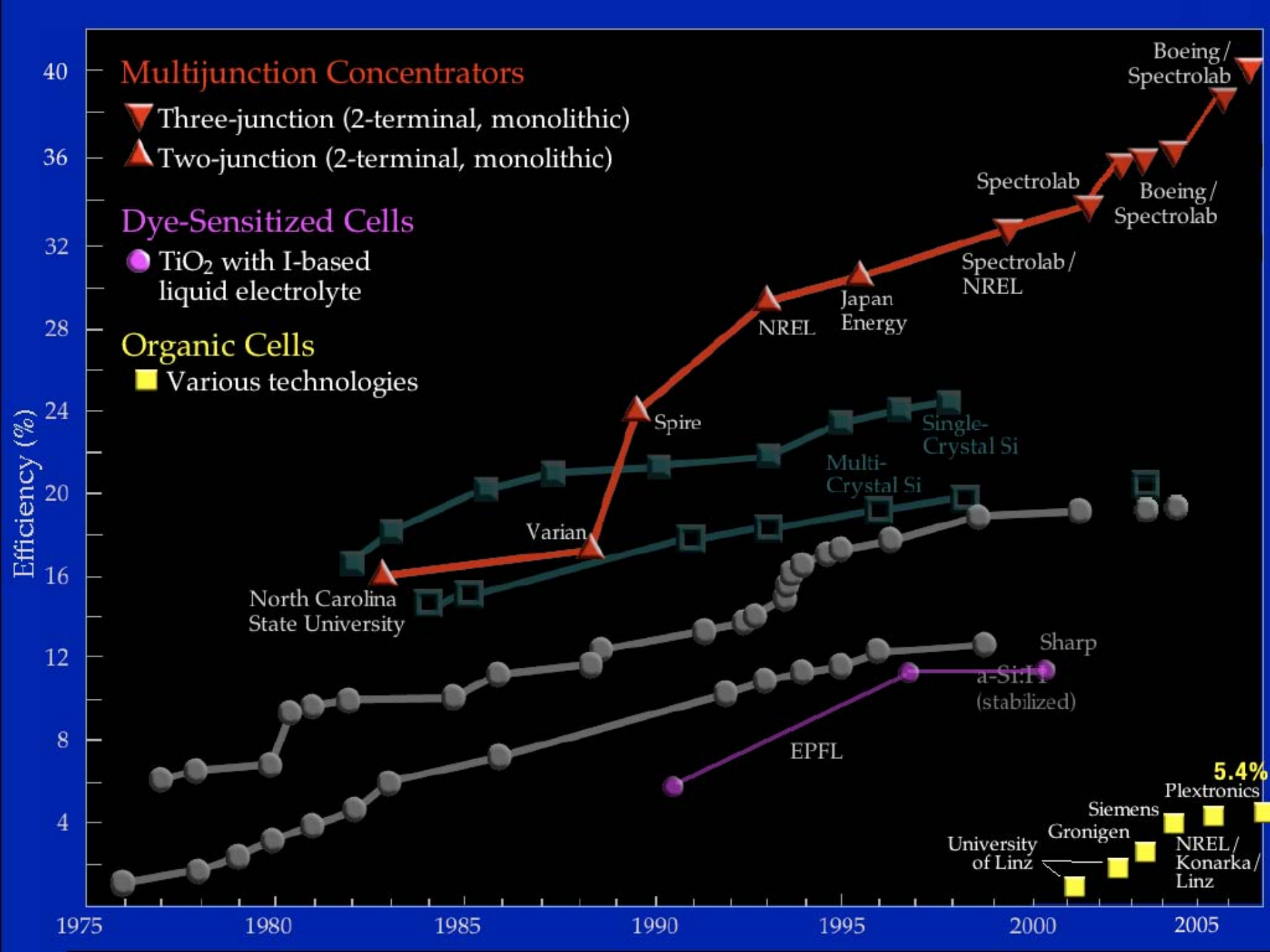
www.soliant-energy.com

Soliant Energy *(500-suns)*

Commercial rooftops and utility targeted


40.7%
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
Varian
North Carolina State University
a-Si:H (stabilized)


Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO2 with I-based liquid electrolyte
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Single-Crystal Si
Sharp
11.1%
(stabilized)
EPFL
Conducting glass electrode
Pt mirror
Electrolyte with redox mediator (I⁻ / I3⁻)
TiO2 with adsorbed dye
TCO glass electrode
Load
e⁻
Sunlight


Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Dye-Sensitized Cells
TiO_2 with I-based liquid electrolyte
Organic Cells
Various technologies
Efficiency (%)
40
36
32
28
24
20
16
12
8
4
1975
1980
1985
1990
1995
2000
2005
Boeing / Spectrolab
Spectrolab
Boeing / Spectrolab
Spectrolab / NREL
Japan Energy
NREL
Spire
Single-Crystal Si
Multi-Crystal Si
Varian
North Carolina State University
Sharp
a-Si:H (stabilized)
EPFL
5.4%
Plextronics
Siemens
Gronigen
University of Linz
NREL / Konarka / Linz

Technololgy Investment Pathways

Industry-Driven

Applied Science & Technology

1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
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Accelerated Evolutionary
(3-5 years)

Disruptive
(5-15 years)

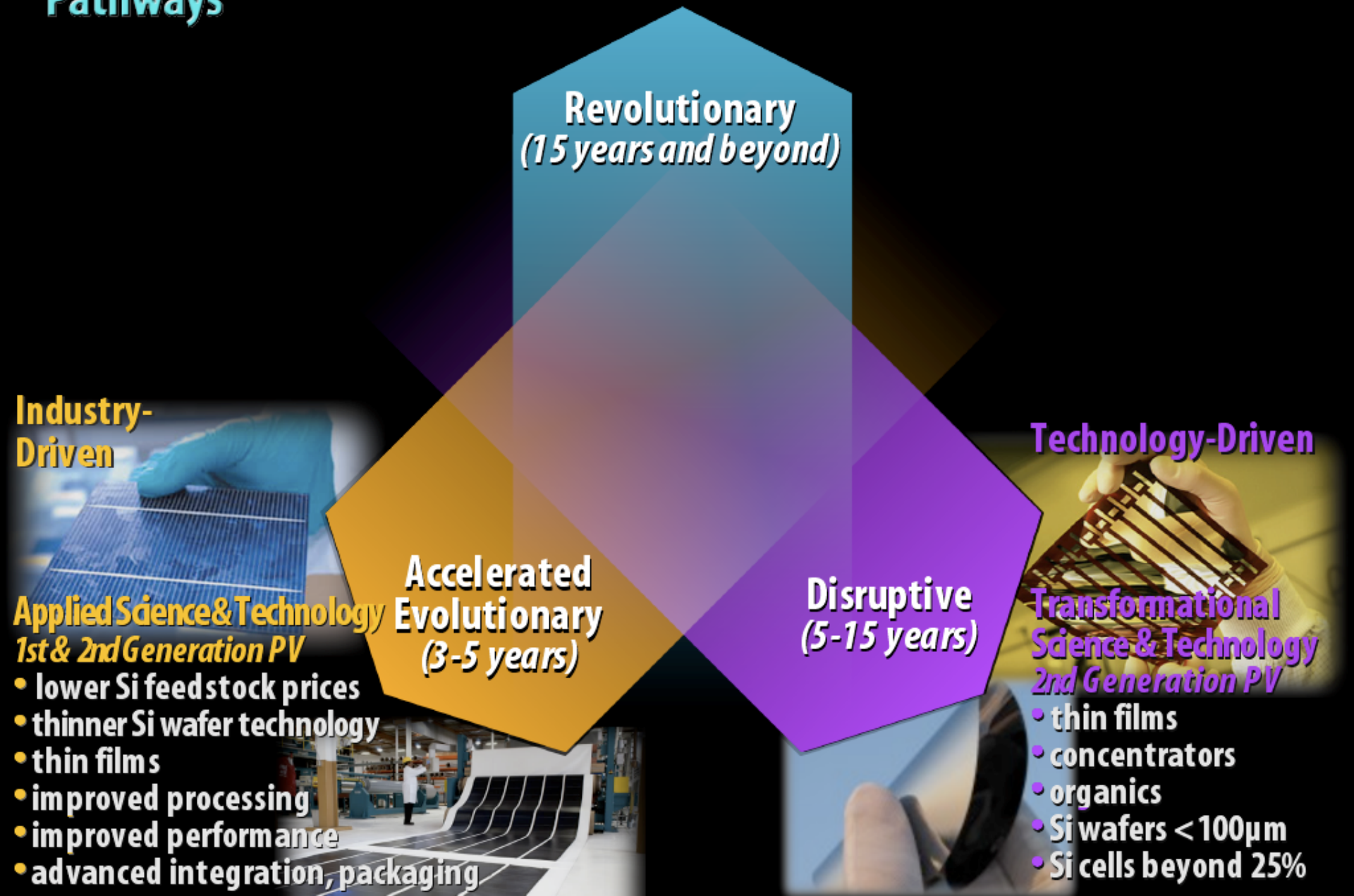
Technology-Driven

Transformational Science & Technology

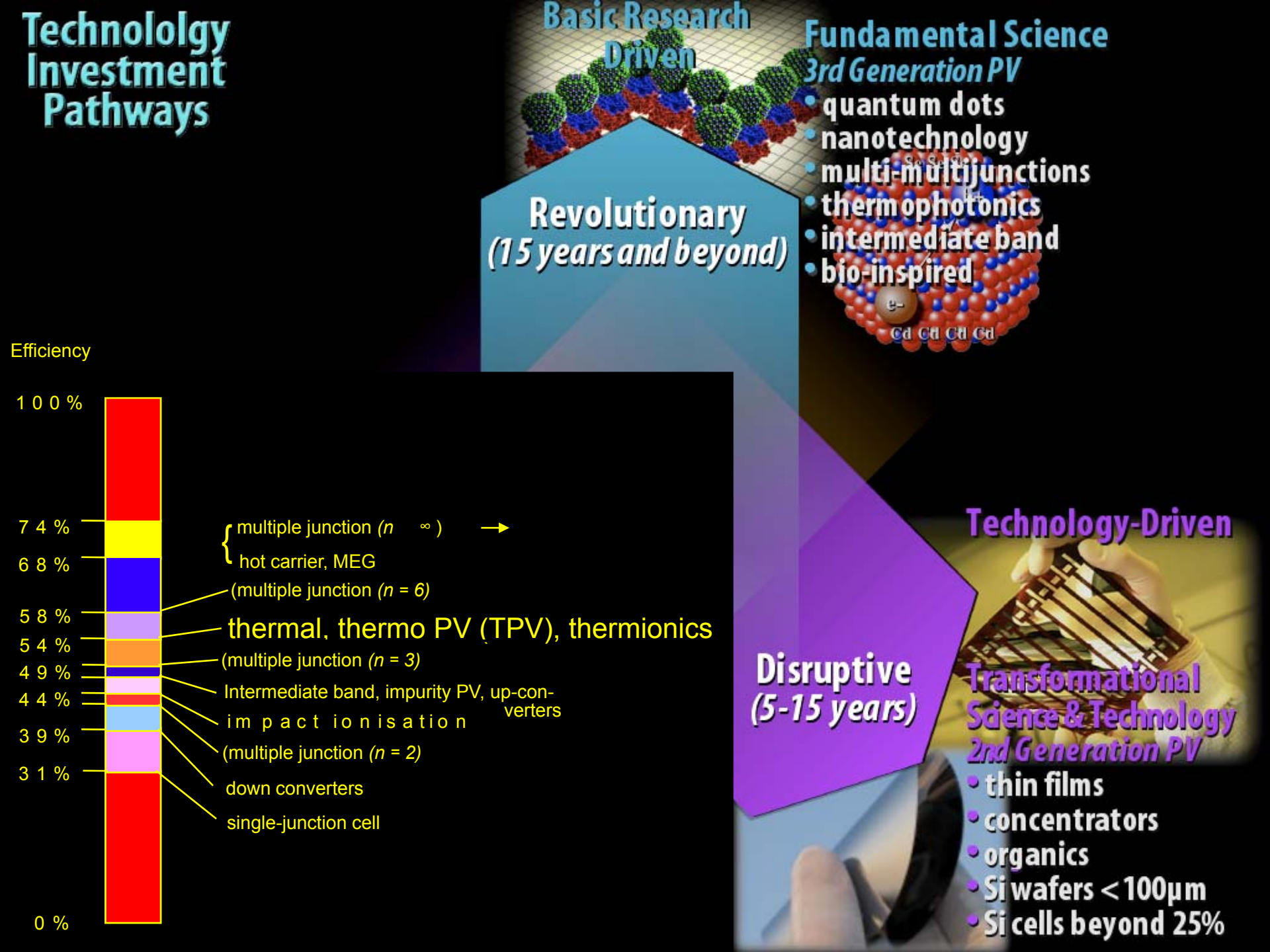
2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%

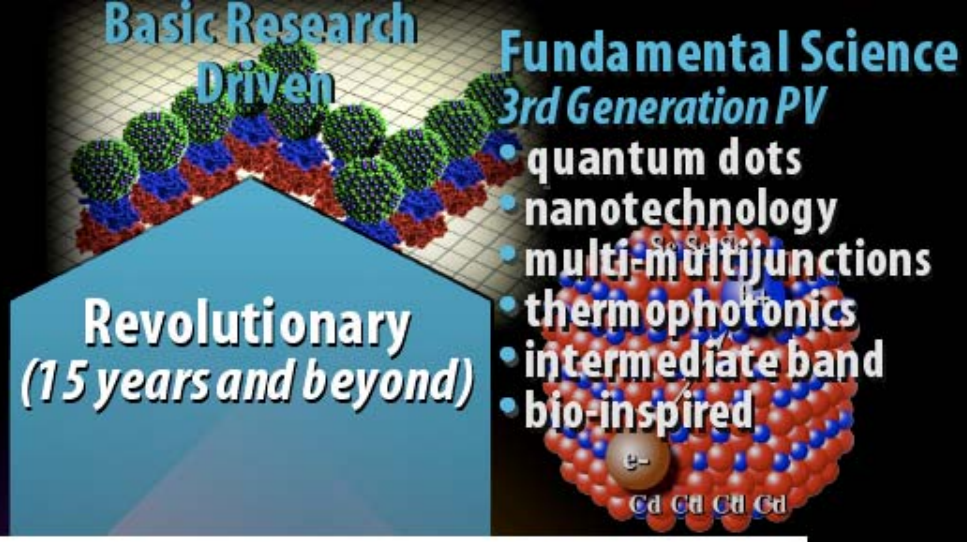
Technololgy Investment Pathways



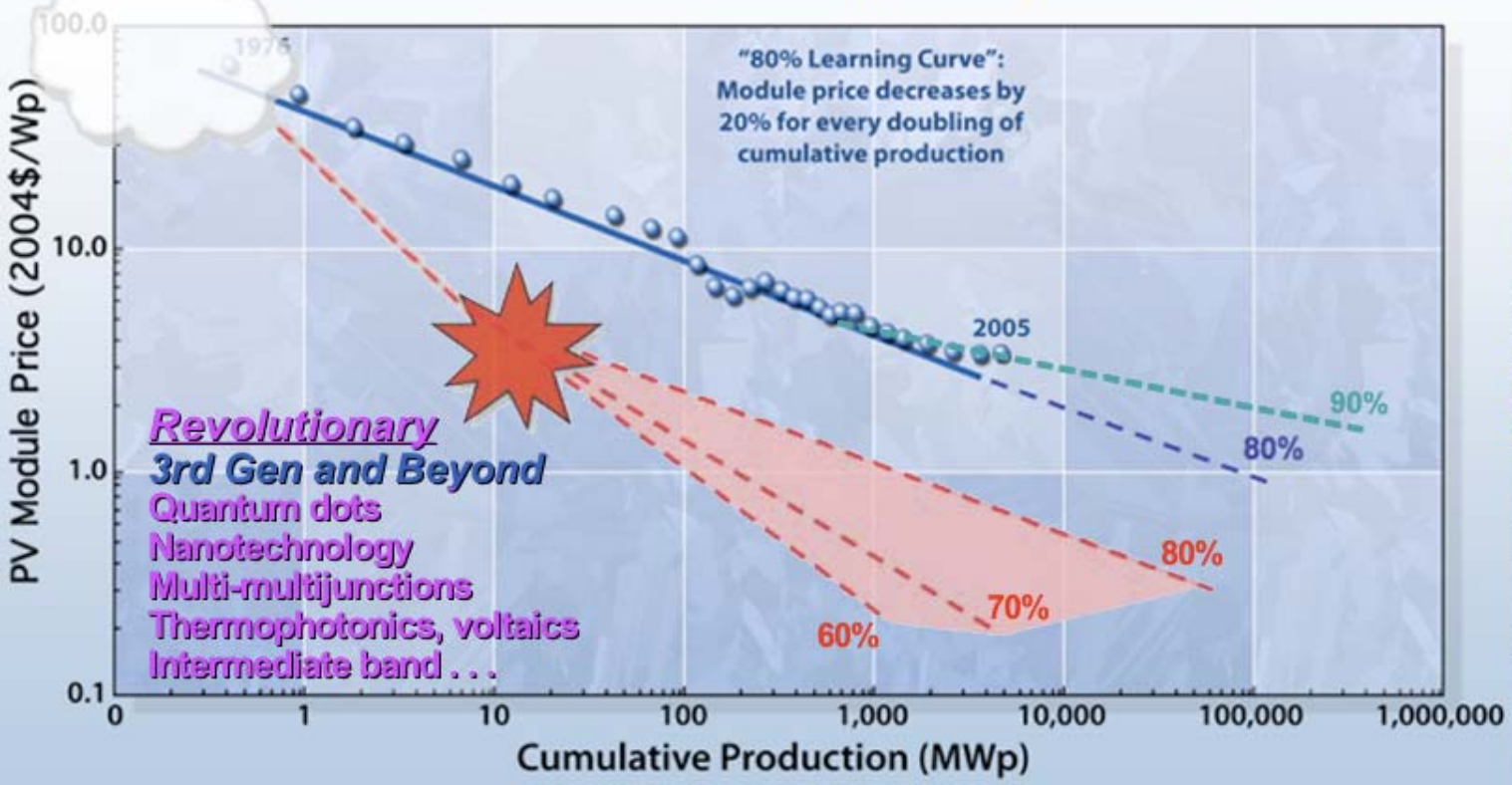
Technololgy Investment Pathways



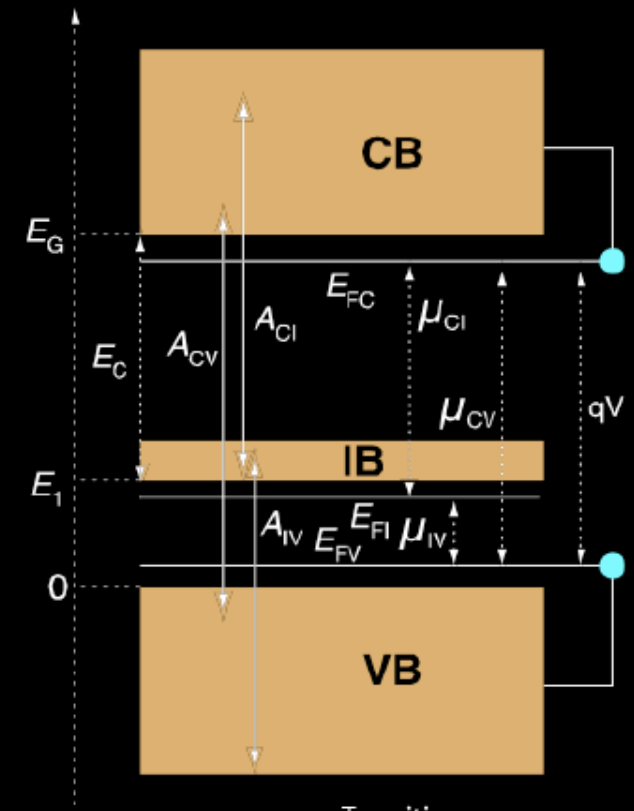
Technololgy Investment Pathways

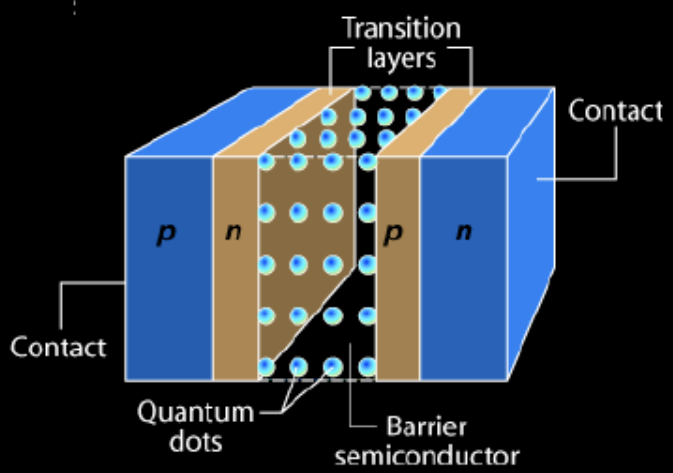


Module Production Learning or Experience Curve



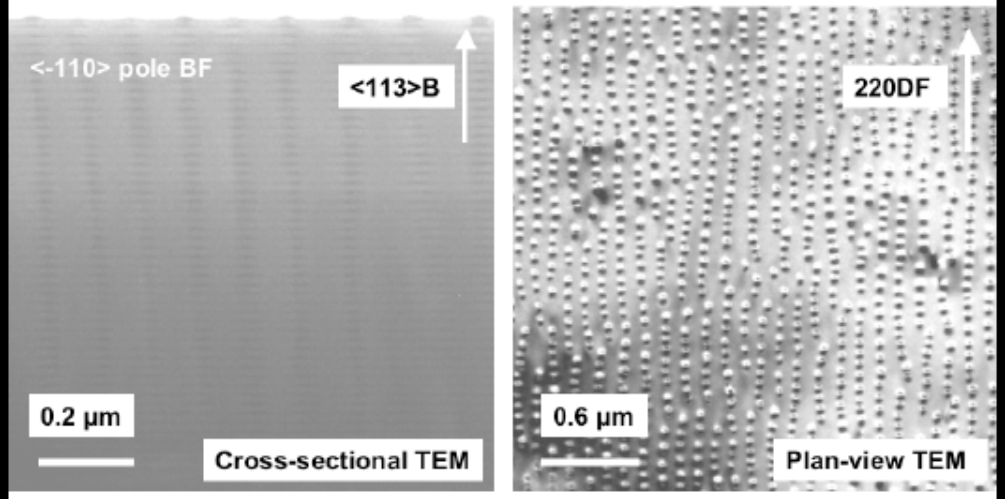
Intermediate Band Solar Cells





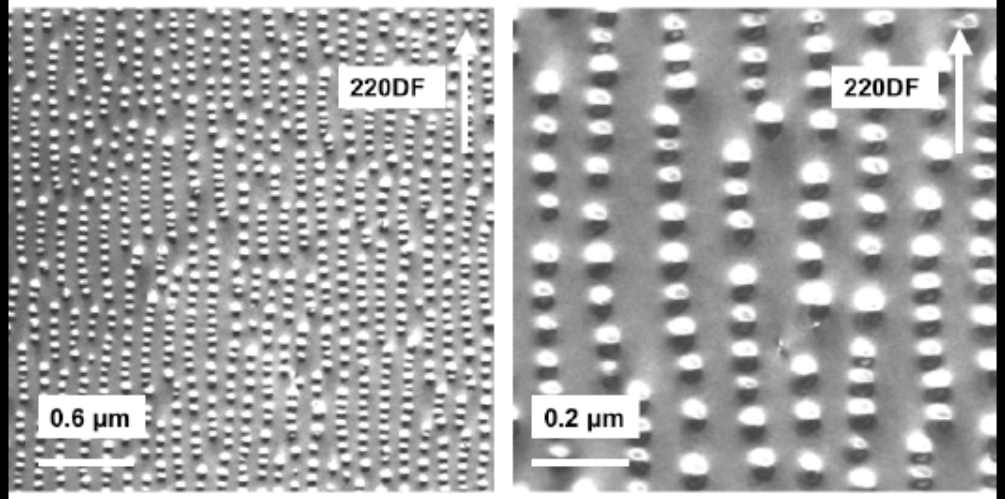
A. Norman, M Romero, and M. Al-Jassim, (NREL), A. Luque, A. Marti, Spain

MOCVD Growth of InGaAs/GaAs QD arrays on (113)B GaAs substrates for intermediate band solar cells



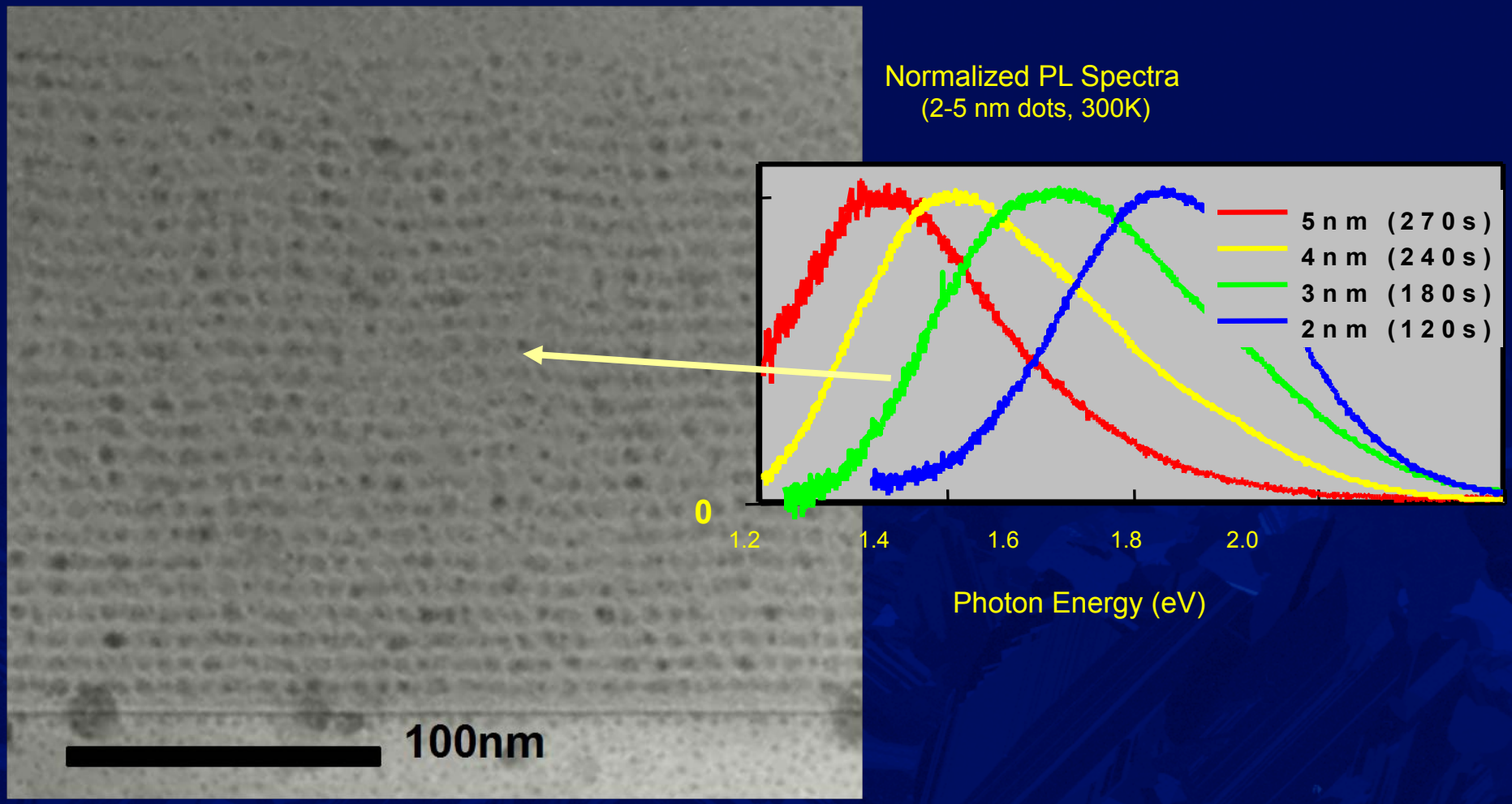
- QD arrays are being grown to test concept of intermediate band solar cell proposed by A. Martí and A. Luque

(311)B 50 period InGaAs/GaAs QD superlattice plan-view TEM



- Chains of quantum dots along <110>

Si quantum dot photoluminescence



Technololgy Investment Pathways

Basic Research Driven

Fundamental Science

3rd Generation PV

- quantum dots
- nanotechnology
- multi-multijunctions
- thermophotonics
- intermediate band
- bio-inspired

Revolutionary
(15 years and beyond)

Industry-Driven

Applied Science & Technology

1st & 2nd Generation PV

- lower Si feedstock prices
- thinner Si wafer technology
- thin films
- improved processing
- improved performance
- advanced integration, packaging

Accelerated Evolutionary
(3-5 years)

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Transformational Science & Technology

2nd Generation PV

- thin films
- concentrators
- organics
- Si wafers < 100µm
- Si cells beyond 25%

Technololgy Investment Pathways

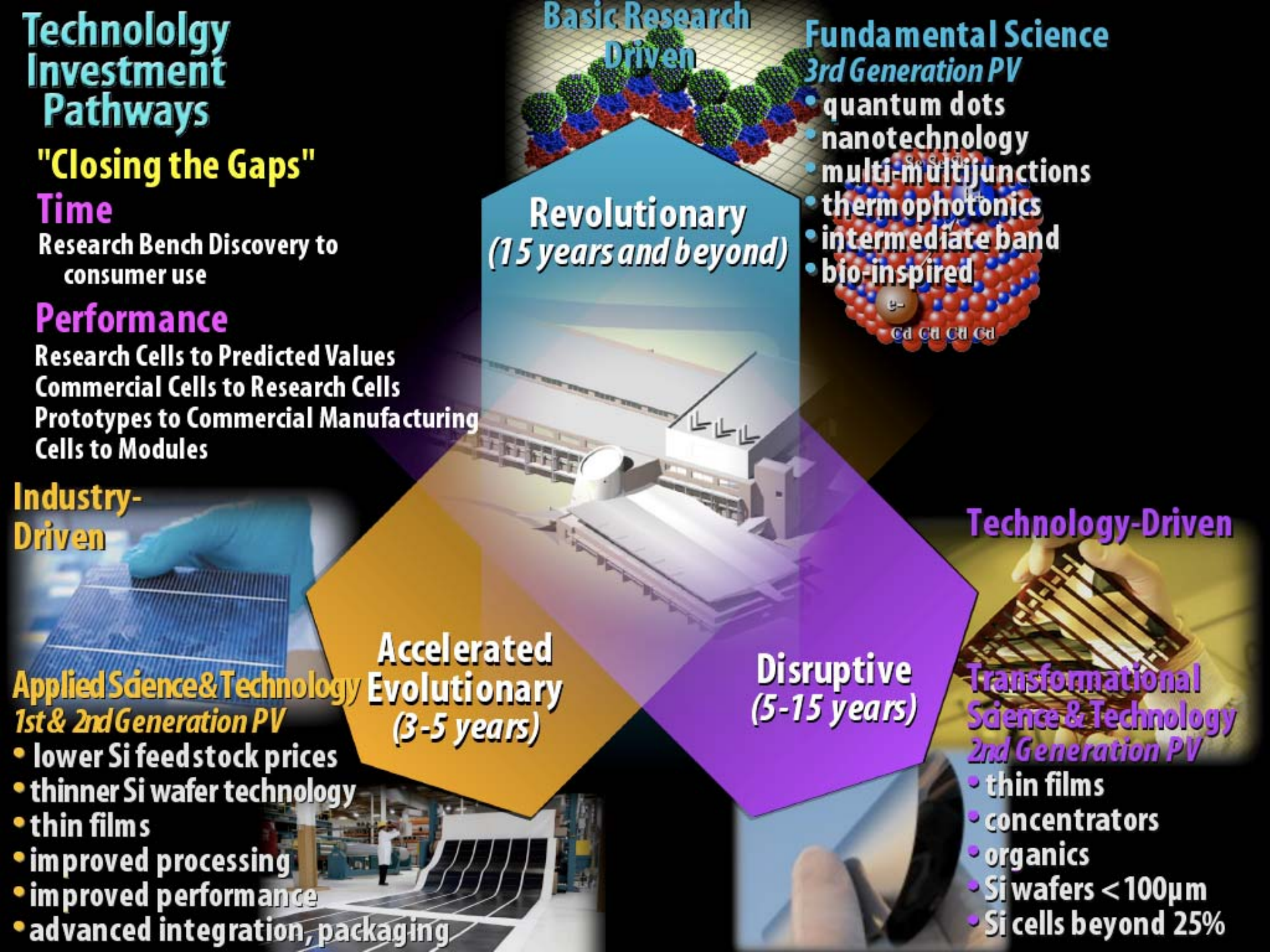
"Closing the Gaps"

Time

Research Bench Discovery to consumer use

Performance

Research Cells to Predicted Values
Commercial Cells to Research Cells
Prototypes to Commercial Manufacturing
Cells to Modules

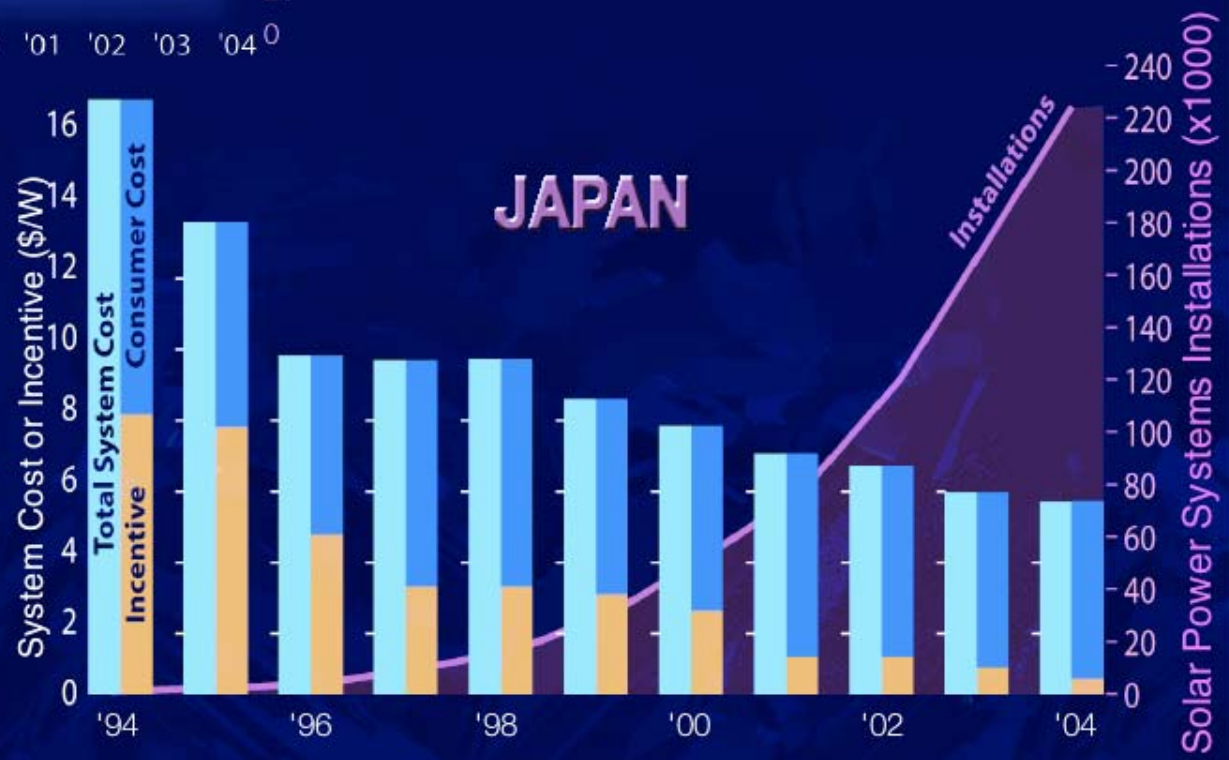


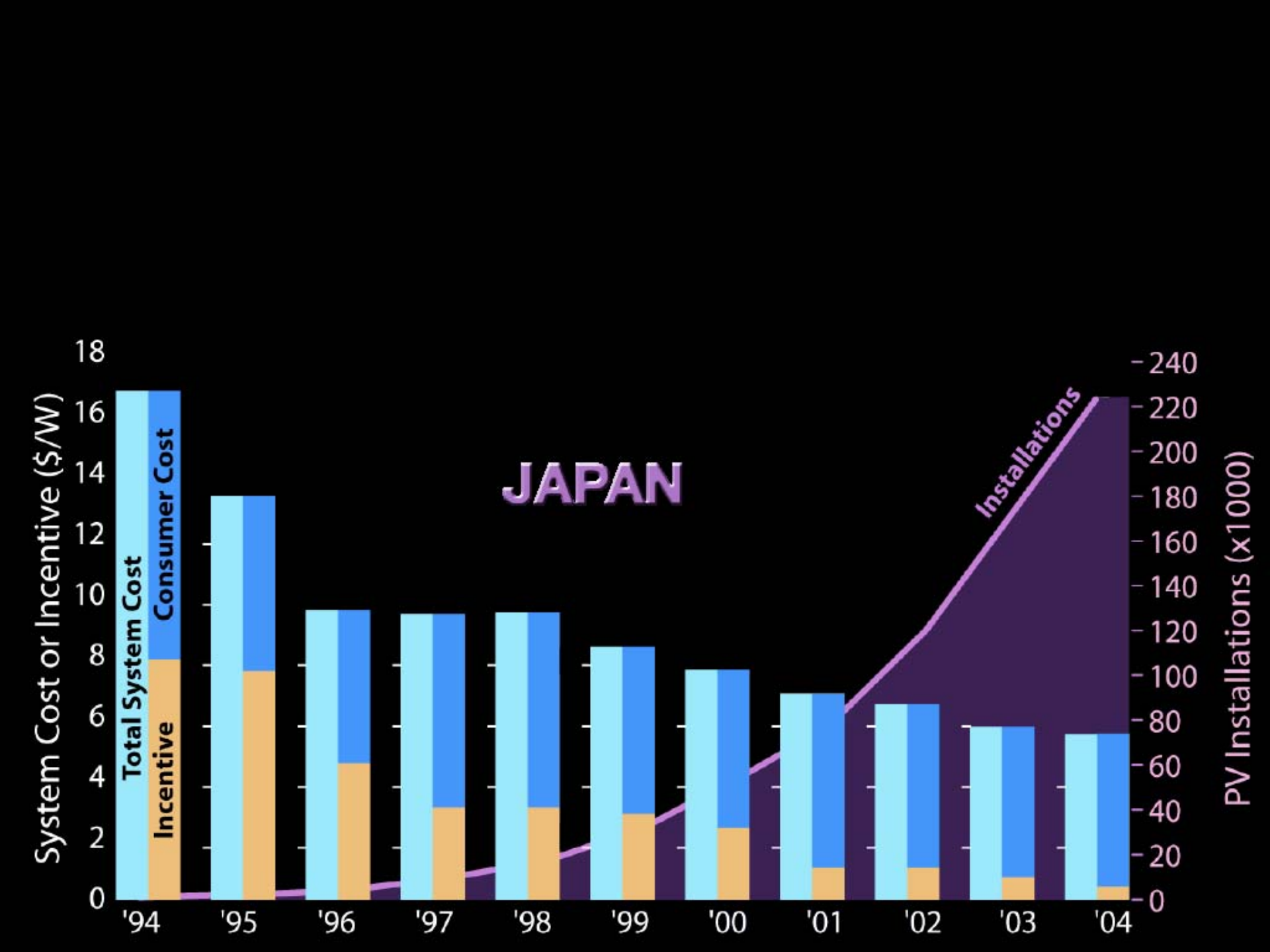
German Feed-In Tarrif Program

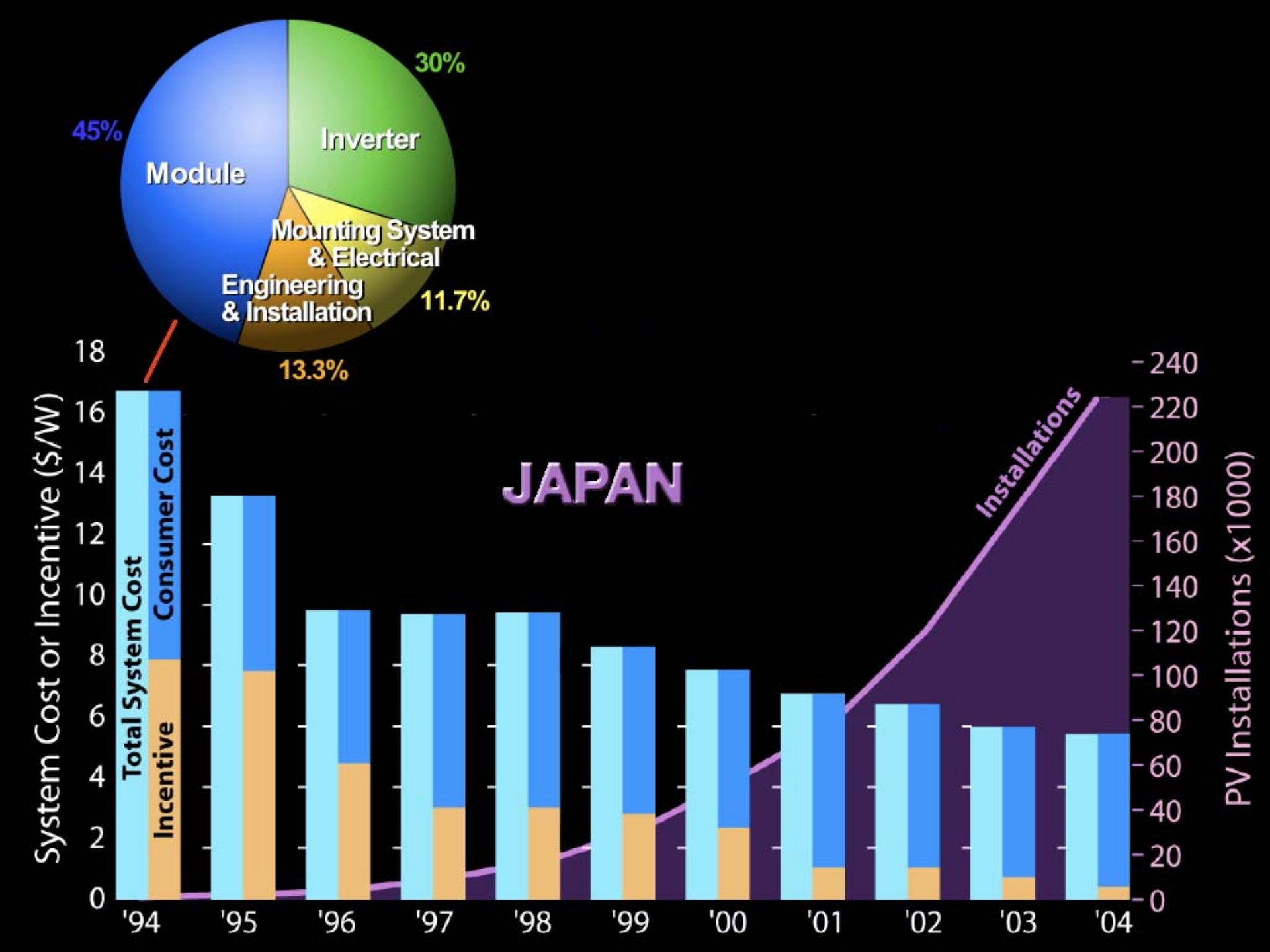
- Pay for kWh produced by PV into grid
- Tariff phase-out:
  Introduction in 2000: *~50 Euro cents for every kWh fed into grid (20 -year guarantee); Price is reduced 5 % every year for subsequent years*
- "100,000 Roofs Program" (provides low-cost loans)
- Result: *20 MW/yr market in 2000;*
  ~ 250 MW/year currently
- Pay? Cost is spread over the entire electricity user rate base—utilities are *not* negatively impacted: no government annual appropriations *(cost to consumer? ~2.5EU/month!)*

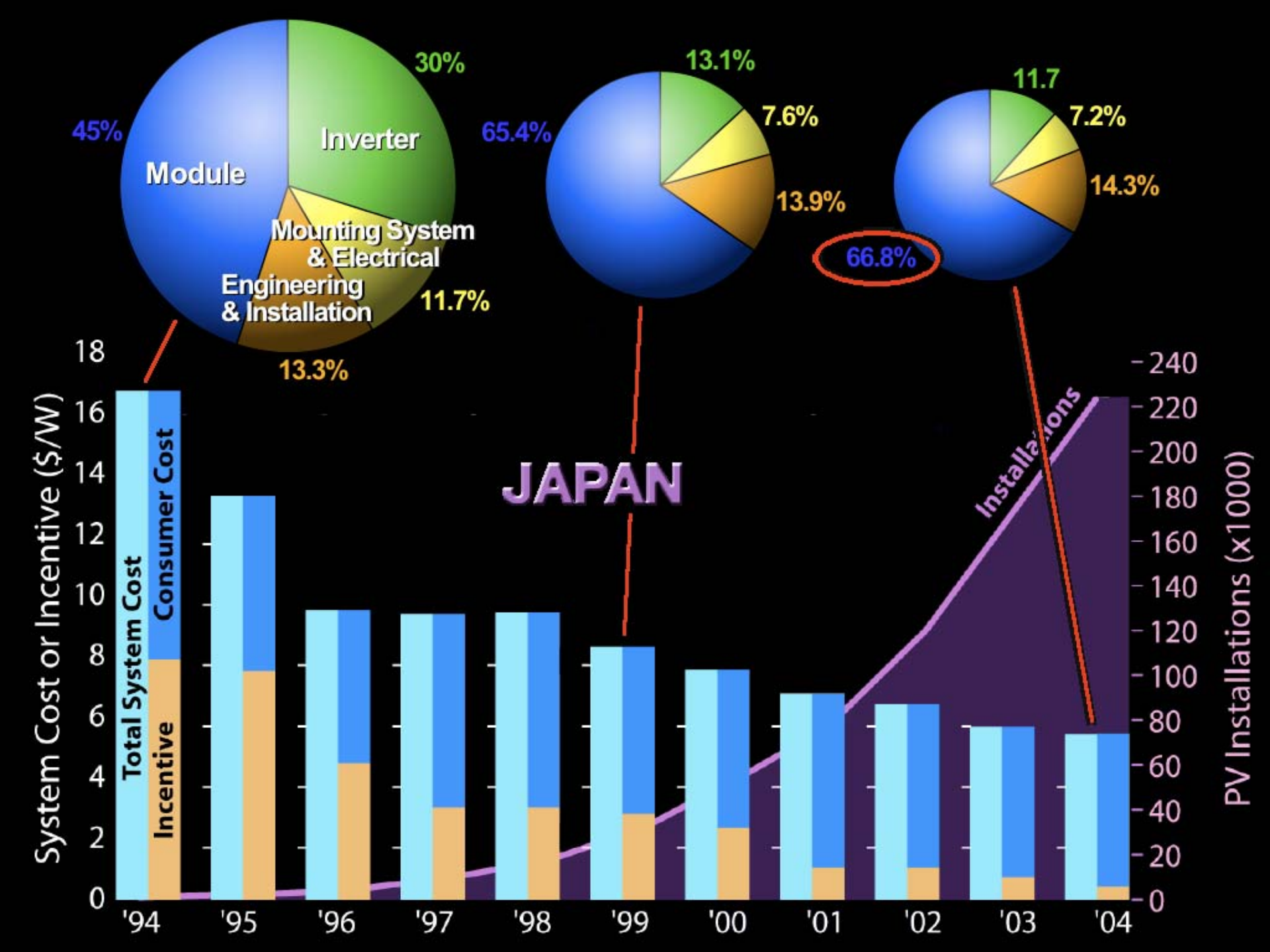
Japan Subsidy Program

- "700,000 Roofs"
- Capital investment buy down
- Subsidy phase-out:
  Introduction: *50% cash subsidy for 3-4 kW grid-connected system*
  Current: *About 7% subsidy this year*
- Result: *500 systems in 1995;*
  230,000 in 2004



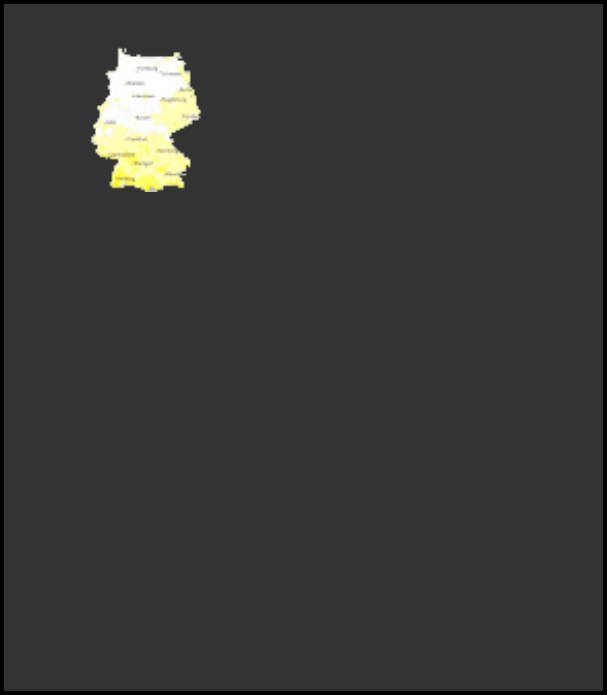

JAPAN
System Cost or Incentive ($/W)
PV Installations (x1000)
Total System Cost
Consumer Cost
Incentive
Installations
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240
'94
'95
'96
'97
'98
'99
'00
'01
'02
'03
'04


30%
45%
Inverter
Module
Mounting System
& Electrical
Engineering
& Installation
11.7%
13.3%
JAPAN
Total System Cost
Consumer Cost
Incentive
Installations
System Cost or Incentive ($/W)
PV Installations (x1000)
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240
'94
'95
'96
'97
'98
'99
'00
'01
'02
'03
'04

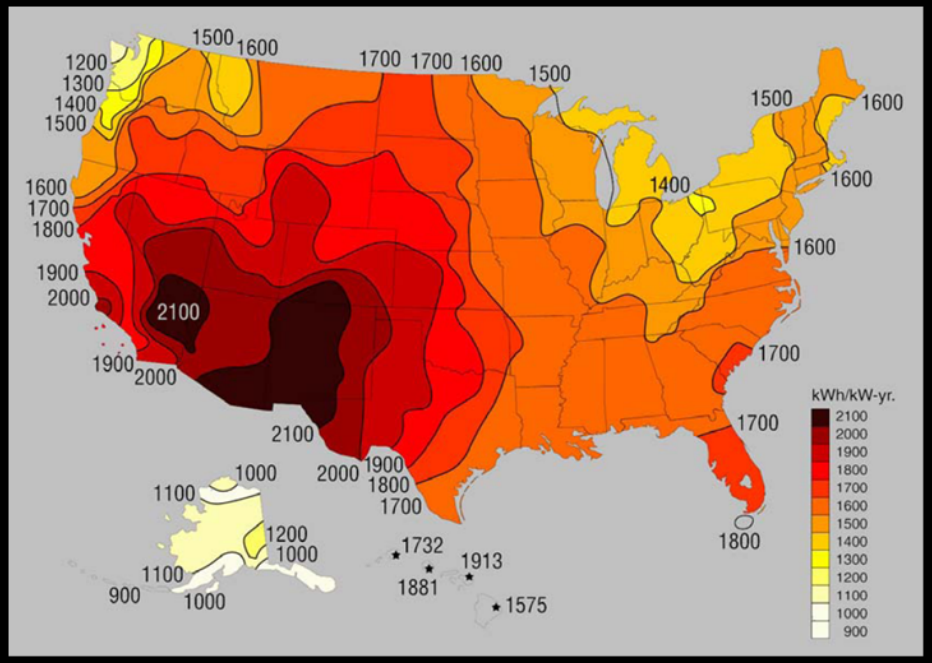

45%
Module
30%
Inverter
Mounting System
& Electrical
Engineering
& Installation
11.7%
13.3%
65.4%
13.1%
7.6%
13.9%
66.8%
11.7
7.2%
14.3%
JAPAN
Total System Cost
Consumer Cost
Incentive
Installations
System Cost or Incentive ($/W)
PV Installations (x1000)
0
2
4
6
8
10
12
14
16
18
0
20
40
60
80
100
120
140
160
180
200
220
240
'94
'95
'96
'97
'98
'99
'00
'01
'02
'03
'04

USA – Looking Good

Germany: 57% world PV



US: 7% world PV



Creating a U.S. Market for Solar Energy, by Rhone Resch, President of the Solar Energy Industries Association.

Challenges in Realizing Solar Electricity

Photovoltaics

Interconnection

- Predictable and reasonable regulations governing interconnection of PV systems are required to assure timely and cost-effective development of PV projects.

Net Metering

- Net metering allows generators interconnected to a utility grid to be compensated for the electricity their PV system produces when it is not used on-site at the time of generation. These provisions are inconsistent across States, and often do not reflect fair market value.

Grid Integration Codes and Standards

- As PV market penetration increases, new codes/standards are needed to maintain grid reliability and economics:
  - Advanced Metering Infrastructure
  - Real-Time Pricing Signals
  - Communications Protocols for DG-Grid Interaction

Concentrating Solar Power

Land Access

- Efficient and predictable permitting processes for use of Federal lands in CSP project development are needed – the current regime is causing protracted timelines and increasing development costs.

Transmission Access

- Development of CSP projects requires construction of new transmission "spurs" and corridors – the current regime does not allow for efficient cost allocation or rapid permitting for new lines.

State CO_2 & RPS Regulations

- Uncertainty about compliance costs for RPS requirements and CO_2 prices introduces complications into power purchase agreement negotiations for CSP project development.

Lack of Long-term Policies and Market Predictability

- PV manufacturers site capacity close to markets, and are reluctant to make major capacity investments in the U.S. while long-term incentive environment is uncertain, inhibiting scale-up and cost reduction.
- Downstream PV companies are even more reluctant to invest in distribution /installation capacity while long-term incentive structures are uncertain.
- Financing for CSP project development can be secured only on the basis of a negotiated off-take contract (PPA) with a utility – uncertainty in long-term incentive environment complicates transactions.

Making Transformational Change

Requires an integrated approach

Unleashing market-driven innovation

FILL technology pipeline

INFORM decision makers about choices

ENSURE appropriate market price signals

National Renewable Energy Laboratory

Innovation for Our Energy Future

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